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USA Dam Removal Experience and Planning

U.S. Department of the Interior

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Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

About this Document

Information about the USA experience with dam removal was requested by Brazil's National Water Agency, Agência Nacional de Águas e Saneamento Básico (ANA). In response, this report has been prepared for dam owners, dam engineers, and other professionals in Brazil who need to evaluate dam removal as a project alternative. Information is provided regarding the U.S. experience with dam removal, reasons for dam removal, and dam removal planning, design, monitoring, and selected case studies.

Cover: Elwha Dam during the beginning of dam removal near Port Angeles, Washington on October 17, 2011. Photograph courtesy of Olympic National Park web camera.

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Acronyms and Abbreviations

°C	Celsius
ANA	*Agência Nacional de Águas e Saneamento Básico*
ASCE	American Society of Civil Engineers
ASDSO	Association of State Dam Safety Officials
BIA	Bureau of Indian Affairs (a Federal agency in DOI)
BLM	Bureau of Land Management (a Federal agency in DOI)
CAW	California American Water
CEQ	Council on Environmental Quality
cm	centimeters
CRRDR	Carmel River Reroute and Dam Removal
CSCC	California State Coastal Conservancy
CWA	Clean Water Act
DOI	U.S. Department of the Interior
DRIP	Dam Removal Information Portal
EA	environmental assessment
EIS	environmental impact statement
EPA	U.S. Environmental Protection Agency
ESA	Endangered Species Act
FEMA	Federal Emergency Management Agency (a Federal agency in the Department of Homeland Security)
FERC	Federal Energy Regulatory Commission (an independent Federal agency in the Department of Energy)
km	kilometer
km2	square kilometer
m	meter
m3	square meter
m/s	meters per second
m3/s	cubic meters per second
Mm3	millions of cubic meters
MDCR-ODS	Massachusetts Department of Conservation and Recreation Office of Dam Safety
NEPA	National Environmental Policy Act
NGO	non-governmental organization
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NRC	National Research Council
NWP	nation-wide permit
PADEP	Pennsylvania Department of Environmental Protection
PCB	polychlorinated biphenyls
PMF	Probable Maximum Flood
Reclamation	Bureau of Reclamation
RFF	Resources for the Future
USA	United States
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USSD	U.S. Society of Dams

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1. Introduction

This report provides information about the United States' (USA), and particularly the Bureau of Reclamation's (Reclamation) experience with dam removal; reasons for dam removal; concepts for dam removal planning, design, and monitoring; and examples from selected case studies. Dam removal planning and evaluation requires consideration of economics, engineering design, hydraulics, sediment transport, and environmental effects. These guidelines are primarily focused on the engineering considerations of design, hydraulics, sediment transport, and the physical environmental effects to the reservoir and stream channel.

Dams provide society with many useful benefits such as surface water diversion; water storage for irrigation, municipal, and industrial use; flood risk reduction; navigation; lake recreation; and hydroelectric power (U.S. Society of Dams [USSD] 2020 [Benefits][1] and ASDSO 2021 [Dams]). Water storage reservoirs can provide society with a more reliable supply of water than a stream with highly variable flows. However, dams can also impact river ecosystems by reducing or preventing fish passage, altering natural stream flows, trapping sediment (clay, silt, sand, and gravel) as well as wood, downstream changes to water temperature, downstream channel degradation, and upstream channel sedimentation (Collier et al. 1996). Dams must also be properly designed to withstand natural hazards and maintained to ensure safe operating conditions that avoid risks to downstream flooding and erosion.

Some common dam safety improvements needed to maintain older dams are to:

- Increase in spillway discharge capacity
- Replace inlet and outlet structures, gates, and valves
- Increase stability of concrete and masonry dams
- Control seepage and piping potential in embankment dams
- Improve erosion control in embankment dams and unlined spillways
- Protect dams from overtopping

Dam removal is sometimes considered to eliminate safety hazards or implement river restoration in response to changing societal preferences and needs. Continued sedimentation from clay, silt, sand, and gravel in large reservoirs reduces storage capacity and project benefits over time (Randle et al. 2019). Less funding may be available to safely maintain dams with diminished project benefits. When the benefits provided by a dam have diminished over time, dam removal may be a less expensive alternative to continued maintenance and repair, or upgrades needed to address new dam safety or environmental concerns. For example, new estimates of risk from potential earthquakes or floods may require work to increase stability for the dam structure or to enlarge a spillway. New environmental requirements for fish passage or water quality may require installing fish passage facilities or temperature control structures. For a few water supply

[1] This document distinguishes references with the same author and year by keyword. See the reference section.

reservoirs, the remaining water storage capacity might now be met with alternative sources or infrastructure.

Dam removal can be a preferred alternative when:

- the cost to safely maintain the dam in an environmentally acceptable condition is more than the cost to remove the dam, or in some cases,
- the environmental benefits from removing the dam and restoring the river are greater than the benefits of maintaining the dam.

From the owner's perspective, dam removal can avoid the future costs of operation and maintenance, capital improvements, and legal liability if the structure failed. From society's perspective, dam removal can have significant economic benefits resulting from restoring stream channels and ecosystems (Loomis 2006 and Headwaters Economics 2016). These economic benefits can take the form of non-use or passive use values (Loomis et al. 2005). Dam removal typically restores a river's natural function including fish passage and habitat. Removing large dams can restore natural stream flow, water temperature, and sediment and wood in the river system. Dam removal can also restore river recreation opportunities, including boat passage, and eliminate drowning deaths associated with people passing over low-head dams (Kern et al. 2015, Hotchkiss and Kern 2018, and Walls 2020). The economic costs and benefits of removing a specific dam should be compared with the costs and benefits of maintaining the dam in a safe and environmentally acceptable condition (Aspen Institute 2002).

USS) defines "dam removal as the full or partial removing an existing dam and its associated facilities such that the statutory definition of a dam is no longer met, or the structure no longer presents a downstream hazard" (USSD 2015). A dam could be partially removed to reduce the reservoir impoundment and loads on the structure. Alternatively, the portion of a dam blocking fish passage could be removed and the remaining structures left behind for historic preservation.

2. Dam Removal in the United States

This chapter describes existing dams' purpose and structure to provide a context for understanding dam removal strategies and considerations. Historical trends are presented that infer future trends. Legal requirements and the institutions involved in dam removal are discussed. Lastly, existing dam removal guidelines and resources are presented.

2.1. Overall Dam Removal Strategies and Considerations

As of 2021, more than 90,000 dams were listed in the National Inventory of Dams (U.S. Army Corps of Engineers [USACE] 2021). Dams listed in this national inventory are classified as either significant or high hazard, depending on the risks posed downstream should they ever fail.[2] In addition, dams in the inventory have to meet both height and storage requirements:

- at least 7.6 meters (m) high with more than 19,000 cubic meters (m^3) of reservoir storage, or
- at least 2 m high with more than 62,000 m^3 of reservoir storage.

There are perhaps several million more smaller dams (including farm pond dams) that are classified as low hazard, which are too small to be included in the National Inventory of Dams (National Research Council [NRC] 1992 and Johnston Associates 1989).

Dams have various purposes as well as differing structural design, and the materials used in their construction (e.g., concrete, compacted earth, rock, steel, and timber). See USSD 2020 (Dam Types) for a listing of dams classified by purpose and construction.

- **Dam purpose:**
  - *Coffer dams* are temporary structures that enclose all or part of a construction site so the area can be dewatered.
  - *Diversion dams* create a reservoir impoundment at a high enough elevation so water can be diverted into a canal, pipeline, or other water course.
  - *Water storage dams* store water during periods of high inflow and downstream release or diversion during periods of low inflow.
  - *Flood control dams* temporarily store flood inflows to reduce the risk of downstream flooding and impacts to people, infrastructure, and property.

[2] In the USA, a dam is classified as "high hazard" if a dam failure would likely result in the loss of life. A dam is classified as "significant hazard "if dam failure would result in significant economic or environmental damages, but no fatalities."

  - *Hydropower dams* use the difference in water surface elevation (hydraulic head) between the reservoir impoundment and downstream channel to turn a turbine which generates electricity.
  - *Multipurpose dams* may provide more than one benefit such as water storage, recreation, flood risk reduction, and hydropower.
  - *Sediment retention dams* trap the inflowing sediments within the reservoir impoundment. Typically, the trapped sediments have to be periodically removed from the impoundment to maintain the sediment trap efficiency.
  - *Mine tailings dams* store byproducts from mining operations after separating the ore from the worthless rock or mineral. Tailings can be liquid, solid, or a slurry of fine particles, and are usually highly toxic and potentially radioactive.
  - *Industrial waste dams* store industrial waste products.
- **Structural design and material:**
  - *Embankment dams* are constructed with natural earth materials (e.g., earth dam, hydraulic fill dam, rockfill dam) or of industrial waste materials.
  - *Gravity dams* are typically constructed of concrete or masonry and achieves stability from sliding or overturning by its own weight.
  - *Arch dams* are typically constructed of concrete or masonry and are curved upstream to transfer the loads from the reservoir to the abutments.
  - *Buttress dams* are typically constructed of reinforced concrete. They are composed of an upstream part that has a watertight seal and supported on the downstream side by a series of buttresses, which could be multiple arches.

Different strategies are required for removing dams based on their purpose, structural design, reservoir size, and the materials trapped within the reservoir. If the dam is still serving a useful purpose, then developing either water management strategies one or more replacement structures might be needed to continue to serve that purpose. For example:

- Coffer dams are temporary structures commonly removed after the end of in-river construction activities. If streambanks are disturbed during construction activities, then streambank protection may be needed before removing the coffer dam.
- Diversion dams could be replaced by pumping plants or infiltration galleries.
- Water storage dams may require storing water at another location.
- Flood control dams may require downstream flood easements or levees.
- Hydroelectric dams may require developing additional power sources to replace the power generated.

Reservoir sediments might be released to the downstream channel during and after dam removal. However, contaminated sediments, mine tailings, or industrial waste would have to be stabilized or removed and relocated prior to dam removal.

Draining the reservoir and caring for stream flows are important considerations during dam removal. Many low-head dams have low-level gates that can be used to drain the reservoir during low stream flows. Outlets to larger dams are typically meters above the original streambed and cannot be used to completely drain the reservoir. Constructing new diversion channels or tunnels may be necessary to drain the reservoirs and manage stream flows. In some cases, diversion channels or tunnels through the dam or abutment may need to be constructed.

Concrete dams tend to be more stable during removal than earth dams. Removing larger structures may require using a crane. Constructing coffer dams may be required during some dam removals—especially if new structures are built in wetted areas.

2.2. Dam Removal Trends

In the USA, dam removals have been increasing since 1980 (Figure 1) while dam construction has significantly slowed because there are already dams on virtually every river in the 48 conterminous states (states that share a common boundary) (Collier et al. 1996, O'Connor et al. 2015). Despite the increasing trend, the total number of dams removed is still relatively small, less than 1 percent, of the total number of dams present in the USA.

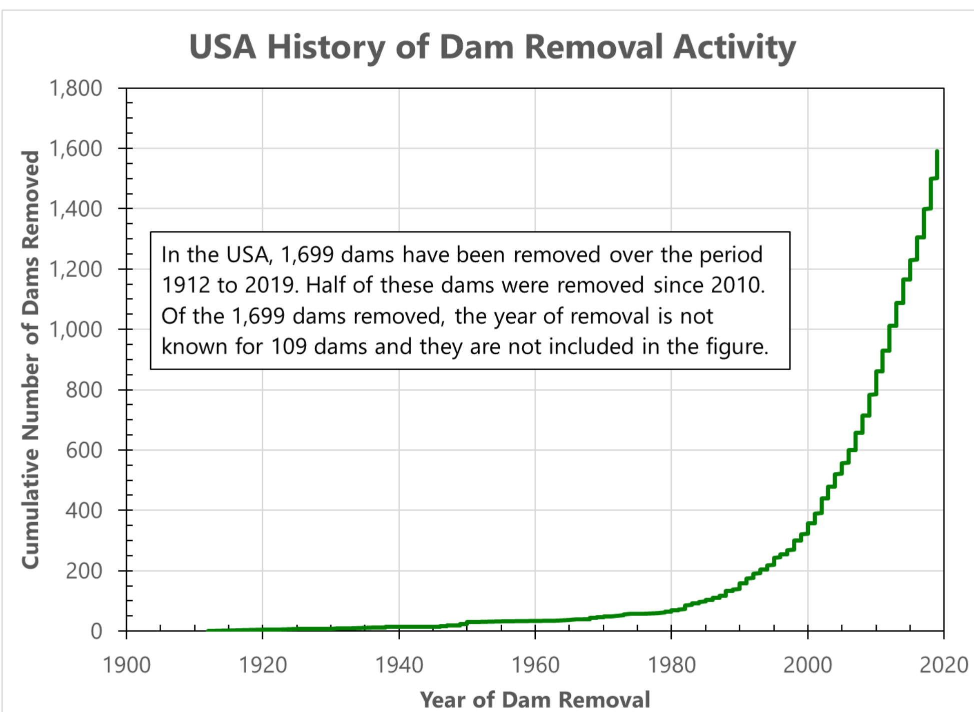

Figure 1. Cumulative number of dams removed in the USA (data source, American Rivers, 2019).

American Rivers, a non-profit organization in the United States, maintains a database of all dam removal locations. American Rivers (2021 [Database]) reports that 1,768 dams have been removed over the period 1912 to 2020 and half of these dams were removed after 2010. As of 2020, half of all dams removed in the USA were from five states: Pennsylvania (20.6%), California (10.5%), Wisconsin (8.3%), Michigan (5.7%), and Ohio (5.0%) (Figure 2).

As of 2020, the tallest dam removed was the 64-m high Glines Canyon Dam on the Elwha River near Port Angeles, Washington. Elwha Dam, Washington was 32 m high and was removed from the same river around the same time (Warrick et al. 2015). Condit Dam was 38 m high and removed from the White Salmon River in Washington State.

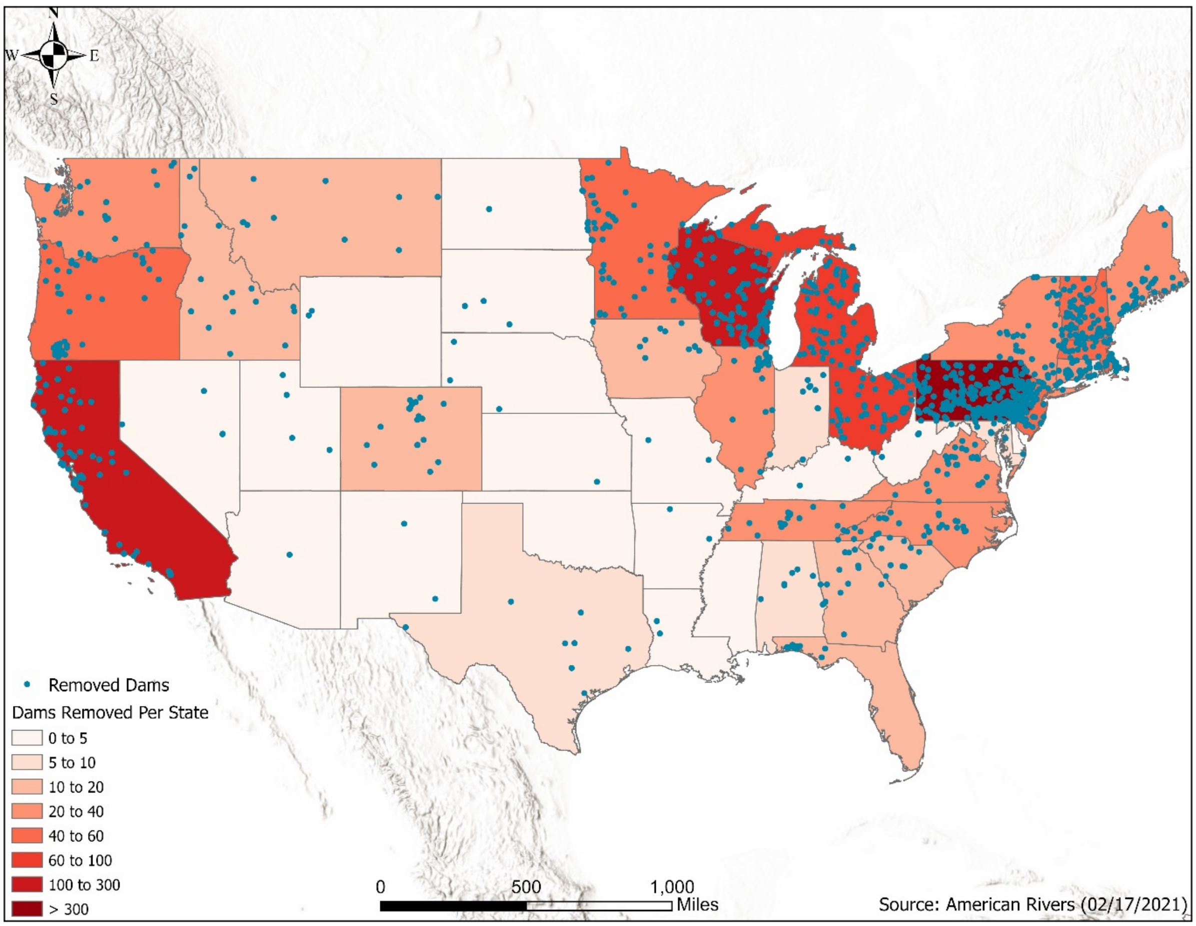

Figure 2. Locations of USA dam removal reported by American Rivers (2020).

O'Connor, et al. (2015) reviewed published studies from about 100 USA dam removals and at least 26 dam removals outside of the USA. A major finding of their review was "that rivers are resilient, with many responding quickly to dam removal. Most river channels stabilize within months or years, not decades."

Nearly all types of dams have been removed. However, nearly half of the dams removed were less than 6 m high (Figure 3). Of the dams removed, Habel et al. (2020) reports that "28% were used to produce electric energy, 22% for recreation, 14% for freshwater supply, 13% for mining, 7% for mills and sawmills, and 16% for miscellaneous purposes." However, dams in the American Rivers dam removal database have only been classified by their construction materials and data are only available for about 40 percent of the dams removed. For the 40 percent that have data reported, about half the dams were constructed of concrete, about one-fourth constructed of earth materials, about one-fifth were constructed of rock or masonry, and a small portion were constructed of timber.

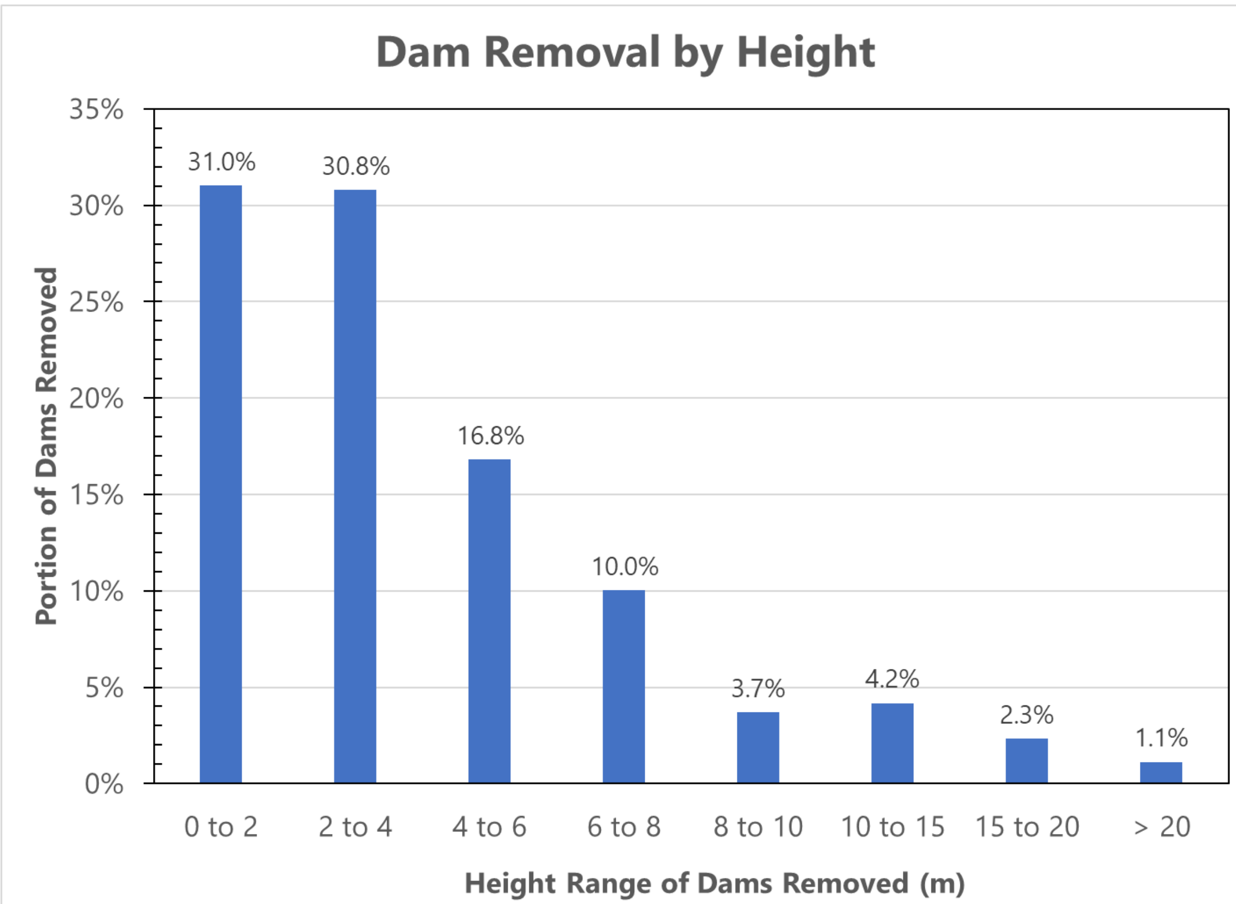

Figure 3. Distribution of dam removals by reported dam height.

Policies, funding strategies, and collaborative partnerships have made it easier to remove dams. Walls (2020) identified policies of some states the result in a greater number of dam removals:

- Strict enforcement of dam safety regulations
- Dam safety program engagement with dam owners that includes a discussion of dam removal
- State dam safety staff collaborate with staff from environmental and natural resource agencies

- Non-governmental organizations (NGO) actively advocate for and work on dam removal
- State funding to assist with dam removal
- Streamlined permitting process for dam removal

2.3. Legal Dam Removal Requirements

Dam removals in the United States are subject to Federal, state, and local laws and regulations. There is consistency in the implementation of Federal regulations, but the implementation of state and local regulations does vary. The Association of Dam Safety Officials (ASDSO) provides a list of state regulations (ASDSO 2020).

2.3.1. Dam Safety Inspections

For non-Federal dams, state dam safety officials in the United States are empowered to inspect and authorize emergency repairs of a dam or removing the structure if necessary for the protection of life and property. Most state dam safety programs follow guidance from the Federal Emergency Management Agency (FEMA) and ASDSO. Each state establishes jurisdictional authority for dams that have at least a certain height (generally 3 to 7.6 m) and storage capacity (generally 19,000 to 62,000 m^3). Most states follow the ASDSO four-level classification system for condition ratings: satisfactory, fair, poor, and unsatisfactory. However, the dam condition ratings are often not assigned to low-hazard dams (Walls 2020).

2.3.2. Hydropower Licensing

The Federal Energy Regulatory Commission (FERC) has jurisdictional authority over non-Federal hydropower dams and can require removing dams that are not safe or no longer economically viable (USSD 2015). In addition, if the dam's environmental impacts would threaten the continued existence of endangered species, Federal agencies are not allowed to take actions at hydropower dams such as approving or renewing permits for that dam.

Licenses for hydroelectric dams must seek a relicense from FERC every 50 years. During this process, FERC may consider dam removal as an alternative to relicensing the dam. FERC licensing processes have changed in the last few decades to consider the dam's condition, community perception, compliance with regulations, and whether it is fulfilling its current purposes. As Drechsler (2021) notes, "The notion that dam decommissioning is a viable alternative to the renewal of a license has progressed recently." For example, FERC has recently transferred licenses to four dams on the Klamath River in Oregon from PacifiCorp, the power company, to the Klamath River Renewal Corporation and the states of Oregon and California. This license surrender clears the way to remove the dams and restore the river. These four dams had been built before modern regulations for fish passage (Active Norcal 2021).

2.3.3. Dam Removal Permits

USA permits for dam removal are managed by Federal and state regulatory agencies. USACE may approve two types of permits for dam removal:

- Clean Water Act (CWA) Section 404 Dredge and Fill Permit. The permit for dam removal can be issued if the dam removal meets these project conditions:

a) Should not cause or contribute to significant degradation of the waters or result in a net loss of wetlands. In cases where a dam removal will result in a net loss of wetlands, there must be a finding that the environmental benefits of dam removal outweigh the loss of wetlands.

b) Should be designed to have minimal adverse impact.

c) Should not have any practicable alternatives.

d) Should be in the public interest.

- Rivers and Harbors Act Permit. A permit may be issued if the dam removal would not have an adverse impact on interstate stream navigation.

USACE (2017) established Nationwide Permit (NWP) 53 to remove low-head dams. "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 this NWP. 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."

The USSD Guidelines for Dam Decommissioning Projects (2015) describes the possible need for a variety of other permits for actions affecting endangered species, air quality, dam safety, waterways, Indian Tribes, and roadways:

- Under the Endangered Species Act, U.S. Fish and Wildlife Service (USFWS) and/or National Oceanic and Atmospheric Administration (NOAA) Fisheries are charged with making determinations (biological opinions) on whether or not proposed actions would impact the continued existence of threatened or endangered species.

- Under the Clean Air Act, the U.S. Environmental Protection Agency (EPA) oversees permits related to air quality, which could be affected by construction activities and exposed reservoir sedimentation.

- For dam safety, the state water resource agency having regulatory authority over dams will typically require a permit to modify or remove a dam.

- Proposed actions affecting Indian Tribal interests, including fishing rights, cultural resources, and traditional cultural properties will involve the affected Tribal governments and the Bureau of Indian Affairs (BIA).

- Any potential impacts to roadways or bridges spanning the dam or reservoir impoundment area may require permits from government landowners (Federal, state, county, or municipal agencies) or permission from railroad companies.

- County governments may require a demolition permit and regulate the transportation and disposal of waste materials within their jurisdiction.

In addition to permits from Federal agencies, permits from state agencies must also be obtained. Each state may require additional permits and they have their own procedures and processes. For example, the State of Oregon may issue permits from:

- Oregon Department of Fish and Wildlife, Endangered Species Act (ESA) permits
- Oregon Department of Environmental Quality, 401 permit
- Oregon Department of State Lands, in-water fill/excavation permit
- Oregon Watershed Enhancement Board

State permits may include:

- A water quality permit
- Changes to the stream channel may require a permit from the state fish and wildlife agency. For example, changes to a stream channel in the State of California would require a streambed alteration permit (Section 1602) from the California Department of Fish and Wildlife.

2.3.4. National Environmental Policy Act

For more information, see Reclamation's *NEPA Handbook* (2012).

Actions taken by Federal agencies, including granting permits, are subject to the National Environmental Policy Act (NEPA) which requires some level of public notice and opportunities for public involvement and may require preparation of an environmental assessment or environmental impact statement. An environmental assessment is adequate if there is a finding of no significant impact. However, an environmental impact statement would be required if there would be significant environmental impacts or significant controversy regarding the Federal action—regardless of the project's size or dam height.

NEPA's primary purpose is to ensure that environmental considerations are evaluated at a comparable level with other considerations in the decision-making process undertaken by Federal agencies (Reclamation 2012 and USSD 2015). NEPA requires "all agencies of the Federal Government" to prepare an environmental impact statement (EIS) before authorizing any "major Federal action significantly affecting the quality of the human environment" (United States Code 2006). The major Federal action applies to the implementation of Federal projects or approval of permits for non-Federal projects.

An environmental assessment (EA) could be prepared first to determine if there will be significant impacts. An EA results in either a finding of no significant impact or a finding that an EIS must be prepared to further investigate the potential for significant impacts. The EA or EIS documents disclose the potential environmental effects of proposed Federal agency actions. Preparing an EA is less onerous than an EIS. The amount of effort to prepare an EIS or EA increases with the project complexity, degree of impacts or environmental consequences, and degree of public concern. The degree of impacts for a dam removal would generally increase with reservoir size, but more importantly with the ratio of reservoir sediment volume to the river's mean annual sediment load. A simple project with public support and small or moderate impacts will take much less time (months) and effort than a complex project with significant impacts and public opposition (years).

These environmental compliance documents follow the outline for good planning, as described in Section 4. *Dam Removal Planning.* An EIS or EA begins with a description of the purpose and need for Federal action. The next chapter is a description of the alternatives and a summary of the environmental consequences, which is the heart of the EIS or EA. Subsequent chapters include a description of the affected environment, a more detailed description of environmental consequences, and a description of public involvement, consultation, and coordination (Reclamation 2012).

The description of the affected environment includes the existing environmental and regulatory settings, the applicable laws, regulations, permits, and policies associated with each resource. The chapter on the affected environment should not be exhaustive but provide important context for subsequent descriptions of environmental impacts or consequences. The chapter on environmental consequences of reasonable alternatives (including any proposed action) should be presented in comparative form to provide a clear basis for choice among the alternatives by the decision maker and by the public about whether to proceed with a proposed action or project. The environmental consequences should include the identification of any adverse environmental effects, or any irreversible and irretrievable commitments of resources, which cannot be avoided should an alternative be implemented. In addition, the EIS should present the relationship between the "short-term uses of the environment and the maintenance and enhancement of long-term productivity" (Reclamation 2012).

Public involvement is an important, and required, component of the NEPA process and with other regulatory processes pertaining to dam removal (USSD 2015). In the NEPA process, the project purpose is presented to the public and scoping is used to gather their input, including their issues and concerns. The public input is combined with the technical input from federal agencies to determine the scope of issues to be addressed in the EIS. In addition, public participation is normally encouraged throughout the development of the EIS.

NEPA requires that the EIS present the environmental consequences of each alternative to a wide range of potentially affected resources, compared with the "No Action Alternative" (Reclamation 2012 and USSD 2015). The "No Action" alternative is commonly used as the baseline for determining the significance of the environmental impacts. Under this alternative, the existing dam is assumed to remain in place without added dam safety or environmental improvements. A description of the environmental consequences includes an assessment of impacts, including any lost project benefits. Resource mitigation should be incorporated directly into each alternative. Under NEPA, the significance of an impact generally relies upon professional judgment, considering the context of the environment where the impact would occur.

Cumulative environmental impacts must also be described, which result from the incremental impacts of an alternative when added to other past, present, and reasonably foreseeable future actions. Cumulative impacts can result from individually minor, but collectively significant actions taking place over a period of years or decades.

"The purpose of an EIS is not to recommend approval or rejection of a project, but to provide information to aid the public and permitting agencies in the decision-making process. The decision-making process for a major Federal action under NEPA, such as for a dam decommissioning project, would include the following steps: (USSD 2015):

- Issuance of a Notice of Intent for preparation of the EIS.
- Public scoping for the EIS and receipt of public and agency comments.
- Preparation of a draft EIS for the proposed action and range of alternatives.
- Issuance of a Notice of Availability of the draft EIS, and circulation of the draft EIS for a minimum 60-day public and agency review and comment period.
- Preparation of a final EIS (including responses to all comments received) and identification of the recommended project alternative (Proposed Action, or preferred alternative).
- Filing of the final EIS with the EPA and publication of the Notice of Availability of the final EIS in the Federal Register.
- Final EIS 30-day no-action period.
- Filing of a Federal Record of Decision regarding the project alternative to be implemented, or Proposed Action."

Following this process, the responsible Federal, state, and local decision makers must then decide whether or not to approve, authorize, and/or appropriate funding for implementation of the Proposed Action (Reclamation 2012 and USSD 2015). The entire NEPA process can take many months to years, depending on the degree of environmental consequences and the degree of public concern.

For example, removing two large dams on the Elwha River, near Port Angeles, Washington (Glines Canyon Dam and Elwha Dam), the entire NEPA process involved three EISs and took a couple of decades (USSD 2015 and Hepler 2013). In contrast, a small dam decommissioning project, not requiring an EIS, may be completed in much less time (USSD 2015) as Helper (2020) relates: "Saeltzer Dam in California was removed in 2000, requiring only 9 months from the start of design, through preparation and approval of the EA and associated Federal and state permits, to project completion and site restoration. . . Removing the 6-m-high concrete gravity dam had strong local, state, and Federal support, with no local opposition, and was performed by a small business contractor under a design-build contract with the Bureau of Reclamation."

Based on a comparison of the environmental impacts for each of the action alternatives, the environmentally preferred alternative should be identified by the Federal lead agency in the final EIS and record of decision (Reclamation 2012 and USSD 2015). The environmentally preferred alternative refers to the alternative that causes the least damage to the physical environment or the alternative that best protects, preserves, and enhances historic, cultural, and natural resources. The Federal lead agency is not obligated to select the environmentally preferred alternative as the Proposed Action.

2.3.5. National Historic Preservation Act

The National Historic Preservation Act requires protecting cultural resources and preserving or documenting historic properties, including the dam itself if eligible for the National Register of Historic Places.

Federal legislation would be needed to authorize the removing a federally-owned dam. In one case, a Federal law was passed to authorize the purchase and remove two privately owned dams. In 1992, U.S. Congress passed the Elwha River Ecosystem and Fisheries Restoration Act, which authorized the Secretary of the Interior to purchase and remove two large dams on the Elwha River (Glines Canyon Dam and Elwha Dam) if the Secretary determined that removing the dams was necessary for full restoration of the Elwha River ecosystem and fisheries (U.S. Congress, 1992).

2.4. Institutions Involved in Removal

Federal agencies are responsible for the proper operation and maintenance of dams that are owned by the agency or that are under its jurisdiction (USSD 2015). The *Federal Guidelines for Dam Safety* (FEMA 2004) apply to the management practices for dam safety of all Federal agencies responsible for planning, designing, constructing, operating, regulating, and removing dams. State dam safety offices regulate approximately 80 percent of the 90,000 dams listed in the National Inventory of Dams, and establish their own regulations.

Many dam removals involve Federal and state agencies to provide technical designs or funding. The Pennsylvania Fish and Boat Commission has assisted in the design, permitting, and funding for tens of dam removals in the State of Pennsylvania. Many states have natural resource programs that provide an opportunity to apply for dam removal funding when related to dam safety concerns or improving environmental benefits. Reclamation has performed the environmental analysis and project design for a few dam removals where there was a Federal interest. Many dam removals have been at least partially financed by the USFWS' National Fish Passage Program, NOAA's grant programs that focus on threatened and endangered species, or the National Fish and Wildlife Foundation (Walls 2020).

In addition to the Federal and state agencies that regulate dam safety and issues permits, various organizations and consultants may assist with dam removal. Many American citizens support river restoration and provide contributions to NGOs) that promote river restoration, including dam removal. Many of the NGOs advocating dam removal have focused on habitat restoration and fish passage (Walls 2020). Several geographic information system tools have been developed by NGOs to help prioritize dam removals to achieve fish passage outcomes. "One of the most active NGOs in raising money for dam removal (and fish passage projects generally) is Trout Unlimited" (Walls 2020).

American Rivers (2021 [Restoration]) has provided technical assistance for dam removals throughout the United States as a non-governmental organization. In addition, private consulting companies provide technical analysis, design, and project management for dam removals throughout the country.

Resources for the Future (RFF) is another non-profit in the United States with a mission focused on improving "environmental, energy, and natural resource decisions through impartial economic research and policy engagement" (RFF 2021). RFF has several publications on their website about how to fund dam removal projects through available governmental programs and how dam removal relates to dam safety in the United States.

The Open Rivers Fund was established in November 2016 with support from the William and Flora Hewlett Foundation as part of a public charity titled "Resources Legacy Fund." The Open Rivers Fund is focused on partnering with local communities to remove obsolete dams, modernize infrastructure, and restore rivers across the Western United States. The approach to select dams for removal is noted as "an assessment of resources, potential partners, challenges, and expected economic, community, and ecological benefits" (Open Rivers Fund 2021).

2.5. Existing Dam Removal Guidelines and Resources

Several guidelines and publications for dam removal have been prepared by professional organizations, state agencies, and non-governmental organizations. Publications related to the general aspects of dam decommissioning or removal include:

- *Removing Small Dams–A Basic Guide for Project Managers* (American River 2015)
- *Exploring Dam Removal* (American Rivers and Trout Unlimited 2002)
- *Guidelines for Dam Decommissionin*g (American Society of Civil Engineers [ASCE] 1997 [Decommissioning])
- *Dam Removal - A New Option for a New Century* (Aspen Institute 2002) focuses on policy decisions related to dam removal
- *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)
- *Weir removal, lowering and modification: A review of best practice* (Elbourne et al. 2013)
- *Frequently Asked Questions on Removing Obsolete Dam*s (EPA 2016)
- *Dam Removal: Science and Decision Making* (Heinz III Center for Science, Economics & The Environment 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* (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
- *Summary of Existing Research on Low-head Dam Removal Project*s, prepared for American Association of State Highway and Transportation Officials (ICF Consulting 2005)
- *Reservoir Sedimentation Handbook*, Chapter 17–Decommissioning of Dams (Morris and Fan 1997)
- *Dam Decommissioning Chapter of the Erosion and Sedimentation Manual* (Reclamation 2006)
- *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 Regulatory Guidance Letter 05-04 (USACE 2005):
- *Nationwide Permit 53* Department of the Army Corps of Engineers Final Notice of Issuance and Modification of Nationwide Permits. Federal Register. Authorized March 19, 2017.Permit for removing low-head dams (USACE 2017) includes dam removal analysis guidelines for sediment.
- *Guidelines for Dam Decommissioning Projects* (USSD 2015) provides an overview of the engineering aspects of dam removal based on information from numerous case studies.

Several state guidelines for dam removal projects are also available, including:

- Massachusetts *Dam Removal and the Wetland Regulations* (Massachusetts Department of Environmental Protection 2007)
- *Dam Removal in Massachusetts - A Basic Guide for Project Proponents* (The Commonwealth of Massachusetts Executive Office of Energy and Environmental Affairs 2007)
- *Michigan Dam Removal Guidelines for Owners* (Michigan Department of Natural Resources 2004)
- *Guidelines to the Regulatory Requirements for Dam Removal Projects in New Hampshire* (New Hampshire Department of Environmental Services, Revised 2018)
- *Draft Evaluation of Sediment Quality Guidance Docum*ent (New Hampshire Department of Environmental Services 2005)
- *Aquatic Connectivity and Barrier Removal: Restoring Free-Flowing Rivers in the Hudson River Watershed* (New York State Department of Environmental Conservation 2021)
- *Texas Dam Removal Guidelines* (Texas Commission on Environmental Quality September 2006)

- *Dam Removal: A Citizen's Guide to Restoring Rivers*. (River Alliance of Wisconsin and Trout Unlimited, 2017)

Other assistance is available, including:

- FEMA Dam Safety Grants to provide financial assistance to the states for strengthening their dam safety programs (https://www.fema.gov/emergency-managers/risk-management/dam-safety/grants).
- The United States Geological Survey, John Wesley Powell Center for Analysis and Synthesis sponsored workshops to synthesis the ecological and physical responses from dam removal: https://www.usgs.gov/centers/powell-ctr/science/dam-removal-synthesis-ecological-and-physical-responses?qt-science_center_objects=0#qt-science_center_objects. Several publications were produced as a result of this workshop: O'Connor and East 2014, Bellmore et al. 2015, O'Connor et al. 2015, Bellmore et al. 2016, Magilligan et al. 2016, Tullos et al. 2016, Collins et al. 2017, Foley et al. 2017 (Listening), Foley et al. 2017 (Context), Major et al. 2017, and Bellmore et al. 2019.

In addition, databases of dam removal project have been developed that provide case study information:

1. American Rivers Dam Removal Database contains some information on nearly 1,700 dam removals (http://www.americanrivers.org/DamRemovalDatabase) (American Rivers, 2021b)
2. Dam Removal Information Portal (DRIP) is a tool to explore trends about dam removal science and query scientific studies that evaluate environmental response to dam removals (https://www.sciencebase.gov/drip/) (Duda et al. 2016).
3. Clearinghouse for Dam Removal Information: Database hosted by the University of California at Riverside (Capelli 2017) provides dam removal project metadata (https://calisphere.org/collections/26143/).

3. Reasons for Dam Removal

Dam removal is considered when a problem has been identified with public safety, fish passage, environmental impacts, or the project economics (USSD 2015). Dams of all sizes have been removed for dam safety and environmental reasons, which include the restoration of fish passage, water quality, and the natural transport of sediment and wood. Some states have additional programs to focus on safety and environmental issues: Pennsylvania, Massachusetts, Ohio, and Wisconsin (Walls 2020). By the end of the 20th century, dams in the United States were removed primarily for environmental, dam safety, and economic reasons, in that order (Pohl 2002). Available data suggested that the primary reason for dam removal shifted from the alleviation of dam safety concerns in the 1980s to environmental restoration by the 1990s. Removing dams to alleviate safety concerns often occurred when the dams were not well maintained or were abandoned (USSD 2015). Public participation has played an increasingly important role in dam removal. As Drechsler (2021) notes, "Currently, the issue of dam removal is primarily negotiated through settlements and is an intricate combination of local, state, and national interests."

3.1. Original Dam Purpose

Dams that no longer serve their original project purposes may be candidates for removal, particularly if they pose a dam safety risk or if their removal could benefit the environment.

A 2019 survey in New Hampshire, an eastern state with dams built in the 1800s for power generation for textile mills, showed that most respondents preferred to remove dams that were no longer serving their original purpose such as hydropower—and when the alternative to dam removal was to keep the dam to preserve property values, history, or recreation. Most respondents prefer to keep dams when dams are still being used for hydropower (Diessner 2019). Two such dams that had outlived their hydropower purposes and that did not meet modern safety standards, the Upper and Lower Sawyer Mill Dams, were removed in 2021 (NOAA Fisheries 2021 [Sawyer]).

3.2. Dam Safety

Dam failures can result in loss of life and large damages to downstream property, infrastructure, and habitat. Therefore, dam safety programs often tend to focus on the risks of dam failure and downstream flood damages—especially for high hazard dams. Walls (2020) notes that while dam removal is an option, most USA dam safety programs promote repairs and upgrades to safely maintain dams.

Dam safety deficiencies may vary from emergency items where immediate action is required to non-emergency items which must be corrected in a timely manner but that do not present an immediate danger. Deficient dams may fail as a result of large floods, earthquakes, progressive deterioration, or lack of maintenance. According to American Rivers Dam Removal Database, the number of deficient high-hazard potential dams now exceeds 2,300.

Perera et al. (2021) reports that while many public safety incidents occurred within the first five years of a dam's operation, a considerable number of failures occurred in dams over 50 years old (Foster et al. 2000 and Zhang et al. 2009). Older dams combined with poor maintenance represent a higher risk to public safety, particularly for downstream areas. Perera et al. (2021) evaluated ASDSO database (ASDSO 2021 [Incidents]) on dam incidents and found that over 75 percent of dam failures in the USA occurred after the dam was older than 50 years.

3.3. Environmental Restoration

Dam removal restores some of the natural conditions of a river segment and provides a wide range of environmental benefits, including improved aquatic habitat and fish passage. According to Walls (2020), “Improving fish habitat and fish passage is the biggest driving force behind the efforts to remove dams.” For example, the Glines Canyon Dam and Elwha Dam on the Elwha River were removed during 2011-2014 to help restore ecosystem and native anadromous fisheries. This effort required an Act of Congress (*Elwha River Ecosystem and Fisheries Restoration Act -- Public Law 102-495*), involved multiple agencies, and took a few decades to complete. The reports are listed at https://www.nps.gov/olym/learn/nature/elwha-restoration-docs.htm (NPS 2021). Dams have contributed to significant declines in anadromous fish populations on in coastal streams in both the eastern and western coastlines in the U.S. (NOAA 2015, Columbia Riverkeeper 2018, Virginia Department of Wildlife Resources 2020, and Walls 2020). In addition, dams can block the migration of trout and other freshwater species (Walls 2020 and Williams et al. 2015).

3.4. Reservoir Sedimentation

Reservoir sedimentation will increasingly become a reason to remove large water storage dams. For example, San Clemente Dam near Carmel, California was removed in 2015 after the reservoir had filled with sediment (Harrison et al. 2018). Matilija Dam near Ventura, California has also filled with sediment and plans for dam removal are underway (Ventura County Public Works Agency 2021).

Low-head dams, for example surface water diversion dams, were typically constructed with sluice gates to pass inflowing sediments downstream. These low-head dams typically filled with sediment to some equilibrium level within the first few years of operation (Randle and Bountry 2017). However, almost all large water storage reservoirs in the U.S. were designed and constructed so that the dam outlets would be above the sedimentation level during their sediment design life, typically 50 or 100 years. The constructed height of the dam outlet, above the original streambed, was a function of the expected reservoir sedimentation rate and spatial distribution. The greater the expected sedimentation rate, the greater the height of the dam outlet above the original streambed. For example, the outlet for Paonia Reservoir in Colorado was constructed 21 m above the streambed to provide a 50-year sediment design life (Figure 4). After 50 years of operation, 25 percent of the reservoir storage capacity had filled with sediment, and the outlet became plugged with sediment and woody debris (Figure 5 and Figure 6) (Randle et al. 2019).

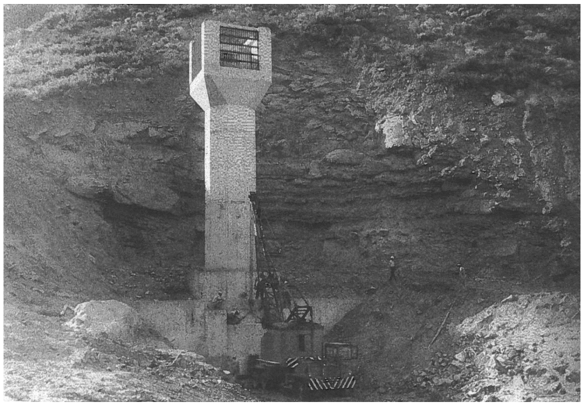

Figure 4. The outlet for Paonia Dam, near Paonia, Colorado, was constructed 21 m above the valley bottom in July 1961.

Figure 5. By November 2014, sedimentation and woody debris began to plug the dam outlet.

Figure 6. By 2014, reservoir sedimentation had filled 25 percent of the storage capacity and plugged the dam outlet at Paonia Reservoir in Colorado.

Emergency sediment removal will become necessary after a dam outlet has become plugged. Continued reservoir sedimentation will require additional sediment removal. As operation of the dam outlet becomes less reliable, the benefits of the water storage capacity will diminish. Eventually, a reservoir with substantial sedimentation will become more of a liability than an asset and removed, for example, San Clemente Dam and Matilija Dam, both in California.

3.5. Economic

Dam owners sometimes decide to remove an older dam to avoid costly upgrades and repairs (Gonzales and Walls 2020). Upgrades are sometimes required to address increased dam safety risks from floods and earthquakes. Dam removal may be the lower-cost option, especially if the dam no longer provides valuable benefits.

3.6. Recreational Safety

Low-hazard and low-head dams can present serious safety hazards for boaters, anglers, and other recreationists. In addition, the State of Iowa has a unique program to help fund recreational improvements at low-head dams, including their removal (Iowa Department of Natural Resources 2018). Some local communities may want to remove a dam to improve river safety and recreation opportunities but are able to obtain dam removal funding to remove the dam for fish passage (Walls 2020).

3.7. Water Quality

Contaminated water or sediments left behind an unmaintained dam can have disastrous long-term implications if the dam fails, thus posing a water quality safety risk. Dams can also release water with too-high temperatures and too-low oxygen. The Massachusetts Division of Ecological Restoration study (2021) from 2014 to 2016 on small dams found that "dam impoundments consistently had lower water quality compared to their upstream and downstream waters."
The State of Ohio has provided funding for dam removal to improve water quality through their Clean Water State Revolving Fund (Walls 2020). Ohio allows stormwater operators to meet water quality criteria by funding watershed restoration projects rather than upgrading stormwater systems in some situations. Dam removal can change flow regimes and thus increase dissolved oxygen, reduce sedimentation, and reduce temperatures to improve benthic communities (Walls 2020).

4. Dam Removal Planning

Planning for dam removal generally includes these steps:

- Define the purpose and need for action
- Identify and engage stakeholders
- Assess the present downstream safety or environmental hazard risks
- Formulate alternatives, including removing the dam or repairing, improving, or maintaining the dam
- Assess environmental impacts under a range of reasonable alternatives
- Assess economic and financial costs and benefits under a range of reasonable alternatives

The normal planning process, in the absence of emergencies, is described in subsections 4.2 through 4.7. Emergencies may dictate the time and pace of dam removal planning; however, these steps are still considered.

4.1. Emergency Actions

For dam safety emergencies, expedited actions are needed to protect life, infrastructure, property, and environmental resources.

4.1.1. Prepare Before an Emergency

Preparation before an emergency occurs can help save lives and reduce property damage. Each dam should have an emergency action plan to build and maintain preparedness capabilities. Reclamation's Directives and Standards, *Emergency Management Program for Water Impoundment Structures* (FAC 01-01; Reclamation 2017), mandates a standard program to develop, coordinate, and maintain Emergency Action Plans for dams with a potential for controlled or uncontrolled water releases that pose a threat (for example, high hazard dams). State and privately owned dams may not have standard emergency action preparation for each dam. ASDSO has helped foster a unified dam safety community within the United States, and helps local governments (Drechsler 2021).

4.1.2. Follow Emergency Action Procedures

If an emergency occurs, first determine the severity of the issue and immediate risks. If the dam is at immediate risk, then follow the emergency plan developed for the dam. Expedited actions include:

- Relocating residents and follow the dam safety plan and emergency action plan
- Regulating reservoirs upstream to hold more water to minimize flows

- Regulating downstream reservoirs to increase discharge and save room for reservoir outflows
- Increasing real-time monitoring frequency for weather and flow
- Setting up an Engineering Design Team (described in Section 4.4.) to monitor and optimize the removal plan based on the rate of progress and real-time situation
- Setting up a team to monitor road and infrastructure conditions and repair as needed.

Lui (2014) describes using these steps to remove a landslide triggered by an earthquake that formed a natural dam. This experience showed that integrating emergency planning and coordination between all agencies into normal state management is the key to "make coordinated decisions to deal with any emergency in this constantly changing environment."

4.1.3. Lower Water Levels

If there is an unacceptable risk of dam failure, then lowering reservoir water surface elevations, to the extent possible, is a common method for reducing that risk. Coordinated actions both upstream (to minimize stream flows) and downstream (to maximize flood storage capacity) can help provide operational flexibility to address changing conditions. The controlled lowering of the reservoir is essential to prevent damages to downstream areas from high flows. Water levels can be lowered first through existing spillway gates and dam outlets. These gates may be opened or removed if needed.

As time allows, water levels can be lowered by excavating a notch in a dam, or lowering the entire crest elevation A notch excavated through a concrete dam would generally be more stable than a notch through an earth embankment dam. The perimeter of the notch must be resistant to erosion from overtopping flows. For an earth embankment dam, the notch can be located in the rock abutment or the notch perimeter in the earth materials could be armored with rock, incorporating filter and drainage blankets where required (Hepler 2013 and USSD 2015). Other ways to lower water levels include:

- Constructing a new river diversion channel or tunnel through a dam abutment.
- Using large capacity pumps to help drain very small reservoirs.
- Using a partial breach through an earthen dam after the reservoir pool has been drained.

However, any protective measures may require long-term maintenance.

4.1.4. Determine Mitigation Actions

Mitigation actions could be to remove the dam, and the steps explained in the rest of this section would be taken. These can be expedited but would still need to be followed. In some cases, the dam may be removed during the emergency. For example, the Maich Dam, a small embankment dam near Lochwinnoch, Renfrewshire, Scotland, was removed during emergency operations when it was overtopped during a flood (Mann 2009). This small earthen dam was had been in poor condition, as noted by Estates Factor, Ian McIlwraith said: "Part of the dam wall collapsed three years ago. The wall was constructed before the dam was formed and the foundations of the wall were under water." (Glasgow Evening Times 2008).

Mitigation actions could be to repair the dam. At Coal Ridge Waste Dam in Colorado, a sinkhole next to the outlet vault structure formed when contractors removed some poor quality concrete at the outlet structure. The reservoir was drained, and mitigation measures were considered. Rather than remove the dam, the owners decided to slip-line and grout and install a new outlet pipe with a new control gate on the upstream face of the dam (Myers et al. 2016).

Other considerations during dam repair or removal include:

- **Managing sediment.** Reservoir sediment management may also be necessary during the controlled lowering of the reservoir. See Section 6 for the steps needed to form a sediment management plan.
- **Protecting remaining structures and channels.** Clean up floating debris to protect dam intakes downstream (Lui 2014). At the damsite, measures may have to be taken to protect any remaining structures or channels during subsequent floods or earthquakes.
- **Identifying and handling hazardous waste safely.** Reclamation's Directive and Standard *Hazardous Waste Operations and Emergency Response* (Reclamation 1996 ENV 02-06) details standard procedures to ensure that personnel are trained to recognize, and respond safely to hazardous waste.

4.1.5. Determine Liability and Costs

Costs for emergency removal can be more expensive than proactively identifying hazardous dams and repairing or replacing them in a cooperative and timely manner. In Scotland, the council billed the dam owner for the £70,000 cost for the emergency actions alone to remove the Maich Dam, near Lochwinnoch, Renfrewshire, in an emergency operation (Speirs 2008).

4.2. Define the Purpose and Need for Action

A clear statement of the purpose and need for the proposed action will explain to the regulatory agencies and stakeholders why the proposed action is needed and how the identified problems will be addressed. See Section 3 for reasons for dam removal.

The project purpose and need for action should be defined so that a reasonable range of alternatives can be formulated. The alternatives are different plans for achieving the defined project purpose. The alternatives will then be evaluated based on their cost and ability to meet the project purpose. There are several different kinds of project purposes for which dam removal would be a reasonable alternative. This concept is illustrated in Table 1.

Table 1. Examples of project purposes and needs and the corresponding range of reasonable alternatives.

Possible project purpose and need	Potential range of reasonable alternatives
Reduce the risk of dam failure to protect life, infrastructure, property, and environmental resources	• Improve the structural safety of the dam • Maintain a lower reservoir water surface elevation • Remove the entire dam or at least enough of the structure to eliminate the hazard
Reduce the risk of people drowning in recirculating currents immediately below the dam	• Spillway channel modifications to eliminate dangerous recirculating flow currents • Public education and site access restrictions • Remove the entire dam or at least enough of the structure to eliminate dangerous currents
Increase the net economic benefits or reduce project costs	• Develop greater benefits from the dam and reservoir • Find more cost-effective ways of operating the dam • Remove the entire dam or at least enough of the structure to eliminate future costs and liabilities
River restoration through improved upstream fish passage	• Construct an engineered riffle to improve fish passage • Construct a fish bypass channel • Remove the entire dam or at least the portion of the dam that is blocking fish passage
Improve water quality for people and aquatic species	• Remove any contaminated reservoir sedimentation • Aerate reservoir water • Modify the dam outlet structure to withdrawal water from multiple reservoir depths • Remove the entire dam or at least enough of the structure to eliminate the reservoir pool

Historically, dams removed in the USA were not providing significant storage for water supply or flood risk reduction. For some older dams, the original benefits for which the dam was designed may no longer be needed or the dam can no longer be economically maintained to achieve these benefits. If a dam that was providing significant water supply or flood risk reduction were removed the lost reservoir storage capacity, and resulting consequences, would have to be identified and evaluated (USSD 2015). However, if a dam with existing benefits were to be removed, then those benefits may have to be replaced in some other way or the loss of benefits will have to be identified.

- Lost reservoir storage capacity for water supply or flood risk reduction could be difficult to replace. A combination of water conservation measures and alternate water sources could mitigate lost reservoir water storage.

- Removing structures from floodplains or flood proofing the remaining structures could mitigate lost flood storage capacity.
- Lost power generation at a removed dam could be replaced by energy conservation and other power plants.
- Lake recreation could be replaced by river recreation.
- Legal rights to water diversions may need to be addressed.
- Groundwater levels will typically lower to more natural conditions around the former reservoir. This could impact any local wells constructed after the existence of the reservoir.

After defining the purpose and need, clearly state the goals and final objectives for the project. Ensure that restoration goals are realistic. As noted in Foley (2017 [Listening]), returning to pre-dam conditions may not be possible, as local and watershed-scale changes since the dam was built may preclude this.

4.3. Identify and Engage Stakeholders

For more information, see Reclamation's *Public Involvement Manual* *(2001).*

Early and frequent engagement with stakeholders will help identify their interests and concerns and provide opportunities disseminate information about the project purpose and need. Some stakeholders may be concerned about any proposed changes to a dam, reservoir, or river channel and how they, or their organization, or the environment might be affected by those changes. Stakeholders may have similar or opposing views of whether these changes are beneficial or adverse.

Once those stakeholder issues and concerns are identified, alternative actions can be formulated. Studies can be conducted to evaluate the environmental impacts of those actions. Sharing information from engineering and scientific studies with stakeholders in clearly communicated ways that are easy to understand can help them, and decision makers, better understand the expected magnitude, extent, and duration of effects on the reservoir and river. When stakeholders have an opportunity to contribute to the planning process, and their concerns are heard and considered, there is greater opportunity to reach decisions that are widely accepted or at least understood. Therefore, public outreach efforts should identify stakeholders early in the process and allow for stakeholders to enter the planning process when they are ready to engage.

Possible stakeholders include:

- Individuals who live, work, or recreate along the reservoir or downstream river channel or people who just value its resources. In addition, members of the public that may be impacted by site access or mobilization efforts during dam repair or removal.
- Public or private utilities that may have infrastructure along or crossing a reservoir or river channel.

- Landowners and businesses associated with the dam or reservoir or who are located along the reservoir or downstream river channel.
- Water users or water-right holders associated the reservoir or river channel.
- Non-governmental organizations concerned about resources related to the dam, reservoir, or river. In the U.S., interested NGOs may include The Nature Conservancy, American Rivers, Trout Unlimited, Friends of the Earth, and Resources for the Future.
- Government agencies in charge of regulations or issuing permits related to dams, reservoirs, and rivers.

Dam removal projects in the USA will typically require the involvement of Federal, state, and local government agencies, and any affected Indian Tribes (USSD 2015). For example, modifications to a hydroelectric facility licensed by the Federal Energy Regulatory Commission will require an amended license or surrender of the license. Agencies with authority to issue permits related to dam removal would need to be involved. Under the Clean Water Act, USACE has the authority to issue a permit for the discharge of dredged or fill material into waters of the United States (Section 404 of the Clean Water Act). Each state water quality agency has authority for issuing water quality certifications and permits (under Sections 401 and 402 of the Clean Water Act).

4.4. Assemble an Expert Team

As each dam situation is unique, with different dam construction, reservoir characteristics, sediment properties, etc., dam removal design will vary for each project. Employing competent and experienced design engineers to evaluate the ongoing situation and to apply state of the art, current technologies and engineering practices increases the likelihood of site-appropriate designs, realistic cost estimates, reduced risk and uncertainty, and optimum results (Aspen 2002). Assemble an engineering design team with the full range of relevant expertise and experience. Include:

- Civil, hydraulic, geotechnical, mechanical, electrical, and construction engineers
- Cost estimators
- Hydrologists
- Geologists
- Geomorphologists
- Land use planners
- Safety professionals
- Chemists and hazardous material specialists
- Fishery scientists
- Ecologists
- Economists
- Archaeologists
- Historians, and
- Permit specialists (Hepler 2013).

An Engineer of Record may need to be designated as the responsible official for the engineering designs, design changes during construction, and site inspections during critical phases of the work to ensure that the design intent is being met.

A Project Manager will need to oversee engineering design, contractor selection, construction management, emergency operations, operation, and maintenance of remaining and added features, administration of funds, and project closeout. The Project Manager may be responsible for coordinating with stakeholders and affected resources during the dam removal.

A Contracting Officer will be responsible for contract administration and for execution of any contract modifications. On smaller projects, the Project Manager may serve as the Contracting Officer.

4.5. Assess Risks

An unacceptable risk of dam failure could result in a decision to remove a dam. The best practices in dam safety risk analysis are described by Reclamation and USACE (2019). FEMA (2015) defines risk as “the product of the likelihood of a structure being loaded, adverse structural performance, and the magnitude of the resulting consequences.” The dam safety risk would be considered small if both the probability of failure and the consequence of failure (e.g., no loss of life or small downstream consequence) were small. In contrast, the dam safety risk would be considered high if there were a significant probability of failure with high downstream consequences.

Even if a dam is too be removed, there may be additional safety risks to consider during and after dam removal. These risks should be identified, evaluated, and mitigated as necessary. For example:

- Risk that the dam structure might fail prior to dam removal—resulting in the sudden or rapid downstream release of the reservoir water. The structural failure could harm of kill people that may be in or around the structure. A flood wave from releasing the remaining reservoir suddenly or rapidly could harm people, infrastructure, or property located downstream.
- Risk that the dam structure might fail during removal—resulting in the sudden or rapid downstream release of the remaining reservoir water. The structural failure could harm or kill people that may be in or around the structure. releasing the remaining reservoir suddenly or rapidly could harm people, infrastructure, or property located downstream.
- Risk of a landslide failure along the reservoir shoreline, induced by rapid lowering of the reservoir pool. Such a landslide could harm people and destroy or bury infrastructure and property. A deep-seated landslide that reaches the reservoir pool could displace a significant volume of reservoir water and create a flood wave over the remaining dam, which could harm people in the reservoir, at the dam, or downstream. An overtopping flood wave could cause the remaining dam structure to fail.

- Risk of environmental harm to people and aquatic resources from the downstream release of contaminated reservoir sediments.
- Risk of environmental harm to downstream aquatic resources, stream-side infrastructure, and increased flood stage from the sudden release decades worth of stored reservoirs sediments.
- Risk of downstream flooding after dam removal. A flood wave passing through the former reservoir area might lack attenuation and result in greater downstream inundation compared with conditions prior to dam removal. Such a condition would mean that the former dam and reservoir were providing some significant flood risk reduction and that the dam would not have failed during the flood.

4.6. Develop Alternatives

As stated in Section 4.2, a reasonable range of alternatives should be formulated so that each alternative could achieve the project purpose. Some alternatives might retain the dam and reservoir while other alternatives would partially or fully remove the dam. In many dam removal cases, the dam is no longer serving its original purpose or the remaining purpose can be met through other means. For example, a low-head dam for diverting surface water into a canal could be replaced with a pumping plant (Figure 7). The energy produced by a hydropower dam could be replaced by another type of power plant. There may be difficulty finding substitutes for flood control or water supply.

Figure 7. Pump station designed and constructed on the Rogue River in Oregon to replace gravity diversions from Savage Rapids Dam. A pipe bridge was constructed so water could be delivered to both sides of the river (USSD 2015) (Reclamation/Hepler).

Dam removal alternatives might focus on different strategies for managing the reservoir sediment. Three basic kinds of reservoir sediment management alternatives are associated with dam removal (Randle and Bountry 2017):

1. River erosion where the sediments are allowed to erode from the reservoir and be transported downstream
2. Mechanical removal and upland placement of the sediments prior to dam removal
3. Stabilization of the sediments within the reservoir area with an engineered channel to convey stream flows

Mitigation measures are structural and non-structural actions that can be implemented under a project alternative to reduce the amount of adverse environmental impacts during and after implementation (Reclamation 2012 and USSD 2015 [more detail is in Section 4.2.3. *Special Design Requirements*]). Any necessary mitigation should be incorporated directly into the alternatives. For example, modifying downstream water intakes or water treatment might be necessary to avoid rapidly releasing decades of sediment accumulation downstream. For example, the timing of dam removal can make a big difference to impacts to fish and wildlife. Dam removal, stream restoration, and site clearing activities may be limited to a particular time of year (typically November through February) to avoid the disturbance of nesting birds.

4.7. Assess Environmental Impacts

An environmental compliance analysis process will be followed. See Section 2.3.4. *National Environmental Policy Act*. These consequences are compared against the consequences of the No Action Alternative, which is considered the baseline (Reclamation 2012 and USSD 2015). For the removing small low-head dams, the environmental impacts are investigated and addressed as part of the regulatory process, but a formal EIS or EA may not be required, especially if the sedimentation volume is small and free of contaminants. These types of smaller projects may only need to meet state and local permitting requirements.

Consequences are described for each resource category that was determined from the scoping process. These resource categories are often included:

- **Dam safety.** Most action alternatives would reduce or eliminate the risk of dam failure and avoid the potential downstream consequences to people, property, infrastructure, and aquatic organisms and their habitats. However, under the No Action Alternative (without removing or repairing the dam), the risk of dam failure and downstream consequences may remain the same or increase over time.
- **Hydrology (surface water and groundwater).** For alternatives that retain the dam and reservoir, there may not be significant impact to the hydrology. However, for dam removal alternatives, there would be a local decrease to groundwater levels surrounding the reservoir and this could affect local wells. If the reservoir provided any flood risk reduction, then dam removal would restore at least some of the natural flood frequency risks, and downstream lands could be inundated more frequently. If the reservoir storage fluctuated seasonally or year-to-year for water supply, then dam removal would restore at least some of the natural base flows and seasonal variability.
- **Water use.** Alternatives that retain the dam and reservoir would likely be able to maintain present water uses. Dam removal alternatives may also include other ways of continuing present water uses. For example, construction of a new pumping plant would provide the ability to take water from the stream channel. Sediment mitigation measures may allow for the continued operation of downstream water intakes. If present water use were discontinued, then those affects would have to be evaluated and described.
- **Power generation.** If a dam produced hydroelectric power, then alternatives that retain the dam and reservoir would likely continue to produce power. For dam removal

alternatives, the affects from the loss of the dam's hydroelectric power on the electrical grid would have to be assessed and described. About 7.3percent of total electricity generation in the United States is from hydropower (U.S. Energy Information Administration 2021), so the loss of an individual hydroelectric dam may not be significant.

- **Sediment transport.** For alternatives that retain the dam, reservoir sedimentation would be expected to continue over time in the absence of sediment management practices. Eventually, continued reservoir sedimentation could lead to dam removal. For dam removal alternatives, there are basically three type of sediment management strategies: (1) river erosion where sediments are eroded from the reservoir and transported downstream, (2), removal of the reservoir sediments and placement at an upland containment area, and (3) stabilization where sediments are protected from erosion within the reservoir after main stem and tributary stream channels have been excavated through the sediments (Randle and Bountry 2017).

  Dam removal alternatives that employ reservoir sediment removal or stabilization reduce or avoid many of the environmental consequences to the downstream channel. However, these sediment management strategies tend to cost more than river erosion and focus impacts on either the reservoir area or upstream placement areas.

  For dam removal alternatives that employ the river erosion strategy, downstream impacts tend to increase with the ratio of the reservoir sedimentation volume to the mean annual sediment load (Randle and Bountry 2017). The sedimentation volume behind many small dams or weirs is equivalent to the sediment load delivered over a period of months to a year and, for these cases, the impacts often may not significant. However, the sedimentation volume behind many large dams is equivalent to the sediment load delivered over a period of years or decades and, for these cases, the impacts may be significant.

  Erosion and downstream transport of exposed reservoir sediments could lead to some deposition along the channel and increased sediment concentrations and turbidity. Eroded coarse reservoir sediments (sand and gravel) may deposit along the downstream river channel eddies, pools, and or other slow-velocity environments. A large and rapid release of coarse sediments from the reservoir could result in higher river stages and greater flooding potential. Downstream water intakes may also be impacted by sediment deposition (Hepler 2013). These impacts are typically minor for low-head dam and reservoirs with small sedimentation volumes.

- **Water quality.** For alternatives that retain the dam, any existing water quality effects from the reservoir (e.g., temperature stratification, decreased dissolved oxygen, increase nutrients, and algae) would continue. Dam removal alternatives that employ reservoir sediment removal or stabilization reduce or avoid many of the water quality consequences to the downstream river. For dam removal alternatives that employ the river erosion strategy, the downstream release of sediment from the reservoir will temporarily affect water quality. This is especially true for fine sediment (clay and silt) because contaminants, if present, are more likely to attach to fine sediment particles. Increased sediment concentrations may affect downstream aquatic species and their habitats. Downstream water users may also be affected with increased water treatment costs. The greatest water quality effects will be temporary as sediment is eroded from the reservoir. If the former reservoir was trapping fine sediments, then dam removal will allow the upstream sediment loads to pass downstream over the long term.

- **Wildlife, fishery, and aquatic communities, and threatened and endangered species.** For alternatives that retain the dam, any existing impacts to fish and wildlife, through water quality or the blockage of fish migration, would continue. For dam removal alternatives, the reservoir environment would be replaced with a river environment. Species of fish and other aquatic organisms suited for a reservoir will likely be replaced with species suited for the river environment. In the absence of barriers (such as the dam), fish and other aquatic organisms would be able to migrate more easily, which could be quite helpful for native species and a potential problem for non-native species. Some fish and other aquatic organisms may experience chronic or lethal effects from high sediment concentrations released from the reservoir. Native species, including threatened and endangered species, may be better suited to higher sediment concentrations than non-native or sport fisheries. However, endangered river mussels may not tolerate sediment burial.
- **Wetlands, vegetation, and habitat.** For alternatives that retain the dam, wetlands, vegetation, and habitat conditions along the reservoir shoreline would generally continue. However, wetlands associated with reservoir deltas along the main arm and tributaries would continue to grow both downstream toward the dam and upstream along their inflowing channels. For dam removal alternatives, wetland habitats associated with reservoir deltas would be converted to upland (drier) habitats, but wetlands downstream of the dam may be enhanced.
- **Invasive species.** For alternatives that retain the dam, the effects of invasive species would tend to be the same as before. For dam removal alternatives, invasive fish species downstream from the dam could be allowed to migrate upstream. With the loss of the reservoir, invasive plants, without mitigation, could colonize the exposed reservoir areas, even if those area are planted with native vegetation. Therefore, control of invasive plants typically would be needed to prevent their colonization. For the Elwha River Restoration Project, comprehensive plans were implemented to control invasive plants, including the hand-pulling and cutting of plants and chemical spot-treatments with herbicides (Chenoweth et al. 2011).
- **Recreation.** For alternatives that retain the dam, reservoir-based recreation activities would continue. However, the area for lake and shoreline reservoir would decrease over time due to continued sedimentation and boat ramps and marinas would eventually become buried without sediment management. For dam removal alternatives, reservoir-based recreation activities likely would be replaced with river-based activities and boats or rafts could navigate past the former dam site.
- **Land use.** For alternatives that retain the dam, surrounding land use would typically remain the same. For dam removal alternatives, land use in the former reservoir area would likely change to uses related to river, floodplain, and terrace topography. Decisions may be necessary regarding the final disposition of lands, easements, and rights-of-way associated with the facilities. According to USSD (2015),

All affected land parcels must be identified, and their ownership rights should be determined. Information regarding any easements, leases, or rights-of-way granted by or to others is necessary to identify any potential restrictions on the future use of the land that could influence retirement options. The sale of land or the release of easements may first require some level of site restoration to remove potential public safety or environmental hazards. Land values and property tax revenues within the project area may be affected by the replacement of the reservoir with a more natural stream channel. Water surface elevations would be lower within the former reservoir area, but downstream flood stage could be higher if the former reservoir provided flood attenuation.

- **Geomorphic processes.** For alternatives that retain the dam and reservoir, the geomorphic processes of reservoir sedimentation and downstream erosion would continue. For reservoirs that only trap small amounts of sediment (see Section 6.1. *Cases of Negligible Sediment*), sedimentation processes and downstream erosion may not be significant. For reservoirs with higher sediment trap efficiencies, the delta may extend beyond the full reservoir pool. Reservoir deltas on rivers with mild slopes tend to be longer than deltas on rivers with steep slopes. Downstream from reservoir that trap sediment, river channels tend to be degraded and have coarser grain sizes. For dam removal alternatives, the restored river channel can be expected to erode through any reservoir delta that may be present and at least some sediment can be expected to deposit along the downstream river channel, resulting in finer sediment grain sizes along the streambed. Allowing upstream sediment loads to pass downstream, would restore geomorphic processes and may cause the channel to become wider, a bit shallower, and more dynamic with more frequent channel migration.
- **Aesthetics.** For alternatives that retain the dam, aesthetics would be related to the reservoir and shoreline areas. For dam removal alternatives, the aesthetics would temporarily be based on the exposed reservoir bottom, which may be composed of sands and soft muds devoid of vegetation, and tree stumps. Odors may be present from organic matter trapped within the former reservoirs, A year or two after dam removal, the aesthetics would be related to a river and floodplain landscape, new vegetation, and any remaining terraces of reservoir sediment.
- **Transportation.** For alternatives that retain the dam, transportation would normally not be affected. For dam removal alternatives, the piers of bridges that might cross the reservoir delta could be subject to erosion as the river incises into the delta. Boats and barges may be able to navigate past the dam site after dam removal, provided there are sufficient water depths. If a removed dam had one or more navigation locks, water depths may not be sufficient for navigation upstream from the dam during low-flow periods.
- **Noise.** For alternatives that retain the dam, any effects of noise would normally continue as before. For dam removal alternatives, noise would be greater during construction activities (e.g., hammering, blasting, hauling, and backup alarms from construction vehicles).
- **Air quality.** For alternatives that retain the dam, there would normally be no effects on air quality. However, many reservoirs produce significant amounts of greenhouse gases

(methane and carbon dioxide) due to decomposing organic matter (Beaulieu et al. 2020). For dam removal alternatives, the exposed lakebed sediments may temporarily produce dust problems until the area is colonized by vegetation. Hauling of material removed from the area will temporarily increase vehicle emissions in the area.

- **Infrastructure and public services and utilities.** Infrastructure along and within the reservoir area could be impacted from dam removal. Shallower water depths could affect boat or barge navigation. Any existing bridge piers, roadway and railroad embankments, levees, drainage culverts, and buried or submerged utilities pipelines within the former reservoir area may become subjected to higher flow velocities, scour, and surface erosion and require protection or relocation. This could especially true if infrastructure were designed and constructed with the reservoir already in place.
- **Cultural resources (historical and archaeological resources and traditional cultural properties).** Older dams and reservoirs may have historic significance and are often located in areas rich in cultural or historical significance (USSD 2015). Reservoirs may have inundated indigenous people's settlements or burial sites, early settlements, or other important cultural sites, and the reservoirs may contain an abundance of artifacts. Lower reservoir levels could expose these sites to erosion or human disturbance. Include plans to address any historical resources found and to coordinate with agencies responsible for historic preservation. Portions of remaining dam structures could be retained for historic preservation and interpretation. Historic documentation (photographs and drawing) of removed structures would help preserve their history and mitigate for their loss.
- **Environmental justice**. Removing the dam and reservoir may represent a loss to the local or regional community. As Aspen (2002) notes, "Reservoirs may have inundated Native American villages or burial sites, early settlements, or other important cultural sites, and the reservoirs may contain an abundance of artifacts. Lower reservoir levels could expose these sites to erosion or human disturbance."

4.8. Conduct Economic and Financial Analyses

4.8.1. Cost Estimates

For more information, see 4.5. *Cost Estimates* in USSD 2015.

Cost estimates for dam removal will be prepared throughout the design process, at higher levels of detail each time—from very approximate costs for an initial level of planning to more detailed and tailored costs through planning budgets to seek funding and contracting/bids. Thus, costs may be classified according to the quality of the information available to prepare the estimate (or degree of project definition), the methods used to estimate, the purpose for the estimate, the expected accuracy level, the level of risk associated with the estimate, and the level of effort to prepare the estimate. See Reclamation (2007) Directives and Standards FAC 09-01, *Cost Estimating*.

Cost assessments should include long-term operation and maintenance costs, restoration costs, as well as potential future replacement costs for any structural elements that remain. This should be detailed enough to be able to identify the least cost alternative and any alternatives that should be eliminated due to cost, safety, or environmental reasons.

ASTM International (2019) uses five class estimates, commensurate with the level of effort and accuracy needed as shown in Table 2. The relative preparation effort suggests that the preparation of a Class 1 estimate may cost up to 100 times the cost to prepare a Class 5 estimate.

Table 2. Cost estimate classification matrix (based on ASTM E2516-11 and USSD 2015)

Reclamation level	Class of Estimate	Degree of Project Definition	Purpose	Expected Accuracy Range	Relative Preparation Effort
Preliminary	Class 5	0 percent to 2 percent	Screening	-30 percent to +50 percent	1
Appraisal	Class 4	1 percent to 15 percent	Planning or Concept	-20 percent to +30 percent	2 to 4
Feasibility (seek authorization)	Class 3	10 percent to 40 percent	Preliminary or Budget	-15 percent to +20 percent	3 to 10
Final design and prevalidation (after authorization)	Class 2	30 percent to 70 percent	Control or Pre-validation	-10 percent to +15 percent	5 to 20
Independent Government Cost Estimate (IGCE)	Class 1	70 percent to 100 percent	Bid/tender	-5 percent to +10 percent	10 to 100

Table 2 reiterates that there is a risk of uncertainty associated with the cost estimates for any construction project, including dam removals. This uncertainty stems from many factors, including unknown conditions within the dam and reservoir, market prices, contractor bids, potential for further non-construction costs such as permitting or analysis.

4.8.2. Cost Estimate Calculations

The cost of dam removal is a function of many variables, including the volume of dam material, reservoir sedimentation volume, water quality mitigation measures, and permitting requirements. While each project will have unique cost drivers (e.g., access, materials, streamflow, waste disposal, sediment, permits, public involvement, environmental conditions, urgency of action), these cost calculations can be valuable for a Screening (Class 5) estimate or Planning or Concept (Class 4) estimate level.

Blachly and Uchida (2017) performed linear regression analyses to correlate the cost of dam removal with dam height. They concluded that each vertical 0.3 m of dam height contributes between \$22,300 and \$30,600 (2016 dollars) toward the cost of dam removal. Each horizontal 0.3 m of dam length contributes between \$1,400 and \$2,800 toward the cost of dam removal. They proposed the following cost model:

$$Cost_{2016} = \beta_1\, Heigth + \beta_2\, Length + \alpha_y + \delta_s + \gamma_{ys} + \varepsilon$$

where:

$Cost_{2016}$ is the cost of removing dam in 2016 USD,
Height is the height of dam, and
Length is the length of dam.

The following terms were included to control for bias from unobserved factors: year of removal (α_y), state (δ_s), year-by-state (γ_{ys}), and an error term (ε).

Magilligan et al. (2016) reported that dam removal costs about $40,000 per vertical meter ($13,000 per 0.3 m). These cost models do not account for reservoir sedimentation and that is likely because most dams that have been removed are low head and likely do not contain decades worth of sediment load.

Gonzales and Walls (2020) developed a similar cost model, but added dam age and type as additional variables.

$$\log(Cost_{2018}) =$$

$$\beta_1\ log(Height) + \beta_2\ log(Length) + \beta_a(Age) + \beta_j(Type) + \epsilon$$

where

$Cost_{2018}$ is the total cost of dam removal in 2018 USD,
Age is the age of the dam removing years,
Type is the type of dam material (e.g., earth, concrete).

Reclamation, U.S. Geological Survey, USACE, and Oregon State University are presently collaborating on research to determine the most significant dam removal cost drivers. Niu and Shah (2021), developed a new model for determining the optimal size of new reservoir storage capacity to maximize lifetime net benefits, while allowing for possible sediment management to extend useful life of the reservoir, and accounting for dam decommissioning costs incurred when the useful life ends.

4.8.3. Cost Considerations and Case Studies

As further detailed in USSD 2015, the total costs of dam decommissioning can be significant, even for small projects. Costs include replacing dam benefits, permits and other legal requirements (Section 2.3), planning as noted in this section; design, construction, and mitigation (Section 5); sediment management (Section 6). Table 3 from USSD provides a summary of the project costs associated with several dams across the United States. (Note that these costs represent costs during the years of dam removal and have not been indexed for inflation.)

Table 3. Selected case history summaries of project costs (USSD 2015)

Dam, River, and State	Dam Type and Height	Year Removed	Total Project Cost	Major Elements of Costs
Chiloquin, Sprague River, Oregon	6.4 m high concrete gravity	2008	$18 million	Demolition and Pumping Plant 50 percent
Elwha, Elwha River, Washington	32 m high concrete gravity	2011-2013	$351 million	Demolition 8 percent; Land 8 percent; Treatment Plants 27 percent
Glines Canyon, Elwha River, Washington	64 m high concrete arch	2011-2013		

Dam, River, and State	Dam Type and Height	Year Removed	Total Project Cost	Major Elements of Costs
Hall Brook, Massachusetts	7.3 m high masonry	2009	$320,000	Engineering 16 percent; Permitting 13 percent; Construction 72 percent
Livermore Pond, Connecticut	3 m high earthfill	2003	$260,000	Engineering 19 percent; Permitting 19 percent; Construction 62 percent
Old Berkshire Mill, Massachusetts	4.3 m high	2000	$1,050,000	Engineering 7 percent; Permitting 12 percent; Construction 81 percent
Saeltzer, Clear Creek, California	6 m high concrete gravity and timber crib	2000	$6 million	Demolition 47 percent; Water rights 42 percent
Savage Rapids, Rogue River, Oregon	10 m high concrete gravity and multiple arch	2009	$39.3 million	Demolition 72 percent *

Note that Savage Rapids Dam cost also includes designing and constructing a new pumping plant before dam removal.

4.8.4. Cost Comparisons

Costs should be compared against the costs for No Action Alternative (which may have high life cycle costs, reduce project benefits, or pose safety threats) and dam repair (which may continue project benefits but may have higher life-cycle maintenance and operational costs).

Dam removal may be a less expensive alternative for dams requiring significant repairs or upgrades to address dam safety hazards. For dams with safety hazards, the No Action Alternative is not acceptable, and the economically least-cost option may be the best alternative. Costs for dam safety improvements can sometimes be substantial and may include the costs for diversion and care of the streamflow during construction activities (USSD 2015). The potential cost of improvements needed to modify a dam to meet current engineering standards and applicable dam safety regulations (Federal or state) may be a critical factor to a dam owner.

In some cases, the cost of dam safety repairs or upgrades may exceed the potential remaining benefits of the project and the river restoration benefits of dam removal could be significant. For example, Cascades Dam was located on the Merced River within Yosemite National Park. This dam was severely damaged during a flood flows and no longer served any useful purpose (USSD 2015). The National Park Service chose to remove the damaged structure rather than make costly repairs to protect park visitors from potential failure and restore that portion of the Merced River.

4.8.5. Benefit-Cost Analysis

The economic analysis considers all of the benefits and costs to society and should be used as the basis for governmental decision making. The economic analyses performed are not concerned about money that might transfer from one group to another, but the net benefits or costs to the nation. The economic analyses may be on a regional or national basis. Economic analyses are incorporated into EAs or EISs and should consider all the benefits and costs to society from each alternative. Economic analyses should consider all benefits and costs of each alternative, regardless of who might benefit or pay. Reclamation follows the Principles and Requirements for Federal Investments in Water Resources. These guidelines define public benefits as encompassing environmental, economic, and social goals, include monetary and nonmonetary effects and allow for the consideration of both quantified and unquantified measures. (Council on Environmental Quality [CEQ] 2013 and the Department of the Interior [DOI] 2015).

Boardman et al. (2018) also describes the concepts and practices for performing the benefit-cost analysis. The text uses a consistent application of a nine-step framework for interpreting a cost-benefit analysis. This is useful as a general introduction and practical guide to cost-benefit analysis, as well as a starting point for exploring advanced topics.

In contrast, a financial analysis considers the benefits and costs to a specific entity or organization, like the dam owner. Therefore, the financial analysis is normally prepared by the concerned entity or organization. The results from economic and financial analyses can be quite different because one group or organization may receive benefits from a dam and reservoir while others might incur the costs or impacts.

4.8.5.1. Public Benefits

Dam removal may result in various public benefits, including reestablishing or improving riverine fisheries near and upstream of the former dam location. Dam removal may also provide new recreational opportunities for river boating (such as rafting, kayaking, and canoeing). Removing diversion facilities and relinquishment of water rights, may result in higher streamflows for fish and recreation. This was the case for the removal Saeltzer Dam in California and the removal of several small diversion dams on Battle Creek, also in California (USSD 2015).

Lake recreation benefits could be replaced by river recreation benefits. The reservoir water surface may provide aesthetic benefits, the natural river landscape may also do this. Landowners along the former lakeshore will lose their lake view but will gain a river view—unless they find themselves some distance from the newly established river channel. Property values may actually increase in some cases following dam removal and river restoration (USSD 2015).

Other potential public benefits resulting from dam removal include improved riverine and watershed health associated with improvements in the populations of birds of prey and other terrestrial species, and a reduction in risk from dam failure or mis-operation of project facilities. Removing an abandoned dam would reduce the financial burden on a local community responsible for maintaining the structure.

4.8.5.2. Dam Owner Benefits

The potential benefits of dam removal generally include avoided or decreased costs for future operation and maintenance, dam safety repair or improvements, and the costs for fish passage. Dam decommissioning projects can be designed to ensure that failure of the dam is no longer a risk or liability. Dam and reservoir project lands may be developed for other purposes.

4.8.6. Financing

In most cases, the owner has paid for dam removal. Walls and Shabman (2020 [Funding]) funding pose some innovative solutions for funding dam removals. They suggest three parties who might pay: "(1) owners, (2) beneficiaries of removal, such as the local community or the wider public at large, and (3) parties who owe compensation for actions that harmed the environment or permittees who are making alterations to the existing aquatic environment and need to meet requirements of the Clean Water Act (CWA)." For example, the Amended Klamath Hydroelectric Settlement Agreement between California and Oregon state agencies and key project stakeholders, details the removal four hydroelectric dams on the Klamath River in California and Oregon and the cost bore by each entity. Of the estimated total cost of $450 million for the removal, $200 million will be paid for by dam owner's customers and $250 million will be paid for by the State of California. The State of Oregon contributed an additional $45 million in contingency funding. The negotiations and agreements for the Klamath project have evolved over the years, and this provides a good example of States and local entities directly addressing issues (Klamath River Renewal Corporation 2021).

Federal and state dam safety programs can generally provide funding for dams owned by Federal and state agencies to address dam safety deficiencies and help ensure public safety. Some states, such as Wisconsin and Pennsylvania, have provided special funding for the removing abandoned dams for which no owner can be found. Environmental and conservation organizations such as The Nature Conservancy, American Rivers, and Friends of the Earth may also provide a source of financial support for a dam removal and river restoration. This funding could be used for dam removal to provide environmental benefits or eliminate the risk to the public of dam failure.

There are numerous Federal and state funding sources for removing privately-owned dams. Walls and Shabman (2020 [Federal]) describes Federal programs that focus on the benefits for that agency from private dam removal, along with some limitations and possible uses, including

- **Fish passage and habitat.** USFWS NOAA Fisheries' Community-Based Restoration Program and Pacific Coastal Salmon Recovery Fund, and EPA's Great Lakes Restoration Initiative, and some USACE projects support dam removals to benefit fish. For example, Federal legislation provided funding through the National Park Service (NPS) for acquiring and removing two privately-owned dams to ecosystem restoration. Reclamation provided technical assistance to the NPS. The Elwha River Ecosystem and Fisheries Restoration Act of 1992 authorized the purchase of Elwha and Glines Canyon Dams by the Interior Department from the James River Corporation, for restoring the Elwha River ecosystem and anadromous fish. Under the terms of the Elwha Act, the dam owner received compensation for the lost hydroelectric power and was released from future liabilities associated with the dams.
- **Improve watershed conditions.** USACE can support removing a non-USACE dam in another part of the watershed to improve the overall watershed, as in the Great Lakes Fishery and Ecosystem Restoration program, for example.
- **Address dam safety and mitigate hazards.** FEMA has grants for this, including assistance after wildfires and floods. For example, the Rattlesnake Creek Dam removal project in Missoula, Montana, received funding from FEMA after a 2018 wildfire disaster.

4.9. Document

Documentation throughout the project, from planning to monitoring after removal, is critical to communicate analysis, findings, and decisions. Clearly showing what was done and why it was done avoids duplicated efforts and allows new participants to see and understand the process to date. Documentation levels will depend on the amount of analysis needed for the project, depending on the size of the dam and the potential for environmental impacts, and risks for hazardous materials as well as permit and other regulatory requirements.

For more information, see 4.6. *Project Documentation* in USSD 2015 and FEMA 2004.

At a minimum, project documentation should include the project purpose and objectives, size of the dam, reservoir, and sediment volume, dam removal method and timing, and the project results. Detailed project documentation would include

- Plans of study
- Site investigation results
- Environmental analysis
- Alternatives developed and considered
- Stakeholder and public comments
- Decisions made records of all major decisions pertaining to the project.
- Design assumptions, criteria, and computations
- Designs and design records
- Quantity estimates
- Permit requirements
- Emergency preparedness plans
- Construction plans
- Construction diary
- Actual field conditions encountered
- Changes in construction and departures from predictions
- Conditions after construction
- Contract modifications
- Post-construction monitoring instructions and records

When starting the project, determine a central location for files and how files will be maintained and archived.

Take photos throughout the process and label each with the date, location, photographer, and description. Put these in a central database.

Monitor and keep records of anything that changes conditions, such as inflows, reservoir drawdowns, downstream conditions, affected environments, and structures. This monitoring should be done at the planning stages, during dam removal, and after dam removal.

4.10. Implement Construction Contracting

Typically, the designated dam removal entity will request proposals or bids and then issue a contract. Details for contracting processes will depend on the entity and regulations for that entity.

For more information, see Section 6.1. *Construction Contracting* in USSD 2015.

Considerations include:

- **Flexibility.** As noted in USSD 2015, "The contractor will be responsible for the preparation of all required submittals, including detailed plans for safety and health, the use of the site, diversion and care of streamflow, structure demolition, waste disposal, and site restoration, as well as for execution of the work in accordance with the contract documents." Contractors should have some flexibility in determining methods to achieve results needed. Overly specific contracts can lead to excessive costs and delays. For example, while an upstream cofferdam can help keep the demolition site dry, it may not be necessary and can add significantly to the cost of a dam removal project. For example, the final portions of Savage Rapids Dam on the Rogue River and Chiloquin Dam on the Sprague River were found to be easier to remove without construction of the planned cofferdams for each site, after the initial portions had been removed using cofferdams and the reservoirs had been drawn down significantly. Thus, contractors and the owner should work together to determine if one is needed for that particular project.
- **Adaptive management and change orders.** An adaptive management program may be used to adjust the reservoir drawdown and dam removal rates to achieve the project objectives.
- **Emergency procedures.** The contractor may be responsible for developing and deploying an emergency action plan.
- **Risk Assumptions.** Potential contractors for most projects should be bonded and meet minimum experience requirements for the proposed work (Hepler, 2013). Bonding requirements will typically depend upon the amount of risk or overall cost of the project. However, note that assuming liability and risk can be expensive. If the owner is willing to assume some role of the risk, then the contractor will be less expensive than if the contractor assumes all of the risk, e.g., Elwha Dam—government assumed the liability for sediment impairing the downstream water treatment plant, which significantly lowered contractor costs.
- **Permitting responsibilities.** The contractor will have to comply with the contract specifications and project permit requirements and conditions (Hepler 2013). Depending upon the size and complexity of the project, construction of other facilities or features might be included in one large contract, or in separate contracts, to either mitigate the consequences of dam removal or replace the need for the dam. For example, the Elwha

River Restoration Project included separate contracts to remove two large dams and to construct two water treatment plants, flood control levees, and a new fish hatchery.

4.11. Plan For and Implement Monitoring and Adaptive Management

For more information, see Section 7. *Performance Monitoring and Mitigation* in USSD 2015.

The dynamic hydraulics and sediment processes involved in dam removal should be monitored and evaluated throughout dam removal and reservoir drawdown and for the duration of significant impacts. A systematic approach to performance monitoring and data collection can help quantify and evaluate impacts to determine how well the project meets objectives, how the reservoir and river are responding to the dam removal, and when adaptive measures may be needed. As noted in USSD 2015, "Monitoring can also help inform adaptive management plans by reducing uncertainty associated with dam decommissioning projects, communicate project results to stakeholders and the public, and advance our understanding of the results of restoration actions for future projects."

During and after dam removal, use flexible decision making that can be adjusted as outcomes from previous management actions and other events become better understood. Agree on the basic framework for monitoring, adaptive management, and decision-making for the overall project (Section 5.2.9) and incorporate that framework into the sedimentation management plan.

Include monitoring as an integral part of the dam removal planning process. NOAA Fisheries has been studying the effects of removing two Penobscot River dams in Maine on ecosystem conditions for salmon and other aquatic species. For this project, "Researchers realized that gathering data on the river conditions and fish dynamics before and after dam removal would be critical for understanding the impacts. Planning for a coordinated monitoring framework began as soon as the agreement was signed." (NOAA Fisheries 2021 [Penobscot]). The program funded nine long-term studies for physical (geomorphological, hydrological) and environmental (fish passage and habitat) components. The study used both pre-removal monitoring data and post-removal data. Partners also coordinated other research projects during that time.

Creating a dedicated government program for monitoring can also help ensure that monitoring is integrated with project and program planning. NOAA Restoration Center's Monitoring, Evaluation, Reporting, and Feedback Framework "establishes a consistent and cost-effective approach to monitoring and evaluating the performance of restoration actions." This approach incorporates systemic monitoring with managing and analyzing data to inform program priorities and actions, which are then monitored as shown in Figure 8 (NOAA 2021 [Restoration]).

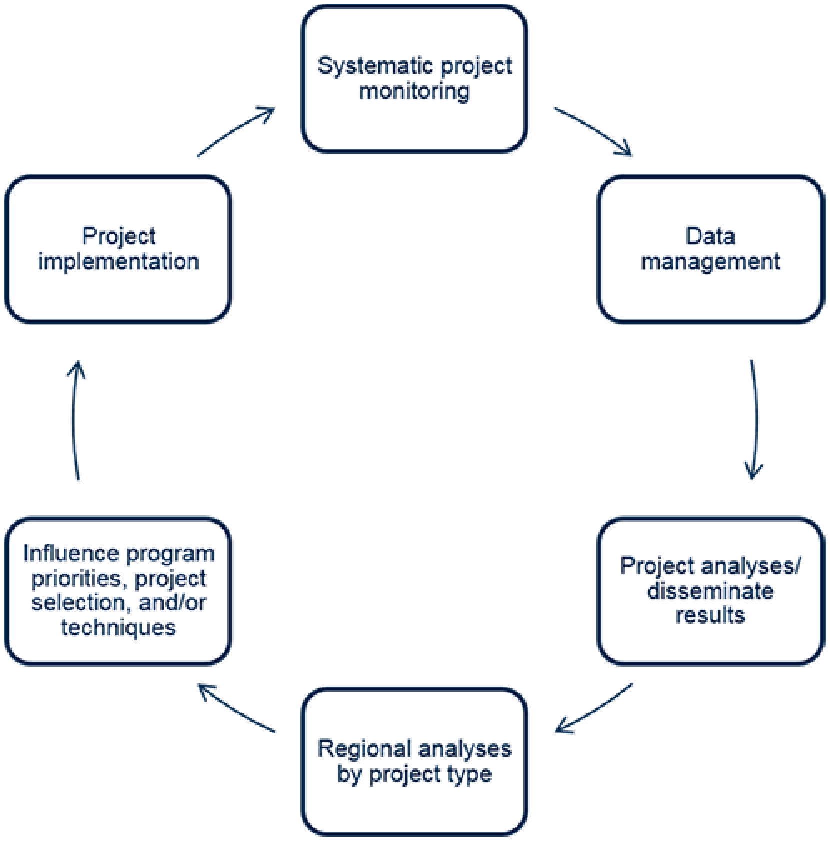

Figure 8. Cycle of monitoring and adaptive management (NOAA 2021 [Restoration]).

For projects with significant uncertainty, use of an adaptive management plan framework is recommended, like the ones described in DOI's guide to Adaptive Management (Williams et al. 2007). Using an adaptive management framework can 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). As noted in Randle and Bountry (2017), real-time monitoring data are a necessary component to measure river responses and evaluations made to 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."

NOAA Fisheries 2021 (Restoration) provides a dam removal specific framework for monitoring, evaluating, reporting, and providing feedback for an adaptive management program. For monitoring related to construction activities, USDD (2015) recommends that monitoring plans document how pre-and post-construction metrics will be assessed. These monitoring plans should be completed during contract award negotiation to ensure that monitoring costs and duration are identified. The construction-related monitoring plans should include:

- project goals and objectives,
- list of monitoring metrics,
- methods to assess and analyze the required pre- and post-construction metrics,
- monitoring schedule (duration and frequency),
- targets for each metric (or methods for determining targets), and
- references used to establish targets.

Construction performance monitoring may include the following topics:

- **Multiple sites.** The geomorphic responses of the upstream and downstream channels vary considerably. Thus, it is necessary to monitor several sites to adequately represent the range of fluvial habitat, geology, physiography, sediment grain size, climate, etc.
- **Turbidity levels (permit compliance monitoring).** Monitor to assure that suspended sediment concentrations remain within a range specified in a permit governing work at the site.
- **Work progression (implementation monitoring—short term).** Compare an as-built survey done just after completion of dam removal construction to the design to evaluate whether the project has been carried out as designed and meets basic structural goals.
- **Environmental conditions (ecological effectiveness monitoring—long-term).** Evaluate the functional success of the dam removal by monitoring and documenting the physical, biological, and geochemical response of the river.

As noted in USSD 2015, "Over-engineered solutions that are rigid and cannot adjust to a dynamic, natural system could result in higher project costs, greater adverse environmental impacts over time, or project failure." A plan to monitor and adapt to changing conditions in real time during dam removal is critical for projects with large uncertainty. In this performance monitoring plan:

- Develop early agreements among stakeholders and the Engineering Design Team on the scientific and engineering principles to use to gather information, conduct and interpret studies and monitoring.
- Determine communication and decision processes, contingency plans, and thresholds for change and actions.
- Identify monitoring needs and delegate responsibilities for interpreting those monitoring results and determining the need for action to most effectively meet the purpose, needs, and goals.
- Determine how levels of risk and uncertainty will be evaluated, communicated, and considered (Aspen 2002).

5. Dam Removal Design

The level of effort needed to design a dam removal should be based on the size of the dam and level of risk to the public, environment, and downstream property and infrastructure. The removal of a small weir may not require a detailed design. However, the removal of a large dam would require a detailed design to help ensure the safe and successful project implementation and within the budget and schedule constraints. This chapter provides summary information on the dam removal designs with some updates. The Guidelines for Dam Decommissioning Projects by the United States Society on Dams (USSD 2015) provides more technical information.

5.1. Design Considerations and Questions

5.1.1. What Structures Will Be Removed?

For more information, see Section 4.2.1. *Structure Removal Limits* in USSD 2015

Whether the dam structure can be completely removed or partially removed depends on project purpose, site characteristics, and restoration plan. Full removal generally means removing the dam and appurtenant structures to either just below the original streambed level (to avoid future structure exposure) or to an alternate grade offering improved channel stability. Partial dam removal allows some structures, or portions of structures, to remain in place without any significant reservoir impoundment or hazard potential. For most small dams, removal to a depth of 1 m below the streambed or pre-dam topographic surface may be sufficient. Portions of the structures may remain buried on site, especially below the predam topographic ground surface.

A partial dam removal is typically designed so that the remaining structure no longer creates a significant reservoir pool and is no longer legally defined as a dam. Leaving portions of the dam along the abutments would provide opportunities for historic preservation. The lowest portion of a concrete dam could be retained as a weir to hold back reservoir sediments. However, such a weir may require a fish passage facility. The final stream channel alignment could be around a remaining dam structure. Any remaining structures (regardless of where they are located) must be stable capable of performing satisfactorily in the future under anticipated flood and earthquake loading conditions. Some remaining structures may have to be modified for public safety.

Some portions of structures may be repurposed. As shown in Figure 9, portions of the Glines Canyon Dam were retained for historical purposes as well as to enhance visitor experiences.

Figure 9. At Glines Canyon Dam, the left-side spillway gates and the right abutment thrust block were retained for a public overlook within Olympic National Park in Washington (Reclamation/Randle).

These topics should be considered when determining the scope and extent of dam removal:

- **Restoration goals and purposes.** Satisfy the restoration project goals and objectives, such as fish passage, connectivity, sustainability, and restoring natural riverine processes, and floodplain function and capacity. Depending on the desired outcomes, **lowering the crest elevation** while retraining the rest of the dam crest may be an option. This may be appropriate for addressing dam safety issues where no environmental considerations are present. For example, Agency Dam was a 10-m-high dam on the Rocky Boys Indian Reservation in north-central Montana where no fish passage was required. This dam was notched to the elevation of the upstream reservoir sediments to retain them within the reservoir and to reduce downstream flood risk in the event of dam failure.
- **Type of dam.** Composite dams consisting of embankment and concrete sections generally include the spillways and outlets within the concrete section. Recent dam removal studies, such as for the Lower Snake River Dams in Washington, have suggested that the embankment section be removed and that the concrete section be retained to reduce project costs, although any remaining potential liability and future maintenance costs must be considered in this assessment. Partial removal of a timber crib dam is normally not recommended due to the difficulty of ensuring long-term stability.
- **Aesthetics.** Aesthetic factors may affect a decision for partial dam removal, especially in areas subject to public view.

- **Historical values**. The dam and appurtenant structures may be protected under the National Historic Preservation Act, and retention of portions of the dam may be desirable to preserve a particular element of the original design for posterity.
- **Future use and land ownership.** Land-use and landowner and stakeholder preferences should also be taken into consideration when establishing structure removal limits. Potential future ownership and development may also be a consideration.
- **Costs.** Removing only the portions of the dam, and apparent structures, required to meet the project purposes is generally less expensive than removing everything. The retention of some structures may help with historic preservation and may help stabilize stream channel banks in the vicinity of the removed dam. For example, portions of Savage Rapids Dam in Oregon were retained on both abutments to protect the streambanks and to reduce project costs.
- **Future stability.** Potential earthquake loadings and seismic stability should be considered for the retention of any large, tower-like structures (Hepler 2013).

Ancillary dam structures such as towers, poles, powerlines, and foundations should also be investigated to determine the extent and method of removal. The presence of utility lines extending through the dam or reservoir should be determined and if they need to be relocated. Transmission and distribution lines associated with hydroelectric dams may extend for several kilometers and may need to be retained to supply power from other sources. "Hydroelectric facilities may be directly connected to the local distribution grid, and the loss of this service capability should be evaluated. Separate active transmission or utility lines may be underhung on the poles and would need to be retained" (USSD 2015). If a diversion dam is removed, a new location and means of diverting water from the stream may have to be established and connections made to existing canals and pipelines.

5.1.2. How Can These Structures Be Removed Safely?

Site conditions, dam materials, and dam safety considerations will influence the choice of demolition methods and dam removal cost. Large dams require more time for removal than smaller dams and contain greater volumes of materials for which disposal sites must be found (ASCE 1997). Consider the following treatments of materials and features:

For more information, see Section 6.6. *Demolition and Removal* in USSD 2015

- **Embedded materials.** Any available drawings should be carefully consulted to determine the presence of embedded materials (for example, steel rebar, grouted post-tensioned tendons, wood). Historic construction photographs (if available) can also provide clues regarding embedded materials. Mechanical and electrical items that are not embedded in the concrete should be removed prior to concrete demolition. Many dams have embedded materials that are not documented—so planners and contractors should prepare for encountering the unexpected.
- **Electric power** should be shut off and hydraulic fluids should be drained.
- **Hazardous materials** should be identified prior to demolition and handled appropriately.
- **Structure stability**. The stability of remaining structures should be considered at all times during demolition. For example, removing a downstream stability berm at the toe

of a concrete gravity structure, while under hydrostatic pressure, could result in a sliding failure or a foundation blowout. Similarly, a drainage blanket and downstream berm may have been added to an embankment dam to control seepage and protect against internal erosion failure. The long-term stability of any structures to be retained should also be considered, especially those subject to hydraulic forces.

- **Public safety.** Some site modifications may be required to ensure public safety; such as permanently closing abandoned tunnels; backfilling canals; and installing fencing, warning signs, and guardrails.

Removal methods for concrete dams include:

- **Drilling and Blasting.** For large concrete volumes, drilling and controlled blasting are generally the most economical and effective demolition methods, where permissible (USSD 2015). Controlled blasting may also be used to topple tall metal structures such as surge tanks for powerplants.
- **Mechanical Demolition.** Mechanical demolition methods are very common for smaller dam removal projects and can be used in larger projects as well (Figure 10). For example, a large reinforced concrete intake tower at Glines Canyon Dam was toppled by line drilling and blasting near the base, and then removed by mechanical methods.

Figure 10. Mechanical excavation of the upper portion of Glines Canyon Dam in Washington, using a hydraulic excavator on a barge (USSD 2015). (Photograph courtesy of National Park Service, January 14, 2012).

- **Diamond-wire sawcutting.** Diamond-wire sawcutting uses a continuous loop of diamond-impregnated wire to sawcut concrete. This method normally requires some drill holes and rollers to establish the wire loop. This method is more expensive than blasting or mechanical demolition, but may be useful for special applications or conditions, such as the removing a concrete gravity weir without impacting an adjoining abutment wall.

- **Chemical demolition.** Chemical expansive agents mixed with water in drilled holes may be used to produce cracks in concrete or rock without sound or vibration. Concrete fractures can occur within 10 minutes to 24 hours, depending upon the mixture and site conditions. The cracked concrete or rock can then be removed by mechanical methods.
- **Hydroblasting.** Hydroblasting uses high water pressures, typically for removing weaker surface material on a concrete face.
- **Flame-cutting.** Flame cutting uses an oxygen thermal lance (reaching 3,000 degrees Celsius [°C] or higher) for cutting high-strength, heavily reinforced concrete and steel pipes.

Earthfill and rockfill embankment dam removals should follow a sequence and may be removed using common excavation methods and earth-moving equipment:

1. First, remove and dispose of ancillary materials to the extent possible. These materials would include embedded instruments, sheet pile or concrete core walls, roadway pavements, guardrails, and concrete slope protection.
2. Remove the dam from the top down to avoid forming steep slopes. A controlled dam breach under reservoir head may be considered for removing a small, low hazard embankment dam, or for removing the lower portion of a large embankment dam—provided the resulting outflow and erosion of earth materials would not cause significant erosion along the downstream channel or harm humans, property, or streamside infrastructure.

5.1.3. How Will Construction Equipment, Materials, and Staff Access the Site?

See USSD 2015, Section 6. for more detailed information.

> For more information, see Section 6. 2 *Site Access and Mobilization* in USSD 2015

Construction access to the project site and waste disposal areas should be considered upfront and will often drive construction processes (e.g., need for blasting) and cost estimates (as more difficult access will require more equipment or more costly alternatives to truck hauling). Access roads may not be suitable for modern construction equipment or current safety requirements. A narrow, deep canyon site, or a remote location, may severely restrict construction access, and may require creative options to move equipment and materials. Example access options are:

Improve existing access roads. Significant improvements to existing access roads and bridges may be required to perform the work, and should be considered in the project cost and construction schedule.

- **Construct a new site access road.** At Elwha Dam, in Washington, contractors improved an old logging trail on the left abutment of Elwha Dam to remove heavy construction equipment after dam removal and restoration.
- **Use a helicopter or barge.** Helicopters were required for the removing Bluebird Dam in a remote location of Rocky Mountain National Park, Colorado as described in Section 7.2. At Glines Canyon Dam, Washington, contractors floated construction equipment on a barge in the reservoir pool.

- **Erect a large crane on one or both abutments**. At Glines Canyon Dam, Washington, contractors used a large ringer crane on the left abutment of the large concrete arch dam to support demolition activities (Figure 11).
- **Install an overhead cableway across the canyon.** The cableway can then be used to move equipment and materials to and from the bottom of the canyon and to either side of the canyon.

Additional areas may be required for construction offices and for temporary stockpile and storage sites. Site restoration requirements should specify whether the cleared areas, site access roads, or other removal infrastructure will be preserved or removed, depending on the future land use.

Figure 11. A large ringer crane was employed at Glines Canyon Dam, Washington in 2015 (Reclamation/Randle).

5.1.4. What Will Be Done with the Dam Structure Materials?

As USSD 2015 notes, "the volume of material in an earth or rockfill dam is normally much greater than that required for a concrete dam of the same height, but excavation and disposal of the earth and rockfill materials is usually much easier." Determine waste disposal compositions, locations, methods, and hazardous waste concerns:

For more information, see Section 6.7 *Disposal of Removed Materials* in USSD 2015

- **Determine waste compositions and final use.** Determine the composition of each material to determine appropriate disposal methods. For example:
    - On-site burial within a scour hole in the river channel may be most desirable where possible. For example, concrete rubble up to 40 centimeters (cm) in diameter was allowed to be buried on site in 0.6-m lifts during the removal of Elwha Dam. Scour holes often form immediately downstream from dams and those scour holes would otherwise fill with sediment after dam removal.

- On-site disposal may require special permits and approvals from state and local entities and may be limited to the burying of earth materials and concrete rubble.
- Recycling and reuse. Costs can be reduced by recycling. Concrete crushing and recycling may be an economical option for waste disposal (Hepler 2013). Waste concrete can be crushed for reuse as a road base or other construction materials in areas where supplies are limited. Mechanical and electrical items should be evaluated for potential salvage value, either intact for its commercial or historic value, or recycled for its metallic components (such as steel, stainless steel, bronze, cast iron, and copper). Costs to remove Spoonville Dam in Connecticut were fully paid by recycling waste materials (USSD 2015). Earth and rockfill embankments can provide a source of clay, sand, gravel, cobbles, and rock for site restoration or for local commercial use.

- **Identify suitable waste disposal sites.** The Engineering Design Team or the contractor should identify these sites within a reasonable haul distance and determine haul routes, timing, and haul capacity. As planning and permitting for developing a new disposal sites can take years, investigate existing sites thoroughly. For example, borrow areas used for the original construction may be used for waste disposal if available.
- **Determine disposal methods for each material.** Some waste disposal sites may require special separation of materials prior to disposal, such as removing reinforcing steel from concrete, separating combustible and non-combustible materials.
- **Identify and handle hazardous materials**. Dam removal materials may include petroleum products, contaminated coatings (such as lead-based paint), asbestos insulation, polychlorinated biphenyls (PCB), batteries, chemicals, and other contaminants which will require special handling and disposal in accordance with Federal, state, and local laws. Detailed records and current testing results may be required to ensure proper handling of waste materials. The type and amount of contamination will affect the degree of special handling required (ASCE 1997). In the USA, testing, labeling, manifesting, transporting, and disposing of hazardous materials are regulated by Federal and state law. Additional testing is often required during the construction phase as more areas and features become accessible.

For any disposal site, consider the potential for groundwater contamination and site restoration:

- **Groundwater contamination.** Impermeable linings or deep cutoff walls may be required around the perimeter of a site to contain disposal materials without increasing the potential for groundwater contamination. Observation wells may be required for monitoring potential groundwater movement and contamination (ASCE 1997).
- **Restoration.** Restoring the disposal site may include placing topsoil, seeding, and other plantings. See Section 5.1.9. *What Will Need to Be Restored?*

5.1.5. How Will Organisms and Materials in the Reservoir Be Handled?

Determine how to handle fish, sediment, and historic properties.

- **Fish.** Identify fisheries resources in the environmental assessment, and consult biologists and other experts on relocating native fish.
- **Sediment.** Determine how reservoir sediment will be managed (See Section 6. *Sedimentation Management and Monitoring*).
- **Historic Properties.** Special handling and cataloging of historic and prehistoric artifacts and cultural resources found in the dam or uncovered in the reservoir. Historic artifacts may be found within the reservoir area. The original cofferdam used for construction of the dam will often be found upon reservoir drawdown and generally should be anticipated. Historic properties experts can be consulted when these artifacts are uncovered.
- **Other Materials**. Construction debris, abandoned cars, and trash will also have to be removed. Plan for a disposal process.

5.1.6. How Will the Reservoir Be Drawn Down?

For more information, see Section 6.3 *Reservoir Drawdown* in USSD 2015

During drawdown, reservoir releases will exceed inflow by the volume and rate of reservoir drawdown, which can be significant for a large reservoir. Reservoir capacity tables, storage-elevation curves, streamflow records, and operational records should be examined to determine mean, minimum, and maximum releases and daily flows during reservoir drawdown. Consider the planned drawdown timing, release capacity of the dam and reservoir, and storage characteristics of the reservoir:

- **Seasonal timing.** Reservoirs may already be drawn down at the end of the low-flow season, reducing the remaining drawdown requirements and the potential for increased flows downstream. The removal of San Clemente Dam only occurred during the low-flow summer months over three years (see Section 7.5). When possible, scheduling reservoir drawdown in advance of dam removal can provide additional flood storage within the reservoir.
- **Discharge rating curves.** These curves predict the discharge released from the reservoir through dam outlets and spillways as a function of a specific gate opening and the reservoir water surface elevation.
- **Operating and dam safety restrictions.** Average reservoir drawdown rates may have to be limited to avoid landslides along the reservoir shoreline and avoid fish stranding. Reservoir drawdown rates may be limited to between 0.3 and 0.6 m per day. Even these rates may not be slow enough if slopes along the reservoir shoreline are composed of slow draining materials that are marginally stable. However, rapid reservoir drawdown may be appropriate for smaller dam removal projects or where slope stability is not a concern. The reservoir behind Condit Dam on the White Salmon River in Washington was drained within about an hour when a large hole was blasted through the arch dam near its base. The rapid rate of reservoir drawdown did induce numerous slope instabilities along the reservoir shoreline.

- **Maximum discharge rate.** Determine safe discharge rates from the dam to avoid potential downstream consequences. The safe discharge rates are based on the release capacities of the spillway and outlet structures and the safe channel capacity of the downstream channel. Flood hazard analyses, emergency action plans, or downstream inundation maps should be consulted to determine to safe channel capacities. Be aware that any new downstream residential or commercial developments may have encroached on previously established flow boundaries. Any low-water crossings may be inundated or even eroded by sustained releases and mitigation may be required.
- **Modifying the dam or adding pumps.** For example, siphons or pumps may be added to a dam or spillway crest to temporarily increase the upper level release capacity for reservoir drawdown; however, siphons are normally limited to a lift height of 6 m between water surface and crest, and pipe flow velocities may be limited to 3 meters per second (m/s).
- **Reservoir siphons and pumps.** Siphons or pumps could be added to a dam or spillway crest to temporarily increase the discharge capacity for drawing down the upper level of the reservoir drawdown. However, siphons are normally limited to a lift height of 6 m between reservoir water surface and dam crest elevation. Pipe flow velocities may be limited to 3 m/s.
- **Potential blockages.** Consider the potential for flow blockages through the dam outlets from debris and sediment, which may need to be removed prior to, and during, dam removal.
- **Sediment management.** Coordinate with the sediment management plan (See Section 6.3. *Sediment Management Alternatives*). The rate of reservoir sediment erosion is primarily a function of the rate of reservoir drawdown (Randle and Bountry 2017). The rate of reservoir drawdown is often linked to the rate of dam removal. For reservoirs that have only trapped less than one or two years of upstream sediment load, the rate of erosion may not be that important. However, for reservoirs that have trapped decades of upstream sediment load, the rate of sediment erosion and downstream release can be quite important. Rapid rates of sediment release from the reservoir can cause substantial downstream deposition, bank erosion and channel widening, increased flood stage, and even channel avulsion. These impacts can be avoided by slowing the rate of reservoir drawdown. However, the rate of reservoir drawdown should not be so slow that many years are required to remove the dam and drain the reservoir. For example, the rate of reservoir drawdown for removing Elwha Dam and Glines Canyon Dam in Washington was limited to a maximum of 1 m every 48 hours, with hold periods of 14 days for every 4.6 m of drawdown, for sediment management considerations (Hepler 2013 and Randle et al. 2015). Higher flows may be needed to transport the eroded sediment downstream, which could result in further delays to the dam removal and reservoir drawdown process.
- **Fish passage.** Avoiding downstream impacts to fish from high sediment concentrations and turbidity could be accomplished by halting reservoir drawdown during certain time periods important to fish. This was implemented during the Elwha River Restoration Project (Hepler 2013 and Randle et al. 2015). Three time periods were established, known as “fish windows,” covering a total period of 5-$^{1}/_{2}$ months per year: May through June, August 1 through September 14, and November through December. For this

project, turbidity only significantly lowered during the fish window of August 1 through September 14 when reservoir inflows were low (Bountry et al. 2018). Turbidity remained high during the other two fish windows—but likely would have been even higher without the fish windows. The three fish windows did allow more time for reservoir sediment erosion and downstream transport, which avoided sedimentation impacts to the downstream channel, stream-side infrastructure, and property.

- **Contaminated or Hazardous Materials.** Contaminated water or sediment may also contain hazardous materials. Section 6.2.3 describes how to evaluate the potential for contaminated sediments. Water with toxic or other pollutants may need to be treated or isolated before dam removal. Even accidental dam removals where a dam or plug holds back contaminated water can cause environmental impacts. For example, the Gold King Mine spill in 2015 occurred when pressurized water was accidentally released from tunnel entrance (adit) excavations. This spilled over 11 million liters of wastewater—affecting fish, wildlife, tourism, and agriculture. EPA agreed to fund $3 million in clean water projects in Utah and give another $360 million to the state for remediation projects at abandoned mine sites in a settlement, and other lawsuits are still pending (McCombs 2020).

5.1.7. How Will the Remaining Water Be Drained?

For more information, see Section 6.3 *Reservoir Drawdown* in USSD 2015

While ideally, outlet works would be near the original streambed and be large enough to drain the reservoir (ASCE 1997). However, a reservoir pool will usually remain behind the dam after releasing the most water through the existing spillways and outlets. To remove water from the remaining reservoir pool, at least some portion of the dam will have to be removed. Engineering options for draining the lower part of the reservoir are listed below. For each project, determine the economic costs and benefits of each option.

- **Putting a hole in bottom of the dam.** This can create an effective way to move a smaller amount of water behind a dam. The reservoir behind the 38-m high Condit Dam, on the White River in Washington, was lowered in 90 minutes after a hole was drilled through the bottom of the dam (See the National Geographic video, Spectacular Time Lapse Dam "Removal" Video https://www.youtube.com/watch?v=4LxMHmw3Z-U). The rapid reservoir drawdown produced very high sediment erosion rates, slope instabilities along the reservoir shoreline, and hyper-concentrated flows downstream (Wilcox et al. 2014). After the reservoir was drained, the entire dam above the river level was removed in the dry.
- **Restoring or modifying historic outlets.** The discharge capacity through a dam might be increased by restoring or modifying old outlet structures. Original dam construction plans and photographs may provide details of water conveyance features used during construction that might not otherwise be evident. Restoring an old river diversion channel or tunnel for reservoir drawdown may be economically feasible for larger projects. For example, restoring a diversion conduit and two diversion tunnels was proposed for the removing three large hydroelectric dams on the Klamath River in Oregon and California.

- **Notching.** A series of notches on alternating sides can be excavated by the contractor through a concrete dam to permit reservoir drawdown and then to remove portions of the dam in the dry. For Glines Canyon Dam in Washington, the upper portion of the concrete arch was notched from the upstream face using a hydraulic excavator on a barge; the lower portion was notched by drilling and blasting from the excavated crest surface (Figure 12).

Figure 12. Drilling and blasting notches to excavate the lower portion of Glines Canyon Dam in Washington (USSD 2015) (Photograph courtesy of National Park Service, July 1, 2012).

5.1.8. How Will Inflows During Dam Removal Be Handled?

For more information, see Section 6.5. *Streamflow Diversion* in USSD 2015

The ability to safely pass streamflow during dam removal is often critical to the dam removal process, especially for an embankment dam, which is much more vulnerable to erosion from overtopping stream flows than a concrete dam. Hydrologic streamflow and weather records should be evaluated to determine probability of high inflows during construction. Precipitation and stream gage monitoring can be used to provide warning of potential high inflows. Some options to aid in streamflow diversion during dam removal are summarized below:

- **Use an upstream storage or diversion.** Reduce reservoir inflows by storing or diverting flows upstream of the project site.

- **Use alternative diversion methods around the dam**. Some form of flow control should generally be provided for the diversion facilities, especially for those requiring streamflow to pass through the dam or abutment well below the reservoir surface. Methods for diverting flows around dam removal area include:
    - A surface diversion channel around the existing dam and reservoir, as was done for removing Saeltzer Dam in California. Surface diversion channels may consist of an excavated rock channel, a lined earth channel, or a temporary flume or pipeline
    - An upstream cofferdam and temporary pipes for the diversion of streamflow through the worksite as was done on Battle Creek (Figure 13).
    - A new diversion tunnel through one of the abutments may be considered (where suitable geologic conditions exist) (Hepler 2013).
    - A modified or new diversion outlet. An ungated outlet was excavated through the base of Condit Dam in Washington for reservoir drawdown, with the final blast producing a controlled breach of the upstream face and rapid releases, draining the small reservoir within 90 minutes.

Figure 13. Temporary cofferdam and diversion pipeline designed and constructed to isolate the left end of Wildcat Dam on the North Fork of Battle Creek in California (Reclamation).

- **Use temporary structures.** Temporary cofferdams, bypass channels, flumes, culverts, and pipelines may be used, along with dewatering wells and erosion protection, to provide dry conditions for dam removal construction activities. Dry conditions may be needed for some projects, especially removing earthen dams. However, many concrete dams could be removed in the wet without using coffer dams. Input from the construction organization will be helpful for determining the need for construction under dry conditions. For example:
    - A sheet pile cofferdam and a lined bypass channel were constructed while removing Saeltzer Dam in California and to excavate contaminated sediments from the small impoundment area (Figure 14).
    - Sheet piles and geotextile fabric were used to construct a cofferdam to isolate the right end of Savage Rapids Dam in Oregon.
    - Large sandbags or water bladders were used for cofferdams on Battle Creek in California, with streamflow diverted through temporary pipes.

Figure 14. Lined bypass channel designed and constructed for removing Saeltzer Dam and contaminated sediments from Clear Creek in California (USSD 2015) (Reclamation/Hepler).

- **Plan for floods**. Critical operations during dam removal may require some degree of flood protection, depending upon the estimated duration for the work and the potential consequences in the event of failure. Seasonal frequency floods for the time of year planned for dam removal should normally be developed in advance to help assess the risk of inundation or overtopping. Use overtopping protection, freeboard, and riprap to ensure the remaining dam structures are protected during potential floods. For many small dam removals, the construction window is so short that this level of flood protection may not be needed.
- **Remove in wet conditions.** Removing small concrete dams may be permitted in the wet, without the need of coffer dams and streamflow diversion.

5.1.9. What Will Need to Be Restored?

For more information, see Section 6.8 *Site Restoration* in USSD 2015

Restoring the construction area and former reservoir will be based on the project purpose, long-term land use plans, and permitting requirements. Long-term ownership and maintenance of any retained structures must be considered. The former reservoir area, any remaining structures, and downstream channel may have to be modified to ensure public safety, restore habitat, or to reduce long-term operation and maintenance requirements. The overall restoration plan should be developed as part of the larger project plan. Natural physical and biological processes of the river should be incorporated into the restoration plan to the extent possible. Elements of the restoration plan include:

- **Stream channels.** The stream channel is normally restored to a natural (equilibrium) alignment and grade. Stream flows may naturally form a channel through the former reservoir and dam site. Excavating a pilot channel may be necessary through wide reservoirs to restore the pre-dam channel alignment. If a channel has to be constructed, use of natural streambed materials and allowing room for future channel migration will often be less costly than the construction and maintenance of an armored and confined channel. A low-flow or stepped channel could be designed for smaller projects to help control the stream location through the former reservoir area. A stepped channel was constructed after removing Hall Brook Dam in Massachusetts (See Section 7.3). In some cases, a weir structure may be needed to retain a portion of the reservoir sediments or prevent the upstream passage of invasive fish.
- **Fish passage.** For dams that had some fish passage facilities, continued fish passage may be desired, or required, during dam removal. Any retained portions of the dam must be stable and may have to accommodate fish passage for a certain range of flows.
- **Flood flows.** Remaining portions of the dam may need to be evaluated and modified to ensure that they can safely withstand a design flood of a certain frequency (e.g., 100-year flood peak). The design flood would depend on the potential consequences of failure or as required by regulatory agencies. downstream sediment aggradation is anticipated, dikes or levees may be needed to avoid potential flood damage.
- **Ground surface elevations.** Stilling basins, downstream plunge pools, powerplant tailrace areas, building foundations, and canals may have to be backfilled to the pre-dam ground surface. Steep slopes may need recontouring to provide stability.
- **Unstable slopes or other areas.** Stability berms or retaining walls may be required to stabilize potentially unstable slopes or landslide areas following reservoir drawdown.
- **Remaining structures**. Remaining structures may require some long-term operation and maintenance activities, and eventual replacement, that should be considered in any decision for partial removal. Buried pipelines should generally be removed or stabilized to prevent future deterioration and collapse. Tall and slender structures, such as intake towers and surge tanks, may be susceptible to toppling during an earthquake and should be removed to avoid potential risks. Heating systems may be required to reduce the potential for temperature-related structural damage in colder climates, and roofs may need to be maintained to avoid water damage. Electric service may need to be maintained at the site to meet these requirements.

- **Vegetation.** Newly exposed areas of the reservoir may be vulnerable to invasive species. Therefore, planting native vegetation and controlling invasive species may be required. Topsoil and seeding should generally be provided over any backfilled areas to promote revegetation (ASCE 1997) unless sufficient organic material is already present in the sediment. Depending upon site access, revegetation may be performed by hand, truck, barge, or helicopter.
- **Cultural resources protection.** The dam may deserve historic preservation under the National Historic Preservation Act of 1966 and as amended through 1992 (Public Law 102-575). Historic preservation could be through the retainment of structures or the documentation of features through as-built drawings, photographs, and reports about operations, maintenance, repairs, and upgrades. Cultural resources of Indian tribes (archeological sites and traditional cultural properties) may have been impacted by the construction of the dam and reservoir. Dam removal may present opportunities to preserve or restore some of these impacted cultural resources. Draining the reservoir may allow for the restoration of historic landscapes, but may also make some cultural resources vulnerable to theft and vandalism. Local Indian Tribes should be consulted on how best to preserve these cultural resources.
- **Public access.** Interpretive signs, walkways, safety railings, and restrooms may be needed to facilitate public use. Special accommodations for disabled visitors may be necessary in accordance with the Americans with Disabilities Act (ADA), including paved ramps and accessible restroom facilities (ASCE 1997).
- **Safety and Security.** Remaining portions of the dam and ancillary facilities may need site security (e.g., fences and warning signs) for public safety and to reduce liability. Remaining portions of dams and appurtenant structures may pose an attractive nuisance for recreation or may invite trespassing and vandalism. Tunnel portals may need to be plugged or backfilled to prevent entry, with possible special provisions for future inspection and drainage (Figure 15).

Figure 15. At Glines Canyon Dam, Washington, the upstream tunnel barrier (left) was blocked using precast concrete panels while the downstream tunnel barrier (right) was blocked using metal panels (USSD 2015) (Reclamation/Hepler).

5.2. Design Process

The Engineering Design Team will need to gather design data, determine the basis of design, develop the design, review and revise the design, and then monitor construction activities to determine if the project can be completed according to the design and specification, and if changes are needed to successfully complete the project. While these steps may be streamlined and accelerated in an emergency dam removal, the same basic principles and processes will apply.

5.2.1. Collect Data

The more that is known and understood about the dam's composition, design, and history, the more likely the successful completion of the project. The collection of sediment design data is discussed in more detail in Section 6, Sediment Management and Monitoring.

For more information, see Section 4.2.2. *Design Data Collection.* in USSD 2015

Data collection types include:

- **Structural.** Collect historic design, inspection, and operating data for all structures at the dam site and within the reservoir area, as well as all upstream and downstream structures that may be impacted by removing the dam, such as bridges, pipelines, groundwater wells, and transmission lines. New as-built drawings, reflecting current conditions, may have to be prepared based on field measurements, borings, and topographic surveys. These data would be necessary for the preparation of drawings, specifications, and quantity estimates. Try to obtain information about the operating history and present condition of gated spillways and outlet works for reservoir drawdown. Develop a complete inventory of mechanical and electrical equipment to be removed, including weights (if available) and data on overhead and subsurface utilities and embedded items. Drawings prepared for the dam removal specifications may be useful for preparation of the required Historic American Buildings Survey and Historic American Engineering Record documents (https://www.nps.gov/hdp/). Determine locations and haul distances for backfill materials and for disposal of waste materials.
- **Stability.** The site's geology and soil conditions should be assessed so that any necessary measures can be implemented to avoid slope stability issues (such as landslides or reservoir or embankment slope failures)
- **Hydrology.** Streamflow and precipitation data should be compiled and evaluated to understand the probability of flood flows during dam removal and over the long term. Information needed would include flood frequency peaks, simulated routings of floods, and streamflow stage-discharge relationships.
- **Sediment transport.** Channel hydraulic data (profiles of water surface elevation and water depth, channel and floodplain bathymetry and topography, and bed-material grain size distribution) may also be required for sediment transport and river erosion models to predict important changes to water surface elevations, flow depths, velocities and erosion and deposition of sediments.

5.2.2. Provide Feasibility Designs to Evaluate Alternatives

For more information, see 4.3.1 Feasibility Study in USSD 2015

Prepare feasibility designs for a range of alternatives of sufficient detail to define major cost drivers and obtain quantity data for cost estimating purposes. Cost assessments should include dam removal construction activities, dam site and reservoir restoration costs, and any long-term operation and maintenance costs. The designs and cost estimates should be detailed and accurate enough to identify the least cost alternative and any alternatives that should be eliminated due to cost, safety, or environmental reasons. One or more project alternatives may be selected for further evaluation. A Feasibility Report (or Detailed Plan Report) would normally be prepared for larger projects to summarize these design studies and alternative evaluations.

One or more project alternatives may be selected for further evaluation. A Feasibility Report (or Detailed Plan Report) would normally be prepared for larger projects to summarize these design studies and alternative evaluations.

5.2.3. Refine Designs

Some of the feasibility designs and cost estimates may need further refinement to select a preferred alternative. In addition, a promising alternative may need to be redesigned to address review comments from the Engineering Design Team, stakeholders, and decisionmakers. This may require collecting additional data, providing greater design detail, and addressing any issues identified during the feasibility design review.

5.2.4. Develop the Preferred Alternative Design: 30 Percent Design

This more advanced design is developed for the preferred alternative (or proposed action) to reflect the necessary design changes and to update project cost estimates. A "Basis of Design" report is written to establish the final design data and design assumptions. This design stage may correspond with the "30-percent design" for a private, state, or Federal project and will normally include preliminary drawings of the primary project features. The 30-percent design package for can be used as the basis of a final design-build contract as was done for San Clemente Dam in California. (See Section 7.5.) Value engineering studies and an independent review may be required to evaluate the preliminary design for technical adequacy and potential cost savings or improved performance.

5.2.5. Project Funding and Approval

Project funding should be obtained before issuing a contract or soliciting requests for proposals. Final project approval by a regulatory agency (such as a FERC determination for modification of a licensed hydroelectric project) may be required before the award of a construction contract.

While having all permits issued prior to contract award is best, this may not be necessary and could cause a project delay. The specifications will normally indicate the status of critical permits for larger projects, but may require the contractor to apply for one or more permits.

5.2.6. Prepare the Final Design and Specifications

For more information, see 4.3.4 Final Design in USSD 2015 and Reclamation Final Design Process Guidelines (2017), available on request from authors.

A final design summary should be prepared for a large project to document both the design process and any design changes made during construction. Final designs and specifications are based on the 30-percent design for the preferred alternative after regulatory agencies and key stakeholders express approval and a funding source is identified.

Final design specifications for dam removal include:

- **Existing site details.** Include as-built drawings of existing structures.
- **Project requirements.** Contractors usually develop the specific construction and action methods to meet these requirements (for example, streamflow diversion and structure demolition), which the Engineering Design Team and Project Managers/Decisionmakers approve through a specified submittal and review process.
- **Special resource considerations and mitigation measures**. Develop these from the environmental assessment of impacts conducted in Section 4.7.
- **Special site restrictions.** Examples include reservoir drawdown rate limitations or the prohibition of blasting; construction sequence requirements; additional site explorations, such as hazardous material assessments and sediment characterization; protection of existing structures and utilities; and public protection requirements; or any environmental constraints, such as in-water work periods and noise restrictions should be included in the specifications.

5.2.7. Determine the Final Construction Schedule

The final design for a dam removal project should identify the major construction activities, sequence, estimated resource requirements and durations, and a proposed schedule incorporating any constraints on reservoir drawdown or construction activities. Any necessary work downstream from the dam in the stream channel (for example, removing old construction debris) should be performed before dam removal. Features providing project benefits should be removed as late as possible to maximize benefits. As noted in USSD 2015, “For large projects, an independent constructability review may be required to ensure that the construction approach is sound and that nothing of significance has been overlooked. For smaller projects, the engineer may seek input from experienced contractors during the final design stage.”

Construction schedule considerations include:

- **Environmental requirements.** Negotiate when work is permissible based on environmental requirements. The final design specifications should include any potential schedule constraints including key fish spawning, bird nesting, or winter hibernation periods of sensitive species that could be affected by the project.
- **Flow timing.** In-water work should be scheduled while upstream diversions are available to minimize streamflow through the worksite. In-stream work should normally not be scheduled during periods that could be interrupted by high flows, as defined by river stage or by flow rate, unless necessary to meet project requirements. Allowances for adverse weather conditions and potential flood flows should be considered in the schedule by providing extra time.

- **Downstream impacts and mitigation.** Downstream structures may need to be retained as fish barriers until upstream work is completed. Mitigation measures such as water treatment plants, new wells and flood protection levees may be required before dam removal and the natural release of impounded sediments, as was the case for Elwha and Glines Canyon Dam removals in Washington.
- **Materials**. Excavated and removed materials should be handled as few times as possible to reduce costs. A materials distribution plan can be developed during final design to identify the volumes of various excavated materials, including hazardous materials and their intended use in final construction, reuse, or disposal.

5.2.8. Issue and Oversee Contracts

Construction oversight is necessary to ensure that project goals are met, and the project is implemented safely. Contractors performing the work may have more efficient methods to improve project outcomes or decrease costs. Open and constructive communication between the organization issuing the contracts and the contractors performing the work will foster a team approach and more likely lead to an even more successful project (e.g., improved safety, improved restoration, and less cost).

5.2.9. Monitor and Manage for Change for Dam Removal

Changes to the final design may be necessary during construction, depending upon the actual site conditions encountered. Old buried dams and other structures may be encountered in the reservoir area or dam site for the first time during project implementation. Such structures may require changes to the contract, which are normally handled as contract modifications for a price negotiated with the contractor.

6. Sediment Management and Monitoring

Reservoir sediment management is often a critical issue related to dam removal when many years or decades of upstream sediment load have been trapped within the reservoir. Many small dams that have been removed only trapped up to a couple of years of upstream sediment load and the downstream release of this sediment generally did not cause large and sustained environmental impacts. However, the erosion and subsequent release of much larger reservoir sediment volumes can result in significant effects to downstream water quality and sediment deposition, which can result in a wider range of grain sizes, shallower pools, wider channel widths, increased rates of channel migration, and increased flood stage (Greimann 2004 and Randle and Bountry 2017).

Rivers naturally transport sediment at various rates, depending on hydrologic, geologic, biologic, and human-influenced factors (Randle and Bountry 2017). Thus, when a dam is constructed and the reservoir is filled with water, sediment that would normally have continued downstream accumulates over time in the tranquil waters of the reservoir. Sediment accumulates at all elevations of a reservoir with coarse particles depositing first at the upstream end to form a delta and fine sediment depositing farther downstream along the reservoir bottom (lakebed sediments). Small reservoirs may fill with sediment (to their sediment-storage capacity) within the first few years of operation, so that additional sediments, supplied from upstream, pass through the reservoir. However, large reservoirs can continue to trap sediments for many decades. Therefore, when many years or decades of upstream sediment load have been trapped within the reservoir, sediment monitoring and management is a critical component of dam removal. The sediment management and monitoring plan should be integrated into the overall dam removal planning process, as described in Section 4.

If the reservoir contains significant quantities of sediment, a sediment management plan should be developed to understand and mitigate potential impacts from sediment erosion, transport, and deposition (Shuman 2002 and Macbroom and Schiff 2013). The Dam Removal Analysis Guidelines for Sediment (Randle and Bountry 2017) provide a ten-step procedure for engineers and scientists to follow. These ten steps identify sediment concerns, assess the risk of impacts, develop alternative sediment management plans, analyze impacts, and develop adaptive management monitoring plans (Figure 16). A risk-based approach is recommended so that the level of data collection and analyses are proportional to the level of risk. The sediment analysis guidelines are applicable for reservoirs with small, medium, and large sediment volumes. However, many small dams have been removed with little or no sediment and no significant sediment impacts. Therefore, there are special criteria for reservoirs with a negligible sediment volume.

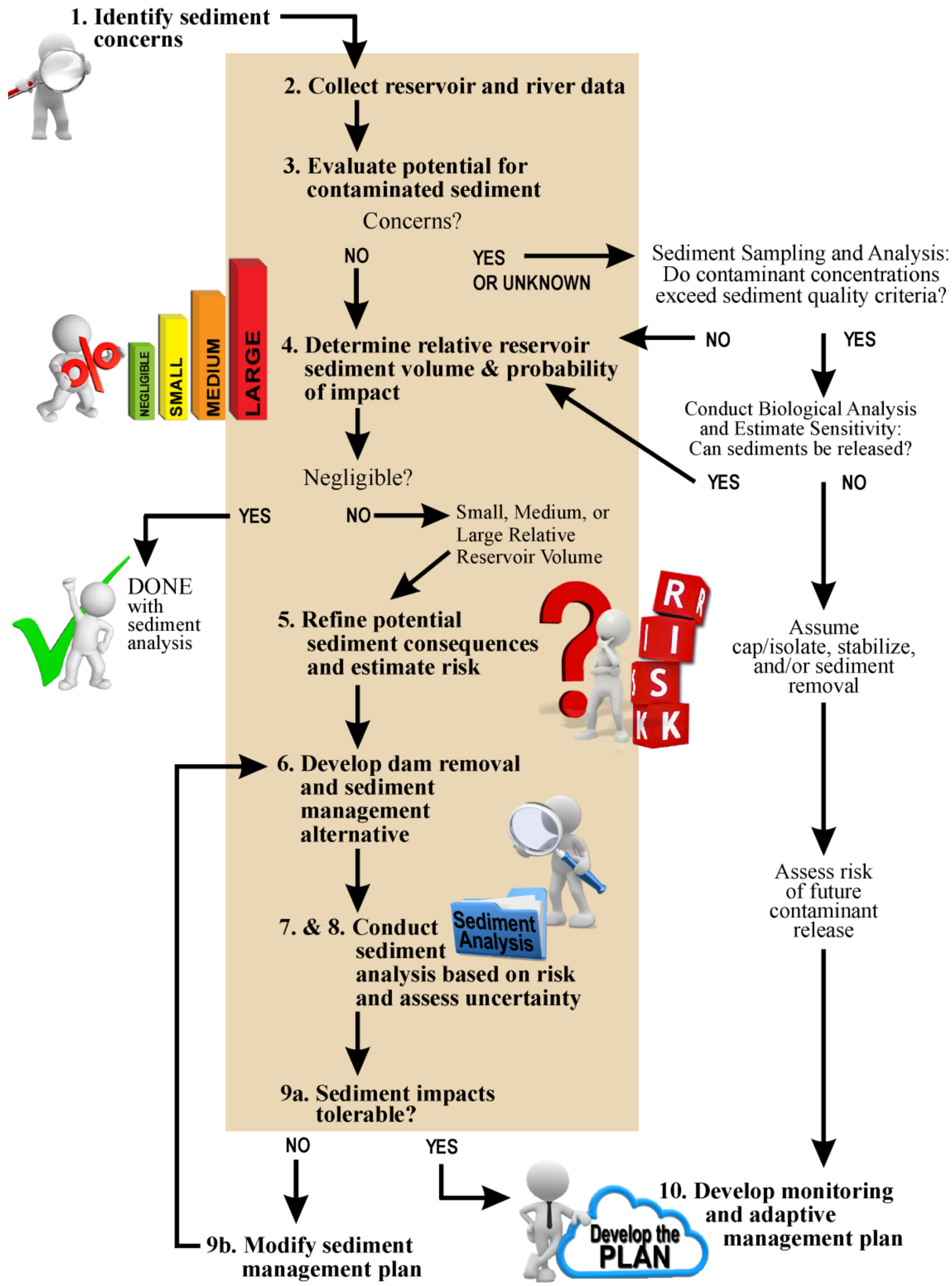

Figure 16. Sediment analysis steps for dam removal (Randle and Bountry 2017).

6.1. Cases of Negligible Reservoir Sediment

For more information, see *Cases of negligible reservoir sediment* in Randle and Bountry 2017.

Reservoir impoundments with little or no sediment are typically behind low-head dams that are operated as run-of-the river facilities. The water volumes of these small impoundment are typically no more than 0.1 percent of the mean-annual river flow.

When the reservoir sediment volume is low, streamflows would be expected to rapidly erode and transport such a negligible volume. When there is little to no risk of sediment-related impacts, there is no need for extensive sediment data collection and analysis and no need to develop a comprehensive sediment management plan. The design team can focus on structural and river hydraulic issues related to removing the dam—rather than on assessing sediment impacts. (Randle and Bountry 2017). For example, the Gold Hill Dam, Oregon, was a run-of-the-river dam that had less reservoir sediment than the typical upstream gravel bar. As there were no contaminants found in the sediment, the river was allowed to erode and transport the 350 m^3 of reservoir sediment downstream—and no significant sediment impacts were detected (Randle and Bountry 2017).

When the reservoir sediment volume is less than the typical volume of sand or gravel bars along the stream channel, or less than 10 percent of the river's average annual sediment load, then reservoir volume can be considered negligible. The reservoir sediment volume can be estimated from a map of the reservoir bottom that shows the sediment thickness based either on measurements that probe the sediment thickness down to the pre-dam surface or underwater dive visual inspections when there is little or no fine sediment. The determination of a negligible sediment volume can be confirmed when the hydraulic height of the dam is comparable to the depths of deep river pools on the same or comparable stream channels. In addition, the longitudinal profile of the river and reservoir bottom (upstream and downstream of the dam) will not exhibit an elevated reservoir bottom, relative to the upstream and downstream channel reaches. Randle and Bountry (2017) provide methods to determine if the sediment volumes are negligible.

For a negligible reservoir sediment volume, the project may be eligible for a USACE Nationwide Permit 53 (USACE 2016). Compensatory mitigation is generally not required.

If the reservoir sediment volume is greater than negligible, or if contaminants are present and thought to be harmful, then the sediment analysis should proceed to the analysis steps described in Section 6.2.

6.2. Sediment Analysis Steps for Dam Removal

For more information, see *Step 1: Identify Sediment Concerns and Benefits* in Randle and Bountry 2017.

For reservoirs with more than a negligible sediment volume, sediment analysis and plan formulation will be needed. Analysis Steps 1 to 4 (Figure 16) identify potential sediment concerns from stakeholders, collect data, evaluate potential for contaminates, and determine the probability of impacts. Steps 5 and 6 focus on estimating the risk of sediment-related impacts and the development of alternative sediment management plans. Steps 7, 8, 9, and 10 focus on the assessment of impacts, uncertainty, refinement of the sediment management plans, and the development of monitoring and adaptive management plans.

Randle and Bountry (2017) recommend applying guideline steps 2 through 9 in an iterative approach. First, apply the guidelines with readily available information and develop the initial scope of sediment data collection, synthesis, analysis, and risk assessment. Initially, assumptions can be made, but these assumptions will need to be updated as more information becomes available. For reservoirs with only a few years of mean annual sediment load stored within the reservoir, consider an alternative with complete and rapid dam removal combined with a river erosion of the reservoir sedimentation. Analyzing this alternative 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 a rough estimate of sediment impacts (what is really important and what is less important). This iterative approach should identify where best to spend resources on data collection and analysis.

As more refined information becomes available, revisit guideline steps 2 through 9. Evaluate the predicted sediment consequences to determine if additional mitigation, monitoring, and adaptive management of sediment-related processes needs to be added to the alternative.

6.2.1. Identify Sediment Concerns and Benefits

In this step, the scope of the sediment analysis is determined based on the sediment concerns and benefits. Communication with stakeholders is necessary to identify these concerns and benefits.

Developing and presenting a conceptual model may help identify the concerns and benefits of releasing reservoir sediment as a result of dam removal. The conceptual model can be developed from literature (Doyle et al. 2002 and 2003, Cannatelli and Curran 2012, and Randle and Bountry 2017) and readily available project information. The model should qualitatively describe how the reservoir sediment may respond to dam removal and the potential downstream fate of eroded reservoir sediment. The model should be revised throughout the planning process as more information becomes available.

Stakeholder "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" (Randle and Bountry 2017). Sediment-related effects may occur within the reservoir and along the upstream and downstream river channels. Upstream effects are typically associated with incision through the reservoir delta rather than through the pre-dam topography.

Stream-side infrastructure (such as roads, bridges, and pipelines) constructed upstream and after reservoir sedimentation, could be subject to erosion during and after dam removal.

Within the reservoir, multiple channels may erode through the sediment deposits. Typically, one erosion channel will ultimately capture flow and erosion potential from the other channels. Channel erosion widths will tend to be narrow where the sediment is cohesive (clays, silts, and organic material) and wide where the sediment is non-cohesive. The effects of sediment cohesion were observed on Lake Aldwell and Lake Mills on the Elwha River in Washington (Figure 17 and Figure 18). For wide reservoirs, there is a risk that the alignment of the dominate erosion channel could end up along the reservoir margin and over an erosion resistant surface (such as boulders or bedrock), resulting in a waterfall that may block fish passage. If this were to occur, the pre-dam channel alignment and gradient through the reservoir would not be restored.

Figure 17. The effective cohesion of fine sediments (primarily silt) in Lake Aldwell, combined with the roughness provided by large wood, reduced lateral erosion of reservoir sediments during and after the removing Elwha Dam on the Elwha River near Port Angeles, Washington (photograph courtesy of National Park Service; August 18, 2014).

Figure 18. The absence of cohesion in Lake Mills sediments resulted in a wide, braided channel that laterally eroded the wide delta (in the absence of floods) while removing Glines Canyon Dam on the Elwha River near Port Angeles, Washington (photograph courtesy of National Park Service; June 2012).

Some portion of the sediment may remain as terraces within the reservoir after dam removal. However, additional erosion of these terraces may occur from post dam removal floods and tributary gully erosion from local runoff. The rate of post dam removal erosion will typically follow an exponential decay as the most vulnerable areas are eroded first, channels widen, floodplains form, and vegetation grows on sediment terraces (Randle and Bountry 2017). These processes were experienced along the Elwha River after the removing Elwha and Glines Canyon Dams near Port Angeles, Washington (Randle et al. 2015 and Bountry et al. 2018).

Tullos et al. (2016) evaluated the published results from several dam removals and identified common management concerns (expressed as questions), synthesized the results, and presented key findings which are summarized below. Many of the environmental effects are temporary and may be balanced by the long-term effects of river restoration.

- **What will the degree and rate of reservoir sediment erosion be?** The rate of reservoir lowering or drawdown tends to have a greater influence on the rate of reservoir sediment erosion than hydrology, except for large floods. The slower the rate of reservoir lowering, the slower the rate of sediment erosion. After dam removal, the timing and magnitude of subsequent floods determines the final equilibrium extent of lateral erosion. Of the reservoirs evaluated, the portion of reservoir sediment eroded and released to the downstream channel (one year after dam removal) ranged from less than 10 percent (where structures were installed to limit erosion) to 70 percent without sediment management (Tullos et al. 2016). More sediment was found to be retained within the reservoir when there was a high proportion of fine and consolidated sediment (predominantly clay) and when the reservoir was much wider than the river channel.

- **Will there be excessive channel incision upstream of reservoirs?** Incision through deltas, at the upstream ends of reservoirs and along inflowing streams, may create erosion problems for streambanks and infrastructure constructed after the reservoir sedimentation. Tullos et al. (2016) found that at any location, the maximum depth of incision through the reservoir sediment was generally equivalent to the thickness of the sediment deposit above the pre-dam reservoir bottom (Figure 19). Upstream incision stopped after the pre-dam river gradient was achieved. Erosion of the pre-dam surface is possible in wide reservoirs where the eroding channel is along a different alignment than the pre-dam river channel.

Figure 19. Over 15 m of sediment from the Elwha River was deposited in Rica Canyon upstream from Lake Mills since the construction of Glines Canyon Dam. This sediment subsequently eroded as Glines Canyon Dam, Washington, was removed (USSD 2015) (Reclamation/Randle November 12, 2013).

- **How much downstream sediment aggradation (deposition) can be expected?** Downstream sediment deposition can impact aquatic habitats and human water and land uses (Tullos et al. 2016). The volume of sediment aggradation and the duration that it persists are functions of the sediment volume eroded from the reservoir, the rate of that erosion, and river’s sediment transport capacity. Aggradation will increase with the ratio of the reservoir sediment volume to the mean annual sediment load. The greater the transport capacity, the smaller the volume of aggradation and the shorter duration that it will persist. Where the channel may have degraded downstream from the dam after its construction, at least some sediment aggradation can be expected to persist over the long term. The thickness of sediment aggradation tends to be greatest below the dam and then decreases with distance downstream. However, sediment transport capacity may be more important than the distance from the dam. Sediment aggradation will be greatest in river pools, eddies, and slack water areas and less in high-velocities areas such as rapids and riffles. Downstream lakes and reservoirs will often trap sediment released from upstream reservoirs. If sediment is transported to a coastal delta, then delta aggradation can be expected. Downstream water intakes may be vulnerable to sediment deposition if they are in slow velocity areas or if they withdraw a large portion of the total river flow.

- **What will the effects of elevated downstream turbidity be?** Suspended sediment and turbidity are naturally occurring and necessary components of many biophysical processes (Tullos et al. 2016). However, unnaturally high levels can have deleterious effects on the aquatic environment and for human uses. For example, elevated turbidity can prevent some fish species from finding prey and high sediment concentrations can cause abrasion to fish gills. Human uses such as drinking water, irrigation, recreation, and esthetics can be affected by increased sediment concentration and turbidity. Water treatment costs increase with increases in sediment concentration. Irrigation water can receive more nutrients, but larger size sediment could plug sprinkler or drip irrigation lines. Any contaminants could pose safety risks to recreation users. A river with elevated turbidity may have less esthetic value.

  Downstream suspended sediment concentrations and turbidity will increase as sediment is eroded from a reservoir. The magnitude and duration of increased sediment concentrations will increase with the ratio of the reservoir sediment volume to the mean annual sediment load. Turbidity will increase with the portion of fine sediment eroded from the reservoir. For many small dam removals, the increased magnitude and duration of turbidity is analogous to that of a natural storm (Tullos et al. 2016). However, for reservoirs that have been trapping sediment for decades, downstream sediment concentrations and turbidities could temporarily increase by an order of magnitude (Magirl et al. 2015).

- **How might reservoir drawdown affect local water wells and surface water intakes?** The loss of the reservoir would locally decrease groundwater elevations, which could lower the yield of wells that are hydraulically influenced by the reservoir (Tullos et al. 2016). Drilling new wells at deeper depths is the typical mitigation. Downstream water intakes could be affected by sedimentation deposition (clogging) and increased treatment costs for municipal and industrial water uses.

- **How will the reservoir bottom and remaining sediments be affected by the colonization of nonnative plants?** Invasive (nonnative) plants have the potential to out-compete and hybridize with native plants, restructure food webs, and undermine ecosystem diversity and productivity (Tullos et al. 2016). The variables that influence the colonization of nonnative plants include the landform type (e.g., floodplain, terrace, hillslope), sediment grain size and chemistry, revegetation and weed control activities, and local seed sources of nonnative plants. Active control of invasive species is often needed to ensure the successful colonization of the former reservoir by native plants.

- **How will dam removal effect the expansion of invasive fish?** Dams often act as barriers to fish migration and dam removal often allows for the upstream migration of aquatic species. Dam removal may also allow invasive or nonnative fish to migrate upstream, assuming that the upstream river conditions provide suitable habitat (Tullos et al. 2016). The mere presence of nonnative aquatic species downstream from a dam does not predispose its spread and establishment upstream after dam removal.

- **Where are reservoir sediments likely to be contaminated?** Reservoir sediment contamination is most likely to occur in reservoirs with high proportions of fine sediment and watershed land use histories that suggest contaminant releases were possible (Tullos et al. 2016). An assessment of reservoir contaminants begins with an assessment of the historic and present upstream land-use activities (Randle and Bountry 2017).

While the downstream release of reservoir sediment may cause temporary impacts, restoration of sediment loads to the downstream river channel often initiates long-term ecosystem responses that are helpful to native species. Examples of potential benefits from dam removal and sediment release include:

- Restoring riverine habitat within the former reservoir area
- Restoring the natural range of sediment grain sizes and sediment bars that support development of more diverse channel bathymetry, including channel spawning gravels, islands, large wood features, and side channels
- Facilitating growth of invertebrate communities
- Creating the natural disturbance and sedimentation required for riparian vegetation
- Replenishing sediment sources to coastal beaches at the mouths of rivers
- Providing cover protection from predators with increased turbidity, which may benefit native species (e.g., humpback chub and razorback sucker on Colorado River)
- Helping reconnect floodplains where lack of sediment supply has caused channel degradation
- Restoring connectivity of nutrients and organic matter (vegetation and all sizes of woody material) from the upper watershed
- Restoring the floodplain and sediment bars for wildlife use
- Enhancing river recreation opportunities

6.2.2. Collect Reservoir and River Data

Baseline data are needed to estimate the reservoir sedimentation volume, spatial distribution, grain size, and other characteristics, including any contamination.

For more information, see *Step 2* in Randle and Bountry 2017 and Section 5.1.1. *Reservoir Sediment Impact Indicators* in USSD 2015

Uncertainty about the reservoir sediment volume and its properties is typically greatest at the start of the analysis. Initially, compile and synthesize available information about the dam, reservoir, and upstream watershed. Use existing information to develop the sediment estimates and then collect more data as needed to reduce uncertainty to an acceptable level before implementing a sediment management plan. Many projects have historical information, designs, monitoring information, and more sources of information. Document the existing physical conditions of the reservoir sedimentation and develop a working diagram (at the watershed scale) of sediment sources and potential areas of sediment impacts.

Synthesize available information to understand how the dam and reservoir have changed the river system, how sediment is transported and the location of sediment sources and sinks (for example, the reservoir), and how processes may be restored once the dam is removed. This synthesis should include the channel upstream from the reservoir, and all downstream reservoirs, channels and floodplain reaches that might be affected.

Using available topographic data, plot the longitudinal river profile upstream and downstream of the reservoir to estimate which reaches have the highest and lowest sediment transport capacity.

After the available information has been compiled and synthesized, conduct a reservoir sedimentation survey. If reservoir sedimentation thicknesses are likely less than 2 m, then the thicknesses should be probed as part of a reconnaissance field investigation. A drill rig floating on a barge may be needed to directly measure thicknesses greater than 2 m. Information from the reconnaissance investigation can be used to design the reservoir sedimentation survey and sampling program. The reservoir survey should provide enough detail to create a longitudinal profile through the reservoir and upstream river channel. A change in slope along this profile can be used to identify the upstream extent of reservoir sedimentation.

In addition to the reservoir survey, collect data along the downstream river channel to identify potential impacts from reservoir sedimentation. Visually estimate the composition of streambed materials (including the median and maximum grain size) along the river channel upstream and downstream of the reservoir. River channel surveys may be needed for numerical modeling in reaches where there is a concern about sediment deposition from the erosion of upstream reservoir sediments.

6.2.3. Evaluate the Potential for Contaminated Sediment

The watersheds upstream from some reservoirs may be in a near pristine condition where the source of contaminants, if any, would be limited to naturally occurring elements (such as arsenic, iron, chromium, manganese, lead, zinc, and copper). Even when contaminants are present with the reservoir sediments, they may not be a problem unless they occur in concentrations greater than background levels. In contrast, some upstream watersheds may have been subjected to industrial or mining operations, which may have contaminated the reservoir sediments or soils along the pre-dam river channel.

For more information, see *Step 3* in Randle and Bountry 2017 and Section 5.1.1.5 *Relative Concentration of Contaminants* in USSD 2015.

Impacts to the downstream environment could be severe if contaminated sediments were released from the reservoir, depending on the amount and concentration of the contaminants (Randle and Bountry 2017). The required mitigation for substantial amounts of contaminated sediments can have a dramatic impact on dam removal costs and may render dam removal infeasible, such was the case for Rising Pond Dam in Massachusetts (See Section 7.4), or require the mechanical excavation and disposal of sediments, as for Milltown Dam in Montana. Another option is to stabilize the contaminated sediments within the reservoir. Even when the dam is retained, contaminated sediments may be transported through the reservoir when the trap efficiency is low or eroded from the reservoir during floods.

Even small dam removal projects with low sediment volumes may require sedimentation management for contaminants. For example, sediments at Saeltzer Dam, California, were excavated, removed, and buried outside the floodplain (the mercury contamination was below the maximum allowable limits for burial). On the other hand, if there are no contaminants, then only monitoring may be required for the sediment management plan. For example, Savage Rapids Reservoir near Grants Pass, Oregon, had 98 percent coarse sediment (sand sized or greater) stored in the reservoir with only 2 percent fine sediment (Bountry et al. 2013). The sediment analysis focused on coarse sediment because the fine sediment volume was too small to cause any significant water quality impacts. No contaminants were found in coarse or fine sediments above screening-level concentrations. During the actual dam removal, there were only small spikes in turbidity that lasted hours to days, and these turbidity spikes were comparable to turbidity levels during typical storms (Bountry et al. 2013 and Tullos et al. 2016).

Perform these tasks to identify whether contamination within the sediments would be a concern:

- Examine present and past land use (e.g., agricultural, sanitation and wastewater, urban areas, factories, and mining) or other natural contaminant sources in the upstream watershed.
- Conduct reservoir sediment sampling and analysis. At Saeltzer Dam in California, numerous sediment samples were collected from drill hole borings to determine the extent of mercury contamination from past mining activities. Sediment sampling using hand probes may be sufficient for other projects with small sediment volumes. Toxicity analyses could be performed to determine if the contaminants are harmful to species.
- Locate and evaluate reservoir sediment that may be near septic systems or underground storage tanks.

6.2.4. Determine the Relative Reservoir Sediment Volume and Probability of Impact

The greater the reservoir sediment volume, the greater the probability of impact. The important considerations are the amount of sediment that the upstream river delivers and the amount that is trapped within the reservoir. The ratio of the reservoir sediment volume in millions of cubic meters (Mm^3) to the mean annual sediment load upstream of the dam (Mm^3/yr) determines the probability of impact. This ratio represents how many years that the reservoir has been accumulating sediment. Large reservoirs (with a storage capacity more than 30 percent of the mean annual inflow) will typically have a sediment trap efficiency approaching 100 percent, so the relative reservoir sediment volume for these reservoirs is nearly equal to the age of the reservoir. For example, a large reservoir that is 80 years old will have a relative sediment volume of about 80 years. Randle and Bountry (2017) provide several methods to estimate the mean annual river sediment load and reservoir trap efficiency.

> For more information, see *Step 4* in Randle and Bountry 2017 and Section 5.1.1. *Reservoir Sediment Impact Indicators* in USSD 2015.

A logarithmic scale is used to classify the relative reservoir sedimentation volume into negligible, small, medium, and large reservoir sediment volumes (Figure 20). The larger the relative reservoir sediment volume or mass, the greater the probability of impact.

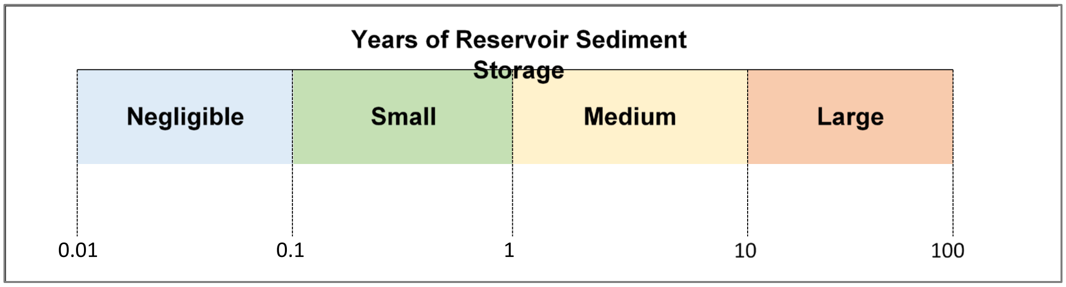

Figure 20. Relative probability of sediment impact based on ratio of reservoir sediment volume or mass to average annual sediment load. Small is less than one year, medium is less than one decade, and large is over a decade of accumulated average annual sediment load (Randle and Bountry 2017, used by permission).

6.2.5. Refine Potential Consequences and Estimate Risk

For more information, see *Step 5* in Randle and Bountry 2017 and Section 5.1.2. *Primary Issues* in USSD 2015.

Examine the risks of sediment impacts (how likely is the event and how large would the consequences be?) The higher the risk, the more sediment data collection, analysis, modeling, and management is recommended. The 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 (see step 4). Consequences are assessed qualitatively and then applied in a matrix with the probability of impact to estimate the qualitative risk.

Sediment eroded and released from a reservoir will typically produce elevated sediment concentrations and at least some deposition. However, the consequences of these effects to humans (for example, water quality, land, and infrastructure) or to ecological systems (such as aquatic or terrestrial) is what ultimately matters. The qualitative assessment of consequences is determined by regulations and based on the perceptions 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.

Generate a list of potential sediment-related consequences by building on the identified sediment concerns from step 1. Consider potential consequences to water quality, infrastructure, fish and other aquatic organisms, wildlife, flood inundation, cultural resources, and recreation. Also remember to consider sediment benefits. For each resource, qualitatively assess the level of consequence as either low, moderate, or high. The level of sediment effects will increase with the reservoir sediment volume and concentrations of any contaminants. The effects will also vary with sediment grain size, the pace of dam removal and reservoir drawdown, and the duration that sediment continues to erode from the reservoir after dam removal.

Once the level of consequences has been estimated, the risk of sediment impacts can be estimated using the matrix provided in Table 4. The level of sediment analysis and modeling is then guided by the level of risk.

Table 4. Matrix to estimate the risk of sediment impacts from the probability of occurrence and the consequence should the impact occur (Randle and Bountry 2017).

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

6.2.6. Develop Sediment Management Alternatives

For more information, see *Step 6* in Randle and Bountry 2017 and Section 5.2. *Sediment Management Alternatives* in USSD 2015.

Alternative sediment management plans need to be formulated and integrated with the dam removal plans so that the environmental consequences can be estimated and evaluated. For reservoirs with low or moderate risk of sediment consequences, initially assume that the entire dam is removed rapidly. Dam removal at a slower pace and partial dam removal can be considered if the sediment consequences from complete and rapid dam removal are unacceptable. Each sediment management alternative should include proper mitigation to make the alternative as feasible as possible.

Determine the sediment removal method based on sediment size, depth, and volume, access to waste sites, and if the sediment would be removed under wet or dry conditions. Methods include:

- Conventional excavation in dry conditions by dozers and front-end loaders. In some cases, excavators at the edge of the reservoir pool can be used to remove submerged sediment
- Mechanical dredging using a clamshell or dragline, in wet conditions, and allowing material to drain before hauling
- Hydraulic dredging of submerged sediments

Removed sediments can be transported by a sediment slurry pipeline, truck, or conveyor belt to a disposal site. For dredged sediments containing water, the disposal facility should be large enough to provide adequate settling times so that the effluent return flow meets regulatory criteria.

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

6.2.6.1. No Action

Under the No Action Alternative, the existing dam and reservoir sediments are left in place. The reservoir would continue to fill with sediment unless—or until—the sediment storage capacity becomes full.

6.2.6.2. River Erosion

River erosion relies on stream flows to erode sediment from the reservoir and transport it downstream. River erosion is a frequently employed sediment management practice associated with dam removals of all sizes if the downstream impacts can be accepted or mitigated (Figure 21) (USSD 2015). Allowing the reservoir sediments to erode and discharge into the downstream river channel through natural processes may be the least costly alternative as it may avoid sediment management actions. However, mitigation may be required to make consequences of this alternative acceptable. Mitigation may include incrementally lowering the reservoir over a period of months or years, modifying existing water treatment plants or constructing new plants, modifying existing water intakes or constructing new intakes, raising the height of existing levees or constructing new levees.

Figure 21. River erosion of reservoir sediments past Savage Rapids Dam near Grants Pass, Oregon, following dam removal (USSD 2015) (Reclamation/Bountry October 2009).

For wide reservoirs with thick sediment deposits, excavating a pilot channel (prior to reservoir drawdown) may be necessary to ensure that the eroding channel will find the alignment of the pre-dam stream channel (Figure 22). Otherwise, a stream channel flowing along the margins of the reservoir delta will tend to incise along the margins during reservoir drawdown. The alignment of many delta channels is along the reservoir margins, which may be over erosion-resistant materials, such as bedrock. If the incising channel encounters an erosion-resistant material, the channel alignment may become locked in place and a steep rapid or waterfall may form.

If a pilot channel is excavated through the reservoir delta, the alignment should be along the center of the reservoir (to maximize erosion) or along the pre-dam channel alignment, if known. The pilot channel bottom should be excavated to a lower elevation than other existing channels flowing along the reservoir delta—so the eroding pilot channel will capture the majority of stream flows during reservoir drawdown. The pilot channel should be long enough to guide stream flows to the center of the reservoir at the downstream end of the delta.

Figure 22. A pilot channel excavated through the Lake Mills delta and alder forest growing on the delta was cleared in preparation to remove Glines Canyon Dam near Port Angeles, Washington (USSD 2015) (Reclamation, December 2010).

The slower the rate of reservoir lowering, the slower the rate of sediment erosion. Reservoir drawdowns can be slowed by incrementally and progressively lowering the reservoir over a period of weeks, months, or years, depending on the size of the dam and the volume of the reservoir sediments. For reservoirs with large sediment volumes, the rate of reservoir drawdown should be slow enough so that the resulting sediment loads do not bury the downstream channel, but should be fast enough so that multiple generations of fish are not severely impacted.

In some cases, there may be benefits from the controlled release of reservoir sediments, such as the introduction of spawning gravel, wood, and nutrients for restoring downstream fish habitats.

6.2.6.3. Mechanical Removal

Removing all or part of the reservoir sediments before reservoir drawdown will prevent their release to the downstream channel. Mechanical removal is often the most expensive sediment management alternative, but this is especially useful when the sediments are contaminated or when the downstream release would cause unacceptable consequences or is not allowed. Costs can be reduced by removing only sediment portions that are of concern. For example, removing fine lakebed sediments would substantially reduce downstream suspended sediment concentrations and the potential release of any contaminants potentially associated with those fine sediments. In contrast, releasing coarse sediments, especially gravels, could benefit downstream habitats.

6.2.6.4. Stabilization

Stabilizing the reservoir's sediments in place would reduce the potential of releasing these sediments into the downstream river channel. A stream channel would have to be excavated through or around the reservoir. Additional channels would also have to be excavated for any tributary channels. Excavated sediments would then be relocated and stabilized within the reservoir. The excavated channels should be wide enough to include a stream channel and floodplains. Streambank protection for the excavated channels may be necessary to prevent the erosion of the stabilized sediment. The cost for this alternative may be more expensive than river erosion, but less expensive than mechanical removal, because only the excavated sediment would have to be moved and then only for short distances. The success of the stabilization alternative may depend the sediments remaining in the reservoir and not eroding during floods. For example, sediment stabilization was performed prior to the removal of San Clemente Dam near Carmel, California. Sediments were excavated from the left tributary branch of the reservoir and relocated to the right branch. The left tributary stream channel was realigned via an excavation through the native topography to the right tributary channel.

6.2.7. Conduct Sediment Analysis Based on Risk

For more information, see *Step 7* in Randle and Bountry 2017.

The level of analysis should be proportional to the level of sediment risk. Sediment analyses should be performed to help answer important management questions. For example, what will eventually happen to the reservoir sediment and what will the effects be on the aquatic environment, human use, infrastructure, and property? Typically, stakeholders are also interested to know what the new reservoir landscape will look like after dam removal.

Several analysis tools are available that range from simple calculations to complex numerical and physical modeling. Randle and Bountry (2017) explain how to use these analysis tools and have developed a chart to help determine when to use these tools based on the amount of risk the sediment poses (Figure 23).

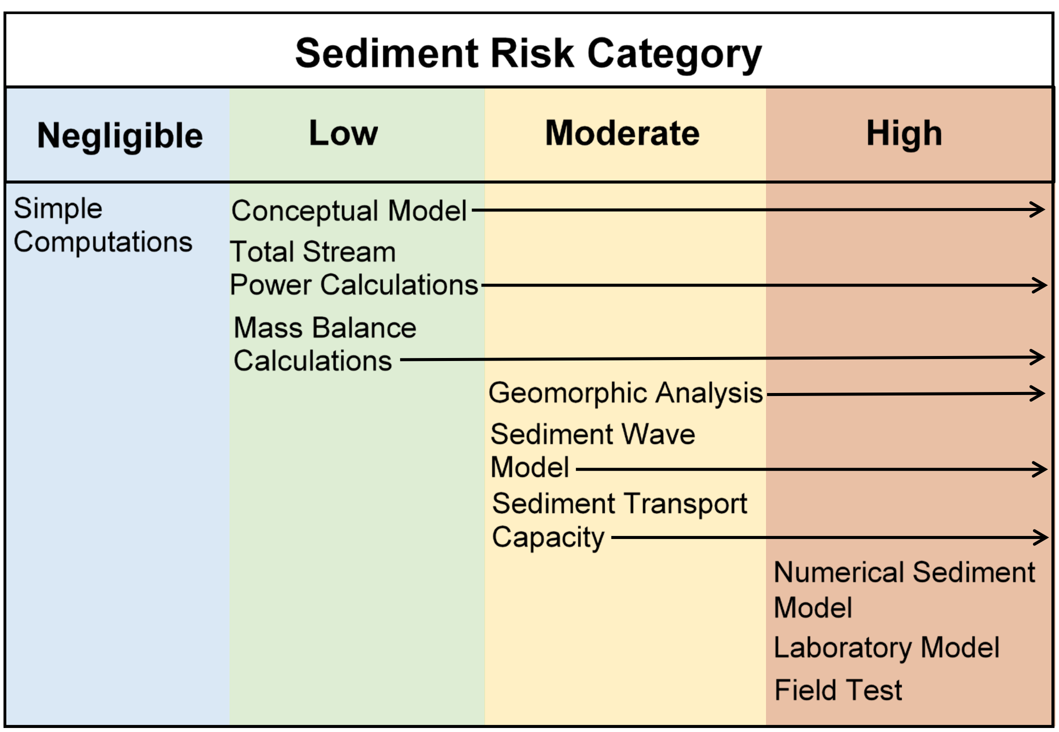

Figure 23. Sediment analysis and modeling options for each sediment risk category (Randle and Bountry 2017, used by permission).

6.2.7.1. Tools for All Risk Categories

A **conceptual model** qualitatively describes what will happen to the reservoir sediment as a result of dam removal, including the water quality and geomorphic effects on the downstream channel, where the sediment will eventually deposit, and what will happen to the landscape of the former reservoir.

The computation of **total stream power** along the river channel provides a good indication of which river reaches are likely to transport sediment and the reaches where sediment is likely to deposit. This is calculated by multiplying the local longitudinal channel slope, stream discharge, and the unit weight of water at various points along the river channel. Channel slopes tend to be steepest at the highest elevations of the drainage area and decrease with distance downstream. However, there can be river reaches with alternating steep and mild slopes. The local longitudinal channel slope can be measured from surveys or estimated from topographic maps or digital surface models of the watershed. Stream discharge for a given flow frequency (such as a 2-year flood) tends to increase with distance downstream.

Randle and Bountry (2017) recommend **simple mass balance computation**s 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. For example, the reservoir sediment volume may be equivalent to so many sand or gravel bars. Compute what the average thickness would be if the reservoir sediment volume were to deposit evenly across the width of the downstream channel and along the river reach of interest. Such computations can help identify the potential magnitude of sediment effects. Average thicknesses of many meters may require additional analysis while an average thicknesses of centimeters may not require further investigation.

6.2.7.2. Tools for Moderate and High Risk Categories

The **geomorphic analysis** provides qualitative and quantitative information about how the stream channel may have functioned prior to dam construction, how it evolved after dam construction and how the channel will likely respond after dam removal. The geomorphic analysis uses data from historical maps and aerial photographs; stream-channel measurements of width, depth, and planform; sediment grain size; geologic maps; floodplain and terrace vegetation characteristics; and land-use maps.

Sediment wave models simulate the downstream transport and dispersion of the reservoir sediment as a long wave where the wave amplitude decreases with time and distance downstream while the length of the wave increases over time (Greimann et al. 2006 and Greimann 2011).

6.2.7.3. Tools for High Risk Categories

Numerical sediment transport models use computers to simulate the water depth, stream-flow velocity, and sediment transport capacity along the river channel for discharges of interest. Simulations can be performed assuming there are no changes to the channel bed (fixed-bed simulation) or sediment transport, erosion and deposition can be simulated (mobile-bed simulation). Numerical models have to make certain assumptions about the physics of stream flow and sediment transport, but can simulate processes over long time and space scales.

Scaled physical models are developed in the laboratory and simulate channel hydraulics and the sediment transport, erosion, and deposition. Physical models simulate the three-dimensional physics of stream flow and sediment transport. However, the vertical and horizontal scales are often different, as are the scales for hydraulics and sediment.

Field experiments are like physical models—but at the full field scale. Controlling all the variables may be difficult, but the results can be quite informative if permission can be obtained to perform the experiment.

6.2.7.4. Tools for Aggradation, Water Quality, and Groundwater

The sediment analysis tools may help answer questions related to sediment deposition along the downstream channel (aggradation), effects to water quality from the increase in sediment concentration and turbidity, and changes to groundwater. The applicability of each of the analysis tools to aggradation, water quality, and groundwater is presented in (Table 5).

Table 5. Applicability of sediment analysis and modeling tools to help address sediment impact categories (Randle and Bountry 2017).

	Sediment Impact Categories		
Sediment Analysis & Modeling	**Aggradation**	**Water Quality**	**Groundwater**
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	√	√	√

6.2.8. Assess Uncertainty of Predictions

Every project entails varying levels of accuracy within measurements and models, which can lead to uncertainties in the predictions. For example, the predictions for the Elwha Dam removal were qualitatively correct for process predictions, but actual measurements differed somewhat from the prediction (Bountry et al. 2018).

For more information, see *Step 8* in Randle and Bountry 2017.

Sediment transport and deposition need to be estimated with enough certainty to determine where deposition is most likely to occur and if the deposition will be significant for a given dam removal scenario. Randle and Bountry (2017) provide methods to manage uncertainty and to estimate 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.

Make the best, conservative estimate of what the uncertainties might be and add contingency factors as appropriate. This allows for planning and handling the worst-case situation if that does happen, and avoids the higher consequences associated with surprises.

Uncertainty can be from three basic sources:

1. **Observational uncertainty:** How accurate are the measurements and data? If the sediment volume uncertainty is significant, put a range of sediment volumes, sediment grain size distribution, and reasonably possible hydrologic time series into the numerical model to provide a range of potential sediment impacts. Collect enough samples to accurately determine the presence and concentrations of contaminants.
2. **Model input (parameter) uncertainty:** How well defined and calibrated are the model inputs, including hydraulic roughness values, the reference shear stress (or a similar parameter in the sediment transport formula), and the active layer thickness in the model? Calibrate by comparing model values to observed conditions. If there are no observed conditions or data, then perform sensitivity analysis testing for model input parameters by using a range of possible values.
3. **Model structure uncertainty:** How well does the model represent the physical complexities of sediment accumulation and transport? 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. Apply multiple numerical models and sediment transport formulas within a model to estimate a range of potential results. Multiple methods can be used to estimate uncertainty (e.g., Tehrani et al. 2008, Sawaske and Freyberg 2012, Oh et al. 2015, Randle and Bountry 2017, and Ateeq-Ur-Rehman et al. 2018).

   Compare the numerical model results with predictions from the conceptual model. For example, a sediment transport model might underpredict the rate at which sediment can be eroded uniformly from the reservoir, and thus require mechanical removal. However, a conceptual model might qualitatively describe how the river would rapidly incise a channel through the sediments, which would widen over time and not require a mechanical removal. Comparing these numerical models with qualitative models based on observations can provide more accurate predictions.

The uncertainty from each source should be evaluated to determine if additional data collection and analyses are needed to make management decisions.

6.2.9. Determine if Sediment Impacts are Tolerable and Modify Sediment Management Plan

Once the sediment consequences have been estimated from the sediment analysis, re-assess the potential impacts to the resources and issues identified in Step 1 (Section 6.2.1.) with the analysis results. Determine if the impacts to humans and the aquatic environment are acceptable to decision makers and other stakeholders. Work with stakeholders to present the tradeoffs and impacts.

For more information, see *Step 9* in Randle and Bountry 2017.

If the potential impacts are at acceptable levels, document that there are no impacts or that the impacts are tolerable. Develop the sediment monitoring and adaptive management plan.

If these impacts are too high, revise the sediment management plan so that the impacts would be acceptable. Consider using an additional sediment management alternative (Section 6.2.6) or various options within the sediment management alternatives, including:

- Removing the dam incrementally or in phases to slow erosion and downstream release of reservoir sediment.
- Increasing the rate of dam removal to reduce the duration of turbidity impacts.
- 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 using one or more of these methods:
    - Sediment removal prior to dam removal
    - Sediment stabilization within the reservoir prior to dam removal
    - Leave a portion of the dam in place

6.2.10. Develop a Monitoring and Adaptive Management Plan for Sediment

The monitoring plan should be based on the predictions for the sediment transport, aggradation, and erosion processes as a result of dam removal. Monitoring these changes will inform adaptive management decisions, and documenting these as a case study can provide useful analogs for planning and predicting other dam removals.

For more information, see *Step 10* in Randle and Bountry 2017.

If real-time monitoring results confirm predictions, then dam removal and reservoir drawdown may proceed as planned. If monitoring results are different than expected, then try to determine why and if the sediment management plan needs to be modified before proceeding and if the predictions need to be modified. Depending on the potential consequences, dam removal may need to halt temporarily to address the issues uncovered. For example, if deposition along the downstream river channel caused the river stage to increase more than predicted or if the rate of dam removal and reservoir drawdown is faster than the rate that the river can erode the reservoir sediments, it might be prudent to temporarily stop or slow the rate of removal.

7. Case Studies

This chapter discusses challenges and solutions for five dam removals spanning 25 years. All five of the dam removal case studies began with dam safety concerns that involved potential loss of human life and damage to infrastructure and the environment.

While some projects begin with the goal of dam removal, other projects began with the goal of dam repair but shifted to dam removal as project stakeholders compared alternatives. One of the case studies presents a contrasting sequence, where the dam owner was interested in removing the dam, but project concerns led to repair of the dam instead. In all of the case studies presented, stakeholders included both dam safety and environmental agencies. The main reasons for removing the dam often included failing structural components and newer understandings of earthquake and flood loadings that now exceed what the dam was originally designed for.

For these case studies, removing the dam was only one of the design challenges. Another common dam removal challenge was reservoir sediment management. Sediment management proved to be one of the most expensive portions of dam removal in multiple case studies. In all cases, it was clear that communication between owners, stakeholders, and oversight agencies is critically important for project success—and that communication sometimes leads to unique dam removal solutions.

7.1. Birch Run Dam, near Fayetteville, Pennsylvania

7.1.1. Background

Birch Run Dam on Conococheague Creek was in Micheaux State Forest in south central Pennsylvania before its removal in 2005 (Johnston et al. 2007 and USSD 2015). The dam, which was built in 1933, was an earth-filled dam 20 m high and 200 m long used for water supply (Figure 24). The 35-m-wide concrete spillway was along the right abutment of the dam. The dam was number one on the list of unsafe dams developed by the Pennsylvania Department of Environmental Protection's (PADEP) Division of Dam Safety because it represented a high hazard potential to downstream populations. The dam was owned by the Borough of Chambersburg.

Figure 24. Birch Run Dam before breaching. The spillway can be seen on the right dam abutment (USSD 2015) (Photo courtesy of Johnson et al. 2007, all rights reserved).

7.1.2. Dam Alternatives Analysis and Removal

Birch Run Dam suffered from two major dam safety issues (Johnston et al. 2007 and USSD 2015). In the late 1970s, USACE found that uncontrolled seepage had led to wet areas on the downstream side of the dam. In addition, the spillway was determined to be undersized based on updated hydrological forecasting in the 1990s. According to an updated Probable Maximum Flood (PMF), the spillway could only pass 20 percent of the estimated peak discharge. The dam embankment would overtop with a depth of 2.4 m during passage of the PMF. A potential failure of the dam could be initiated at just a 0.3-m overtopping depth. The Borough of Chambersburg was interested in retaining the dam for water supply purposes and, after the 1970s report, installed a new drainage system to address seepage concerns. However, the overtopping concerns remained.

Conceptual engineering studies for several alternatives were conducted, including dam repair, replacement, lowering, and removal. The conceptual studies led to project cost estimates for dam repair, replacement, and lowering between $16 and $27 million. In comparison, the dam removal alternative was only $2.1 million. Part of the reason for the expensive repair cost was the unique location of the dam. Environmentally, the dam was in a mature state forest and upstream of a high-quality cold-water fishery. The left abutment had poor foundation conditions, further complicating dam repair or replacement. Next to the dam, there was a highway built into the mountainside on the right side of the dam where the spillway was located. Therefore, enlarging the spillway would have been expensive. In addition, water surface elevations in the reservoir could rapidly increase due to the dam's relatively small 76-cm outlet conduit, large upstream drainage area, and frequent rainstorms.

A cost-benefit assessment for each of the dam repair, replacement, lowering, and removal alternatives was conducted to understand the relationship between cost and retaining safe yield of the water resource. Based on this analysis, and in combination with water rates and meeting water system demands, the Borough of Chambersburg decided to remove the dam.

Several local, state, and Federal regulatory agencies participated in the dam removal (Table 6). An adapted water allocation permit was closely coordinated with PADEP during the dam alternatives analysis, which facilitated the dam removal. The dam removal process was streamlined by the PADEP Stream Restoration Authorization Process.

Table 6. Participating Stakeholders in Removing Birch Run Dam and Their Roles

Stakeholder	Project Role
PADEP	Chapter 105 Stream Restoration Authorization Process, which facilitated the regulatory review process
Pennsylvania Fish & Boat Commission	Regulatory review process
USACE	Regulatory review process and on-site field reconnaissance to delineate wetland boundaries and project disturbance limits
PADEP Division of Water Use Planning	Resolution of future conservation requirements

PADEP Bureau of Waterways Engineering	On-site field reconnaissance to delineate wetland boundaries and project disturbance limits
Pennsylvania Bureau of Forestry	Forestry impact limitations during construction, acceptable final disposition of dam embankment, identification and use of spoil areas, and restoration of the reservoir bed
Adams County Conservation District	Critical sediment and pollution control requirements
Pennsylvania Department of Transportation	Roadway drainage impacts and construction access requirements

Five major design features and provisions in the dam removal plan were: restoring historic stream channel alignment, protecting the forest, providing flexibility for using spoil areas, protecting waterways, and restoring the site for future use. Sediment management was a key element to several of these design provisions. Conococheague Creek was restored to its historic alignment (Figure 25). Restoring the original stream grade before dam breaching helped prevent sediment, and any contaminants, from entering the creek downstream of the dam and reduced the need to clean sediment from the Borough of Chambersburg's water intake. Spoil material was also used to fill the existing spillway, reservoir rim areas, and abandoned control tower. Backfilling of the spillway and control tower prevented future access and eliminated potential safety hazards. Finally, because of the sensitive habitat that Conococheague Creek provides, biodegradable fabric silt barriers were integral to protecting the stream from construction impacts.

Figure 25. Conococheague Creek restored to its historic alignment with the breached Birch Run Dam downstream (USSD 2015) (Photo courtesy of Johnson et al. 2007, all rights reserved).

The contract for the dam breach was ultimately awarded at a cost of $1.35 million. Dam removal began in July 2005 and the work was continuous (24 hours a day, 7 days a week). These dam removal operations continued until the dam was removed. Dam removal had to proceed quickly because of concerns that a storm could fill the reservoir behind the partially lowered dam. If the lowered dam were to have overtopped during or after a storm, the remaining dam could have failed and resulted in damages to downstream property and potential loss of life. Dam materials were removed, and spoil locations (including the filled spillway) were reseeded while the reservoir bed was reforested (Figure 26).

Figure 26. Aerial photographs of Birch Run Dam before, soon after, and 5 years after dam breaching.

7.1.3. Lessons Learned

- The dam removal alternative was considerably less expensive than dam repair, replacement or lowering alternatives.
- The dam removal alternative was achievable through close partnerships with stakeholders and the coordination with other regulatory matters.
- A well-defined sediment management plan provided benefits toward mitigation of potential future sediment impacts and spoil material was useful in restoration strategies.
- Safety concerns regarding possible dam overtopping and failure during dam removal meant that the construction activities were continuous until proper stream grade was reached at the bottom of the dam.

7.2. Bluebird Dam, Rocky Mountain National Park, near Estes Park, Colorado

7.2.1. Background

Bluebird Dam on Ouzel Creek was constructed between 1914 and 1923 at approximately 3,400 m in elevation within the bounds of Rocky Mountain National Park, Colorado but built before the park was established (Karpowicz et al. 2010 and USSD 2015). The concrete arch dam had a crest length of 60 m and was 18 m high with a maximum water storage capacity of 1.2 million m^3 of water, which was stored as irrigation water for the City of Longmont (who owned the dam before 1987). The National Park Service (NPS) bought the water rights and Bluebird Dam in 1987 at a cost of $1.9 million. USACE classified the dam as intermediate size. Bluebird Dam Removal began in 1989 and was completed in 1990.

7.2.2. Dam Removal

Removing Bluebird Dam was inspired by the 1982 failure of Lawn Lake Dam, which was another non-NPS alpine dam within Rocky Mountain National Park. The Lawn Lake Dam failure resulted in three deaths, inflicted $68 million in damages, and caused a lot of destruction to natural resources. Immediately after the Lawn Lake Dam failure, all dams within the national park were inspected and Bluebird Dam as well as two other dams were found to be seriously deficient and given the Significant Hazard Potential classification (Karpowicz et al. 2010). The City of Longmont was given until 1985 to repair or remove the dam. NPS eventually removed the dam after the transfer of ownership.

Prior to dam removal, an environmental assessment (see Section 2.3.4), archeological inventory, and "Section 106 Compliance" report (a National Historic Preservation Act requirement) were all completed. Although the dam was deemed to have significant historical value because of its location and as one of the earliest concrete arch dams, the safety and environmental concerns were considered more significant, and NPS was successful with their challenge to the Advisory Council on Historic Preservation. This allowed dam removal to proceed.

Removing Bluebird Dam and associated materials presented some unique challenges based on its alpine location in a national park. Overall, the removal and restoration cost $1.2 million, and the Rocky Mountain National Park maintenance division conducted most of the work. Although the original proposal called for using dynamite to demolish the dam, a Schaeff Walking Excavator with hydraulic hammer was brought in for a more controlled demolition to avoid impacting downstream populations of greenback cutthroat trout, a threatened species (Figure 27).

Figure 27. Schaeff Walking Excavator with hydraulic hammer was used in the deconstruction of Bluebird Dam to reduce concrete impacts on downstream greenback cutthroat trout populations (USSD 2015). (Photo credit Karpowicz et al. 2010).

Rubble material could not be buried near the dam site because the concrete dam was built on top of existing bedrock. Therefore, over 2,300 metric tons of concrete were transported by helicopter more than 11 km away where it was then loaded into trucks and driven to a borrow pit still within the national park boundaries. In total, helicopter flights cost $770,000 and carried away more than 2,500 metric tons of equipment, supplies, fill dirt, rubble, and rebar. The dam removal included approximately 12,440 person hours—without any injuries in this complex operation and demanding terrain.

As might be expected for a dam removal occurring within a national park, avoiding or mitigating environmental impacts was of the utmost concern (Friends of the Earth et al. 1999). Using a pump and siphon system, the upstream Bluebird Lake was drained to a natural sill to dry the channel at the dam site and to reduce dust that could harm the greenback cutthroat trout. In addition, helicopter flight paths were restricted to reduce impacts to native ptarmigan birds and big horn sheep. During demolition and restoration, no adverse impacts to trout were observed. The presence of helicopter noise and people did drive away ptarmigan, but their populations were reported to have increased to prior levels only two years after dam removal. Native willows were replanted around the lake in areas that were previously flooded by the higher reservoir water surface elevations.

7.2.3. Lessons Learned

- Failure of Lawn Lake Dam (prior to removing Bluebird Dam), demonstrates the impact of not monitoring dam conditions. In addition to loss of human life, dam failure can result in damages that far exceed the cost of removal.
- The high alpine dam location and steep terrain led to unique dam removal solutions for improving the safety of park visitors and removing concerns related to infrastructure and the potential environmental impacts from dam failure.
- Dam safety outweighed concerns regarding historical preservation and regulators were willing to adjust requirements to improve safety.

7.3. Hall Brook Dam, near Adams, Massachusetts

7.3.1. Background

Hall Brook Dam was 3 m high and 41-m long and of stone masonry construction, located in the Town of Adams, Massachusetts (Leone 2010 and USSD 2015) (Figure 28). The privately owned dam was reportedly constructed in 1886 on Hoxie Brook upstream of the more densely populated downtown Adams. The dam had an 8,000-m^2 reservoir impoundment that was filled with sediment by the time of removal. The Massachusetts Department of Conservation and Recreation Office of Dam Safety (MDCR-ODS) classified the dam as an Intermediate Size, Significant Hazard Class structure. In 2007, the dam was labeled as “unsafe” and deteriorating based on visual inspection reports and site visits. Significant problems included seepage, movement of the stone masonry blocks, large voids in the downstream face of the dam, and limited freeboard. The MDCR-ODS issued a Dam Safety Order that required the owner to either completely repair the dam to comply with current dam safety standards or remove the dam.

Figure 28. Downstream face of Hall Brook Dam prior to removal (USSD 2015) (Photo courtesy of Leone et al. 2010, all rights reserved).

A preliminary analysis was conducted to assess the feasibility and costs associated with dam repair and dam removal alternatives. Because of the dam's condition, repairing the dam may not have been possible. This repair may have required constructing a new dam, with estimated costs of over a million dollars—which did not include the costs associated with continued operation, maintenance, inspection, and liability associated with a repaired dam. The dam removal alternative (which included demolishing and removing the dam structure, excavating and stabilizing the impounded sediment, and reconstructing the stream channel) was originally estimated to cost $290,000. The owner chose to pursue the dam removal alternative based on the smaller costs, reduced responsibility, and environmental benefits.

7.3.2. Dam Removal Planning and Implementation

After the dam removal alternative was selected, four approaches to stream channel restoration and slope stabilization were proposed: 1) natural stream development, 2) excavation to bedrock channel, 3) a "chute" channel design, or 4) a "stepped channel" with stone weirs. The first three options were removed from consideration because of perceived sediment impacts to a downstream culvert under natural stream development conditions, instability of lateral hillslopes if the channel was excavated to underlying bedrock, and high flow velocities leading to increased scour potential and poor fish passage in the chute design alternative. The stepped channel design was ultimately altered to a "step-pool" design that was deemed to provide stability and beneficial stream habitat through the restored stream channel reach. After an initial estimate of $290,000, the project was awarded to a contractor for approximately $230,000. During the dam removal and regrading of the river channel and bank slopes, design plans needed to be adapted due to bedrock outcroppings. Vegetative restoration and monitoring continued into 2010.

Agencies and stakeholders that participated in permitting for the dam removal and stream restoration projects are summarized in Table 7. In addition, adjacent property owners were also interested in dam removal plans. Ultimately, all stakeholders were interested in controlling sediment transport during and after the dam removal.

Table 7. Permitting agencies in the removing Hall Brook Dam and restoring Hoxie Brook.

Agency	**Specific Permit (if identified)**
Executive Office of Energy and Environmental Affairs	Massachusetts Environmental Policy Act
Massachusetts Historical Commission	
USACE	Section 404 of Clean Water Act, Massachusetts Programmatic General Permit, Category 2
Massachusetts Department of Environmental Protection	Section 401 of Clean Water Act, Dredge and Fill Permit – Water Quality Certification
Department of Conservation and Recreation	Chapter 253 Dam Safety Permit
Town of Adams Conservation Commission	Notice of Intent, Wetlands Protection Act
Town of Adams Zoning Board	Special Permit for Soil Removal
Berkshire Regional Planning Council	
Massachusetts Division of Fisheries and Wildlife	
EPA	

With the permits granted by local, state, and Federal agencies, the dam was removed in 2009 (Figure 29).

Figure 29. The restored step-pool system constructed in Hoxie Brook (USSD 2015) (Photo courtesy of Leone et al. 2010, all rights reserved)

7.3.3. Lessons Learned

- Dam repair costs can exceed dam removal costs
- Dam removal can release dam owners from the costs of dam maintenance and liability
- Dam removal can include a large number of stakeholders, but goals from all can be balanced

7.4. Rising Pond Dam in Great Barrington, Massachusetts

7.4.1. Background

Rising Pond Dam i in Great Barrington, Massachusetts, is a run-of-the river dam with an embankment that is 9-m long and 11-m high and a spillway that is 37-m long and 7.6-m high (Hover 1994 and USSD 2015) (Figure 30). Historically, the dam provided hydropower for a mill. The dam was likely constructed in the mid-1800s. The dam and spillway were modified or repaired in 1934, 1949, and 1953. The dam, which is along the Housatonic River, was listed as a historic structure impounding Rising Pond. The drainage area upstream from the dam was 723 square kilometers (km^2). Rising Pond was 1,200 m long and 120 m wide. While Rising Pond Dam was classified as small based on storage capacity and height as well as a significant hazard based on the potential for loss of life if failure were to occur.

Figure 30. Looking upstream of the earth embankment and wetted spillway at the repaired dam (EPA 2020).

7.4.2. Dam Removal and Repair Investigation

The owner purchased the vacant mill and dam with the knowledge that the dam was in poor condition and intended to remove the dam. Many dam safety concerns were recorded during scoping for dam removal. Structural and geotechnical issues included problems with differential settlement of the spillway crest, seepage at several locations, significant cracking of a training wall, erosion beneath spillway—and many other issues, including inadequate safety factors on the spillway and downstream embankment slopes. Hydraulic analyses also suggested the spillway was not capable of passing 100- and 500-year return period floods. Therefore, the dam would seem to be a perfect candidate for removal. However, agencies were concerned about sediments trapped behind the dam that contained PCBs, petroleum hydrocarbons, and other heavy metals from historical industrial river uses.

Alternative dam repair and removal plans were developed concurrently to determine the least-cost option to address dam safety and environmental concerns (GZA GeoEnvironmental, Inc., 2020). The dam removal alternative included removing the contaminated sediment, constructing an armored channel, installing new hydraulic structures, and demolishing the dam. The dam removal alternative was determined to be at least 50 percent more expensive than the dam repair alternative because of the contaminated sediment removal and construction of an armored channel. In addition, there was a lot of uncertainty about the ability to obtain the required permits to remove the dam. For these reasons, the dam owner ultimately decided to repair Rising Pond Dam, rather than remove it, to meet safety requirements. The dam continues to contain contaminated sediments that were in the reservoir. (Figure 31).

Figure 31. Repaired Rising Pond spillway and right embankment. (EPA 2020)

7.4.3. Lessons Learned

- Dam removal can be more expensive than dam repair in certain circumstances.
- Uncertainty about dam removal costs, permitting, and environmental remediation can lead a dam owner to repair a dam rather than remove it.

7.5. San Clemente Dam near Carmel, California

7.5.1. Background

San Clemente Dam was a thin arch concrete dam 32.3 m high constructed in 1921 (USSD2015). The reservoir stored water for diversions from the Carmel River which supported economic development of the Monterey Peninsula for generations after its completion (Maven's Notebook 2019). The dam crest was 90 m long, and the spillway consisted of 24 bays that were each 1.6 m wide (Hepler et al. 2011) (Figure 32). A fish ladder added to the dam for steelhead fish passage, but it was relatively steep and long was not in an effective location, which severely impaired fish passage.

The dam was at the confluence of the Carmel River and San Clemente Creek near Carmel, California, approximately 30 km upstream from the Pacific Ocean (Maven's Notebook 2019). The dam, which created a reservoir with an original storage capacity of 1.76 million cubic meters (m^3) was owned and operated by California American Water (CAW) Company. San Clemente Dam was built to divert water to CAW customers; however, over 1.9 million m^3 of sediment had filled in most of the available storage capacity of the dam. In addition to extensive reservoir sedimentation, in 1992 the dam was found to have deficiencies that could result in failure during the Maximum Credible Earthquake and during the Probable Maximum Flood (PMF) (Figure 33). After a couple of decades of planning, the dam was removed in 2015.

Figure 32. San Clemente Dam at low flows (Photo courtesy of San Clemente Dam Removal and Carmel River Restoration, all rights reserved).

Figure 33. San Clemente Dam at flood stage (Photo courtesy of San Clemente Dam Removal and Carmel River Restoration, all rights reserved).

7.5.2. Alternatives for Dam Repair and Removal

Original concern about the integrity of San Clemente Dam stemmed from the 1992 Seismic and Flood Stability Evaluation requested by the California Division of Safety of Dams (Hepler et al. 2011, Marven's Notebook 2019, and San Clemente Dam Removal and Carmel River Restoration 2021). The Seismic and Flood Stability Evaluation report documented the susceptibility to dam failure by earthquake or flooding. It was found that the spillway had an approximate discharge capacity of 589 cubic meters per second (m^3/s) while the PMF inflow was estimated at 2,300 m^3/s, which would cause the dam to be overtopped by 4.3 m. CAW produced several reports over the next 5 to 10 years addressing dam safety and proposing dam repair alternatives that would also minimizing impacts to the environment.

A number of alternatives were investigated that would repair the dam: strengthen the dam by thickening the structure, lower the dam crest by notching, strengthen the dam and raise the crest by 3 m, strengthen the dam and raise the crest by 6 m, and strengthen the dam and raise the crest by 6 m and dredge sediment from the reservoir to restore storage capacity (Hepler et al. 2011). CAW preferred the dam strengthening alternative because it was the least-cost alternative that met the dam safety and environmental impact requirements. This alternative would have included thickening the dam with concrete, strengthening the right abutment, modifying the spillway to allow more flow to pass, raising the dam crest, and armoring abutments with reinforced concrete to prevent erosion. The project would have also included a new fish ladder for environmental purposes and a new sluiceway to manage sediment. The estimated cost of this project was $49 million.

While CAW preferred the least-cost alternative (strengthen the dam), other agencies were more interested in removing the dam. One of those agencies, the California State Coastal Conservancy (CSCC), was appointed the lead state agency in the project. However, many agencies and stakeholders ended up participating in the oversight of alternative analysis and the dam removal process as summarized in Table 8.

Table 8. Stakeholders involved in the analysis, planning, permitting, and approval of the Sam Clemente Dam removal.

Agency/Stakeholder	**Project Role**
California American Water Company	Dam owner
CSC	State government lead agency; planning, permitting, securing of funds
California Division of Safety of Dams	Dam safety oversight
National Marine Fisheries Service	Project partner; securing funds; environmental stakeholder
USFWS	Environmental stakeholder
California Department of Fish and Game	Environmental stakeholder
California Department of Water Resources	Environmental stakeholder
Monterey Peninsula Water Management District	Environmental stakeholder
USACE	Permits for Clean Water Act
Bureau of Land Management (BLM)	Project partner; landowner at end of project
California Public Utilities Commission	Project approval

Dam removal alternatives were investigated, and the preferred alternative was termed the Carmel River Reroute and Dam Removal (CRRDR) (Hepler et al. 2011). This alternative included a unique strategy to reroute the Carmel River channel to create a confluence with San Clemente Creek further upstream from the original location (Figure 34). This was accomplished by blasting and excavating a channel 140-m long through the natural topographic ridge separating the two stream channels and constructing a diversion dike across the Carmel River channel. Sedimentation was removed from the San Clemente arm of the reservoir and relocated to the Carmel River arm of the reservoir in a sediment stockpile area, immediately downstream from the diversion dike (Capelli 2007). Material excavated from the topographic ridge was also relocated to the sediment stockpile area. The rubble from the deconstructed dam was used to create a stabilized sediment slope at the downstream end of the sediment stockpile area. The goals of the CRRDR were to eliminate the dam safety hazard, restore the natural character of the river through the reach, and reconnect 40 km of upstream fish habitat with the 30 km of river downstream from the dam. An initial cost estimate for this alternative was $75 million, which was later updated to $83 million. Disposing of sediment offsite would have increased the project cost by $40 million.

The CSCC organized several feasibility studies to pursue the CRRDR with the understanding that this alternative would lead to the largest public benefits (Capelli 2007). For each major portion of the CRRDR plan, care was taken to prevent future erosion of the sediments and ridge materials stabilized within the sediment stockpile are and ensure fish passage. Various disciplines were used to assess the performance of the alternative: geotechnical, civil, hydraulic, hydrologic, geomorphologic, landscape design, environmental restoration, and construction operations.

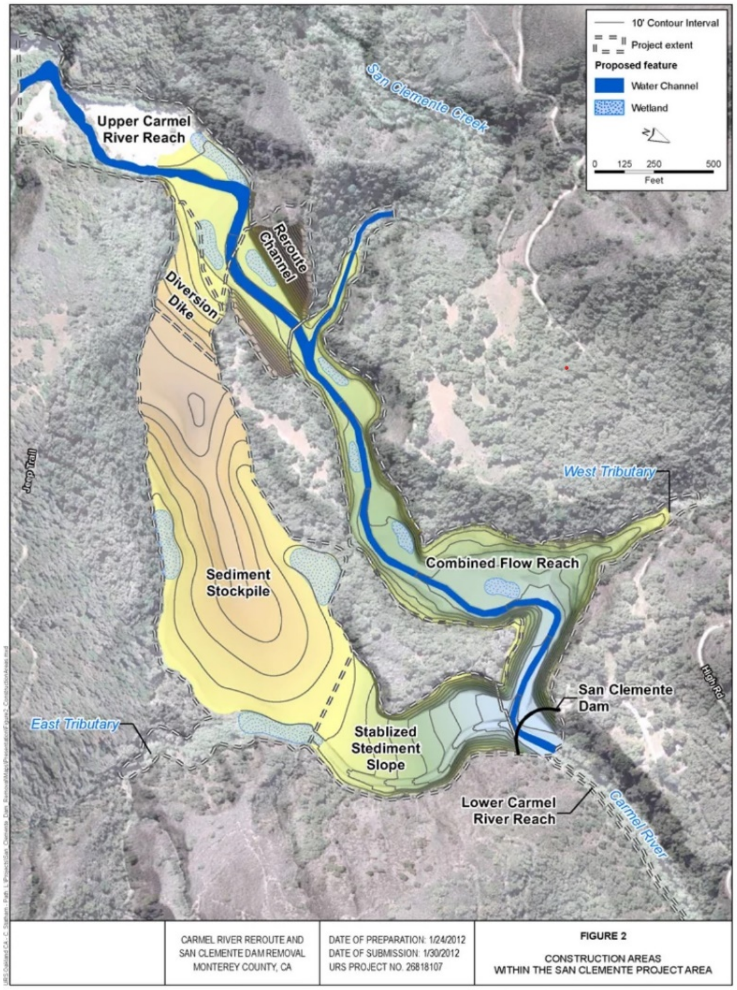

Figure 34. Design plans for rerouting the Carmel River and sediment stockpiling and stabilization for the CRRDR alternative (figure courtesy of San Clemente Dam Removal and Carmel River Restoration, all rights reserved).

In 2008, CAW, CSCC, and the NOAA Fisheries Service entered into an agreement to implement the CRRDR alternative (California Public Utilities Commission 2012). Because the dam removal alternative cost more than dam strengthening alternative (CAW preferred the dam strengthening alternative), an agreement was reached so that CAW was responsible for funding the cost equivalent to the dam strengthening alternative. CSCC would then lead the project design and permitting as well as secure an additional $35 million in Federal, state, and private funding with NMFS's assistance. Unfortunately, the economic crisis of 2008 resulted in a lack of funds and CAW backed out of the agreement due to concerns about lack of funding support from other agencies.

In 2009, CAW met with Federal, state, and local agencies to again discuss the possibility of implementing the CRRDR alternative and the obstacles to project implementation that remained. Those obstacles included understanding the uncertainty of the risk associated with the CRRDR alternative in comparison to the dam strengthening alternative, lack of an agency willing to own and manage the project site after CRRDR completion, and the ability of CSCC to meet the $35 million funding agreement (California Public Utilities Commission 2012). Over the course of the next year, the CRRDR alternative was found to have a much lower risk profile than the dam strengthening alternative. In addition, BLM agreed to manage the lands after completion. Finally, CSCC put in place a funding plan to secure state, Federal, and private funding for the project. Funding was ultimately split between CAW, the state of California, Federal funds, and private resources (Table 9). Distribution of project funds to complete the project under the original $83 million estimate are documented in Table 10.

Table 9. Summary of the funding contributions made for the CRRDR

Stakeholder	Funding contribution (millions of dollars)
CAW	51
State of California	29.2
Federal funds	2.5
Settlement funds	2.2
The Nature Conservancy	1
Resources Legacy Fund Foundation	0.4

Table 10. Project tasks and estimated costs associated with the $83 million dam removal estimate.

Task	Cost (millions of dollars)
Design and Permitting	5.9
Construction	39.7
Construction Management	12.0
Mitigation and Monitoring	3.5
Contingency	9.9
Annual Escalation	12.0

After nearly 15 years of planning and overcoming numerous challenges, the California Public Utilities Commission approved the project in 2011. Removing San Clemente Dam was completed in 2015. At the time of removal, it was the largest dam removal project in California. The deconstruction of the dam took place over the course of three years and occurred during California's dry season, which is primarily April to November. First year accomplishments included road access improvements, site preparation, diversion of Carmel River flows into a pipeline around the project site, and draining the reservoir (Maven's Notebook 2019). During the second year, the diversion channel was excavated, the diversion dike was constructed, and sedimentation was removed from the San Clemente Creek arm of the reservoir. During the final year, the San Clemente River was reconstructed, reservoir sediment was stabilized within the stockpile area of the Carmel River bypass reach, the dam was removed, and habitat was restored. Groundwater drains were installed with the sediment stockpile area to prevent liquefaction during a possible earthquake. The dam was removed using two large hoe rams (Figure 35). A new stream channel was constructed with boulders to create a step-pool channel for fish passage. These boulders were subsequently rearranged by a 30-year flood (Maven's Notebook 2019).

Figure 35. Two large hoe rams were used in the demolition of the dam (photo courtesy of San Clemente Dam Removal and Carmel River Restoration, all rights reserved).

Following dam removal, Pacific lamprey were observed in the restored channel and numbers of steelhead fish dramatically increased.

7.5.3. Lessons Learned

- Innovative engineering and environmental solutions can lead to long-term solutions of dam-safety concerns in remote settings subject to extreme natural disaster events
- Agency partnerships and continued stakeholder communication can lead to successful outcomes (Maven’s Notebook 2019)
- Effective risk management helped understand that the unprecedented dam removal, ultimately had less risk than the dam strengthening alternative (Maven’s Notebook 2019)
- The willingness to carefully listen to and consider criticism allowed for project plans to be improved after comments were accepted from academics, consultants, community-based experts, and stakeholders (Maven’s Notebook 2019)
- Design for data and model uncertainty to increase project resiliency (Maven’s Notebook 2019)

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