Reservoir Sediment Management:

Building a Legacy of Sustainable Water Storage Reservoirs

National Reservoir Sedimentation and Sustainability Team White Paper

June 12, 2019

Reservoir Sediment Management:

Building a Legacy of Sustainable Water Storage Reservoirs

National Reservoir Sedimentation and Sustainability Team White Paper

June 12, 2019

Timothy Randle, Bureau of Reclamation, Denver, CO
Gregory Morris, GLM Engineering
Michael Whelan, Anchor QEA, L.L.C.
Bryan Baker, U.S. Army Corps of Engineers
George Annandale, George W. Annandale Consultant
Rollin Hotchkiss, Brigham Young University
Paul Boyd, U.S. Army Corps of Engineers
J. Toby Minear, Cooperative Institute for Research in Environmental Sciences
Stan Ekren, Great Lakes Dredge & Dock Company
Kent Collins, Bureau of Reclamation
Mustafa Altinakar, University of Mississippi
Jon Fripp, USDA-Natural Resource Conservation Service
Meg Jonas, U.S. Army Corps of Engineers (retired)
Kyle Juracek, U.S. Geological Survey
Sean Kimbrel, Bureau of Reclamation
Matt Kondolf, University of California, Berkeley
Doug Raitt, Denver Water
Frank Weirich, University of Iowa
Darrell Eidson, U.S. Army Corps of Engineers
John Shelley, U.S. Army Corps of Engineers
Rene Vermeeren, U.S. Army Corps of Engineers
David Wegner, Woolpert Engineering
Peter Nelson, Colorado State University
Kevin Jensen, McMillen Jacobs Associates
Desirée Tullos, Oregon State University

Acknowledgements

The NRSST would like to thank the following external peer reviewers for their constructive comments on the draft document:

- Paul Makowski, Federal Energy Regulatory Commission
- Mathias Collins, NOAA Fisheries
- Dr. Eddy Langendoen, Agricultural Research Service
- Dr. Blair Greimann, Bureau of Reclamation

Preface

This white paper has been written by the National Reservoir Sedimentation and Sustainability Team (NRSST). The NRSST is composed of engineers and scientists from federal agencies, consulting firms, industry, and universities who have expertise and experience with sedimentation.

The purpose of this white paper is to inform dam owners and operators, government decision makers and regulators, and the interested public about reservoir sedimentation and the need for long-term sediment management strategies to preserve the benefits of the nation's reservoirs for our own children and future generations.

Executive Summary

This executive summary was previously published in the proceedings of the SEDHYD-2019 conference by the same authors of this white paper (Randle, et al., 2019).

Introduction

The United States economy and welfare depends on a continuous and reliable system of water supply and infrastructure for municipal, industrial, agricultural, flood control, and hydropower uses. Water storage reservoirs are essential for regulating highly variable river flows, making water available whenever needed, creating a singularly important, but often unseen foundation for modern society. These water systems are also important for environmental management, recreation, and groundwater aquifer recharge. The estimated 90,000 dams and reservoirs in the U.S. (National Inventory on Dams, 2017) constitute a critical component of the nation's water infrastructure. There are perhaps more than a million additional dams that are too small to be included in the national inventory.

The vast majority of the nation's water storage reservoirs were constructed decades ago, and since construction, they have been trapping the sediment (clay, silt, sand, and gravel) eroded from the land surface of the upstream watershed, and carried downstream by river flow (Morris and Fan, 1998). The downstream transport of sediment by river flow is particularly evident during floods, when waters run turbid with eroded soil. In most reservoirs, the accumulating sediment consists of clay, silt, sand, and gravel particles (Morris and Fan, 1998; Randle and Greimann, 2006; and Morris et al., 2007).

Without active management, the continual accumulation of sediments gradually displaces the storage volume in a reservoir, which risks ultimately rendering the reservoir useless for capturing and storing water. In addition, long before the reservoir has lost its water storage capacity, numerous problematic sedimentation impacts can occur, including reduction in the reliability of water supply, burial of dam outlets and intakes for water supply and power production, damage to hydropower and pumping equipment, burial of boat ramps or marinas, impairment to navigation, reduction in the surface area for lake recreation, increased flood levels upstream, downstream channel degradation, and other environmental impacts.

The loss or degradation of legacy water infrastructure will impose significant financial and environmental burdens on future generations, compounded by the fact that replacement sites for most dams and reservoirs are not readily available. The most appropriate dam sites have already been utilized, and they are losing their storage capacity. Removal and storage of large volumes of sediment on land, while technically feasible, can be costly, and there typically isn't room to sustainably store inflowing sediments.

Fortunately, multiple measures are available to manage sediment, to help ensure the long-term viability of reservoirs while minimizing the difficulty and cost of maintaining the nation's water resources.

Sustainable Sediment Management Planning

General strategies for sustainable reservoir sediment management are graphically illustrated in Figure ES-1. Based on Kondolf et al., 2014 and Sumi et al., 2017, these strategies include reducing sediment yield from the upstream watershed (shown in green, e.g., landslide stabilization and check dams), routing the inflowing sediments through or around the reservoir (shown in yellow, e.g., sediment bypassing and pass through), removing or redistributing reservoir sediment deposits (shown in turquoise, e.g., mechanical excavation and hydraulic dredging), and adaptive strategies to better cope with reservoir sedimentation, or a combination of these strategies. A more detailed list of sediment management methods under each of these general strategies is presented in Figure ES-2 (Morris, 2015). For optimum performance, more than one type of strategy or method may be needed, either in sequence or simultaneously.

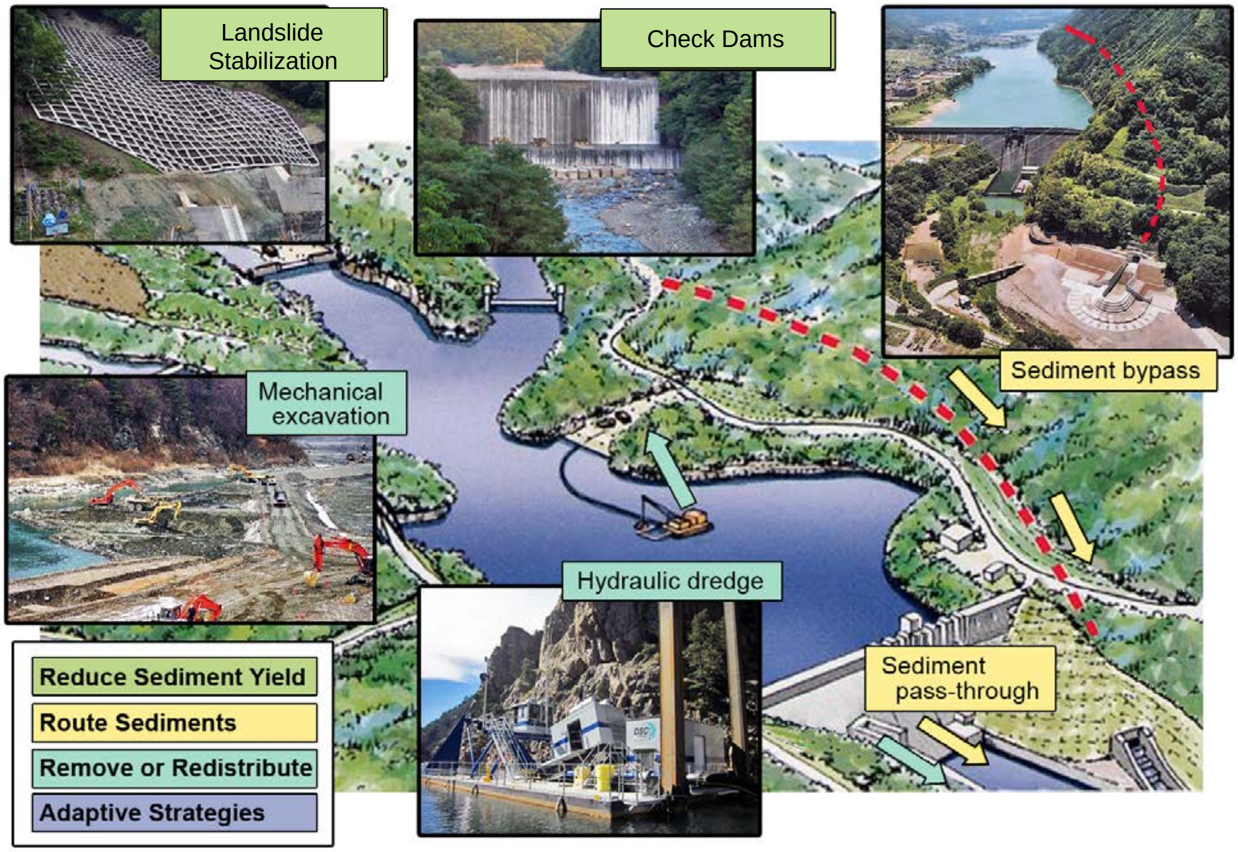


Figure ES-1. Range of reservoir sedimentation management strategies

These include the reduction of sediment yield from the upstream watershed, routing the inflowing sediments through or around the reservoir, removing sedimentation from the reservoir or redistributing sediments within the reservoir, and adaptive strategies to better cope with reservoir sedimentation (modified from Sumi et al., 2017). Adaptive strategies can use a combination of the above-mentioned methods and alternative reservoir operations to manage sediment.

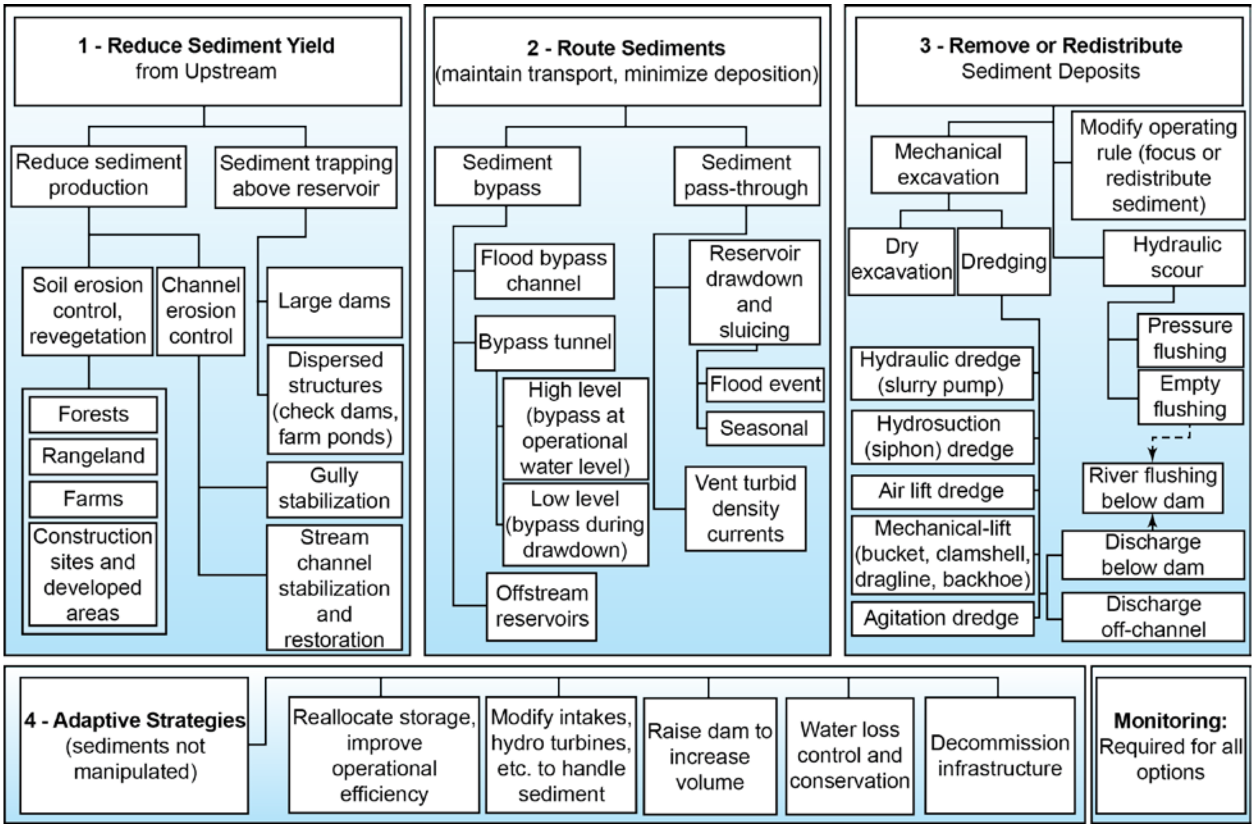


Figure ES-2. Classification of methods to manage reservoir sedimentation
(Morris, 2015)

Conclusions and Recommendations

The present practice of allowing the nation's reservoirs to gradually fill with sediment over time is not sustainable. Once the benefits of a reservoir have been lost to sedimentation, dam removal is often the eventual outcome and can be expensive for large sedimentation volumes. Even after dam removal, significant quantities of sediment may remain in the reservoir which will likely render the area unsuitable for future generations to use for water storage.

Plans to periodically monitor reservoir sedimentation need to be formulated and implemented at each reservoir to document the remaining storage capacity and estimate when important dam and reservoir facilities will be impacted. Meanwhile, long-term reservoir sediment-management plans need to be formulated for each reservoir. These management plans should include either the implementation of sustainable sediment-management practices or the eventual retirement of the reservoir.

A prudent, long-term sustainable goal for reservoir management is to pass inflowing sediments to the downstream channel each year in a quantity similar to the mass or volume of sediments entering the reservoir and, to the extent possible, with similar timing. Reservoir sediments can be allowed to pass downstream by manipulating reservoir operations; installing new gates, bypass channels, or tunnels; and mechanically or hydraulically transporting the sediment. Although environmental permitting laws and regulations may need to be modified to facilitate the approvals process, allowing inflowing reservoir sediments to pass downstream restores natural sediment processes and improves conditions for dependent habitat. Ultimately, with carefully planned sediment management, downstream habitats and infrastructure may benefit from restored sediment continuity (Sholtes, et al., 2017).

The sustainable management of reservoir sedimentation may seem expensive, but the sediment management costs need to be compared with the costs of eventually losing the reservoir benefits and the costs of its removal.

> *"Whereas the twentieth century focused on the construction of new dams, the twenty-first century will necessarily focus on combating sedimentation to extend the life of existing infrastructure. This task will be greatly facilitated if we start today."* (Morris & Fan, 1998).

Table of Contents

Figures

Introduction

The accumulation of sediment in the nation’s reservoirs is an ongoing and frequently overlooked issue that is steadily degrading our ability to regulate water supply and reduce flood risk, both of which are key in supporting our society and the nation’s economic activities. While past generations undertook the task of building and financing the infrastructure required to provide water supply and flood risk reduction, the present and future generations must meet the challenge of sustaining reservoir viability against the relentless inflow of sediment. Because today’s reservoirs were seldom designed to manage sedimentation, new active and vigorous management strategies are needed to achieve reservoir sustainability. This white paper describes the problem of reservoir sedimentation, its origins, current and future implications, and measures to manage this problem to sustain the benefits of water supply and flood risk reduction into the indefinite future.

Reservoirs: A Critical Element of the Nation’s Infrastructure

The nation’s 90,000 dams (National Inventory of Dams, 2017) constitute a critical, but often underappreciated, component of the country’s infrastructure. These dams create an extensive system of reservoirs that provide water supplies for municipal, agricultural, and industrial uses, hydropower production, flood risk management, navigation, and recreation. The ability of reservoirs to store and regulate the flow of water is an issue that affects the very existence of many communities, which are habitable, can grow crops, pursue economic activity, and continue to exist in relative safety, only because of the water supply and flood risk reduction provided by dams and reservoirs. Sustaining reservoir storage capacity is essential to meet these purposes, now and into the indefinite future.

While our growing economy and population make sustainable water supplies increasingly important, sedimentation in our nation’s reservoirs has not been sustainably managed. Although reservoir sedimentation has always been recognized as a threat to our ability to provide reliable water supplies and flood risk reduction, until recently it has been a forgotten problem. While some essential resources, such as energy, can be made available from alternative sources, there is no substitute for water, especially for drinking and for crop irrigation.

The sedimentation problem cannot be solved by simply building new reservoirs, because today’s reservoirs, which are filling with sediment, already occupy the best sites. Today’s inventory of dams and reservoirs simply cannot be rebuilt or replaced at other locations because alternative sites are not widely available. Thus, today’s reservoirs need to be managed under a new paradigm of “sustained use” if the benefits we have come to take for granted are to be sustained into the future.

The Sedimentation Process and its Fundamental Causes

All rivers naturally transport sediment particles eroded from upstream watersheds, including stream beds and banks. Erosion and sediment transport are natural processes, but erosion rates can be greatly accelerated by human activities that disturb soils (e.g., agriculture, mining, construction, logging, grazing, etc.), or that alter stream channel processes, such as the increase in erosion during floods that are amplified by urban development. Forest fires, which are affecting increasing areas of land in the western states (Congressional Research Service, 2018), also accelerate erosion and sediment yield[1]. The use of best management practices for land and streams throughout the watershed can reduce erosion to rates that are closer to natural background levels, but erosion and sediment yield will never (and should not) reach zero, even in an undisturbed watershed.

Some eroded sediments may temporarily reside on hillsides and in floodplains. Other sediments are transported downstream by rivers, but as flow velocities decrease in reservoirs, some or all of these sediments settle to the bottom and become "trapped". This long-term process of sediment accumulation is termed "reservoir sedimentation". This sedimentation process is illustrated in Figure 1.

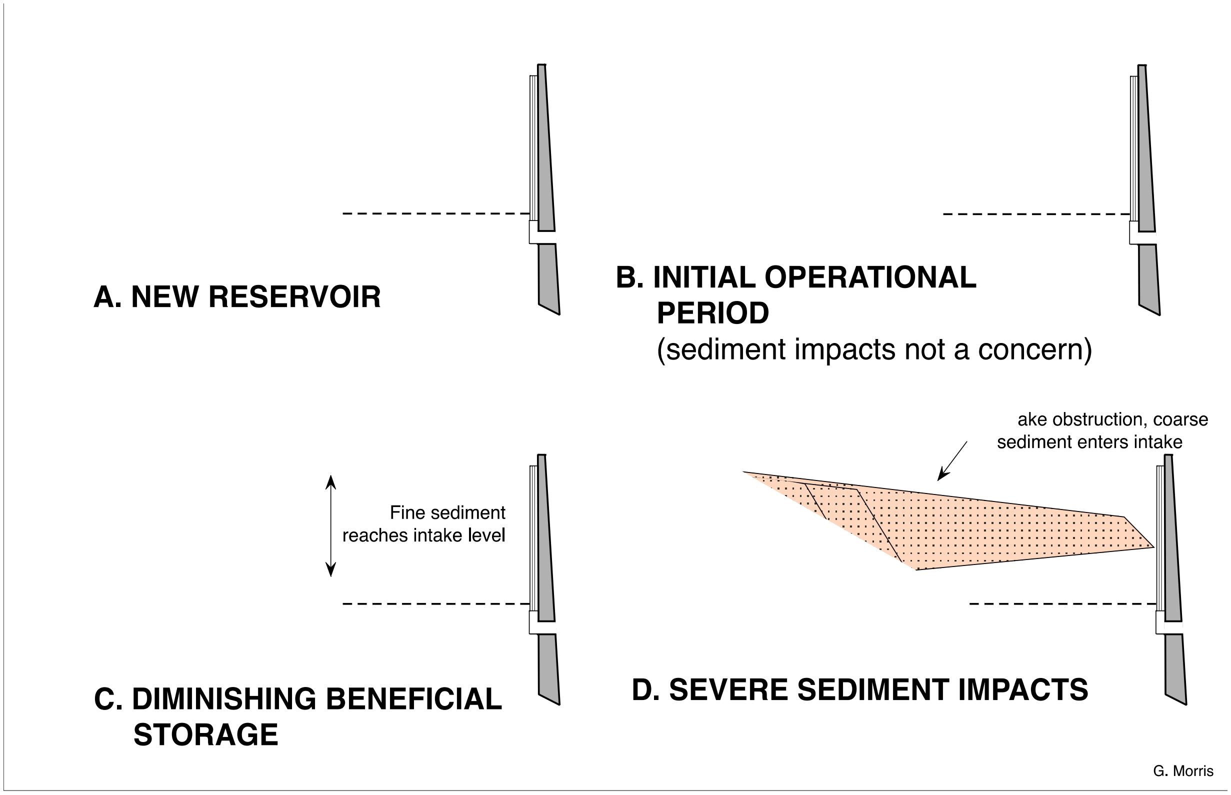


Figure 1. Process of reservoir sedimentation

A) new reservoir showing zone of beneficial storage and the designated sediment storage pool; B) initial operational period with minimal sediment impacts, showing the deposition pattern for both coarse and fine sediments; C) significant sediment encroachment into the beneficial pool with substantial growth of the delta; and D) severe sediment impacts including loss of beneficial storage, intake obstruction and upstream progression of the delta.

The nation's dams and reservoirs were originally sized with enough capacity to store sediment over the "sediment design life", typically 50 or 100 years, without interfering with the storage volume by reaching the lowest dam outlet. However, this approach did not include plans to manage the sediment

---

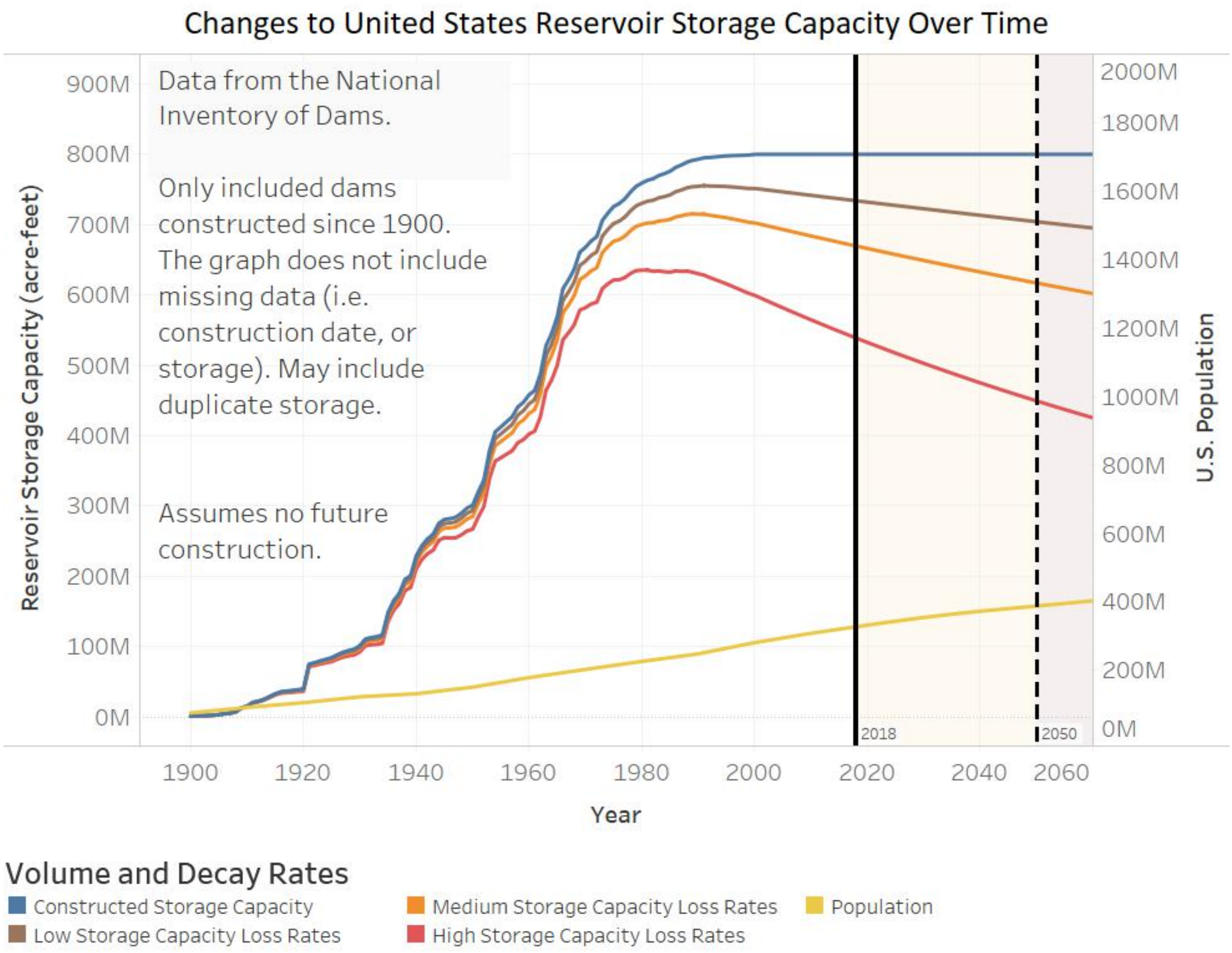
[1] Sediment yield is the amount of sediment eroded from a watershed by flowing water or wind per unit area per unit time.

after this sediment design life. Many of the nation's reservoirs are now at the point that their dedicated sediment storage pools are full, and sedimentation is diminishing the water storage capacity required for beneficial uses.

Dangerous Implications for the Nation's Reservoirs

Sedimentation reduces the reliability of water supply and results in the burial of dam outlets and water supply intakes, damage to hydropower and pumping equipment, burial of boat ramps or marinas, and impairment of navigation. Continued sedimentation threatens both the water storage capacity and the ability to operate dam outlets and reservoir water intakes at many reservoirs, yet the problem may be overlooked until an acute issue occurs, such as drought or a clogged outlet at the dam. Despite an increasing incidence of sediment-related problems as reservoirs age, all the options available to mitigate this problem are not well known.

Both nationally and globally, the past 30 years have experienced reservoir sedimentation reducing storage capacity at a faster pace than new storage is added by new dam and reservoir construction (Figure 2). This trend of continuing reservoir sedimentation and declining water storage capacity means that future water supplies will be less reliable. When reservoir storage capacity is computed on a per capita basis, the available storage volume per capita is declining even more rapidly due to the combined effects of sedimentation and increasing population (Figure 3). As a result, in 2018 our nation's per capita reservoir storage capacity was approximately equal to the capacity in the 1960s, but with one very important difference. In the 1960s storage volume was trending upward due to the continued construction of new dams and reservoirs, but today reservoir storage capacity is trending downward.



Data from the National Inventory of Dams.

Only included dams constructed since 1900. The graph does not include missing data (i.e. construction date, or storage). May include duplicate storage.

Assumes no future construction.

Figure 2. Changes to United States reservoir storage capacity over time due to dam construction and reservoir sedimentation

The curves presented in this plot are based on data from the National Inventory of Dams (constructed reservoir storage capacity, shown on vertical axis) and assumed rates of storage capacity loss due to sedimentation. Constructed reservoir storage capacity data are based on 68,000 dams in the national inventory that were constructed since 1900. Assumed annual storage capacity loss due to sedimentation was 0.4, 1.0, and 2.0 percent per year (Graf et al., 2010) for small reservoirs (constructed storage capacity less than 100,000 acre-feet) and 0.1, 0.2, and 0.5 percent per year for large reservoirs (greater than 100,000 acre-feet) based on experience at larger Federal reservoirs. The three curves show a range in storage capacity loss over time and represent the range of uncertainty. A systematic reservoir sedimentation monitoring program for the nation's reservoirs would be needed to reduce this uncertainty. The U.S. population data from the U.S. Census Bureau (2018a and 2018b).

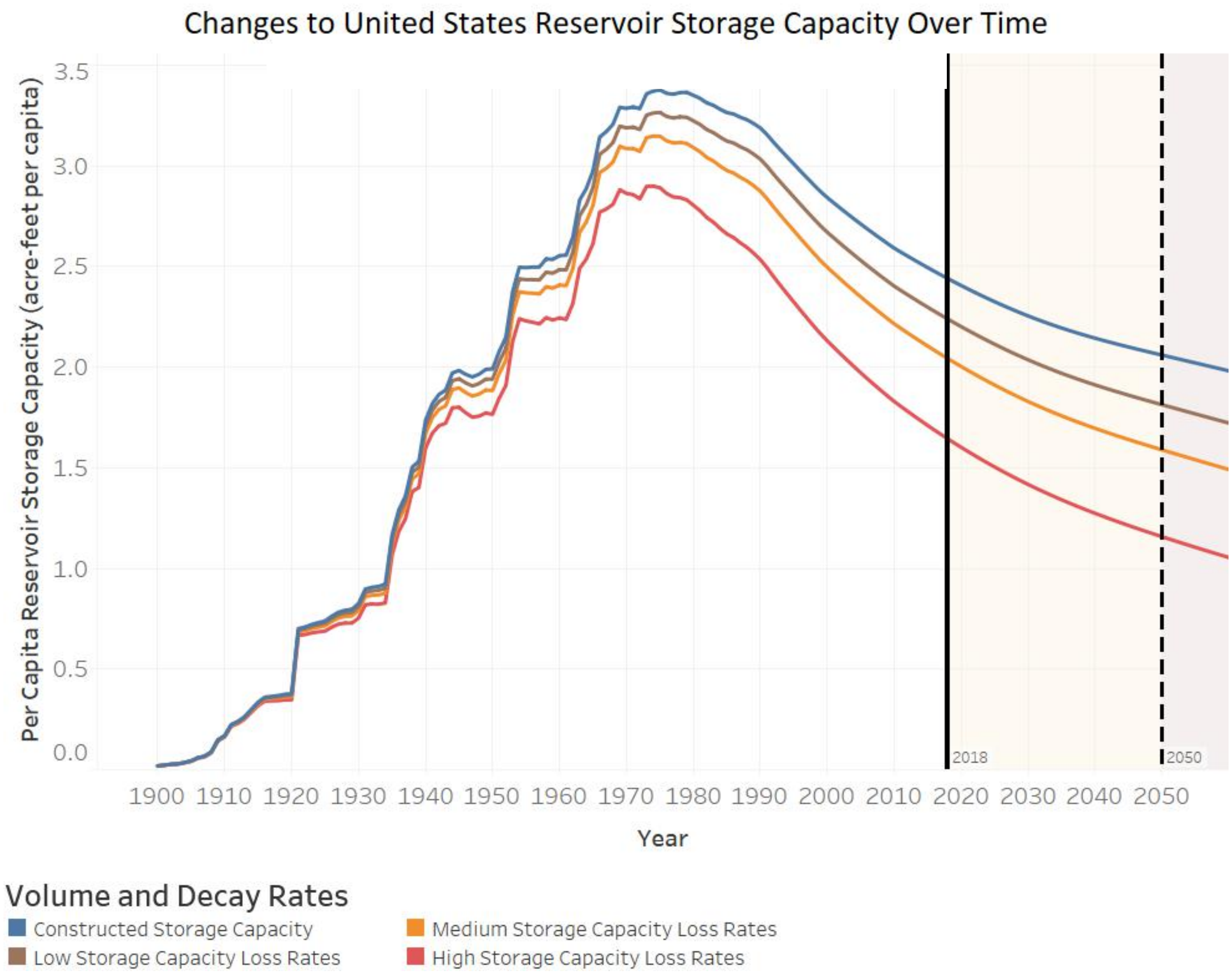


Figure 3. Per capita changes to United States reservoir storage capacity over time due to dam construction, reservoir sedimentation, and population increase

The per capita reservoir storage in 2018 is about the same as in was in the 1940s or 1950s. See Figure 2 for a description of the data.

As reservoirs fill with sediment, the following impacts can be anticipated.

- **Diminishing water supplies.** As the storage capacity available to capture stream flows diminishes, the ability to deliver reliable water supplies to users also diminishes. These diminished deliveries may not be noticeable in years of above normal or normal rainfall or snowmelt, but both the frequency and severity of rationing will increase rapidly during dry years. The shrinking ability to reliably supply water to users ranging from urban population centers to irrigators is a critical issue.
- **Interference with dam outlets and water intakes.** When sediment approaches the dam's outlet works, it can be drawn into pump stations, hydropower turbines, irrigation canals, or other infrastructure. This impact can occur long before the reservoir fills with sediment, because these sediments can first be carried into the dam outlet works when the reservoir is partially emptied during seasonal drawdown for water delivery. In severe cases, and absent preventive actions, sedimentation can render equipment such as hydropower turbines or pump stations unusable. In

screened intakes, the combination of sediment plus submerged woody debris can clog the outlet or water intake, rendering it inoperable (Figure 4). Because floods transport large volumes of both sediment and woody debris, this clogging can occur quite suddenly, even if it was preceded by years of steady sedimentation that went unattended and, absent monitoring, perhaps even unnoticed.

- **Increased flood hazard**. Many reservoirs reduce downstream flood risks by temporarily capturing flood peaks and releasing the captured water downstream at a reduced rate over a longer time period. Sedimentation progressively diminishes the reservoir's ability to capture water to mitigate flooding. The sedimentation pattern shown in Figure 5 illustrates the sediment delta growing downstream into a flood control reservoir. Excessive deltaic sedimentation can extend along the upstream channel, beyond the reservoir's normal operating pool, increasing the water table elevation and flood risks for upstream communities. Flood stage will increase for a given stream flow and there will be less clearance under bridges to convey flood flows. In a similar fashion, a heightened water table will raise local ground water elevations and may cause soil waterlogging problems, which could impair upstream land use.
- **Increased risks to dam safety.** Dams are normally designed to withstand earthquake shaking when filled with water. However, the accumulation of sediment against the structure can increase the load during earthquakes, which could lead to a dam safety problem. Sedimentation may also pose a dam safety hazard by increasing both the frequency of spillway use and the peak spillway discharge due to the loss of flood storage volume. Spillways typically have a shorter service life than dam outlets and are used only after the outlet discharge capacity has been exceeded.
- **Burial of ancillary reservoir features.** Navigation channels, boat ramps, marinas, and overall surface area and water depth available for recreation are all vulnerable to disruption by reservoir sedimentation.
- **Degradation of downstream channel.** Dam construction interrupts the natural flow of sediment along a river, producing sediment accumulation in the reservoir and a sediment-starved channel below the dam. Sediment-starved alluvial channels erode over time, creating both bed incision and increased bank erosion with impacts to the environment and riverbank infrastructure such as roads, bridges and pipeline crossings, while impairing stream and floodplain habitat for fish and wildlife. The trapping of sediment behind dams also reduces the delivery of sand to coastal areas, contributing to the erosion of shorelines and river deltas.

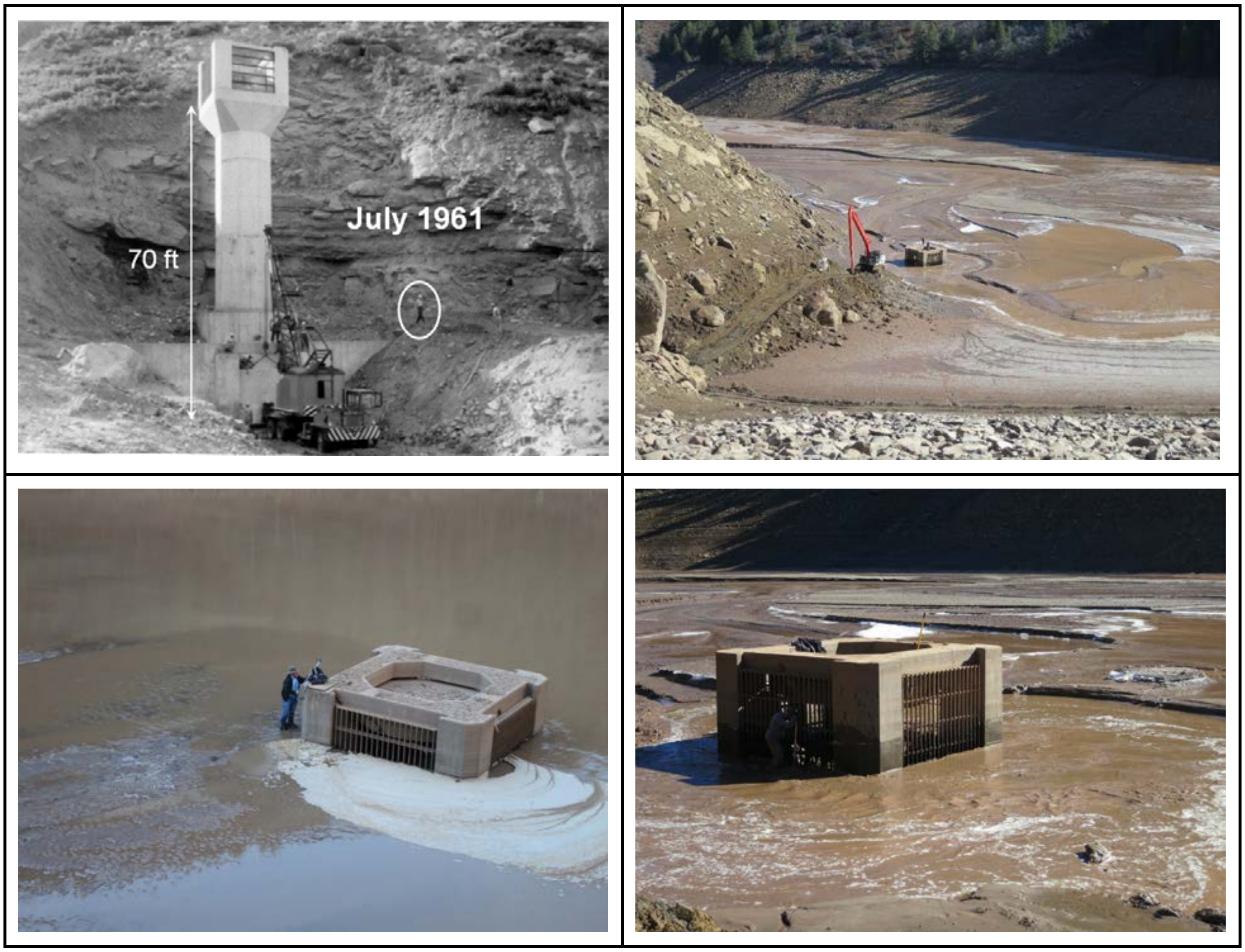


Figure 4. Example of sedimentation interference with dam outlet structure (Paonia Reservoir, Colorado)
Paonia Reservoir reached the end of its sediment design life after 50 years when the outlet became clogged with sediment and woody debris. The outlet works was constructed in 1961, 70 feet above the reservoir bottom (top left). During 2014, a long-reach excavator was used to clear wood and sediment (top right). The sediment level at the dam was 3 feet higher than the outlet works (bottom left and right).

The nation's dams and reservoirs are aging and losing their capacity to deliver their design benefits, but our society will continue to need the water supply, hydropower, flood risk reduction, recreation, and other benefits that reservoirs supply into the indefinite future. To mitigate these impacts, active sedimentation management methods are needed to extend the life of our reservoirs, converting them from non-sustainable resources to sustainable resources. This will require a variety of interventions to our existing and aging hydraulic infrastructure, to achieve a sustainable natural resource. The types of interventions that may be used are described later in this white paper.

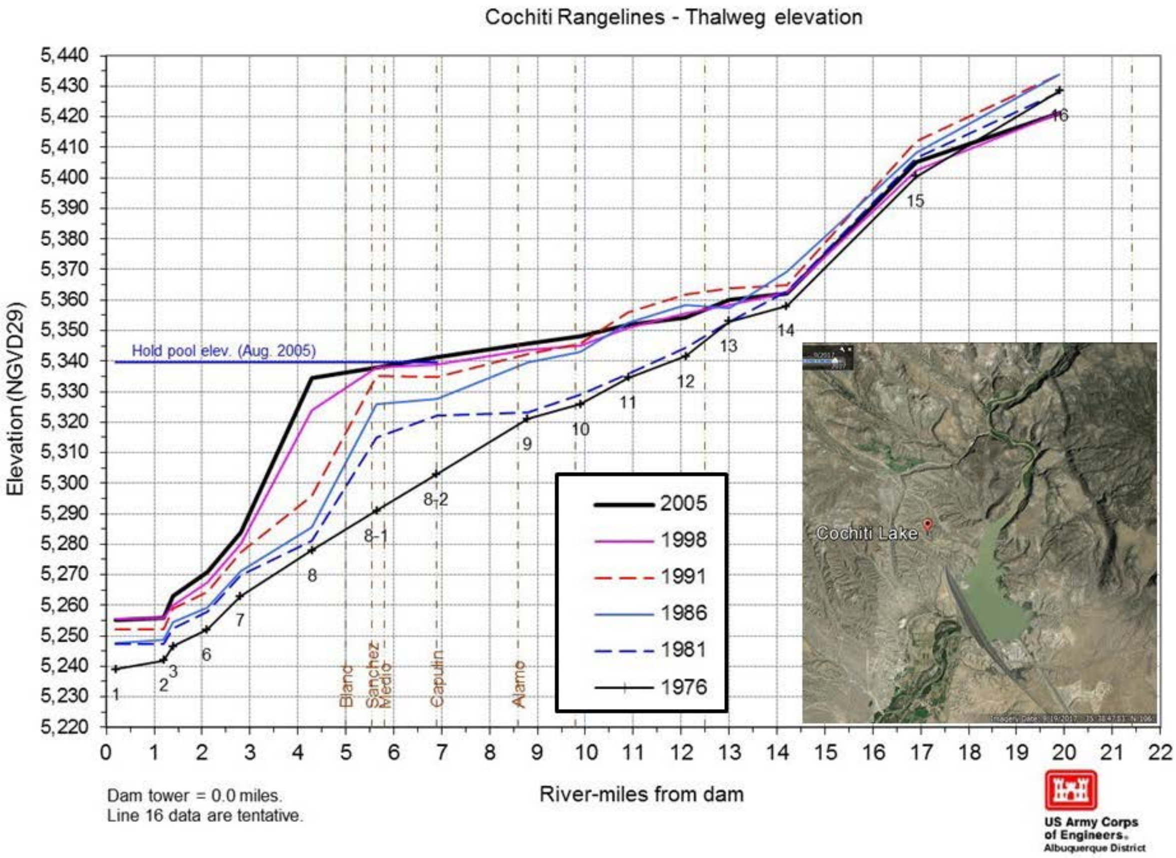


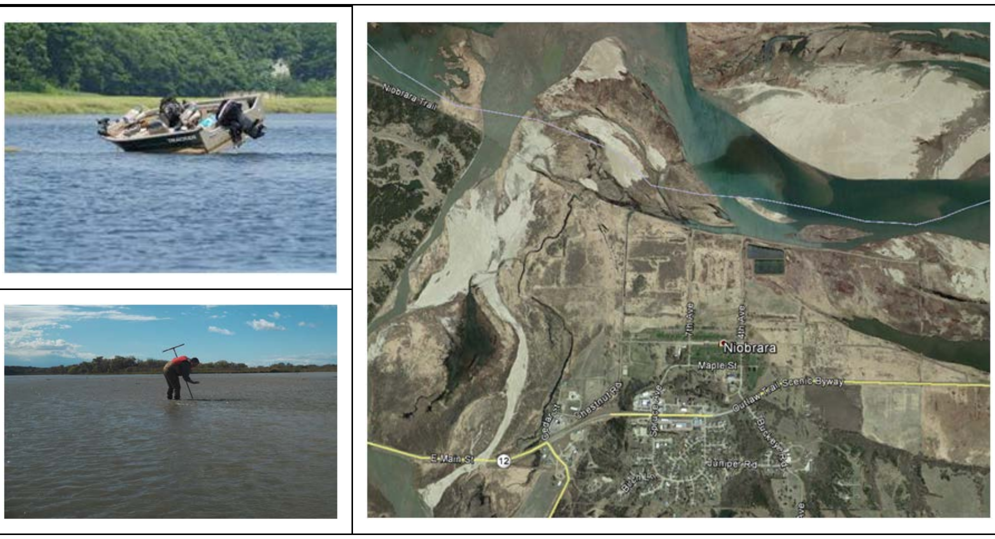
Figure 5. Example of sediment accumulation into reservoir and upstream river channel (Cochiti Reservoir, New Mexico)

Sedimentation in Cochiti Reservoir on the Rio Grande (50 miles north of Albuquerque, NM) has affected all elevations of the reservoir and has also extended upstream, increasing the river channel elevations. In the 29 years between 1976 and 2005, the top surface of the delta has advanced nearly 8 miles downstream toward the dam and raised Rio Grande water surface elevations 2 miles upstream from the original reservoir pool.

Reservoir Sedimentation Examples

The issues described in this white paper have been, or are currently being, faced at numerous reservoir sites across the nation. The photographs assembled in Figure 6, below, depict real examples of reservoir sedimentation problems and management actions from around the country.

a. San Clemente Reservoir, CA – Photographs from Google Earth spanning two decades (1994 left and 2013 right) show the loss of reservoir storage capacity over time due to sedimentation.

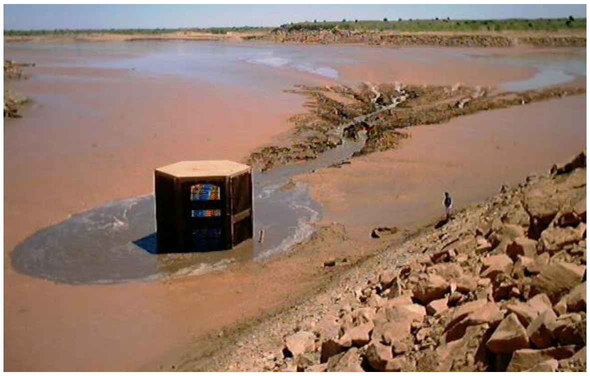


b. Lewis and Clark Lake, SD – Large sediment loads from tributaries have resulted in at least a 30% loss in total storage capacity (USACE, 2013). The upper reservoir is now so shallow that boats can be beached in the middle of the lake (upper left photograph) and the reservoir can be waded (lower left photograph). At least part of the City of Niobrara, NE had to be relocated because of the upstream growth of the sediment delta even though it was upstream from the reservoir pool (right photograph).

c. Grade-control dam on the Little Sioux River, near Sioux City, IA, caused significant sedimentation in the upstream water impoundment.

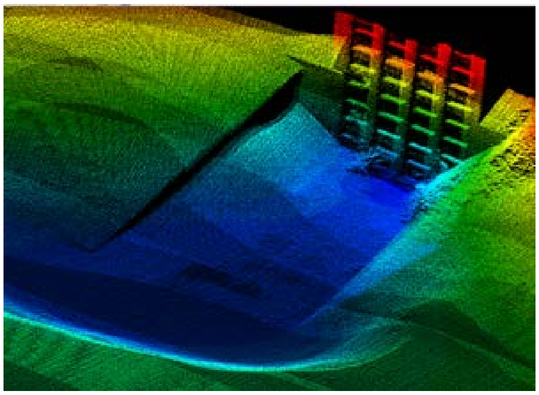
d. Substantial sedimentation behind Askalmore Watershed Dam, Tallahatchie County, MS.

e. *Reservoir sedimentation is beginning to bury the outlet works at Deep Creek Dam, NC, 2007.*

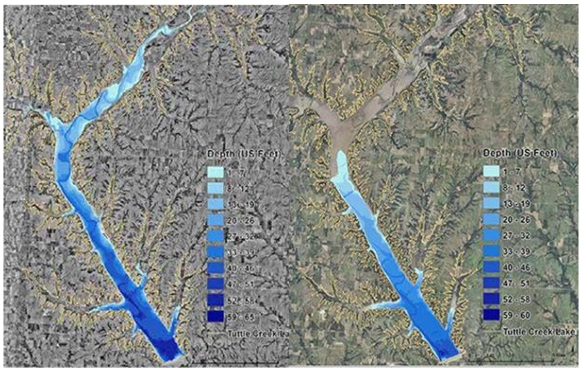


f. *Reservoir sedimentation has buried the outlet at Sumner Dam near Fort Sumner, NM.*

g. *Post-fire accelerated sedimentation rates in Santa Monica Debris Basin in Carpinteria, CA. The 208,000 yd^3 capacity basin (approximately 100 ft deep) (left photograph) was almost completely filled with sediment after a single storm on Jan. 9, 2018. Rain fell at a rate of 1 in/hour over a burnt watershed area (3.8 mi^2) and produced an influx of over 150,000 yd^3 of sediment within 1 hour. The sediment production rate of 40,000 yd^3/mi^2 after wildfire is not unusual. Rates exceeding 130,000 yd^3/mi^2 have been documented in a single storm in these fire-flood situations. Such events often require intensive emergency sediment removal to restore capacity before additional storms occur. This is a good example of how increased incidence of wildfire can increase sediment yield. Extensive drought (perhaps associated with climate change) can increase the occurrence and severity of wildfire.*



h. *Sediment deposition clogs trash racks and prevents placement of emergency bulkhead at Kanopolis Lake, KS.*



i. *The multi-purpose reservoir pool at Tuttle Creek Lake, KS is over 40% full of sediment and the wetted surface area has shrunk considerably over the period 1962 to 2010 (HNTB, 2012).*

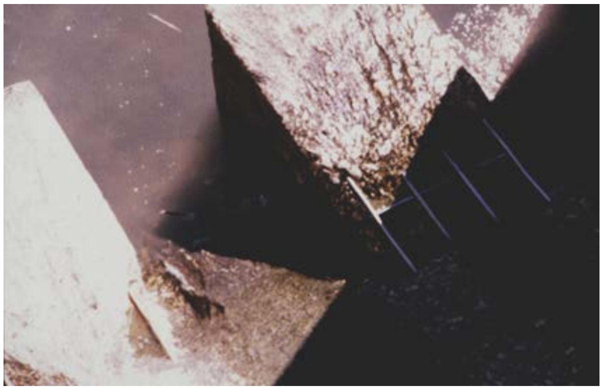
j. Sedimentation has almost completely filled the reservoir behind Matilija Dam near Ventura, CA.

k. The reservoir delta has reduced the surface area available for recreation at Lake Powell near Hite, UT.

l. Channel degradation resulting from lack of upstream sediment source, downstream from Sumner Dam near Fort Sumner, NM.

m. Missouri River channel degradation of at least 10 feet has occurred a few miles downstream from Gavins Point Dam, NE.

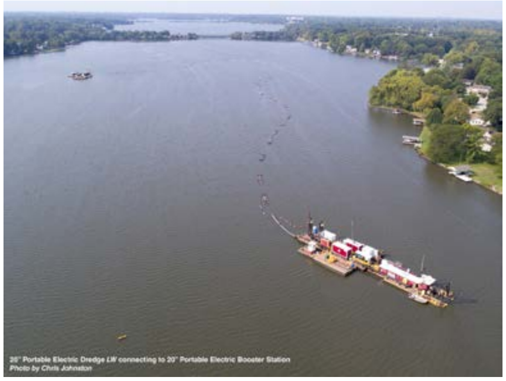
n. Sand has abraded the spillway at the Milburn Diversion Dam near Sargent, NE.



o. Close-up photograph of sand abrasion of the Milburn Diversion Dam spillway near Sargent, NE.

p. Hydraulic dredging of sediments from Strontia Springs Reservoir, near Denver, CO, for transport through a sediment slurry pipeline to downstream areas of Waterton Canyon. Accelerated post-fire sedimentation impacted water quality. Wood and sedimentation have affected the dam outlet (Raitt and Cochran, 2017).

q. Mechanical dredging in Austria (photograph courtesy of Ellicott, Inc.).



r. Example hydraulic dredging of Lake Decatur reservoir near Decatur, IL (photograph courtesy of GLDD Marketing Department).

s. Sediment releases down the spillway of Millsite Dam near Ferron, UT (photograph courtesy of Rollin Hotchkiss).

Figures 6a through 6s. Photographs of reservoir sedimentation examples and their impacts, at sites across the U.S.

Sustainable Sediment Management Planning

Today's challenge is to convert existing reservoirs built under the "design life" paradigm into a sustainable management paradigm, and ensure that new reservoirs also adhere to a "sustainable use" paradigm (Figure 7).

There is currently no consistent federal or state policy to manage reservoirs for long-term sustainable use, nor is there an articulated "exit strategy" for eventual decommissioning[2]. In most cases, the

---

[2] Dam decommissioning would include all necessary activities associated with the full or partial removal of a dam and restoration of the river (USSD, 2015).

management of sediment at existing reservoirs probably represents the most viable option to sustain the benefits of water storage capacity.

In 2014, the Subcommittee on Sedimentation, which includes many Federal agencies concerned with water and sediment, prepared a resolution to encourage Federal agencies to adopt sustainability policies. This resolution was adopted by the parent Federal Advisory Committee on Water Information in August 2014:

> *. . . encourages all Federal agencies to develop long-term reservoir sediment-management plans for the reservoirs that they own or manage by 2030. These management plans should include either the implementation of sustainable sediment-management practices or eventual retirement of the reservoir. Sustainable reservoir sediment-management practices are practices that enable continued reservoir function by reducing reservoir sedimentation and/or removing sediments through mechanisms that are functionally, environmentally, and economically feasible. The costs for implementing either sustainable sediment management practices or retirement plans are likely to be substantial, and sustainable methods to pay for these activities should also be identified.*

The term “retirement” means either leaving the dam in a safe condition or removing it outright. A similar resolution was adopted in 2017 by the U.S. Society on Dams, which:

> *. . . encourages all dam owners to develop long-term reservoir sediment-management plans for the reservoirs that they own or manage by 2030.*

Reservoir sedimentation is a worldwide problem that is not unique to the USA. The World Bank has been very active in promoting sustainable reservoir management worldwide (Annandale, et al., 2016).

The next section describes the types of opportunities available to manage reservoir sedimentation in a sustainable manner.

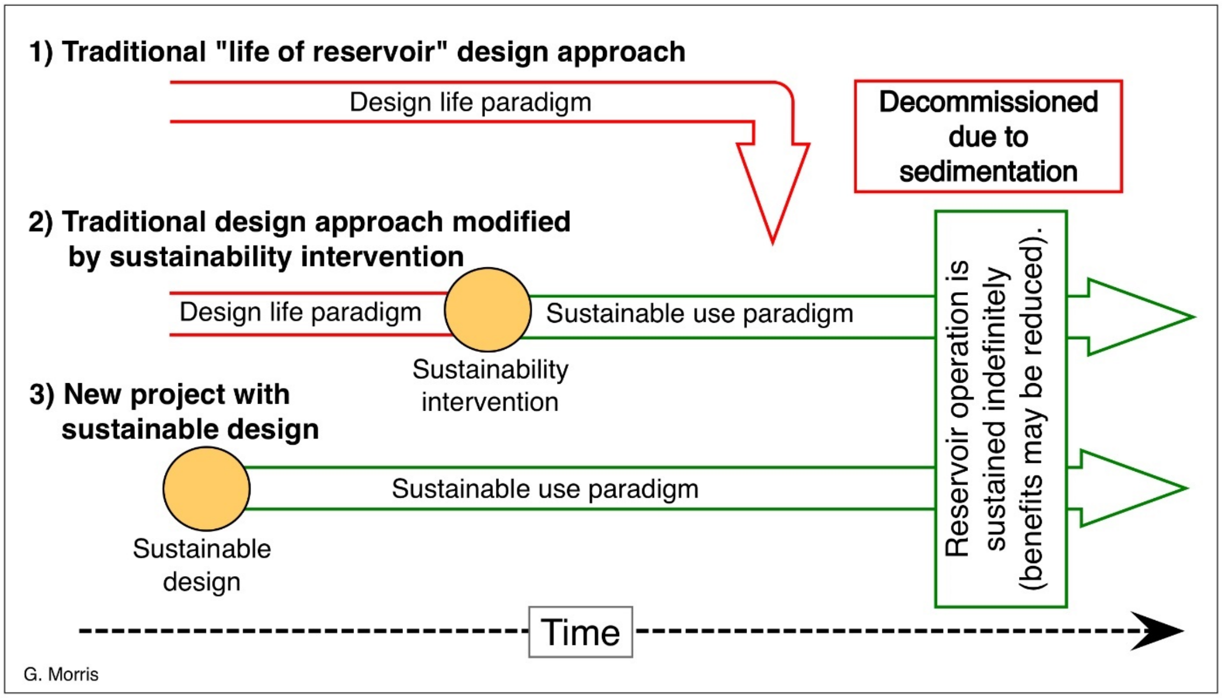


Figure 7. Converting reservoirs from design life paradigm to sustainable use paradigm
(Annandale, Morris, Karki, 2016)

Sediment Management Alternatives

Several sediment management methods exist that can be employed to sustain long-term benefits from reservoirs. These can be classified into four basic categories:

- Reduce sediment yield entering the reservoir (watershed management practices),
- Route sediments away or through the reservoir, to minimize sediment deposition within the reservoir (sediment bypassing or pass-through),
- Remove sediments already deposited in the reservoir (e.g. empty flushing, dredging), and
- Employ adaptive strategies (adapting to reduced storage volume).

These strategies are graphically illustrated in Figure 8, and the specific techniques available under each category are listed in Figure 9.

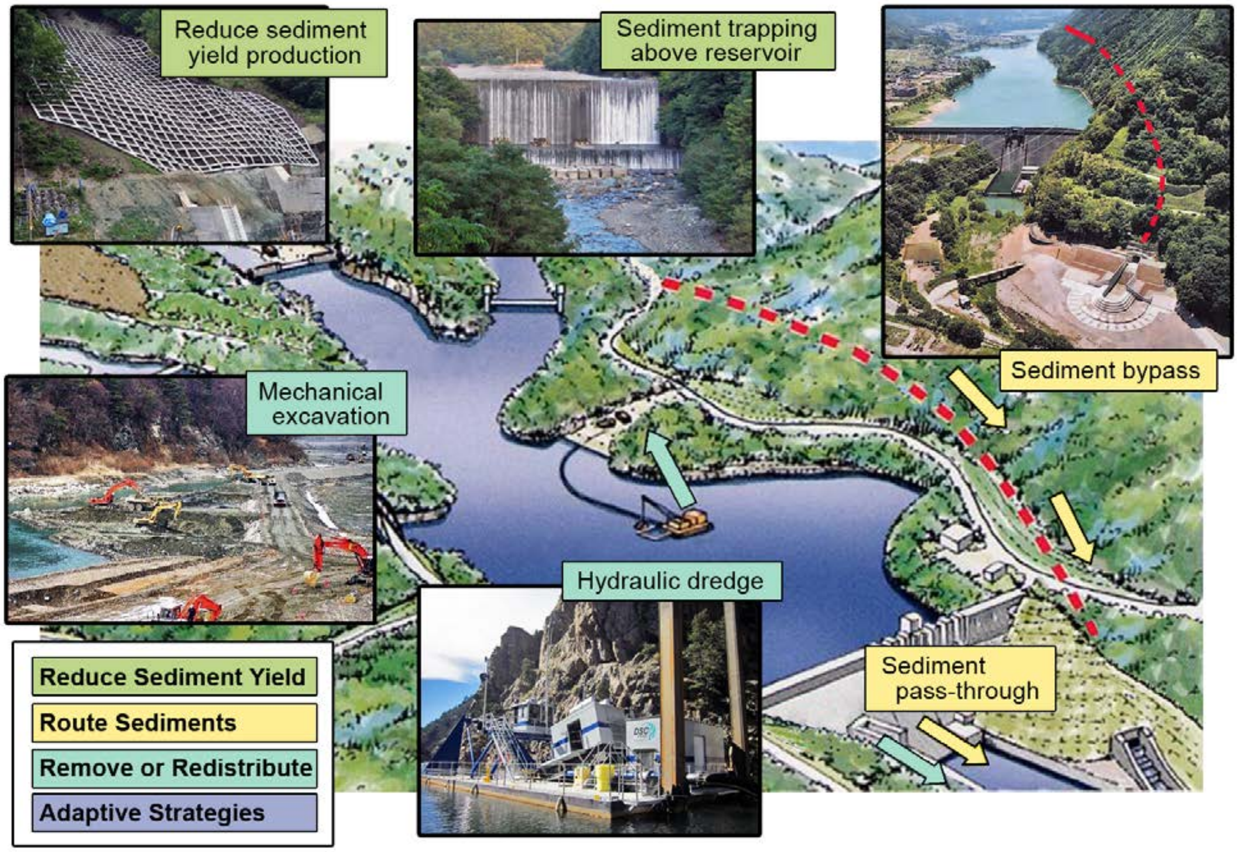


Figure 8. Illustration of sediment management strategies
(modified from Sumi et al., 2017)

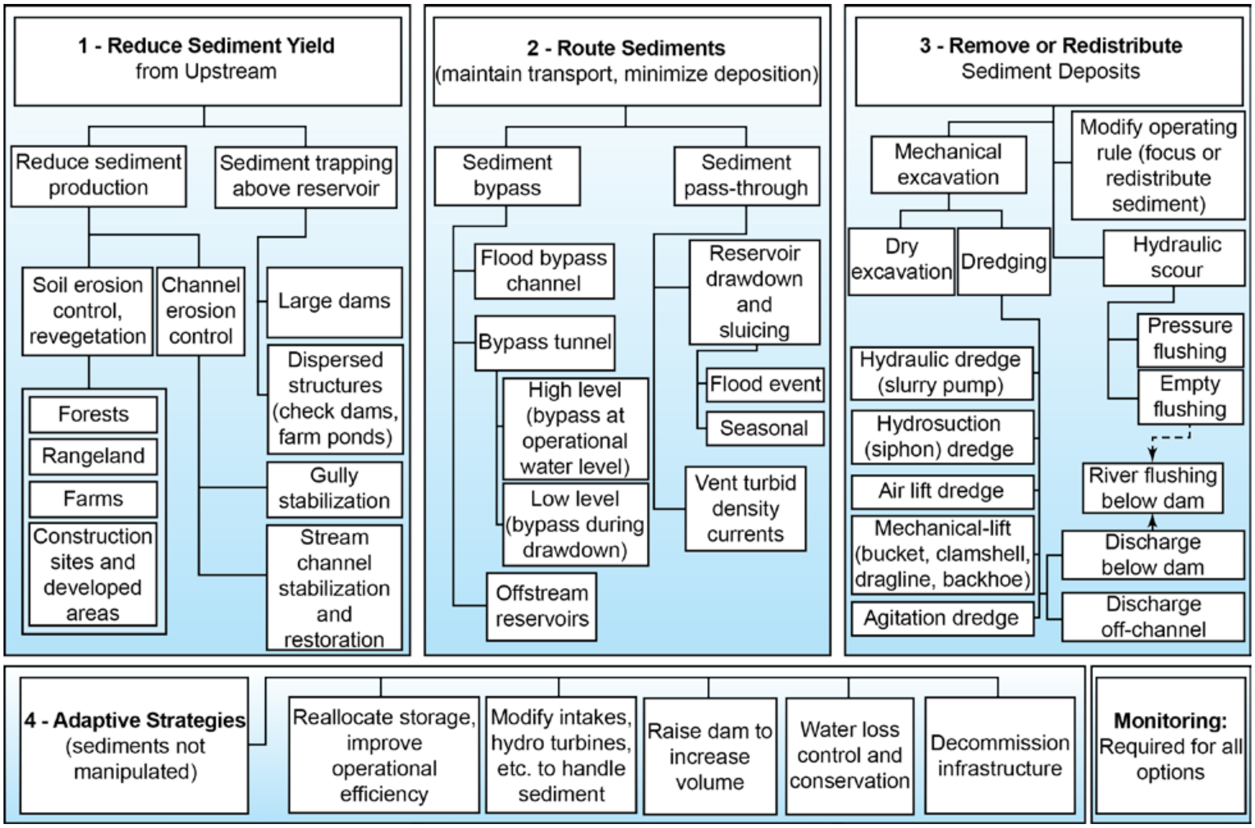


Figure 9. Classification of methods to manage reservoir sedimentation
(Morris, 2015)

A variety of methods are available to manage sedimentation and its impacts. Multiple strategies will typically be employed, either concurrently or sequentially, and selecting the most appropriate strategies will be site-specific. For example, the release of turbidity currents together with watershed protection may be the most relevant strategy early in the reservoir life, but as volume is lost to sedimentation, strategies such as drawdown for sediment sluicing may become more viable. At many sites it may not be economically feasible to sustain current reservoir storage capacity volumes. For this reason, it is important that long-term sustainable-use strategies be identified and implemented as early as possible, thereby reducing the rate of reservoir storage loss, extending reservoir life, and eventually stabilizing storage capacity at the largest feasible volume.

Each of the four principal strategies for managing sediment are briefly described in the sections below.

Appendix A presents a more detailed description of each of these potential methods and strategies.

Developing a Sustainable Sediment Management Plan

Until recently, sediment studies at reservoirs have simply focused on tracking storage loss, without considering its long-term consequences. To convert today's non-sustainable reservoirs into sustainable resources requires commitment to a new conceptual paradigm of long-term utilization, plus the resources required to analyze and implement sediment management. This new paradigm can be accomplished by developing a sustainable sediment management plan as outlined below.

The severity of the sedimentation problem varies from one site to another. Some have looming near-term sedimentation problems, while others may not have significant problems until the next century. Sustainability planning for reservoirs occurs in three stages: (1) ***monitoring and screening*** to identify the most critical reservoirs, (2) ***problem diagnosis and alternative formulation*** at the critical sites, and (3) ***implementation***. Regardless of whether it is a federal agency having responsibility for hundreds of dams, or a local government or private company having one or a few reservoirs under their purview, the concepts outlined below are equally relevant.

Monitoring and Screening

Measuring reservoir sedimentation volume in a systematic fashion provides information required to determine the varying rates and patterns of storage loss, and allows for calibration of numerical models used to predict future sedimentation impacts. Periodic reservoir surveys (below and above water) are the most important monitoring procedure to determine changes in the rate of sedimentation over time, to understand which beneficial uses will be affected, and to predict when the effects will occur. Repeated volumetric survey monitoring is a recognized best management practice for all reservoirs and is a critical proactive step to avoid unanticipated service failure and crisis management. However, many federal reservoirs have not been surveyed since initial filling many decades ago. A recent reservoir survey (within the past decade) is needed to begin sustainable sediment management planning.

Although sustainability interventions are desirable at all sites, it is recognized that this work will start with a small group of high priority reservoirs. Initial screening should be performed to identify the highest priority sites for action. High priority sites may be selected based on factors such as the importance of the threatened beneficial uses, the extent of storage loss, and the type of sediment management opportunities available. Screening may identify some reservoirs as having more potential for a successful intervention than others due to technical, environmental, funding or other considerations. Sites having more potential for successful (and more rapid) implementation may then be prioritized.

Appendix B presents further detail on elements of the reservoir screening and monitoring process.

Problem Diagnosis and Alternative Formulation

For reservoirs selected for potential intervention, it is necessary to perform a diagnosis of the sedimentation problem, and formulate and select the most viable management alternatives, prior to designing and implementing the selected measures.

Diagnosis. Field data collection and analysis are needed to diagnose sediment management opportunities. Typically, a diagnosis would include the following steps:

- Compile and review all available design documents, data and reports related to upstream erosion and sediment yield, prior sedimentation in the reservoir and upstream channel, and any river-channel erosion below the dam.
- Perform an updated reservoir bathymetric survey if no survey data is available from within the past 10 years.
- Sample sediment deposits in the reservoir to characterize grain size, dry bulk density, and any chemistry considered relevant based on potential contaminant sources in the watershed (Randle and Bountry, 2017). Sampling equipment such as vibracore or geotechnical cores should be used instead of sediment surface samples, so that the full depth of deposits can be characterized.
- Quantify the existing reservoir sediment balance in terms of both mass and grain size inflow and outflow rates. Considering installing streamflow and sediment gaging stations (Turnipseed and Sauer, 2010, Diplas et al., 2008, and Gray, J.R. and F.J.M. Simões, 2008) upstream of the reservoir to better understand which inflow events are delivering most of the sediment, as this information will have an impact on the selection of sediment management methods. Installation of a downstream streamflow and sediment gage station can also be helpful in reservoirs which pass an appreciable volume of sediment downstream of the dam. Several years of discharge and sediment load data may be needed to adequately understand the sediment transport dynamics at a given site.
- Determine if historic sedimentation rates are changing due to changes in land use or climate. For example, sedimentation rates could be lower than during past decades due to improved watershed management, or they could be increasing due to increased runoff from urban development, increases in precipitation, or an increased incidence of wild fire in the upstream watershed. If available, data from multiple repeated bathymetric surveys over time will help document long-term changes in sediment yield.
- Forecast the future reservoir sedimentation rate and extent. Estimate the sedimentation impacts on dam and reservoir facilities and the water storage capacity over time. Forecasts are based on historic rates of sedimentation and numerical modeling (Morris and Fan, 1998 and Randle et al., 2006). Sedimentation impacts could include the plugging or burial of dam outlets, reservoir water intakes, boat ramps, and marinas. Quantify future impacts to water supply, hydropower, recreation, and flood risk. Identify properties or infrastructure upstream of the reservoir that could be impacted by reservoir sedimentation and the estimated time frame for the projected impacts.

Alternative Formulation. Develop and describe a range of reasonable sediment management alternatives that meet the project objectives.

- Review available sediment management alternatives previously outlined in Figures 8 and 9. Perform a screening analysis to determine which alternatives may be applicable. Make a preliminary estimate of costs for these alternatives. Both hydrologic and sediment transport modeling will often be necessary to evaluate sediment routing alternatives (e.g., sediment pass-through, by-pass, or flushing).
- Evaluate the decommissioning option, which may include dam removal. Under a “do nothing” sediment management scenario, determine the eventual fate of the dam and its implications to current project benefits. Estimate the costs and if the present benefits generated by the reservoir

will be replaced, and if so, how. If the dam is to be removed, see *Dam Decommissioning Guidelines* (USSD, 2015) and the *Dam Removal Analysis Guidelines for Sediment* (Randle and Bountry, 2017).

- A range of sediment management alternatives may be used, potentially in sequence. For example, the release of turbid density currents (sediment laden inflows that flow along the reservoir bottom) may be used initially, but turbid density currents may no longer transport significant amounts of sediment to the dam as the reservoir fills with sediment and becomes shallower. As the reservoir continue to lose capacity, an alternative sediment pass-through strategy, such as sluicing, may be become increasingly viable.
- The sequence of probable sediment management methods should be identified, along with corresponding structural modifications. For example, sediment sluicing may require large-capacity gates. Structural modifications that may enhance sediment management, include the construction of larger and deeper gates, the installation or improvement of a bypass tunnel or turbidity siphon, and/or the use of dredging geometries that facilitate other complementary sediment management methods.
- Dredging may be considered as a single solution or as a solution complementary to other methods. For example, drawdown sluicing can pass sediment-laden floods through the reservoir, thereby minimizing the amount of sediment to be removed by dredging. On the other hand, dredging can be used to create an underwater hydraulic geometry that enhances sediment release by methods like the venting of turbidity currents to the downstream channel (Appendix A).
- Examine the potential for adaptive measures to improve the effectiveness of sediment management strategies or as a method to offset the loss of benefits by sedimentation. This may include a real-time hydrologic flood-forecast system to optimize reservoir operation (maximizing the benefits from shrinking storage), conjunctive use with groundwater sources, more efficient utilization of a shrinking water supply (water conservation), increasing the dam height to increase water storage capacity, etc. If a turbid density current flowing all the way through the reservoir to dam can be detected, then a low-level dam gate could be opened to vent the density current to the downstream channel (Appendix A).
- When identifying adaptive measures, do not be constrained by existing regulatory or customary practice. If a compelling adaptive measure is identified, it may be of sufficient benefit to warrant a change or work-around to existing regulatory limitations. For example, one of the ways to address water shortages in California has been to over-irrigate during wet years, with the objective of recharging the aquifer to provide an alternative groundwater supply during dry years. This strategy, not contemplated under the historical water management framework, provides sufficient benefit to modify that framework.
- Use a long-term focus in analyzing the management alternatives, identifying those to be recommended for immediate implementation, as well as the additional strategies that may be implemented decades into the future. The objective is to map out the long-term plan to sustainably maintain reservoir capacity, ensuring that activities taken today support the management measures that are expected to be needed in the future.
- Consider the environmental implications of different alternatives, including decommissioning. Some reservoir sediment management alternatives, such as flushing or sluicing, will help restore the

sediment balance along the downstream river, but may cause problems for water users and aquatic species that have become accustomed to having sediment-free water below the dam. Examine various aspects of downstream sediment release, including consideration of (a) the natural sediment regime upstream of the reservoir, compared to the proposed future condition below the dam; (b) the inevitability of eventual sediment releases downstream since the reservoir would otherwise fill with sediment; and (c) the consequences of losing reservoir storage capacity. A substantial loss of reservoir storage capacity may result in environmental, social and financial impacts associated with building a new replacement reservoir or water supply infrastructure, plus the costs and impacts associating with decommissioning the existing dam and reservoir and the possible release of sediment to the downstream river. Recognize that the present clear-water (sediment free) conditions below the dam cannot be sustained once the reservoir has filled with sediment.

Implementation

Following analysis of alternatives and identification of the recommended strategy, the project moves to design, environmental review, and implementation. As mentioned previously, implementation will probably consist of multiple activities or strategies, and may be undertaken gradually and incrementally. The management plan will need to pass certain environmental and cost-benefit thresholds. These might include a comparative analysis of with-project and without-project conditions. An ongoing monitoring program is essential for optimizing sediment management. Short- and long-term monitoring plans should be developed as an integral aspect of the Sustainable Management Plan.

The diagnosis, alternative formulation, impact analysis, permitting, and funding could take a decade or more to complete. Therefore, reservoir sedimentation monitoring and advance planning are needed to avoid crisis management that may occur if a critical dam or reservoir facility is unexpectedly impacted.

Benefit-Cost Evaluation

Analyzing the economic costs and benefits of alternative reservoir sediment management actions, compared to taking no action, is a critical step in deciding whether to undertake that action, and to what extent. An action is deemed to be economically justified if its economic benefits exceed its costs. The benefit-cost analysis compares the net present value of costs to the benefits associated with a sediment management action. Future costs and benefits are discounted into present dollars. The estimation method employed varies based on many factors, but the general framework involves evaluating conditions “with” vs. “without” the action taking place. This allows for the isolation of an action’s economic effects by comparing future conditions with and without the proposed action in place.

The economics of sediment design-life management are conceptually compared for sediment sustainability management approaches in Figure 10. Both economic scenarios include the initial costs of planning, design, and construction of a dam and reservoir. Under the typical sediment design-life management scenario, there are no sediment management costs, but the project benefits gradually decrease over time with reductions in reservoir storage capacity. Eventually, sediment management costs become necessary along with dam decommissioning and the costs associated with planning, design, and construction of a new reservoir, assuming a new reservoir site is available. Under the sediment sustainability management scenario, sediment management costs are incurred on a regular basis, but there is no reduction in project benefits over time and no need to repeat the planning, design, and construction for a new reservoir.

The assumed discount rate used for comparing costs over time can make a large difference on the computed present value of these two economic scenarios. High discount rates heavily favor present generations over future generations and will favor the sediment design-life approach, ignoring future sedimentation consequences. Low discount rates will give more weight to sustaining benefits into the future. A zero-discount rate will equally treat present and future generations.

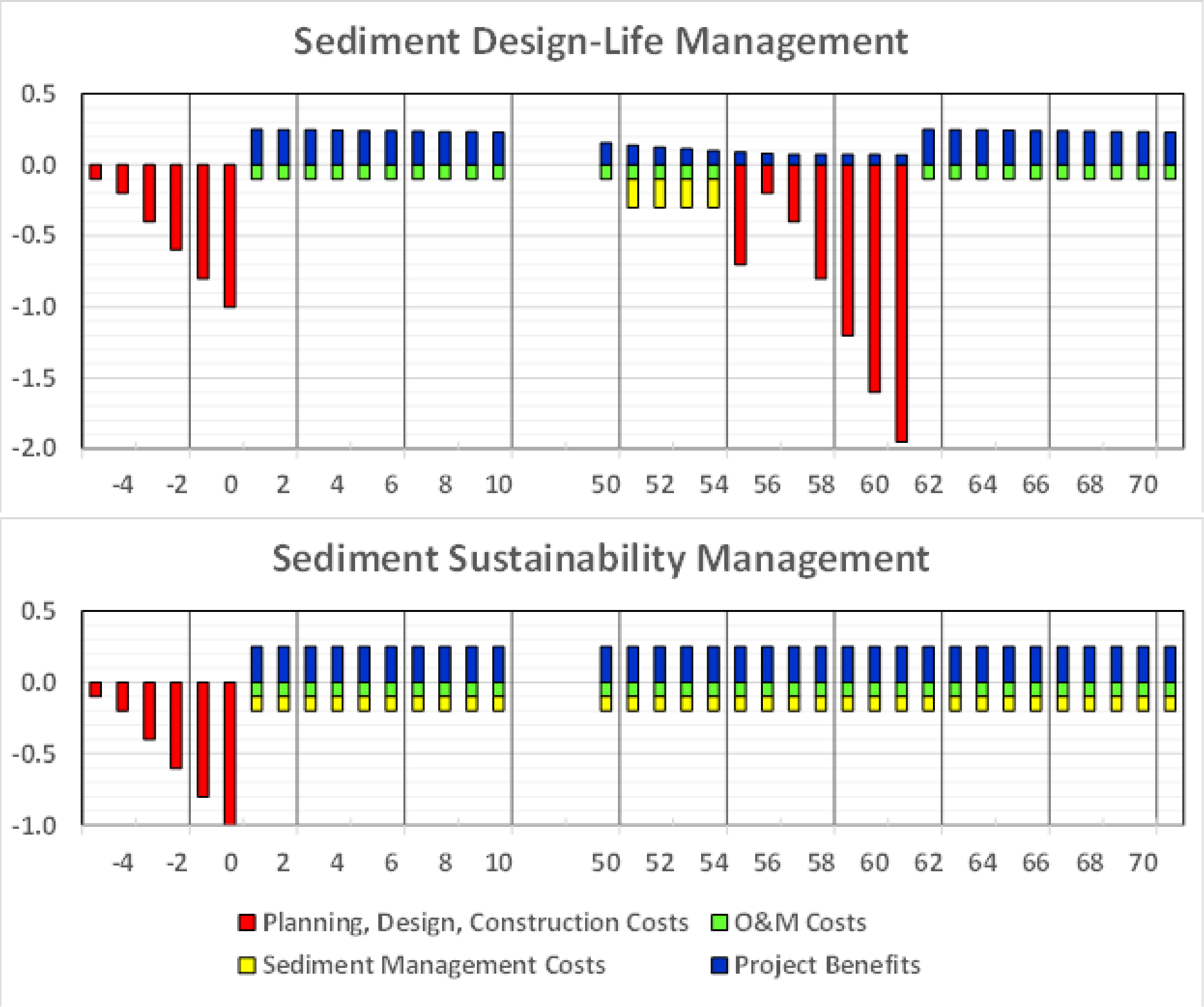


Figure 10. Economic comparison of sediment design life management and sediment sustainability management strategies

For dams already constructed, an operating fee of some kind often may be required to fund reservoir sediment management actions to sustain long-term operations. This practice is common in other natural resources extraction industries where, to prevent the catastrophic over-harvesting of trees, grass, or fish, for example, operators are either limited in their harvesting activities or are required to replace the resource following extraction. For example, a fee requirement could be established toward the beneficial users of reservoir water storage to pay for sustainable sediment management practices.

The past application of the sediment design life management strategy has led to an intergenerational inequity of the scarce resource of reservoir water storage. The generational sequence is described below:

- 1st generation conceives, plans, designs, and constructs a dam and reservoir.
- 2nd generation receives full benefits, repays capital costs, and pays O&M costs.
- 3rd generation receives close to full benefits, finalizes repayment of capital costs, and pays O&M costs.
- 4th generation receives declining benefits and pays O&M costs, but there is no sediment management.
- Last generation is stuck with decommissioning costs and has to develop a new water storage facility at a higher cost.

More information on conducting a benefit-cost evaluation for reservoir sediment management can be found in Appendix C.

Permitting Framework

When considering the design and implementation of a reservoir sediment management action, it is important to bear in mind the permitting framework and requirements that will apply, because time and effort are necessary in order to secure approvals. The current regulatory framework for sediment management associated with reservoirs typically requires review and approval at both the federal and state levels, as well as local or regional approvals. Regulatory interest focuses not only on existing and anticipated reservoir conditions, but also on watershed management programs, sediment transport or passage within the watershed, and the final disposition of the sediments.

Federal agencies must analyze their proposed actions under the National Environmental Policy Act (NEPA). Analysis under NEPA may be triggered by Federal actions or involvements, such as constructing or funding a project, proposing a project on Federal land, or issuing a permit or approval. If a proposed project does not require any Federal action or involvement, NEPA analysis is not required. Many states also have environmental review programs so, in many cases, a project may be required to comply with both federal and state environmental review programs.

For projects in water bodies such as reservoirs, lakes, rivers, streams, wetlands, or the ocean, much of the regulatory framework centers on application of the Clean Water Act (CWA), as implemented by the U.S. Army Corps of Engineers (USACE) and U.S. Environmental Protection Agency at the federal level, and state water quality or public health agencies at a more local level. CWA requirements intersect with sediment management by requiring protections for water quality during and following sediment management operations and requiring analysis of the potential impacts from the final disposition of the sediment within river courses or water bodies. A suite of other federal and state regulations may apply to sediment management operations in reservoirs, including Section 10 of the Rivers and Harbors Act, the Endangered Species Act, the National Historic Preservation Act, and similar state regulations pertaining to protection of wildlife, sensitive habitat, recreation, and public access. Compliance with these regulations is typically linked to project review and analysis under NEPA and state environmental procedures and usually involves coordination among multiple agencies. The federal and state environmental review processes typically include opportunities for public review and comment.

The level of analysis required for a proposed project is intended to be commensurate with the scope and complexity of the project as well as its potential impacts. In some cases, the federal agency or project proponent may elect to perform a more extensive environmental analysis of a project than is nominally required. For example, if a project is highly controversial, or may be subject to litigation, then performing a more extensive environmental impact analysis may avoid later problems. Under NEPA, a federal action may be "categorically excluded" from a detailed environmental analysis if the federal action is judged to not "individually or cumulatively have a significant effect on the human environment" (40 CFR 1508.4). The next level of analysis under NEPA is an environmental assessment (EA). If significant effects on the quality of the human environment are anticipated, then an environmental impact statement (EIS) would be required.

In general, management activities that pass inflowing sediments through the reservoir to the downstream channel will have less impact on the natural environment than trapping the sediments in the reservoir (provided that the sediments are free from chemical contamination above natural background levels). This is especially true when the sediments are passed downstream at rates similar to the natural supply rates from upstream and their variance with seasons and stream flow rates.

Appendix D includes an overview of the permitting process applied to several representative sediment removal projects that have taken place, are currently underway, or are in the planning stages in the U.S. They range from very large (millions of cubic yards of sediment over several phases) to relatively small (several thousands of cubic yards in a single removal effort).

Permitting Strategies and Areas for Further Policy Development

Permits are almost always required to implement sediment management plans. It would be beneficial for stakeholders, water managers, and regulators to explore ways that current regulations, enforced by multiple federal, state, and local agencies, could be improved to facilitate such plans. Improvements to policy could be viewed through the lens of restoring natural sediment loads to downstream channels and sustaining the nation’s reservoirs to provide essential services well into the future. Some potential specific improvement areas for policy and funding are as follows:

- Review and, where feasible, enhance federal and state funding mechanisms for reservoirs as part of the overall review of national infrastructure needs.
- Develop more comprehensive nationwide permits (NWP) and Regional General Permits (RGP) on a watershed-by-watershed basis to streamline reservoir management in these watersheds. Prepare these permits before they are needed by individual projects rather than in a reactive manner. Seek regulatory consistency in the process.
- Develop a better definition of how existing NWPs will be applied among different regions, through formulation of unambiguous criteria.
- Consider refining the definition of “de minimis” or inconsequential effect levels for dredged or fill material in waters of the United States, for cases where material is being replaced downstream of dammed reservoirs.

USACE maintains and renews a set of NWPs every 5 years. The NWP program covers a range of activities where impacts are minimal and generally predictable and is intended to streamline the permit process with the USACE and often the state agency responsible for administering Section 401 of the CWA. While NWP 18 allows for removal of “less than 25 cubic yards of material” from waters of the United States, this amount will have negligible relevance to large-scale reservoir systems, in which the volumes of interest are three to five orders of magnitude greater.

When considering ways to streamline the permit process, one key may be to encourage the USACE to broaden its thinking regarding the definition of de minimis material release. Regulatory Guidance Letter No. 05-04 discusses this under paragraph 4b, where the de minimis amount is not precisely defined but is instead described in the context of sediment releases “that mimic the natural increase and decrease of sediment in a stream” or in amounts “comparable to the amount of material entering the reservoir from upstream” (U.S. Army Corps of Engineers, 2005). Perhaps this is an area to further explore with the USACE and other regulatory agencies. If the sediment load being released can be shown to be similar in magnitude and seasonal pattern to the amount of sediment that would have entered the downstream reach under natural conditions, or if the dam and reservoir did not exist, then that quantity could be considered a de minimis release. There may be a way to devise a relatively simple method for demonstrating de minimis release amounts under a specific set of circumstances, thus establishing a framework to avoid a lengthy individual permit process for numerous reservoirs.

From an implementation viewpoint, the RGP process is probably more feasible than the individual permit process for each individual case at this time, as is mentioned in Regulatory Guidance Letter No. 05-04. The ease of obtaining the RGP will vary with each watershed, reservoir, and downstream area. The RGP is suited for multiple sediment discharge events spaced out over repeated episodes rather than one large sediment release. Because an RGP is intended to streamline the permit process for projects with minimal and predictable impacts, and allows for multiple and regular renewal, it fits a multiple-episode approach. This can be particularly appropriate for cases where each sediment release (or downstream “fill” from the USACE perspective) can be shown to be commensurate to the natural sediment loading that the stream would have experienced under “natural” conditions (“…operation of continuously sluicing structures that mimic the natural increase and decrease of sediment in a stream"). The natural variability of sediment loads and measurement uncertainty should be considered in such an evaluation.

The specifics of an RGP would vary regionally depending on location and many other variables that distinguish one watershed or system from another, but a typical RGP might allow for the following reservoir sediment management actions:

- Removing a defined range of sediment volume per year: as stated above, this could equal the average input per year rather than a larger volume resulting from build-up over multiple seasons
- Limiting or restricting downstream sediment discharge to certain times of the year: both seasonally and to avoid potential effects to sensitive species breeding or foraging
- Requiring applicable best management practices to limit potential effects
- Monitoring physical, chemical, or biological processes

The key for reservoir managers presenting an RGP approach to regulatory agencies would be to demonstrate that the impacts from multiple reservoir sediment discharges are minimal and predictable from episode to episode. A pilot test study could establish the framework of the RGP. Any relevant studies of potential effects, or examples of monitoring reports related to the proposed activity, would be a component of the initial application to the USACE, while a pilot test study would be specific to what is being proposed.

One way that reservoir managers have been successful at developing and improving existing RGPs is by generating a table of "realistic parameters," such as those presented in the bulleted list above, to be included in the RGP. The table would be generated based on stakeholder input and would accomplish or respond to the purpose and need of what is being requested. Additionally, the table would outline existing mechanisms on how the work is currently accomplished and permitted, as well as any deficiencies, addressing why and how they need improvement. Once this table is prepared, the applicant would meet with a USACE District Chief and Regulatory Division representatives to present and walk through the idea.

Conclusions and Recommendations

The nation's 90,000 dams and reservoirs are a critical component of the country's infrastructure. They provide reliable water supplies for municipal, agricultural, and industrial use while also serving key needs for hydropower, flood risk reduction, navigation, and recreation. However, each dam has blocked the natural sediment supply to thousands of miles of downstream riverine ecosystems. The reduced sediment loads result in environmental impacts to sediment-starved rivers below dams and impacts to infrastructure along those streams.

The present practice of allowing the nation's reservoirs to continually fill with sediment over time is not sustainable. Sedimentation will bury important dam and reservoir facilities (e.g., dam outlets, water intakes, boat ramps and marinas), reducing water storage capacity and surface area available for recreation long before the reservoir has completely filled with sediment. Reservoirs cannot trap sediment indefinitely. As the reservoir becomes filled with sediment, in-flowing sediment then will be transported through the reservoir and delivered to the downstream channel in an uncontrolled manner.

Large scale sediment removal to recover decades of lost storage capacity is often cost prohibitive, if it is even feasible at all, and can result in unacceptable environmental impacts if released downstream over a relatively short time period. Once the benefits of a reservoir have been lost to sedimentation, dam decommissioning is often the eventual outcome. Even after complete dam removal, significant quantities of sediment deposits may remain in the reservoir area and render the area unsuitable for future water storage. With 90,000 dams having already been built in the United States, the best dam and reservoir sites are already being utilized, and options for new dam sites are limited. This makes the existing reservoirs that are still providing water storage benefits a limited resource. Our best option for sustaining the nation's water supplies is to sustain the functioning of our existing reservoirs.

The sustainable management of reservoirs to preserve long-term capacity represents a fundamental shift from the traditional design life approach where reservoirs simply continue to fill with sediment until abandonment. A new sustainable-use approach is both necessary and feasible and is being developed and implemented at a growing number of reservoirs worldwide. Achieving sustainable utilization of the nation's water resources will require better monitoring data, changes in reservoir operations, structural modifications to dams, and modifications to the environmental regulatory framework.

A prudent, long-term sustainable goal for reservoir management is to pass inflowing sediments to the downstream channel each year in a quantity similar to the mass or volume of sediments entering the reservoir and, to the extent possible, with similar timing. Inflowing reservoir sediment could be transported downstream primarily during high flows and within the range of natural flow variability. Once sustainable sediment management is implemented, the remaining reservoir storage capacity may be preserved. However, the longer the time needed or chosen to implement sustainable management, the smaller the remaining storage capacity that can be preserved.

Plans to periodically monitor reservoir sedimentation need to be formulated and implemented at each reservoir to document the remaining storage capacity and estimate when important dam and reservoir facilities will be impacted. Estimating when sedimentation will impact reservoir operations or functions well before the impact occurs, is an important proactive step to avoid having to manage a crisis situation. The frequency of monitoring should correspond to the rate of reservoir sedimentation and storage capacity loss.

Long-term reservoir sediment-management plans formulated for each reservoir should include either the implementation of sustainable sediment-management practices or eventual dam decommissioning. Sustainable reservoir sediment-management practices enable continued reservoir function by reducing reservoir sedimentation or removing sediments through mechanisms that are functionally, environmentally, and economically feasible. The costs for implementing either sustainable sediment management practices or dam decommissioning plans are likely to be substantial, and sustainable methods to pay for these activities should also be identified.

Environmental permitting laws and regulations for reservoir sediment management must recognize that reservoirs cannot trap inflowing sediments indefinitely and that reservoir sedimentation leads to downstream channel degradation, impairment of habitat for aquatic and terrestrial resources, and erosion of infrastructure along the downstream channel. In addition, reservoir sedimentation leads to upstream channel aggradation and increases in groundwater levels and flood stage and frequency. Allowing inflowing reservoir sediments to pass downstream restores natural sediment processes and improves conditions for dependent habitat, and can be accomplished by manipulating reservoir operations; installing new gates, bypass channels, or tunnels; or mechanically transporting the sediment.

References

Ackerman, K. V., D. M. Mixon, E. T. Sundquist, R. F. Stallard, G. E. Schwarz, and D. W. Stewart (2009). *RESIS — An updated version of the original Reservoir Sedimentation Survey Information System (RESIS) database*, U.S. Geol. Survey. Data Ser., 434. (Available at http://pubs.usgs. gov/ds/ds434)

Anchor QEA and Great Lakes Dredge and Dock (2019). *Development of Basic Cost Model for Removal of Sediment from Reservoirs*, Technical Memorandum to NRSST, June 2019.

Annandale, G. (2013). Quenching the Thirst, Sustainable Water Supply and Climate Change, Create Space Independent Publishing Platform, North Charleston, SC, 231 pages.

Annandale, G.W., G.L. Morris, and K. Pravin (2016). *Extending the Life of Reservoirs, Sustainable Sediment Management for Dams and Run-of-River Hydropower*, International Bank for Reconstruction and Development / The World Bank, Washington, DC.

Bureau of Reclamation (2016). The Knowledge Stream Reservoir Sedimentation and Sustainability Issue, Spring 2016 Research and Development Office Newsletter, 2016-02, Denver, CO, 44 pages.

Cooper, D. (2015). “USACE Reservoir Sedimentation Survey Database (RESSED) Oracle Conversion” in Proceedings of the 5th Federal Interagency Hydrologic Modeling Conference and the 10th Federal Interagency Sedimentation Conference, Peppermill Hotel, Reno, Nevada, April 19-23, MShttps://acwi.gov/sos/pubs/3rdJFIC/Contents/7C-Cooper.pdf

Congressional Research Service (2018). *Wildfire Statistics*, updated November 16, 2018. https://fas.org/sgp/crs/misc/IF10244.pdf

Diplas, P., R. Kuhnle, J. Gray, D. Glysson, and T. Edwards (2008). “Sediment Transport Measurements,” in Garcia, Marcelo, ed., Sedimentation engineering—Processes, measurements, modeling, and practice, American Society of Civil Engineers Manual 110, chap. 5, p. 307–354.

Ferrari, R. and K. Collins (2006). *Erosion and Reservoir Sedimentation Manual*, *Chapter 9 – Reservoir Survey and Data Analysis,* U.S. Department of the Interior, Bureau of Reclamation. https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/Erosion%20and%20Sedimentation%20Manual.pdf

Ferrari, R.L. (2006). *Reconnaissance Techniques for Reservoir Surveys,* U.S. Department of the Interior, Bureau of Reclamation. https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/ReconnaissanceTechniqueResSurveys04-2006_508.pdf

Graf, W. L., E. Wohl, T. Sinha, and J. L. Sabo (2010). Sedimentation and sustainability of western American reservoirs, *Water Resources Research.*, 46, W12535, doi:10.1029/2009WR008836.

Gray, J.R. and F.J.M. Simões (2008). “Estimating Sediment Discharge,” in Garcia, Marcelo, ed., Sedimentation engineering—Processes, measurements, modeling, and practice, American Society of Civil Engineers Manual 110, Appendix D, p. 1067–1088.

HNTB (2012). Kansas River Basin Reservoir Analysis: Regional Sediment Management Section 204 Tuttle Creek Reservoir. Prepared for the U.S. Army Corps of Engineers, Kansas City District.

Kondolf, G.M.; Gao, Y; Annandale, G.W.; Morris, G.L.; Jiang, E.; Zhang, J.; Cao, Y.; Carling, P.; Fu, K.; Guo, Q.; Hotchkiss, R.; Peteuil, C.; Sumi, T.; Wang, H.W.; Wang, Z.; Wei, Z.; Wu, B.; Wu, C.; and Yang, C.T. (2014). “Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents.” Earth’s Future, 2, doi:10.1002/2013EF000184.

Morris, Gregory L. and Fan, Jiahua. 1998. *Reservoir Sedimentation Handbook*, McGraw-Hill Book Co., New York, New York, https://reservoirsedimentation.com/.

Morris, G.L. (2015). “Collection and Interpretation of Reservoir Data To Support Sustainable Use,” in *Joint Federal Interagency Conference, 10th FICS and 5th FIHMC*, April 19-23, 2015, Reno, Nevada, USA.

National Inventory of Dams (2017). https://catalog.data.gov/dataset/national-inventory-of-dams, accessed December 4, 2018.

Raitt, D. and B. Cochran (2017). “Hydraulic Dredging of the Strontia Springs Reservoir - Lessons Learned,” in United States Society on Dams, *It’s a Small World: Managing Our Water Resources, 37th Annual USSD Conference,* Anaheim, California, April 3-7, 2017.

Randle, T.J., C.T. Yang, and J. Daraio (2006). “Chapter 2, Erosion and Reservoir Sedimentation” in Erosion and Sedimentation Manual, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado. https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/Erosion%20and%20Sedimentation%20Manual.pdf

Randle, T.J., J.A. Bountry, A. Ritchie, and K. Wille (2015). “Large-scale dam removal on the Elwha River, Washington, USA: Erosion of reservoir sediment,” *Geomorphology*, (2015), http://dx.doi.org/10.1016/j.geomorph.2014.12.045

Randle, T.J., and J. Bountry (2017). *Dam Removal Analysis Guidelines for Sediment*, prepared for Advisory Committee on Water Information, Subcommittee on Sedimentation by U.S. Department of the Interior, Bureau of Reclamation, December 2017, Denver, Colorado. https://acwi.gov/sos/pubs/dam_removal_analysis_guidelines_for_sos_final_vote_2017_12_22_508.pdf

Randle, T.J., S. Kimbrel, and K. Collins (2017). “Reservoir Sedimentation and Sustainability,” in United States Society on Dams, *It’s a Small World: Managing Our Water Resources, 37th Annual USSD Conference,* Anaheim, California, April 3-7, 2017.

Randle, T.J., S.W. Ekren, W.H. Hanson, and R.C. Ramsdell (2018). "Sediment Dredging of Reservoirs for Long-Term Sustainable Management," in *United States Society on Dams, A Balancing Act: Dams, Levees and Ecosystems*, April 30 to May 4, 2018, Miami, Florida.

Sholtes, J.S., C. Ubing, T.J. Randle, J. Fripp, D. Cenderelli, and D.C. Baird (2017). *Managing Infrastructure in the Stream Environment*, Advisory Committee on Water Information Subcommittee on Sedimentation Environment and Infrastructure Working Group, 65p. https://acwi.gov/sos/pubs/managing_infrastructure%20_in_the_stream_environment.pdf

Sumi, T., T. Yoshimura, K. Asazaki, and T. Sato, (2015). "Retrofitting and change in operations of cascade dams to facilitate sediment sluicing in the Mimikawa river basin," International Symposium on Flash Floods in Wadi Systems, 14th – 15th of October 2015, Obaku Plaza, Kyoto University, Gokasho, Uji, Kyoto, Japan, pp 597–611. http://ecohyd.dpri.kyoto-u.ac.jp/content/files/sumi-paper/2015/cQ.99-R.45.pdf

Sumi, T., S. Kantoush, T. Esmaeili, and G. Ock (2017). "Reservoir Sediment Flushing and Replenishment Below Dams: Insights from Japanese Case Studies" in *Gravel-Bed Rivers: Process and Disasters*, Chapter 14, edited by D. Tsutsumi and J.B. Laronne, John Wiley & Sons.

Turnipseed, D.P. and V.B. Sauer (2010). Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods book 3, chap. A8, 87 p. (Also available at http://pubs.usgs.gov/tm/tm3-a8/.)

U.S. Army Corps of Engineers (2005). *Regulatory Guidance Letter 05-04*, 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. https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll9/id/1268

U.S. Army Corps of Engineers (2013). Sedimentation Conditions at Lewis and Clark Lake. MRB Sediment Memorandum 29. October 2013.

U.S. Army Corps of Engineers (2018, Draft in Progress) Engineering Manual: Reservoir Studies and Data Collection, EM-1110-2-4000.

U.S. Census Bureau (2018a). *Historical Census Statistics on Population Totals by Race, 1790 to 1990*.

U.S. Census Bureau (2018b). *Projected Population Size and Births, Deaths, and Migration: Main Projections Series for the United States, 2017-2060*. U.S. Census Bureau, Population Division: Washington, DC, March 2018.

USSD (2015). *Guidelines for Dam Decommissioning Projects*, United States Society on Dams (USSD), USSD Committee on Dam Decommissioning, July 2015. https://www.ussdams.org/wp-content/uploads/2016/05/15Decommissioning.pdf

Appendix A: Sediment Management Methods and Strategies

Reduce Sediment Yield

A commonly employed approach for reducing sediment loads entering a reservoir is to implement erosion controls in the upstream watershed and stream channels. This strategy has been practiced, with varying degrees of success, since the 1930s. In the long-run, the most effective methods to control soil erosion are those that focus on increasing vegetative cover and increasing the organic content of the soil. Erosion in ephemeral gullies or channels is typically approached through structural measures such as check dams, which can be effective to the extent that they help restore vegetative controls which in turn become self-maintaining. Otherwise, check dams tend to eventually fail and release their previously stored sediment. Structural controls can also be used to stabilize lateral migration of incised channels, protecting against bank erosion.

Watershed management practices can delay reservoir sedimentation problems but are not a complete solution to the problem. Even when land use improvements are successful, decades may be required for a significant reduction in sediment yield to be realized at the downstream reservoir. Also, there will always be an unavoidable natural or “background” rate of soil erosion and sediment yield, even with undisturbed soils.

Another very important factor reducing sediment yield is the trapping of sediment in upstream reservoirs, even if constructed for other purposes. Dispersed structures such as check dams, farm ponds, and debris basins are good at trapping coarse sediments, while larger dams and reservoirs can also trap fine sediments. When upstream dams are constructed for the purpose of trapping sediments, plans are needed to periodically remove those sediments through hydraulic or mechanical dredging. These removed sediments may provide beneficial uses:

- Soil augmentation for agriculture
- Land development
- Construction fill
- Concrete aggregate
- Construction of wetland and other shallow water habitats
- Shoreline beach development or augmentation

Route Sediments Through or Around a Reservoir

Sediment is primarily eroded and transported by flood events, and “sediment routing” strategies focus on keeping the flood water and its sediment load moving through or around the reservoir to minimize sedimentation (Morris and Fan, 1998).

For an on-stream reservoir, it may be possible to construct and operate a bypass tunnel or channel to pass the sediment-laden flows around the reservoir (Figure A1a and b). In moist climates, hydrologic conditions may favor construction of an off-stream reservoir which accommodates diversions of relatively clean water into the reservoir, while the floods with their high sediment loads, are allowed to remain in the channel and bypass the reservoir (Figure A1c). Under favorable conditions, this may reduce the rate of sediment delivery into a reservoir by over 90%.

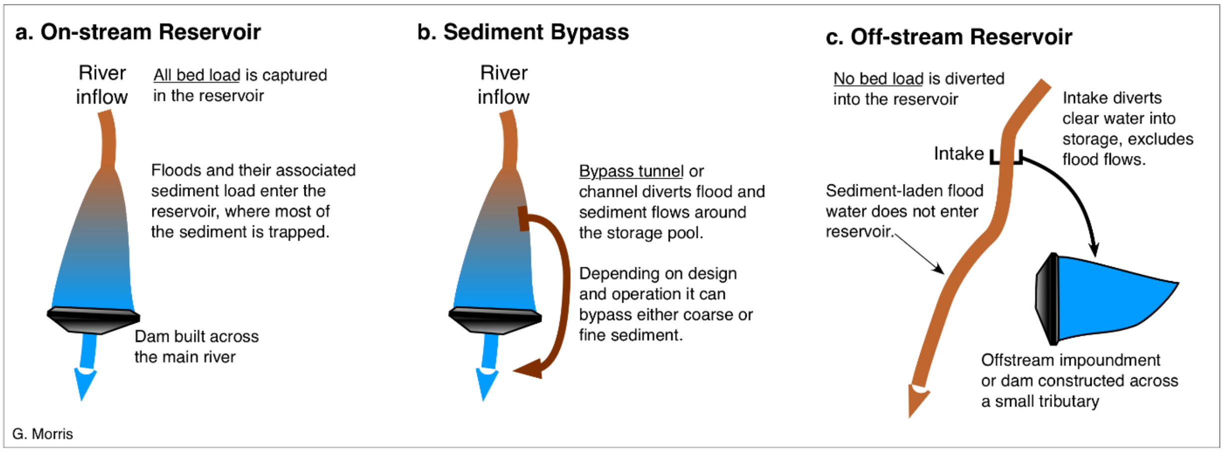


Figure A1. Comparison of sediment routing strategies
Bed load consists of the coarse sediments (typically sand- and gravel-sized) that are transported along the stream bed.

Sediment sluicing refers to the practice of maximizing passage through a reservoir by temporarily lowering the reservoir water level during periods of high sediment load. The lower reservoir water level increases flow velocity and decreases the detention time, thereby keeping sediment particles suspended and in motion for a longer time and reducing the opportunity for the particles to become trapped within the reservoir. This method passes flood-borne sediment downstream at the same rate it is delivered into the reservoir from the upstream watershed. Sluicing can be performed during individual flood events or performed on a seasonal basis, depending on hydrology and other site-specific conditions.

Similarly, a seasonally empty reservoir, such as an irrigation reservoir, may be left empty for the first part of the high-flow season when the sediment load is normally highest. The reservoir is allowed to fill with inflow for the latter part of high-flow season, when sediment concentrations are typically lower. Free flow through the empty reservoir can also scour out some of the deposits from the prior year.

Sluicing is most applicable for hydrologically small reservoirs, which store only a small fraction of annual runoff volume. A low-level and high-capacity dam outlet is required that can pass sediment and woody debris downstream without clogging. Because sedimentation will eventually reduce the storage capacity of even the largest reservoir, sluicing may become attractive later in the reservoir life. Some older concrete dams in Japan have been retrofitted with deep gates to enable sediment sluicing (Sumi et al, 2015).

Hydrologically large reservoirs cannot be drawn down to pass floods, but in some cases, it is possible to release turbid density currents. These subsurface currents occur when sediment-laden flood water, which is denser than the clear reservoir water, plunges and flows along the length of the reservoir bottom, potentially reaching the dam. If this turbid water is released it will reduce the rate of sediment accumulation (Figure A2). In hydropower reservoirs this density current may be released through the turbines, dam outlets, or tunnels. The fine sediment released by turbidity current venting can be expected to be carried downstream for long distances with minimum settling out, unless it passes into another reservoir.

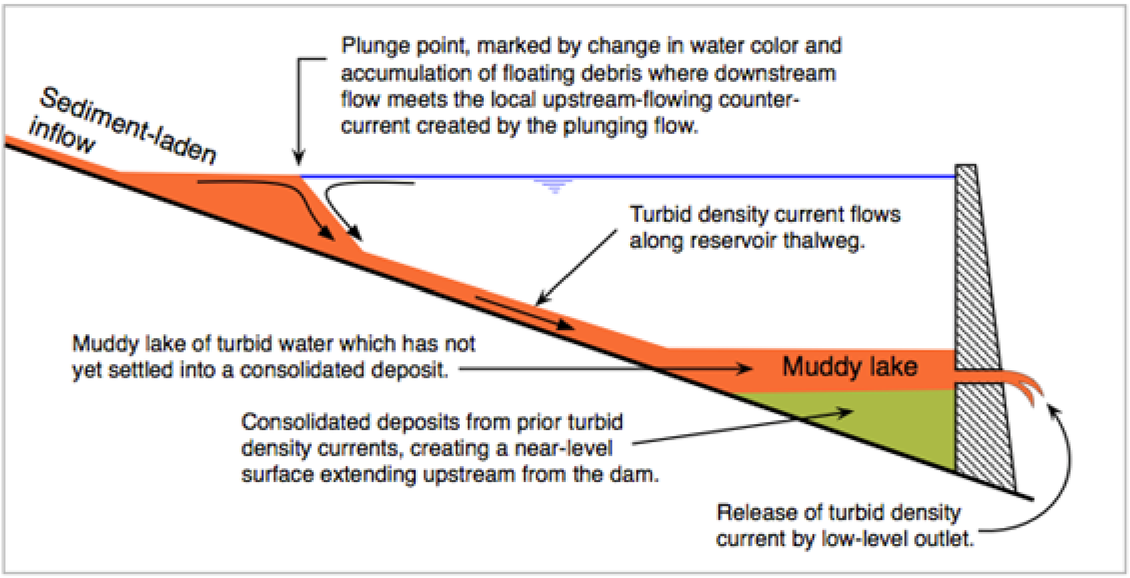


Figure A2. Turbid density currents in reservoirs
Reservoir inflows with high sediment concentrations can form density currents that sink and travel along the reservoir bottom and can be vented through low-level outlets in the dam (modified from Morris and Fan, 1998).

Sediment Removal by Dredging

The third class of management measures involves the removal of previously deposited sediment (Morris and Fan, 1998; Randle et al., 2018). Dredging removes sediment from underwater, most commonly using a cutterhead type hydraulic dredge that pumps material out of the reservoir as a flowable slurry (Figure A3). A modification of this technique, the hydrosuction or siphon dredge, uses the difference in water level between the reservoir and a discharge point at the base of the dam as the driving force to transport the sediment slurry, without the need of a dredge pump. Without a pump, hydrosuction is typically limited to areas within a few thousand feet from the dam. Its effectiveness can be improved by water injection to break up deposited sediments.

Mechanical dredging equipment may also be used, such as a bucket chain dredge, clamshell bucket, dragline, or barge-mounted backhoe. Dry excavation removes exposed (not submerged) sediment using conventional earth-moving equipment when the reservoir pool is low or empty. This strategy is commonly used in normally dry flood control reservoirs and debris basins designed to trap sediment.

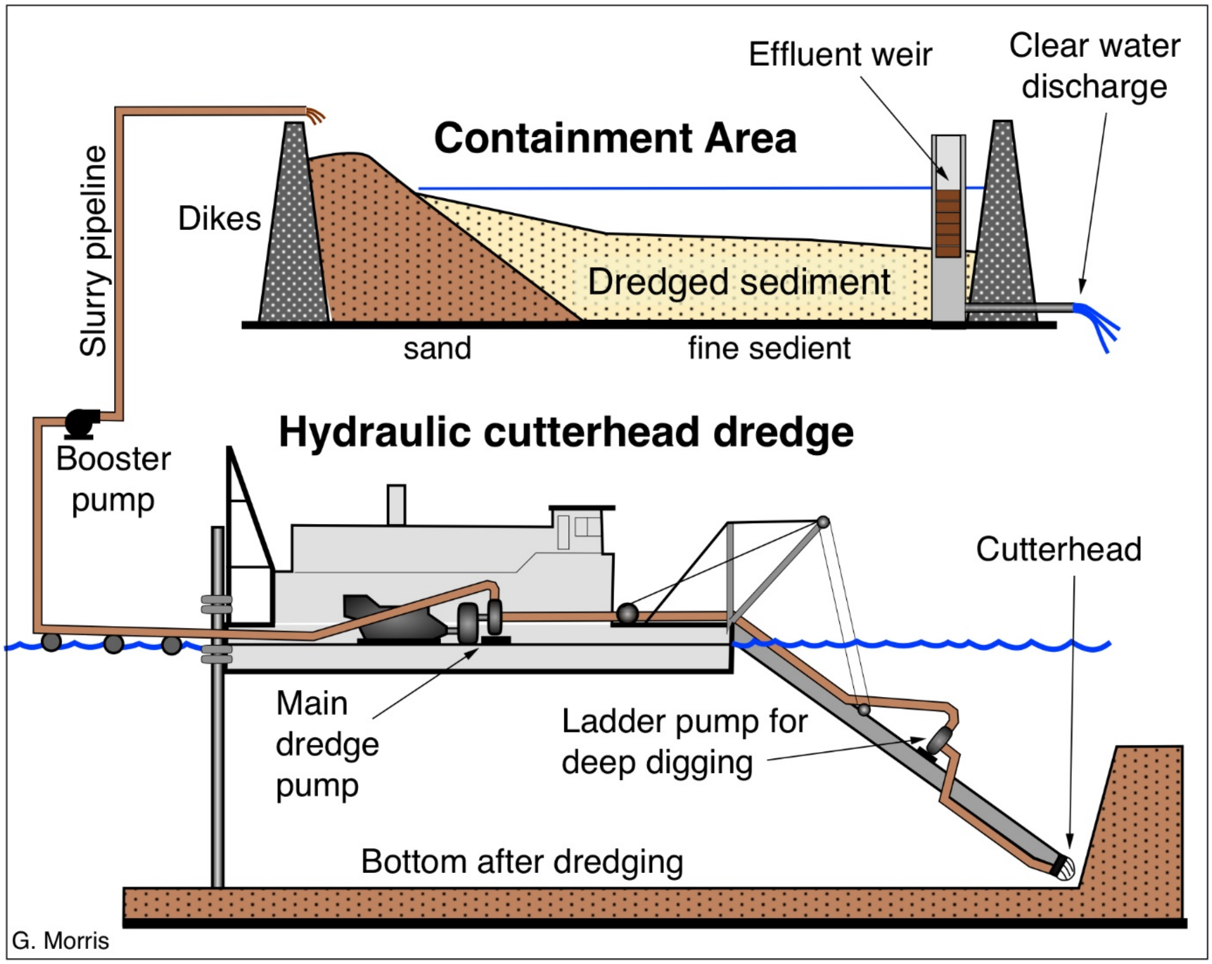


Figure A3. Schematic of components of hydraulic dredging system

From the standpoint of restoring the sediment balance along the river, dredging would ideally return the sediment to the channel below the dam, acting as an ongoing “maintenance” operation so that the sediment discharged in any year approximates the sediment entering the reservoir. Dredged material would be discharged into shallow containment areas downstream from the dam and subsequently eroded from these containment areas (within a year of deposition), thereby mimicking the seasonality of downstream sediment transport by floods. With this type of sustainable operation, sediment would be delivered to the downstream channel in a manner that would mimic the natural conditions as if the dam and reservoir did not exist.

The distance and elevation that sediment will have to be moved, along with its means of transport, will have a major effect on project costs. The presence of any contaminants, above background levels, may mean that the sediments need to be delivered to a confined disposal facility. The viability of sediment removal is limited by a combination of its relatively high cost plus the need to obtaining a permit to discharge the material. There is often a scarcity of sites suitable for the disposal of large volumes of excavated sediment near the reservoir. In some cases, the sands and gravels removed from the reservoir may be used for construction fill or similar purposes. Fine reservoir sediment (silt and clay) may also have beneficial uses such as lightweight aggregate or bricks.

At reservoirs of significant size, the option of *upland disposal* will typically involve acquisition of one or more sediment containment areas, construction of containment dikes for dredge slurry, etc. However, upland disposal of sediment will not be sustainable over the long term for a large reservoir because the annual sediment inflow volumes are too large. While trucking is commonly used to transport sediment for normally dry reservoirs or debris basins, sediment removal from large operational reservoirs generally involves hydraulic dredging due to consideration of lower costs, ability to remove sediment without interfering with reservoir operations, and the convenience of transporting sediment through a slurry pipeline (as opposed to heavy truck traffic). Slurry pipelines must operate at high flow velocities (e.g. >10 ft/s) which incurs correspondingly high friction losses and energy costs for pumping, together with high pipeline abrasion rates. This makes distance to the disposal site a highly important cost criterion.

If dredged reservoir sediment can be discharged to the downstream river channel as a long-term program, and at rates similar to the sediment inflow, then a sustainable balance can be achieved between reservoir sediment inflow and outflow.

Many factors influence the cost of dredging and material management projects for reservoirs, many of which can be estimated in advance, but ultimately depend on the results of site-specific studies (Anchor QEA and Great Lakes Dredge & Dock, 2019). For many reservoirs, the recovery of past storage capacity by dredging or other means will not be economically or environmentally feasible.

Sediment Removal by Flushing

To execute flushing, the reservoir is completely emptied, allowing the river to flow across and erode exposed sediment deposits. The eroded sediment passes through a low-level outlet in the dam and is discharged into the downstream river. Whereas sediment sluicing passes sediment beyond the dam during large floods (and thus requires large capacity outlets), flushing may be performed with lower flows and smaller low-level outlets. However, use of high flow rates for flushing is beneficial from several standpoints: Increased width of the erosion channel, accelerated rates of erosion, and larger flows to transport sediment downstream from the dam.

There are three main challenges to flushing. First, because the reservoir must be completely emptied for flushing to be effective, it is limited to hydrologically small reservoirs. Second, because flushing discharges a large amount of sediment in a short period of time, it generates very high suspended sediment concentrations downstream from the dam. There are strategies for reducing this water quality impact, but it cannot be eliminated. Third, because the flushing channel will typically not be much wider than the original pre-impoundment river channel, it is most applicable to long and narrow reservoirs.

Fluidizing sediment by the means of water injection will suspend the material above existing bottom for improved capture by the river current created by the flushing operation. Water injection helps by eroding sediments that have become compacted over time and further extending the effective sediment removal area during flushing.

Flushing is practiced on a regular basis at some reservoirs outside of the U.S., but within the U.S. is largely limited to a few reservoirs that have been flushing sediment for decades. Obtaining permits to initiate sediment flushing at other reservoirs can be difficult due to concerns with downstream water quality. Downstream impacts can vary greatly, depending on the nature of the deposited sediments and the way flushing is performed. Properly conducted flushing operations may help restore the natural flow of sediment along rivers that have become “sediment-starved” by upstream dam construction.

Adaptive Strategies

Adaptive strategies are available to manage sedimentation effects without actually manipulating reservoir sediment. However, they may not be sustainable over the long term. Several examples are given below:

- **Increasing reservoir storage capacity.** The reservoir storage capacity may be increased by raising the dam height while leaving the sediment deposits intact.
- **Decreasing demand for storage**. For a water supply reservoir, demand may be diminished by water conservation. Similarly, the reduced capacity in a flood control reservoir may be offset by enhancing downstream flood control measures. When water availability is reduced by reservoir sedimentation, users may increase their water use efficiency by implementing conservation measures or by moving away from water-intensive activities with low-economic return.
- **Optimizing storage efficiency.** As storage volume diminishes, a variety of mechanisms may be available to sustain benefits by optimizing management of the remaining reservoir storage or by managing reservoir storage in conjunction with groundwater stored in aquifers.

  The operational rules for many reservoirs, and especially those for flood control, were developed over 50 years ago, prior to the advent of real-time data collection and today’s advances in hydrologic modeling. For example, real-time technology may allow managers to optimize storage use, sharing a portion of the pool between water supply and flood control, depending on time of year plus other hydrologic circumstances. This will often be the least-cost strategy for partially offsetting or delaying the impacts of sedimentation.

  In some regions the conjunctive use of surface and ground water resources can substantially increase the total water yield. For example, during wet periods, reservoir withdrawals may be increased while groundwater use is diminished; during dry periods the situation can be reversed. Reservoir releases during wet periods may be diverted to groundwater recharge, storing water that can be pumped from the aquifer later when reservoirs are depleted by drought.
- **Modifying reservoir infrastructure to better accommodate sedimentation.** This may include reconstruction of dam outlets and water intakes and use of more abrasion-resistant pumps, along with relocation of lakeside marina facilities. In hydropower reservoirs, modifications may include re-construction of intakes to avoid encroaching sediment, conversion to run-of-river operation, and the application of abrasion-resistant coatings to turbine runners.
- **Dam decommissioning.** At some sites, sedimentation may warrant dam decommissioning, particularly with older and smaller dams. Not only will these typically be the first to lose their storage capacity, but their importance with respect to the total water supply may have been

substantially diminished by subsequent larger projects. Dam decommissioning costs can be quite high, especially if the work involves releasing a large volume of reservoir sediment downstream. Even a decommissioned dam may represent an ongoing hazard, requiring attendant management costs. Furthermore, project decommissioning may require construction of other projects to replace the benefits being lost to sedimentation, along with those attendant costs. The cost of developing new alternatives for water supply and flood control is another factor to consider.

Appendix B: Reservoir Screening and Monitoring Protocols

Reservoir screening allows for identification of priority sites and starts with topographic and bathymetric data obtained by monitoring the reservoir. These data should be collected by making repeated surveys, with the frequency of monitoring corresponding to the rate of sedimentation and storage loss. At least two measurements of reservoir sedimentation volume, at different times and using the same method, are required for proper estimation of the extent and rate of storage volume loss over time, and for projection of future trends. In general, perform a baseline survey soon after the reservoir is first filled, and repeat thereafter at 10-year intervals until a consistent trend of storage loss is established. Thereafter, surveys can be conducted periodically, corresponding to estimated increments of 10% storage loss.

LiDAR surveys of the exposed reservoir topography at low water is a highly accurate and relatively low-cost method. Bathymetric surveys of the reservoir bottom from a boat using depth sounders and GPS survey equipment is also often necessary for a complete survey. Inclusion of the survey results in the Federal Reservoir Sedimentation Information (RSI) database is recommended (Cooper, 2015). Measurement of sediment inflow and outflow rates over time is another monitoring method.

For cases when an owner or manager of many dams needs to begin reservoir sedimentation measurements, an initial reconnaissance-level survey is recommended for all reservoirs that have never been surveyed to obtain initial estimates of the level of sedimentation that has occurred, and to prioritize which reservoirs need complete surveys first. The reconnaissance surveys would include the measurement of longitudinal profiles through the reservoir along the main river channel and any major tributary channels.

A suggested frequency for complete reservoir sedimentation surveys is provided by the equation below:

$$Frequency = \frac{Projected\ Reservoir\ Age}{10\ Surveys}$$

Where

Frequency = survey frequency in years per survey,

Projected Reservoir Age = Estimated age of reservoir, in years, when sedimentation will reach the dam’s lowest outlet or other important dam or reservoir facility. Do not use the expected age when the reservoir is completely full of sediment.

Reservoir surveys are also recommended after large floods (>25-year flood peaks) or after floods following wildfire in significant portions of the upstream watershed. For more information on how to monitor reservoir sedimentation, please see Ferrari and Collins (2006), Ferrari (2006), and Morris and Fan (1998).

Monitoring data can be used to plot reservoir storage capacity loss over time. This will help determine if there are long-term changes in the rate of storage loss, which can occur over decades. For example, several midwestern reservoirs have seen their rate of storage loss gradually decline, presumably in response to reduced sediment yield, but the compaction of older sediment deposits may account for some of the apparent decline.

Monitoring data can also be used to identify how reservoir storage loss may impact different beneficial uses and stakeholders and project the rate of storage loss applicable to each use. Initially, the rate of storage loss for the different beneficial uses may be low because much of the sediment is accumulating in the dead pool below the dam’s lowest outlet. However, once the dead pool storage has filled with sediment, all additional sedimentation will impact beneficial uses, accelerating the rate of benefit losses.

Appendix C: Cost-Benefit Analysis Applied to Reservoir Sediment Management

When formulating a discrete plan for reservoir sedimentation management, the timing of an action's costs and benefits (e.g., construction schedule and sedimentation rate) must be considered in order to properly assess its economic realities. Future and past economic impacts are to be placed in present value terms for comparability. The approach for determining the present value of future costs and benefits is termed "discounting" and is accomplished by mathematically applying a "discount rate" to future values. For example, a future benefit of $100, at a time of 100 years from now, would only be worth $5.00 today, assuming a constant discount rate of 3 percent.

Economic planning studies can evaluate the sensitivity of the assumed discount rate or technique. Depending on the timing of costs and benefits, the effects of an alternative discount rate or technique can have a significant impact on the results in a benefit-cost analysis, especially for long-lived investments such as sediment management projects. Variable discount rates may potentially be better suited for analyzing scarce resources (such as reservoirs) than a constant discount rate, due to intergenerational equity concerns and uncertainty about future conditions.

Dams and reservoirs were typically designed to trap sediment over the sediment-design life. The costs of sedimentation over this period were normally not accounted for in the economic studies conducted. Importantly, neither were the costs of continued sedimentation beyond the sediment-design life, such as sediment burial of dam and reservoir facilities, loss of water storage capacity, dam decommissioning, the replacement of lost dam and reservoir benefits, and the like.

The costs associated with the continued loss of reservoir storage capacity will depend on the value of the project benefits and the allocation of the storage loss to the various benefits. The costs of storage loss could also be considered equal to the cost of replacing the lost benefits at some other location or in some other way. Lost hydropower benefits could be replaced by another type of power generation and lake recreation benefits perhaps could be replaced by another type of recreation, although flood-risk reduction and water-supply benefits are difficult to replace in kind.

Eventually, continued reservoir sedimentation will eliminate the remaining project benefits such that dam decommissioning may be necessary to leave the project in an acceptable and safe condition. The costs of dam decommissioning will include planning, public involvement, permitting, initial implementation, and any operation and maintenance costs. The costs associated with reservoir sediment management can be a significant portion of the total decommissioning costs; dam removal costs could be tens of millions to hundreds of millions of dollars for large reservoirs (removal of two large dams on the Elwha River in Washington cost approximately $325 million).

Payment for reservoir sediment management activities depends upon when the management plans are conceived. For new dams, the cost of sediment management can be included in the planned capital costs to construct the project and in the operation and maintenance costs to implement the project. The design and construction of project features, such as low-level dam outlets to pass sediment, can be part of the initial project design and construction. The operation and maintenance costs of sediment management can be paid for through the project's larger operation and maintenance budget or from a fund established at the beginning of the project operations. The costs associated with sediment management will likely be justified using traditional cost-benefit analysis if averted costs due to sediment damages (without management) are included in the economic analysis as benefits. The costs without sediment management will include the future costs of dam decommissioning and associated sediment management and the future costs to replace project benefits.

The assumed discount rate for the economic analysis is very important because the higher the discount rate, the lower the value of future benefits. For example, a benefit worth $100,000 fifty years into the future, would be worth $36,800 today at a 2 percent discount rate, but only worth $5,016 today at a 6 percent discount rate (Figure C1). Future generations could be faced with difficult and expensive reservoir sedimentation problems if decisions are made today that primarily benefit the present generation (Annandale, 2013).

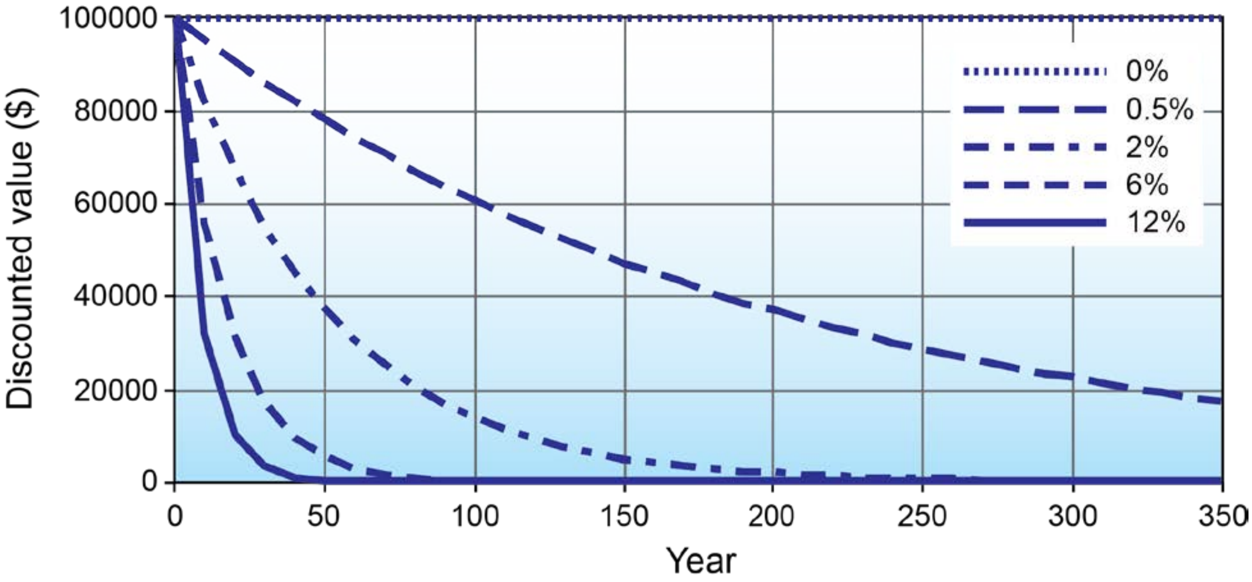


Figure C1. Effect of discount rate on value analysis
The present value decreases with time and with increases in the discount rate.

Since many reservoirs have multiple benefits, such as water supply, flood control, recreation, and fish and wildlife, there may be multiple groups of reservoir beneficiaries, including the general public, that could help pay for sustainable reservoir sediment management.

In conducting the benefit-cost analysis, long-term assets such as a water-supply reservoir may actually represent an essential resource for certain communities. However, benefit-cost analysis (which might normally be limited to a 30-year horizon) may be poorly suited to addressing this type of an issue.

In the case of reservoir sedimentation, the future conditions and management strategies under the with- and without-action alternatives are defined during the multidisciplinary plan formulation phase of project development. The with- and without-action alternatives considered in the benefit-cost analysis should attempt to quantify the following impacts and costs:

- Impacts of sedimentation to reservoir storage and water supply (both the loss and any gain of benefits)
- Impacts to operation and maintenance costs due to sediment accumulation (actual and avoided costs)
- Environmental costs and benefits to downstream channel degradation and upstream channel aggradation
- Dam decommissioning costs incurred if the project cannot be sustained (actual and avoided costs).

For example, under no-action conditions, as reservoirs reach their sediment-design life, reservoir storage and water supply will decline resulting in lost project benefits (irrigation, recreation, power, fish and wildlife, and flood risk reduction). As sediment reaches dam outlet or water intake structures, under without-action conditions, increasing operation and maintenance costs may be necessary to maintain annual benefits. Eventually, the quantity of sediment may reach levels that require dam decommissioning and sediment mitigation costs.

An action or “with sediment management” alternative example may include the costs necessary to manage sediment (e.g., dredging, low-level sluice gates, etc.). In the short term, under the with-action alternative example, potential lost benefits related to water supply or reservoir storage during the dredging or construction period should be quantified. It may be necessary to include dam decommissioning costs, but these may be delayed or unnecessary under this alternative if the project life can be extended to a much longer time period, or the project becomes sustainable. Finally, the with-action alternative may maintain annual project benefits associated with irrigation, recreation, power, fish and wildlife, and flood risk reduction, which should be quantified for the benefit cost analysis.

Appendix D: Permitting for Reservoir Sediment Management

Section 404 of the CWA regulates the discharge of dredged or fill material into waters of the United States. Management of sediment to maintain or restore reservoir capacity may trigger the need for a Section 404 permit, depending on the nature of the activity. The USACE issued Regulatory Guidance Letter No. 05-04 (*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*) in 2005. The purpose of the letter was to provide guidance on which releases of sediments from or through dams require permits from the USACE. The guidance document outlines factors that may be considered by regulators when determining whether a proposed release of sediments is regulated or exempt.

If the USACE determines that a proposed sediment management activity is regulated, there are several types of permits that may be available. Standard individual permits are typically used for projects that may result in greater than minimal individual and cumulative impacts. The standard individual permit process includes preparation of an environment assessment and a public review period. Projects that are likely to result in minimal impacts may be eligible for authorization under a general permit such as the nationwide permit program (NWP) or a regional general permit (RGP).

NWPs are applicable throughout the country, though individual USACE Districts may modify them to address regional needs. They have specific terms and conditions that may make them inappropriate to authorize most reservoir sediment management projects. The NWPs are most applicable to routine, small-scale maintenance projects. For example, USACE NWP 3 covers maintenance activities—specifically, “repair, rehabilitation, or replacement of any previously authorized, currently serviceable structure or fill,” including “removal of accumulated sediment and debris within, and in the immediate vicinity of, the structure or fill.”

RGPs are established by USACE Districts to meet specific local or District-wide needs for specific types of projects. Examples of activities that Districts may develop RGPs to authorize include desilting flood control channels, maintenance dredging of water bodies, beneficial reuse of dredged sediment, and emergency activities. There may be substantial variation in the ways the Districts interpret the existing permit frameworks and implement their regulatory programs, reflecting differences in regional conditions and differences among states that fall within the Districts.

The regulatory permitting process is dependent largely on the fundamental nature of the work and whether it will result in a discharge of sediment into waters of the United States. For example, the distinction of a sediment management project as a continuation of current operations that entail regular passage of sediment incidental to reservoir operations, compared to a change in reservoir operations for the purpose of mobilizing sediment, would likely result in different regulatory review scenarios.

Disposal and placement of removed sediment can be challenging from a permitting perspective, particularly if the sediment is proposed for in-water placement. Permitting for in-water fill placement (as for intentional sediment release or downstream placement of dredged sediment) tends to be highly site-specific and time-consuming and would typically require a standard individual permit. Sediment proposed for in-water placement must usually be characterized physically and chemically and determined compatible with the placement site before placement is authorized. The process is simpler when dredged material is transported to an upland area that is outside waters of the United States. In that case, a Section 404 permit may not be required unless return water from the dredged sediment is allowed to flow back into the reservoir. The return water would be considered a discharge under the CWA. Developing a feasible sediment management plan that is cost-effective and complies with regulatory requirements can be the most challenging element of a sediment removal project.

Below are cases around the nation where sediment management and removal were successfully permitted and accomplished for reservoirs.

Strontia Springs Reservoir, Colorado

In 2011, Denver Water hydraulically dredged more than 200,000 cubic yards (yd^3) of sediment from the Strontia Springs Reservoir in Waterton Canyon on the South Platte River. Sediment was pumped via pipelines over the Strontia Springs Dam to a sediment processing area immediately downstream of the dam, where finer particles were physically separated from gravels and coarse sand. Several dredging and material disposal alternatives were studied prior to starting the dredging project; delivering the sediment directly to the river downstream of the dam was viewed as unfavorable because it would require a USACE dredge and fill permit (Section 404) for impacts to the South Platte River. Similarly, development of improvements to the river upstream of the reservoir would have required a lengthy process for developing an environmental assessment or EIS.

In the end, an environmental assessment was not necessary; nor was an individual permit from the USACE. Denver Water worked with the USACE to obtain a Nationwide Permit (NWP) 16, which addresses controls on return water to the South Platte River from the nearby upland sediment processing and placement areas. Since NWP-16 requires a water quality certification process (per CWA Section 401) for the discharged water, an industrial wastewater discharge permit and a certificate of disposal were received from the Colorado Department of Public Health and the Environment.

Prior to and during the dredging program, Denver Water coordinated with the U.S. Forest Service and maintained regular communications with public users of the popular South Platte River Trail through Waterton Canyon, as the trail needed to be temporarily shut down during the dredging operations to accommodate pipeline construction and maintenance and sediment processing operations.

Wilde Lake, Maryland

This project involved hydraulic dredging of approximately 20,000 yd^3 of sediment from Wilde Lake. The sediment was pumped to an on-site sediment dewatering area and hauled by trucks to an off-site disposal location.

The state has a joint federal and state application process administered by the Maryland Department of the Environment (MDE), Water Management Administration. The joint permit is intended for projects involving “alteration of any floodplain, waterway, tidal, or non-tidal wetland in Maryland.”

The dredging of Wilde Lake qualified for a Maryland State Programmatic General Permit under Category I-9 for Maintenance Dredging. The joint application was reviewed by the MDE, its Dam Safety division, and the USACE Baltimore District. The USACE follows the state discharge requirements for 401 (water quality) and 404 (dredge and fill) considerations. Ultimately, the contractor installed and maintained a continuous floating turbidity curtain to contain any water quality impacts around the point of dredging.

The applicant (Columbia Association) also consulted with state agencies regarding forest conservation and historic resources, endangered species, and essential fish habitat, and local government regarding soil and erosion. For each of these items, a separate permit was determined to be unnecessary.

Lake Decatur, Illinois

The City of Decatur, Illinois, led this project involving hydraulic dredging of 10.5 million yd^3 of sediment to recover some of the water-storage capacity of Lake Decatur and to remove sediment from near the water treatment plant intake. Dredged materials were transported hydraulically to a pre-existing sediment storage facility located more than 0.5 mile away, with discharge of return water from the Oakley Basin contained within the disposal area.

A 404 permit application was submitted to the USACE with an accompanying 401 permit application to the Illinois Environmental Protection Agency for related water discharges. A “no-dredge zone” was established to create a 200-foot-wide buffer area for mapped forested wetlands areas. Elsewhere, dredging was kept 25 feet away from the shoreline and was required to avoid any emergent wetlands areas. Temporary impacts to water quality were anticipated due to re-suspended solids and temporary increases in concentrations of ammonia and nitrogen. Dredging measures related to water quality protection were documented in an Operational Management and Measures Plan. No additional biological characterization was required for the downstream (unnamed) tributary.

Conestoga Reservoir, Nebraska

Consistent with NEPA, the USACE Omaha District completed an environmental assessment of this project that involved a number of improvements to the Conestoga Reservoir, including removal of more than 500,000 yd^3 of sediment, in-lake regrading of sediment, modification of the outlet works, and construction of upstream sediment traps.

The USACE owns and operates the reservoir and its flood control structures, while the fisheries and surrounding public park space are managed by the Nebraska Game and Parks Commission. The USACE determined that the proposed project would not have significant impacts on the environment, so a finding of no significant impact (FONSI) was prepared, and an EIS was not required.

The project qualified for NWP 27 for Aquatic Habitat Restoration, Establishment and Enhancement Activities, and General Permit 98-05 for dredging/filling activities associated with lake maintenance projects. A water quality certification was required from the Nebraska Department of Environmental Quality, per Section 401 requirements.

John Redmond Reservoir, Kansas

The John Redmond Reservoir sediment management plan included a multi-phase effort involving the removal and disposal of 3 million yd^3 of sediment, along with shoreline and streambank improvements. The purpose of the sediment removal was to recover water storage capacity in the reservoir while also improving related aquatic habitat.

Permitting sediment removal for this reservoir was unique - it required a Section 408 USACE permit approval because of the fact the project is being implemented within a federal reservoir by a non-federal party (the Kansas Water Office [KWO]). This project was, in fact, the largest Section 408 request for an inland waterbody to date and has been influential in the USACE's efforts to streamline the Section 408 permitting process (which also received attention in the wake of damages to USACE-controlled levees from Hurricane Katrina).

The NEPA process involved development of a programmatic EIS covering the project over several phases. The EIS was developed concurrently with the USACE's Section 408 permit review, which occurred over a 3-year period. The USACE issued a FONSI for the programmatic EIS, giving the KWO authority to commence the first phase of the multi-phase dredging effort.

As part of the first phase of work, sediment was hydraulically pumped to various upland confined disposal facilities (CDFs), intended to revert to their prior use as farmland after sediment placement was completed. Creation of the upland disposal facilities required dam safety permits from the State Division of Water Resources, as well as National Pollutant Discharge Elimination System (NPDES) permits for water discharge back to the Neosho River.

The first phase of work encompassed approximately 600,000 yd^3 of sediment removal. Future phases will be advanced as funding is available. Approvals for additional sediment removal in subsequent phases, and use of additional CDFs, will be evaluated in the future using the environmental analysis approach established by the programmatic EIS.

Devil's Gate and Pacoima Reservoirs, Los Angeles County, California

The Los Angeles County Public Works and Flood Control District conducts regular sediment removal operations for dammed reservoirs and retention basins to maintain their function for flood control and water storage. The reservoirs are cleaned out at intervals sufficient to ensure that they have enough flood control storage capacity to handle two design-level debris flows (typically a function of precipitation and recent wildfires). Sediments and debris are removed either by excavation after dewatering, or by sluicing through the lowest dam gates (a method referred to by the Flood Control District as "flow-assisted sediment transport", or the acronym FAST).

The Flood Control District's sediment management operations are authorized by a Section 401 permit from the California Regional Water Quality Control Board and a Section 404 permit from the USACE, as well as Streambed Alteration Agreements from California Fish and Game Section 1602 of the State Fish and Game Code. A California Environmental Quality Act (CEQA) process and public involvement is triggered for cleanout operations that have "significant environmental impact," plus other federal regulations to be determined on a case-by-case basis. After the 2009 Station Fire contributed an unusually large amount of sedimentation to these reservoirs, several were slated for sediment removal. Furthermore, cleanouts involving mechanical excavation require coordination with the Public Works Administration for approval.

The Devil's Gate Reservoir and the Pacoima Reservoir initiated CEQA, NEPA, and permit scoping processes in the years following the Station Fire. Formulation of a joint draft CEQA/NEPA document occurred with an environmental impact report orchestrated by the Flood Control District under CEQA and with U.S. Forest Service as the lead for NEPA. Joint documentation was intended to make the process more efficient and improve coordination with the public and between agencies. The joint document formulation required approximately 1 year, followed by a 60-day public comment period, final certification, and decision.