Western Dredging Association

April 2021

Reservoir Dredging: A Practical Overview

A Technical Report Prepared by:
Western Dredging Association (WEDA) Working Group on Reservoir Dredging

Western Dredging Association

April 2021

First Edition; April 2021

Citation

WEDA's Technical Report: "Reservoir Dredging: A Practical Overview"; WEDA, 2021
Available online at: www.westerndredging.org

Western Dredging Association – WEDA

P.O. Box 1393
Bonsall, CA 92003
United States of America

Phone: (949) 422-8231
E-mail: info@westerndredging.org
Web: www.westerndredging.org

Photograph on front cover: "Hydraulic Dredging of the Strontia Springs Reservoir, Colorado, U.S.A."
By: Sevenson Environmental Services, courtesy of Denver Water.

TABLE OF CONTENTS

TABLES

FIGURES

1 Introduction

This technical report provides an overview of the dredging process as applied to reservoirs: the unique technologies and respective capabilities, challenges, and engineering and environmental considerations that apply. As a starting point for the reader, some basic definitions are in order.

First of all, ***dredging*** is defined as the subaqueous or underwater excavation of soils and rock. The dredging process can be separated into four phases: excavation, vertical transport, horizontal transport, and placement or use of the material dredged. Dredging can be done for many different reasons or purposes.

This report is specifically focused on the possible dredging of ***water storage reservoirs*** where the storage capacity provides beneficial uses (e.g., water supply for irrigation, drinking water, and firefighting; flood risk reduction; recreation; hydropower; and fish and wildlife).

Where this report refers to a ***reservoir***, what is meant is "*a waterbody created by an artificial dam, where the dam was constructed to impound the water so it could be made available for some human use.*" Most common human uses for such reservoirs are providing water supply for drinking water, irrigation needs, or firefighting; generating hydropower; reducing flood risk; or creating recreation opportunities.

Reservoir dredging discussed in this report includes the removal of coarse sediments from shallow water deltas at the upstream end of reservoirs and the removal of fine sediments from deep areas of the reservoir bottom. Dredging for sustainable reservoir management would annually move the volume of sediments entering the reservoir to the downstream channel or make it available for some other beneficial use.

This report will use *imperial units*, showing *metric units* in parenthesis.

1.1 The Fundamental Problem of Reservoir Sedimentation

Over the past century, the United States and many other nations have constructed and relied upon reservoirs to provide critical water storage across the globe for hydropower, municipal and industrial use, irrigation, flood risk reduction, firefighting, and recreation (USSD 2020). Most reservoirs were established by constructing dams in existing rivers and streams to impound water in a controllable and reliable manner.

Unfortunately, the benefits provided by these dams and reservoirs are being threatened by the continuous and ongoing process of sedimentation and the gradual accumulation of sediment material within reservoirs. Sediment such as clay, silt, sand, gravel, and cobble is naturally eroded and transported downstream from the upstream watershed during rainfall and snowmelt. Human activities (e.g., intensive land use, deforestation, road construction, and urbanization) are gradually increasing the sediment yields from these watersheds. Since most reservoirs and dams do not have a viable means of allowing the sediment to pass through the reservoir into the downstream river, the result is a trapped mass of reservoir sediment that continues to accumulate over time, reducing depths and available water storage space.

1.2 The Goal of Sustainable Reservoir Management

Continued reservoir sedimentation leads to intergenerational inequity where future generations will end up paying for sediment management with reduced reservoir benefits and/or dam decommissioning, while enjoying only limited remaining reservoir benefits compared to previous generations. Past generations conceived, planned, and constructed dams and reservoirs. While costs for installation, operation and maintenance have been paid for, past generations did not provide or pay for costs associated with sustainable sediment management. As a result, reservoir sedimentation continues to reduce the storage capacity over time and often increases the surface water and groundwater elevations associated with the upstream river channel. Meanwhile, clear water releases from the reservoir tend to gradually degrade the downstream river channel.

In the absence of reservoir sediment management, future generations will eventually have to pay for dam decommissioning and/or the construction of replacement dams and reservoirs if they wish to continue the water storage benefits. With more than 90,000 dams already built in the United States, the best dam sites have already been developed. Future replacement dams and reservoirs will therefore have to be constructed at sites that are less-than-ideal and more expensive than the sites chosen by previous generations.

If reservoir sediments could be allowed to pass downstream, continued impacts of reservoir volume loss, channel degradation, habitat reduction, and erosion of stream-side infrastructure could be slowed or stopped. In some cases, passing sediment will require substantial modifications to dam facilities as well as coordination with downstream facilities, stakeholders, and regulators. Significant capital investments might be required to modify dam facilities and create the infrastructure necessary to pass sediment downstream. Years may be required to accomplish the planning, design, permitting, and construction. However, the costs and time associated with sediment management would be less than the costs and time associated with eventual dam decommissioning in the absence of sediment management.

Statements from professional organizations recognize the need for sustainable reservoir sediment management. In 2014, the Federal Advisory Committee on Water Information and its Subcommittee on Sedimentation passed a resolution (ACWI and SOS 2014) that:

> …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. The costs for implementing either sustainable sediment management practices or retirement plans should be paid for by the current beneficiaries of each reservoir, which could include the American public.
>
> Federal agencies are encouraged to start developing sustainable reservoir sediment-management plans now for one or two reservoirs per year on a pilot basis. From this experience, interagency technical guidelines will be developed for preparing sustainable reservoir-sedimentation plans.

In 2018, the U.S. Society on Dams adopted a similar resolution for owners of all dams (USSD 2018).

1.3 Dredging as Reservoir Management Tool

Dredging is an important and well-established method for removing sediments from a reservoir by mechanical and/or hydraulic methods or other means. As such, it can be used for sustaining reservoir storage capacity for future generations without causing significant reservoir drawdown.

This technical report aims to fill a specific information gap related to reservoir dredging. While a great deal of literature and data exists focusing on reservoirs and reservoir management, along with numerous well-established sources of information available about dredging, the specific subject of reservoir dredging is an emerging issue that has not been widely covered in professional literature, and only recently has started to gain some attention. Increasing numbers of reservoirs in the United States and worldwide are reaching a stage where the sedimentation from the past several decades is severely impairing the reservoir's functionality and/or capacity, thereby threatening the function and benefits of these reservoirs.

As a result of the trends described above, the subject of reservoir dredging is gaining an increasing amount of attention and focus for those involved in reservoir management.

1.4 WEDA – Western Dredging Association

This report has been prepared by the Western Dredging Association (WEDA). WEDA is a nonprofit professional organization for those interested in dredging and dredging-related subjects and is one of the three members of the World Organization of Dredging Associations. WEDA's region consists of North, Central, and South America.

The goals and objectives of WEDA are to promote the exchange of scientific and technical knowledge in fields related to dredging, navigation, marine engineering, and construction, while providing a forum for the communication of such knowledge. This exchange of information is accomplished by compiling, presenting, and publishing scientific and technical papers in those areas of the science and profession; by publicizing the importance of understanding and development of scientific and technical solutions for problems related to the protection and enhancement of the marine environment; and by supporting educational institutions for students interested in pursuing dredging and marine engineering as a career.

More information about WEDA can be found at www.westerndredging.org.

1.5 Working Group on Reservoir Dredging

WEDA's Working Group on Reservoir Dredging authored this technical report. This Working Group was established with the following goals:

- Generate informational material regarding established and innovative approaches to reservoir dredging, their implementation, and cost; access and equipment considerations; and other practical matters related to the dredging process as applied to reservoirs.
- Gather and make available, to WEDA members and others in the WEDA service area (i.e., the Americas) interested in the subject, relevant information on reservoir sediment management and, specifically, on the use or application of dredging for reservoir sediment management.
- Educate and help spread awareness, specifically as it relates to the need for support from the dredging community, on the issue of the increasing reservoir sedimentation problem, the need for sustainable reservoir management, and any future dredging market potential in that area.
- Make available to industry leaders and policy makers information that will allow them to advocate for higher priority on reservoir dredging and sediment management, considering the increasing severity of the problem and impacts to society.

The Working Group members aimed to accomplish these goals by publishing and distributing this technical report along with other avenues for communicating information on reservoir dredging to a wider audience.

The members of the working group were:

- **Jennifer Bountry** (U.S. Bureau of Reclamation)
- **Stan Ekren** (Great Lakes Dredge & Dock)
- **Marcel Hermans** (Port of Portland) – *Chair*
- **Robert Ramsdell** (Great Lakes Dredge & Dock)
- **Alfredo Ranaldi** (Dragflow)
- **Tim Randle** (U.S. Bureau of Reclamation)
- **Greg Smith** (J.F .Brennan Company)
- **Tim Welp** (U.S. Army Corps of Engineers, Engineer Research and Development Center)
- **Bob Wetta** (DSC Dredge, LLC)
- **Michael Whelan** (Anchor QEA, LLC)

Acknowledgements

The authors of this report would like to hereby thank the following individuals for their contributions in making this a high-quality report worth your readership:

Tom Cappellino of WEDA for his support of the Reservoir Dredging Working Group; a prestigious group of experts from several related fields: Jos Clement of WEDA, William Dressel and Angel Gutierrez of the U.S. Bureau of Reclamation, Greg Morris of GLM Engineering, and Meg Jonas of the U.S. Army Corps of Engineers for their helpful critiques and technical input; Terri Scheumann, Sarah Becker, and Tessa Dennis of Anchor QEA for formatting and document editing; and Doug Raitt of Denver Water for providing the dramatic cover photograph.

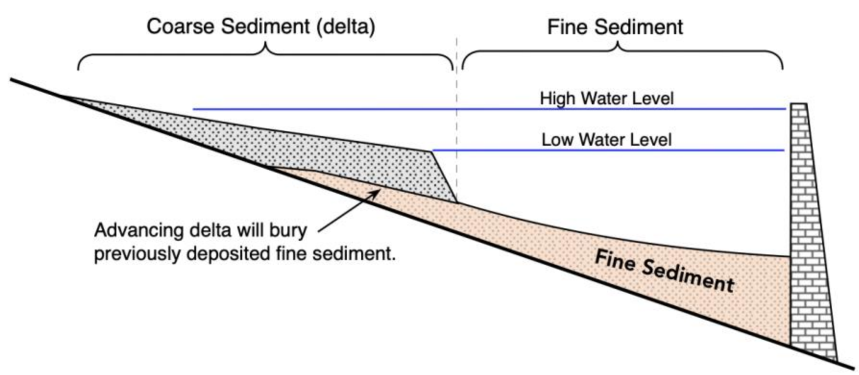
2 Linking Reservoir Sedimentation and Maintenance: Sedimentation Management

2.1 Process of Sediment Accumulation in Reservoirs

As the velocity of water slows down upon entering a reservoir, the water's capacity to suspend and transport sediments is reduced. This "slow flow" through reservoirs allows them to trap large portions of the inflowing sediment loads (sedimentation). As a rule of thumb, reservoirs that store 1.5 percent of the mean-annual inflow from the contributing watershed can be expected to trap about 50 percent of the inflowing sediment (Brune, 1953). The portion of sediment trapped by reservoirs increases to 75 percent when the reservoir storage is about 5 percent of the mean-annual inflow, and further increases to as much as 90 percent when the reservoir storage is about 20 percent of the inflow.

Rivers characteristically transport a wide range of grain sizes into reservoirs, but these sediments are sorted by the sedimentation process and the grain size in the reservoir will vary along its length, As sediment materials deposit within a reservoir, the relatively coarse sediments (sand, gravel, and cobble) generally deposit first and form a delta at the upstream end of the reservoir and at tributary arms of the reservoir. Fine sediments (clay and silt) deposit farther downstream along the reservoir bottom all the way to the dam. Figure 1 illustrates the general sediment profile resulting from this hydraulic sorting process in reservoirs.

Figure 1
Longitudinal Pattern of Sediment Composition Typically Found in a Reservoir



Source: Morris and Fan, 1997

The resulting delta may consist of a mixture of both coarse sediment (gravel and sand) with fines (silt- and clay-sized particles). Gravels may be encountered at the upstream end of the delta, but limited amounts of gravel may be carried further downstream along the river crossing the delta if the reservoir is periodically lowered. As the delta advances further into the reservoir, it will bury previously deposited finer sediment. Thus, although the material on the top of the delta may be coarse, it may become finer at greater depths. Alternating bands of coarse and fine sediments can also occur.

Delta sediments also vary across the width of the reservoir. The coarsest sediments are found along the river channel that crosses the delta while finer sediments are deposited further away from the channel. Thus, a variety of sediment sizes may be encountered when dredging a delta, depending on where the dredging occurs and the digging depth.

In deep reservoirs with a diverse range of incoming sediment grain sizes, the sediment distribution may vary vertically, particularly in the delta region (Morris and Fan 1998). For example, in the former Lake Mills in Washington, drill hole data prior to the Elwha dam removal revealed that the lowest delta unit contained 23% silt/clay and 77% sand/gravel/cobble that progressively coarsened to only 6% silt/clay and 94% sand/gravel/cobble in the top delta unit (Randle, et al. 2015). In wide reservoirs, lateral variation in sediment deposition may be present. It is not uncommon to measure finer sediment deposited along the margins of wide reservoirs in slower velocity shallow areas.

Sands are not transported beyond the delta, and the transition from sandy delta material to uniformly fine sediments usually occurs over a short distance. Although the fine-grained sediments are typically rather uniform, streams that enter the reservoir from either side can deposit localized areas of coarse sediments, creating small lateral deltas.

Most sediments are delivered into reservoirs by floods. If there has not been a flood for some time and the delta has remained submerged, coarse delta sediments can become buried beneath a layer of finer sediment. For this reason, sediment composition cannot be accurately determined using sediment-surface grab samples. Cores are required to penetrate any overlying fines and sample the underlying material. Vibracore sampling can represent a cost-effective approach in this regard.

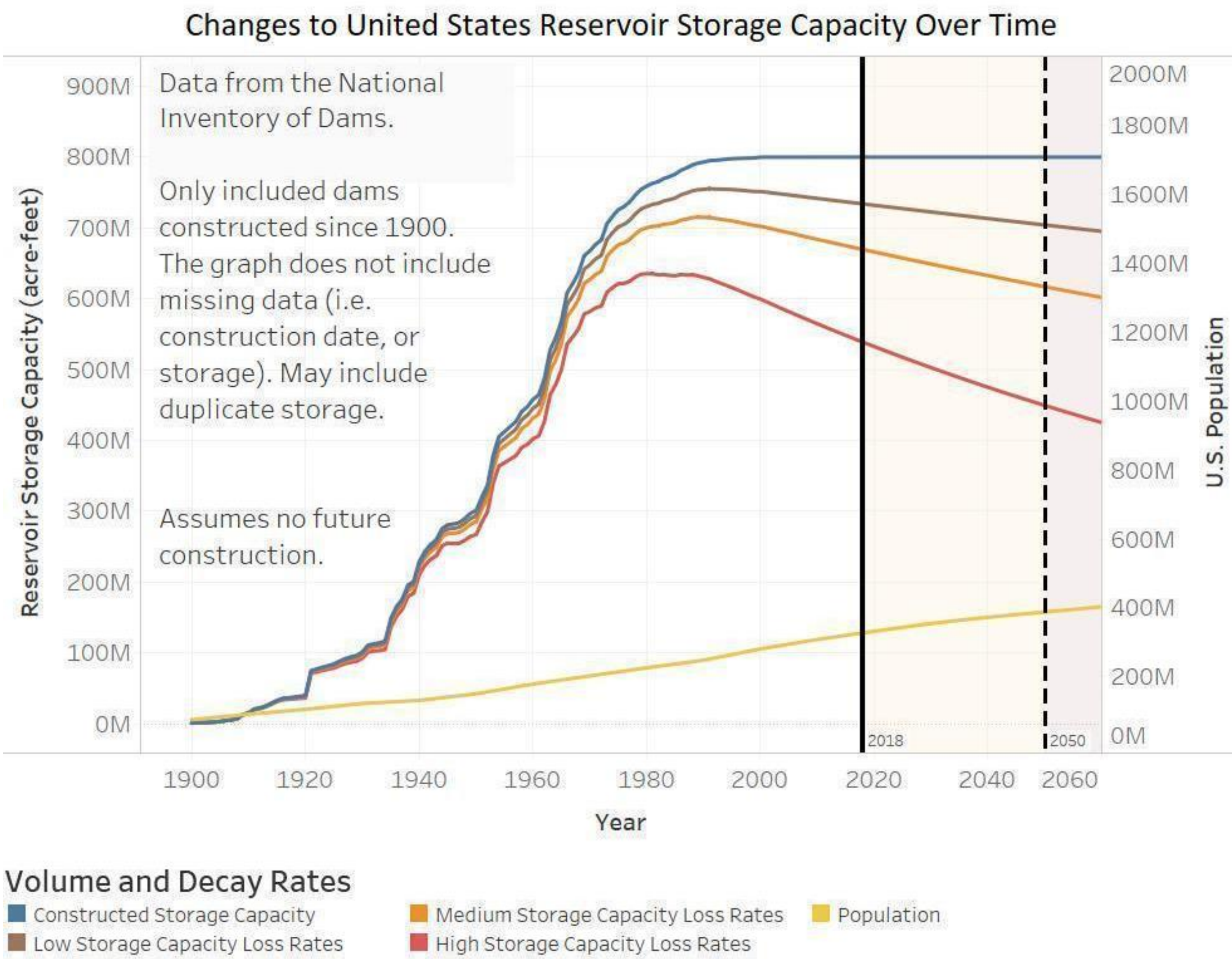
2.2 Impacts of Sedimentation on Reservoir Function

Over time, reservoir sedimentation reduces storage capacity and reduces benefits. Long before the reservoir fills with sediment, various dam and reservoir facilities will become buried, such as dam outlets, water intakes, boat ramps and marinas. The surface area for boat recreation will be reduced in the shallow deltas (Randle et al. 2019). As the delta grows, upstream water surface and groundwater elevations will increase and may affect nearby communities. Clearwater releases may degrade the downstream channel and impact fish and wildlife habitat, streamside infrastructure (bridges, roads, pipelines, and levees), and property.

Dams and reservoirs were typically designed to have a sediment design life of 50 or 100 years before the sedimentation level reaches the dam outlet works or reservoir water intakes. Dam outlets can become plugged with wood and sediment after 25% to 50% of the original storage capacity has filled with sediment. Furthermore, the continued input and accumulation of sediment in a reservoir can lead to an increase in the number of particles carried by water moving through dam infrastructure and appurtenances, causing greater wear and tear, increased repair needs, and shortened design life. Left unaddressed, the benefits provided by the reservoir will continue to decrease until the reservoir ultimately becomes useless and obsolete, leaving the choice to either somehow restore its capacity or decommission the reservoir.

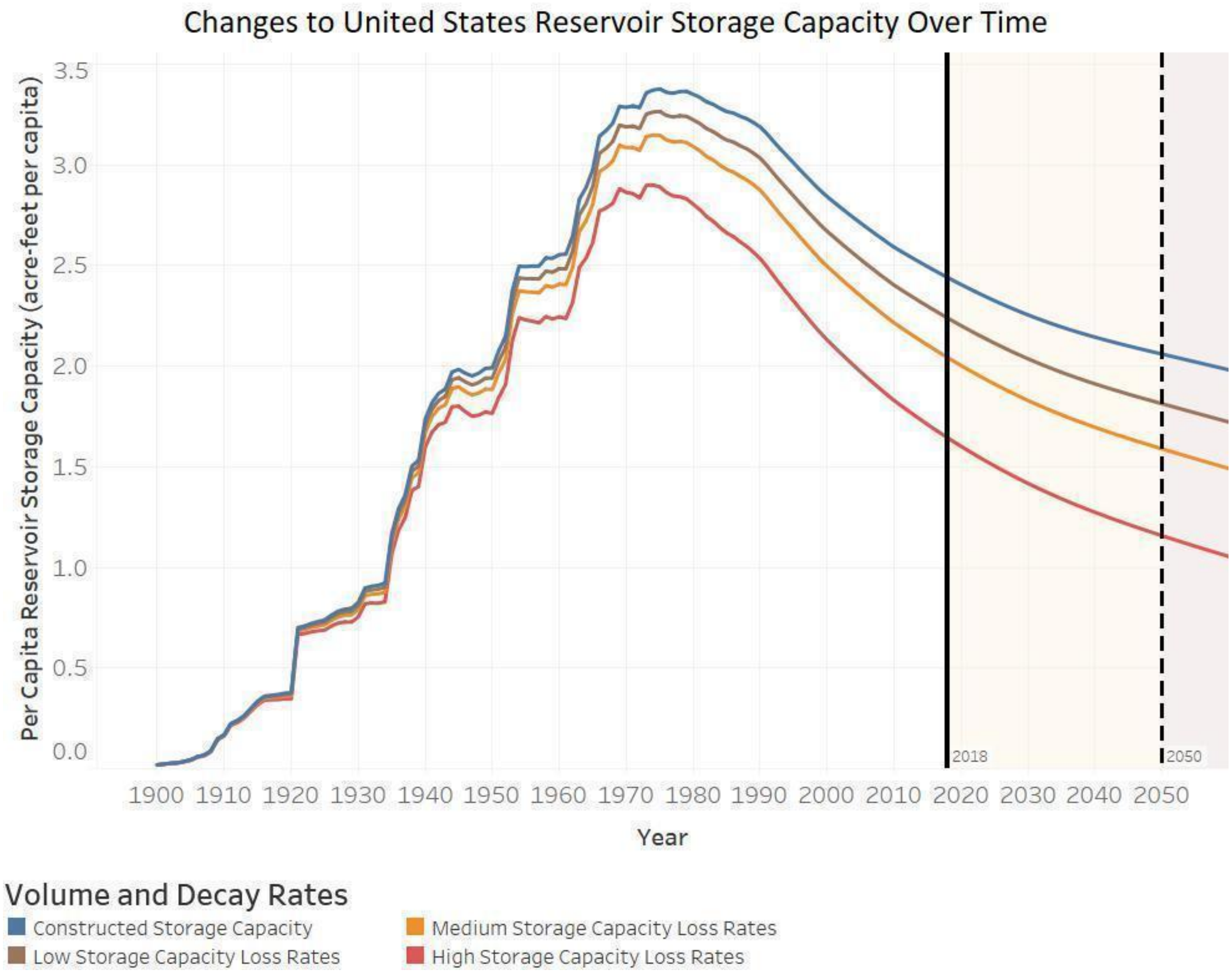
The U.S. National Reservoir Sedimentation and Sustainability Team (NRSST) compiled data on constructed reservoir storage capacity over time and estimated the range in storage capacity loss due to sedimentation (Randle et al. 2019). Cumulative constructed capacity reached 800 million acre-feet (985 cubic kilometers) in the 1990s and has remained nearly constant since (Figure 2). However, the actual storage capacity has been decreasing since that time and may now be equivalent to the constructed capacity in the 1970s. The United States population has been increasing, so the per capita storage capacity reached a maximum in the 1970s and has been decreasing since that time (Figure 3). After accounting for sedimentation, the per capita storage may now be equivalent to that of the 1940s. Historically, per capita storage doubled between 1940 and the mid-1960s.

Figure 2
Changes to United States Capacity Over Time Due to Dam Construction and Reservoir Sedimentation



Source: Randle et al. 2019.

Figure 3
Reservoir Storage Capacity Over Time Due to Dam Construction, Reservoir Sedimentation, and Population Increase



Source: Randle et al. 2019

The curves presented in these plots 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% per year (Graf et al. 2010) for small reservoirs (constructed storage capacity less than 100,000 acre-feet [less than 123 million cubic meters (m^3)]) and 0.1%, 0.2%, and 0.5% per year for large reservoirs (greater than 100,000 acre-feet [greater than 123 million m^3]) 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. Per capita data is based on United States population data from the U.S. Census Bureau.

As sedimentation remains unaddressed and the reservoir ultimately fills up, the reservoir will no longer be able to fulfill its original functions, with dire consequences for the environment and the people who rely on those reservoirs. The inability to contain water per the initial purpose or intent of the reservoir would mean that both water and sediment would theoretically pass the dam at the same rate as it comes in at the upstream end of the reservoir. The reservoir's ability to provide water storage, flood control, hydropower, and other benefits would be seriously degraded or lost altogether.

Such loss of function of a reservoir has the potential to not just threaten infrastructure and the environment upstream and downstream of the reservoir, which have for decades been relying on the water level regulation provided by the dam and the reservoir, but could also threaten the integrity of the dam itself. Sediment-laden water overtopping the dam or finding its way through or around the dam could erode and/or undermine the dam and potentially cause dam failure. When the dam fails, sediments that have accumulated in the reservoir over decades will find their way into the downstream environment in a virtually instantaneous manner, and will overwhelm downstream infrastructure and environments, with a high likelihood of serious consequences.

Examples of reservoirs that were not properly maintained to the degree that the dam ultimately had to be removed because the reservoir had filled up with sediments include the San Clemente Dam and the Matilija Dam. An example of a dam that has failed is the Spencer Dam in Nebraska, which failure is documented in the Spencer Dam Failure Investigation Report (ASDSO 2020).

2.3 Current Tools and Practices for Reservoir Sediment Management

Given that doing nothing is not an acceptable long-term option, alternatives will need to be formulated and evaluated for each reservoir that would either sustainably manage sedimentation over the long term or eventually decommission the dam and reservoir. Sustainable sediment management alternatives would preserve the benefits of reservoir water storage over time while those benefits would be lost under dam decommissioning alternatives.

Water storage reservoirs were typically designed to accommodate at least several decades of sedimentation. For large reservoirs, the removal of past decades of sedimentation would be either cost-prohibitive or environmentally unacceptable if delivered to the downstream river channel. Whenever and wherever sustainable sediment management practices are implemented, more likely than not, past sedimentation will have to be accepted and it is more effective to focus new actions on managing new and continued sedimentation.

Reservoir sediment management practices can be classified into four broad categories (Figure 4) (Morris and Fan 1998; Kondolf et al. 2014; Annandale et al. 2016; Randle et al. 2019):

1. ***Reduce*** **sediment yield** entering the reservoir (watershed management practices).

When watershed sediment erosion has been accelerated due to human activities, it may be possible to reduce the sediment yield back down to natural levels. Dam and reservoir owners often do not have control over the upstream watershed, so implementation of watershed management practices may be administratively difficult and fully solving the sedimentation problem that way will often be cost-prohibitive given the size of some of the drainage basins. Watershed sediment management is an important tool in reducing the incoming sediment load to reservoirs. The best opportunities exist in watersheds where incising channels and extensive bank erosion increase sediment yield above natural levels, and where the channel system acts as an effective conveyer of eroded sediments. Even though working in the upstream watershed may be administratively difficult, the benefits can be enormous: the Delta Headwaters Project in northern Mississippi resulted in computed sediment yield reductions averaging 62% from the use of grade control alone (Leech and Biedenharn 2012).

2. **Route *incoming* sediments** around or through the dam to minimize sediment deposition within the reservoir (sediment bypassing or pass-through).

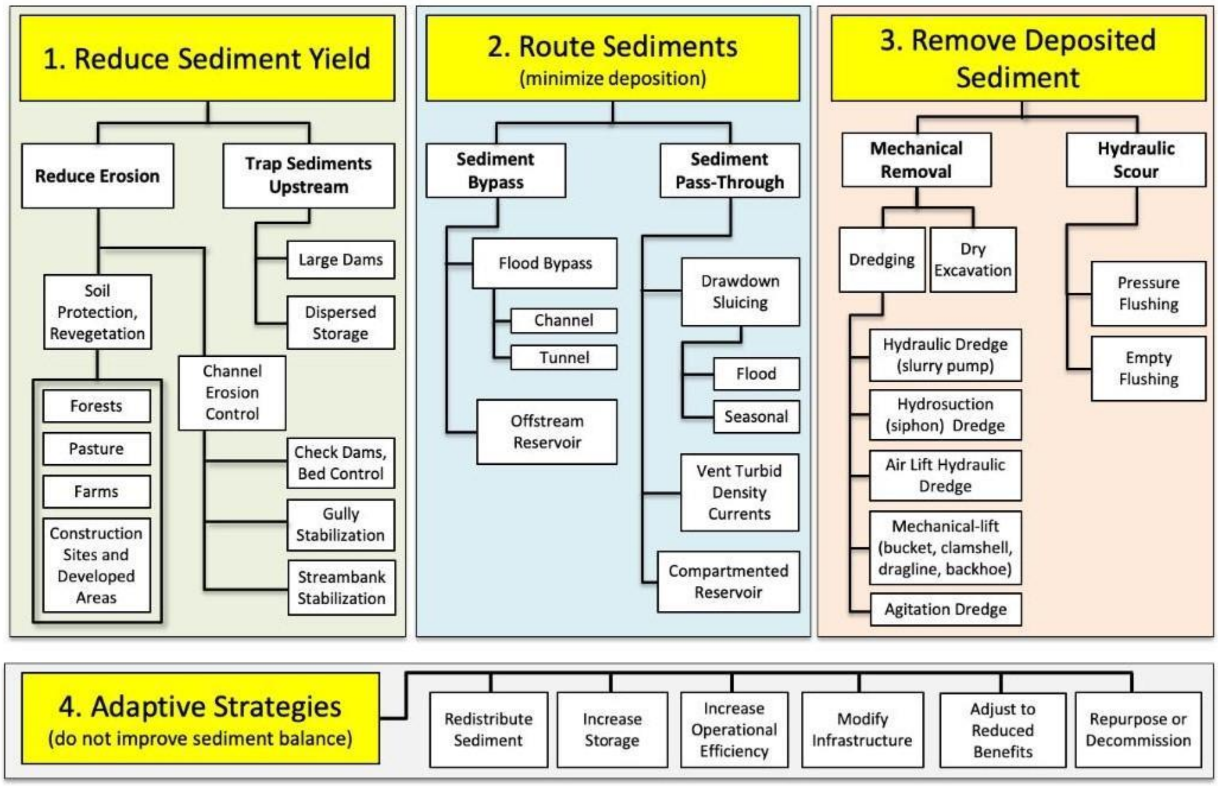
The use of stream flows and reservoir water for sediment management may not be viable in arid environments because the reservoir water may be required for such purposes as irrigation, drinking water, or industrial use. If done right, the routing of sediments through or around a dam can forego the use of significant volumes of water that might otherwise be stored within the reservoir. However, this would typically require specific infrastructure that may not be in place at existing dams.

3. ***Remove or redistribute* sediments** already deposited in the reservoir (e.g., empty flushing and dredging).

The flushing of sediments already deposited within a reservoir often requires significant volumes of reservoir water. If sediment removal is practiced through occasional flushing of the sediments, the hydraulic sediment transport capacity downstream of the reservoir will need to be considered to avoid unsustainable sedimentation build-up downstream from the reservoir. The dredging of reservoir sediments is one method for sustainably managing reservoir sedimentation without the need to release large volumes of reservoir water. Dredging can also be used to clear sediment from around dam outlets and reservoir water intakes.

4. ***Adaptive strategies*** that can be implemented without any manipulation of sediments. This refers to accepting the sedimentation build-up and adapting the management practices around such acceptance.

Figure 4
Classification of Methods to Manage Reservoir Sedimentation



Source: Morris 2020

2.4 Considerations for Evaluating Reservoir Sediment Management Options

The advantages and disadvantages of reservoir sediment management practices need to be carefully considered for the specific situations of each reservoir.

The following factors should be considered:

- **Sustainability:** can the method provide a long-term solution, or does it simply postpone an ultimate system failure?
- **Environmental impacts:** will the sediments after their removal from the reservoir serve or enhance the environment, or could those possibly become a burden to the environment?
- **Financial/economical aspects**: is the monetary cost of the method justified, or is another method available that could provide equal or greater benefits at the same or a lower cost? The costs of sediment management need to be compared against the cost of declining reservoir benefits, eventual dam decommissioning, and lost storage benefits.

2.5 Sustainability of Solutions to Reservoir Sedimentation

Sustainable management of reservoir sedimentation implies ensuring that the long-term reservoir capacity is being maintained for future generations through activities that are economically viable and that minimize adverse environmental impacts. Ignoring continual reservoir sedimentation will ultimately deplete the remaining storage capacity of the reservoir and sacrifice the reservoir's long-term use and functionality. Long before the reservoir is full of sediment, critical functions of the reservoir will be impacted when dam outlets, reservoir water intakes, sluiceways, boat marinas, or important aquatic habitats are buried.

The key to sustainable reservoir management is to ensure that, averaged over time, the volume of sediments entering the reservoir will equal the amount of sediments removed from the reservoir. Because a reservoir is a very efficient sediment trap, some alternative method(s) will need to be deployed to move the incoming sediments out of the reservoir.

One sustainability strategy is to release the trapped reservoir sediment into the downstream river. Clear water (with very low sediment concentrations) is typically released from dams and tends to erode the downstream channel and disconnect floodplains, resulting in a loss of off-channel areas, wetlands, and riparian habitats for fish and wildlife. Channel incision can also cause unstable banks, resulting in erosion and loss of land or damage to streamside infrastructure (e.g., bridges, pipeline, roads, and levees). Providing sediment to the downstream channel would help restore natural processes and could help slow or even reverse previous impacts. Care should be taken to ensure that the annual rate in which reservoir sediment is delivered to the downstream channel does not exceed the stream's hydraulic capacity to transport the reservoir sediment. In most situations, hydraulic transport capacity limits would apply to coarse sediments (sand and gravel) while fine-grained sediments can stay suspended and be carried farther downstream during most stream flows.

If the hydraulic transport capacity of the flows downstream of the dam is not capable of moving all the sediments over time, some portion of the sediments trapped in the reservoir (primarily sand and gravel) will have to be permanently removed from the natural system. In that case, less material should be placed in the downstream channel than the total amount removed from the reservoir. Because coarse reservoir sediment is a potentially valuable resource, finding suitable uses for removed sediments is preferable over simply disposing of such sediments. In addition to the downstream channel, reservoir sediment may also have beneficial uses that could help pay for the dredging program (Randle et al. 2018):

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

What uses may be available and suitable will be very situation-specific, so beneficial uses should be considered on a case-by-case basis.

2.6 Environmental Impacts of Solutions to Reservoir Sedimentation and Associated Permitting Considerations

For relatively large reservoirs, the annual rates of reservoir sedimentation are typically much too large for off-site disposal under a long-term program. Therefore, sediment delivery to the downstream channel must be evaluated. The key to releasing sediments downstream in an environmentally acceptable manner is trying to match the magnitude and timing that sediments would pass downstream in the absence of the reservoir. If reservoir sediments can be delivered downstream, and then also naturally moved along in the stream, at rates similar to the inflow rates, the sediment load to the downstream river will be restored and the reservoir water storage capacity can be sustainable.

The environmental assessment and permitting process will need to recognize the benefits of restoring sediment loads to the downstream channel and avoiding future large, rapid sediment releases during dam decommissioning. Permitting agencies must recognize that clear water releases downstream from dams are not natural and that reservoirs will not be able to trap sediment indefinitely. Eventually, sedimentation will fill a reservoir and in-flowing sediments will pass through to the downstream channel. Eventually, dam removal will be a likely outcome and decades' worth of sediment supply could be released to the downstream channel or may need to be transported to a disposal facility at great cost.

Under historic regulatory practices, the intentional downstream release of reservoir sediments has been prevented, but this will not be possible over the long term after reservoir sedimentation overwhelms the available storage. Therefore, permitting agencies need to develop new guidelines, rules, and procedures, including the role of Clean Water Act section 404 permitting, for sustainable reservoir sediment management practices. This could include the permitting of pilot programs at specific dams and reservoirs. The objective of these new guidelines, rules, and procedures would be to create a viable and more efficient regulatory process to permit implementation of sustainable strategies to maintain reservoir storage capacity and to reduce or eliminate channel erosion downstream from a dam. The new guidelines, rules, and procedures should recognize the inevitable need to pass sediments downstream of dams in a responsible manner to mitigate downstream impacts and preserve reservoir storage capacity.

Native fish and wildlife species downstream from dams evolved under riverine conditions with sediment transport, bars, eddies, pools, and riffles. Therefore, native species should typically respond well to restored sediment loads. However, some introduced species (e.g., sport fisheries) may not respond as well to rivers with restored sediment loads. The effects of restored sediment loads are generally inevitable and can be expected at some future year, even with the dam in place.

In concept, release or placement of sediment originating from a reservoir will have the same environmental considerations that could be relevant for placement of any other type or origin of sediments. Specific environmental factors to consider are whether the sediments have adverse levels and types of contamination, and whether the area where the sediments are being placed has an existing ecological function which is being enhanced or possibly degraded by placement. In this evaluation it may be particularly relevant to compare the proposed condition with re-introduction of sediment against the environmental conditions in the river upstream of the dam, with its natural sediment load, in contrast to comparing the sediment-addition scenario against the existing sediment-starved conditions below the dam. The unnatural condition is where sediments are trapped within the reservoir. If the dam and reservoir didn't exist, then inflowing sediment loads would pass downstream. If the reservoir were ever allowed to fill with sediment, then inflowing sediment loads would pass downstream.

In case of placement in the river system downstream from the dam, a key factor will be whether the sediments will be moved along at the same annual rate as they are being released/introduced into the stream. Fine sediments will transport at most streamflows. However, coarse sediments are transported more readily during floods, and reservoirs typically reduce downstream flood peaks, and therefore the transport capacity for coarser sediments even if not designed for flood control. Hydropower reservoirs with hydropeaking may represent an exception. If sediments are released at a lower rate than the natural carrying capacity, the stream will continue to experience some net erosion; if sediments are being released at a higher rate than the natural carrying capacity, the stream will experience net sedimentation over the short term until stream channel evolution increases the sediment transport capacity.

Each of those outcomes can be acceptable, but they each create a different type of river environment. There are two important things to realize: 1) it is important to keep the timescale in mind when considering these aspects because streams can experience deposition most of the year and experience erosion during just a short time span of the year (during high flows) that could even out or result in net erosion on an annual basis; and 2) either way the movement of sediments is a dynamic process, where both sedimentation and erosion will continuously happen in different places and at different times.

In addition to ecological impacts of sediment releases below the dam, impact(s) to downstream infrastructure should also be evaluated. For example, intakes for water supply are a major consideration for the Tuttle Creek WID demonstration project described in Section 6.4. When a natural river erosion alternative is selected as part of implementing a dam removal, river sediment is allowed to be released downstream to restore sediment continuity and the ecosystem function. These cases can be used as analogies for placing dredged sediment downstream of dams. In the cases of Savage Rapids Dam removal in Oregon and the Elwha and Glines Canyon Dam removals in Washington State, mitigation was required to temporarily treat the increased sediment loads. At Savage Rapids the sediment load was equivalent to about 1 to 2 years average annual supply from the upstream river. Excavation was used in front of an intake for irrigation diversion immediately downstream of the dam to remedy temporary deposition; a few days of higher cost treatment for a municipal supply was incurred to reduce sediment levels about 5 miles downstream. The released sediment was used to create new spawning gravels so had a net ecological benefit. In the Elwha case study, a large-scale temporary water treatment plant was built to address decades worth of released sediment. However, the restored sediment load rebuilt an eroded beach improving the estuarine habitat and approximately 12 miles of alluvial reaches and floodplain between the dams and the river mouth. Once the sediment load returned to near background levels (compared to upstream of the reservoirs in the natural watershed), additional water treatment was no longer needed. By releasing dredged sediment in a manner that matches natural carrying capacity of the stream, impacts can often be avoided or controlled in order to allow any needed mitigation to occur for the purpose of managing impacts.

To determine whether an ecological system might benefit or might be harmed by release or placement of sediments, it can be helpful to define a goal and objective (or goals and objectives) for that system. A goal is a desired result that is typically general and long-term in nature, while an objective is a specific and measurable action that is taken to attain that goal. If the release helps the system reach that goal it is a benefit, and if the release makes it harder to accomplish the goal it is an adverse impact.

2.7 Financial and Economic Aspects to Sediment Management for Reservoirs

Economic analyses should consider all benefits and costs of each alternative for sediment management. Sustainable reservoir sediment management would preserve the reservoir benefits over the long term. The costs and benefits of various sediment management alternatives can be estimated and compared to determine the most efficient alternative(s). The cost of these alternatives should be compared with costs and lost benefits under an alternative without sediment management. These costs and lost benefits could be related to erosion from downstream channels (degradation), sedimentation along the upstream channel (aggradation), reduced storage capacity over time, eventual dam decommissioning, and lost reservoir benefits. Any lost benefits should be counted as costs. For existing reservoirs, the least cost alternative option that is environmentally and socially acceptable can be justified as the best of options even if benefits should not exceed costs because some alternative will eventually have to be implemented.

Economic analyses should consider intergenerational equity and treat reservoirs as an exhaustible resource because there is no substitute for water stored in a reservoir. The time period of economic analysis should be long enough to consider all costs, including those that would apply to dam decommissioning. Costs and benefits assigned to future generations should not be discounted so much that they are effectively ignored.

The concept of designing a dam or reservoir for a finite sediment design life defers significant sedimentation problems to future generations without any easy solutions. The costs of reservoir sediment management may be substantial but are almost always less than the costs associated with declining reservoir benefits , eventual dam decommissioning and the planning, design and construction of a new reservoir. The sediment management costs could be paid for by the reservoir beneficiaries. For US Bureau of Reclamation reservoirs, cost repayment studies identify the various beneficiaries and assign a repayment portion to each beneficiary group. The benefits and repayment for flood risk reduction, recreation, and fish and wildlife have traditionally been assigned to the American public. Benefits related to water supply and hydropower are typically assigned to customer groups.

Further discussion of the economics that apply to managing sediment in reservoirs can be found in Randle et al. (2019) and Kawashima (2007), among other sources.

3 Reservoir Sedimentation Management by Means of Dredging

Dredging is a frequently applied sediment management approach for all manner of waterbodies, but the nature of many reservoirs presents unique conditions and challenges. Therefore, dredging of reservoirs is distinctly different from dredging in general. Some main factors that make reservoir dredging unique include:

- Reservoirs tend to be situated in inland locations, often away from industrial coastlines where the majority of dredging equipment is located.
- Some reservoirs pose significant access challenges, particularly if they are flanked by steep-walled valleys or canyon settings.
- Reservoirs often collect water from large watershed areas, which contribute sediment through natural erosion processes. The eroded sediment ends up being carried downstream, eventually accumulating within the reservoir.
- Reservoirs occupying deep valleys or canyons tend to have relatively deep water, particularly nearest the impounding dam, where much of the critical infrastructure lies.
- Reservoirs situated in areas with exposed, erodible bedrock (such as hilly or mountainous country) will collect a relatively high proportion of coarse and crystalline granular materials, which can complicate the dredging process and cause accelerated wear on equipment and pumps.
- Similarly, reservoirs situated in forested or steeply sloped areas can accumulate a higher proportion of natural debris (logs, organics, rocks, and boulders) than reservoirs in flatter or less forested country.

Ultimately, the location of the reservoir, volume and physical layout of material to be removed, depth of water, material types, and processing, transport and final disposition of the dredged material are the key factors in determining whether dredging is the most appropriate and cost-effective sediment management option for a reservoir. These factors also come into play when defining the most efficient means to dredge sediment from a given reservoir. Ultimately, the viability of dredging, compared to other possible sediment management methods, is influenced by a combination of its cost (as discussed in Section 5) compared against the benefits of sediment mass removal, the well-established technology of dredging, and the potential for reuse of the dredged material (as discussed in Section 4).

3.1 Design Parameters for Reservoir Dredging Operations

To determine the most cost-effective and sustainable sediment management options, geotechnical data are required to understand the location and characteristics of reservoir sediment deposits. Critical data needs for dredging project design include:

- **Volume of reservoir sediment**
  - Reservoir bathymetry and sedimentation thickness
- **Reservoir sediment characteristics**
  - Physical and chemical characteristics of the material to be dredged

- Variation in sediment grain size vertically and/or laterally
- Potential for debris to be encountered (rock and boulders, logs and wood, and other human-derived wastes such as concrete or steel objects)

- **Local site conditions**
  - Conditions of access points at which equipment can enter the reservoir
  - Water levels in reservoir, including potential or planned fluctuations and their timing
  - Long narrow reservoirs subjected to large flooding events can experience rapid water level changes that induce high flow velocities. This phenomenon should be considered in the selection and operation of any dredge plant working in those types of conditions and selection of timing of the dredging.
  - Conditions, size, and topography of sediment removal area(s) in the reservoir
  - Conditions, size, topography, and distance from the reservoir of the areas where sediment will be delivered: the downstream channel or for disposing, placing, or processing of dredged sediment
  - Ability to transport sediment into downstream river course

3.2 Available Resources for Planning and Design

Numerous helpful guidance standards can be found for the design of dredging projects, including dealing with contaminated sediments and selecting and obtaining approval for material disposal sites. Many elements of standard design approaches are described in the following sections. For further details, consult one or more of the following:

- A trio of related Engineer Manuals prepared by the U.S. Army Corps of Engineers (USACE): *Dredging and Dredge Material Management* (EM 1110-2-5025; USACE 2105), *Beneficial Uses of Dredge Material* (EM 1110-2-5026; USACE 1987a), and *Confined Disposal of Dredged Material* (EM 1110-2-5027; USACE 1987b).
- *Testing Manuals for upland and in-water disposal of dredged sediments* (USACE-ERDC 2003 and USEPA and USACE 1998, respectively)
- *A white paper on Reservoir Sediment Management* prepared by the multi-disciplinary National Reservoir Sedimentation and Sustainability Team (Randle et al. 2019)
- *Reservoir Sedimentation Handbook* (Morris and Fan 1998)
- *Sedimentation Engineering: Processes, Management, Modeling and Practice* (edited by Marcelo H. Garcia); Chapter 12, Reservoir Sedimentation, by Morris, Annandale and Hotchkiss (ASCE Manuals and Reports on Engineering Practice No. 110, 2008)

Internet links to many of these documents are provided in the References list.

The following sections present an overview of the basic technologies available for dredging sediment from reservoirs.

3.3 Dredging Technologies Overview

Dredging is accomplished using an array of well-established methods and technologies. This section includes a discussion of dredging technologies in general, while the next section more specifically focuses on their application to sediment removal from reservoirs.

Dredges come in many different types, forms, and sizes. For applications of reservoir dredging, the ability to get a dredge to the reservoir is of course an important factor. Because a dredge may not always be able to reach a reservoir through navigable waters, a dredge may have to be moved to the reservoir over land. In the context of this report, a portable dredge is defined as a dredge that "can be moved easily from one jobsite to the next over existing roadways. If a dredge must be dismantled for transport, it should be constructed for that purpose so dismantling and reassembling can be done easily and quickly" (USACE 1983).

The two main categories of dredging equipment and methodology are **mechanical** (digging or excavation-based) and **hydraulic** (suction- and pumping-based), although there are several variations on these themes that may be appropriate depending on the specific circumstances of the reservoir and its accumulated sediment. The following are brief descriptions of each:

- **Mechanical dredging** typically uses an excavator or crane equipped with open digging or clamshell buckets. When working over water, mechanical excavators would be mounted on a flat deck barge or flexi-floats and pushed/pulled by a work boat to the required work areas, where they would remove sediment and place it into an adjacent scow. Close to shore, mechanical dredging could be conducted by excavators working on land. In cases where water levels can be temporarily drawn down, mechanical excavators can move directly onto the lakebed (in some cases requiring pressure reduction techniques to avoid sinking into soft material). Where the crane or excavator would load sediments into a barge, the sediments would require handling again at the offloading and disposal site, contributing to the total cost of the operation.
- **Hydraulic dredging** involves the use of pumps to convey dredged sediment in a slurry form through temporary pipelines from the point of dredging to a designated repository area. Booster pumps may be required to pump the material to the repository if the pipeline transport distance and/or added elevation difference reduces the dredge pump's discharge slurry velocity so low that the solids start to settle out of suspension. Based on the size of the hydraulic dredge, these booster pumps may be required as much as every mile (1.6 kilometer), depending on pumping distance, material type, and elevation differences.

Water management is a key element of designing and executing dredging projects. Because mechanical dredging produces a relatively low amount of water with the sediment, it can often be accompanied by passive dewatering of the dredged sediments (letting them drain naturally). Hydraulic dredging, on the other hand, produces a sediment-and-water slurry, requiring a relatively large on-land repository area and a means by which the water can be managed as it is separated from the sediment load. Water management for hydraulic dredging is discussed in further detail in Section 3.5.1 (describing the dredging process itself) and in Section 4 (describing material disposal options).

Key benefits of mechanical dredging:

- Able to excavate harder materials, particularly when using clamshell bucket, excavator, standard size backhoe, and the like.
- Can accomplish relatively precise digging and grading.
- Results in relatively low water volumes, simplifying management and storage of sediment on land.
- Produces a relatively high percent of solids by removing sediment at or close to the in-situ state found at the bottom of the reservoir.

Key benefits of hydraulic dredging:

- Pumping from point of dredging directly to point of stockpiling or disposal avoids need for “double handling” of material onto land.
- Proper selection of equipment, piping, and pumps typically results in more efficient production rates than mechanical dredging.

3.4 Selection of Target Areas of Reservoir for Dredging

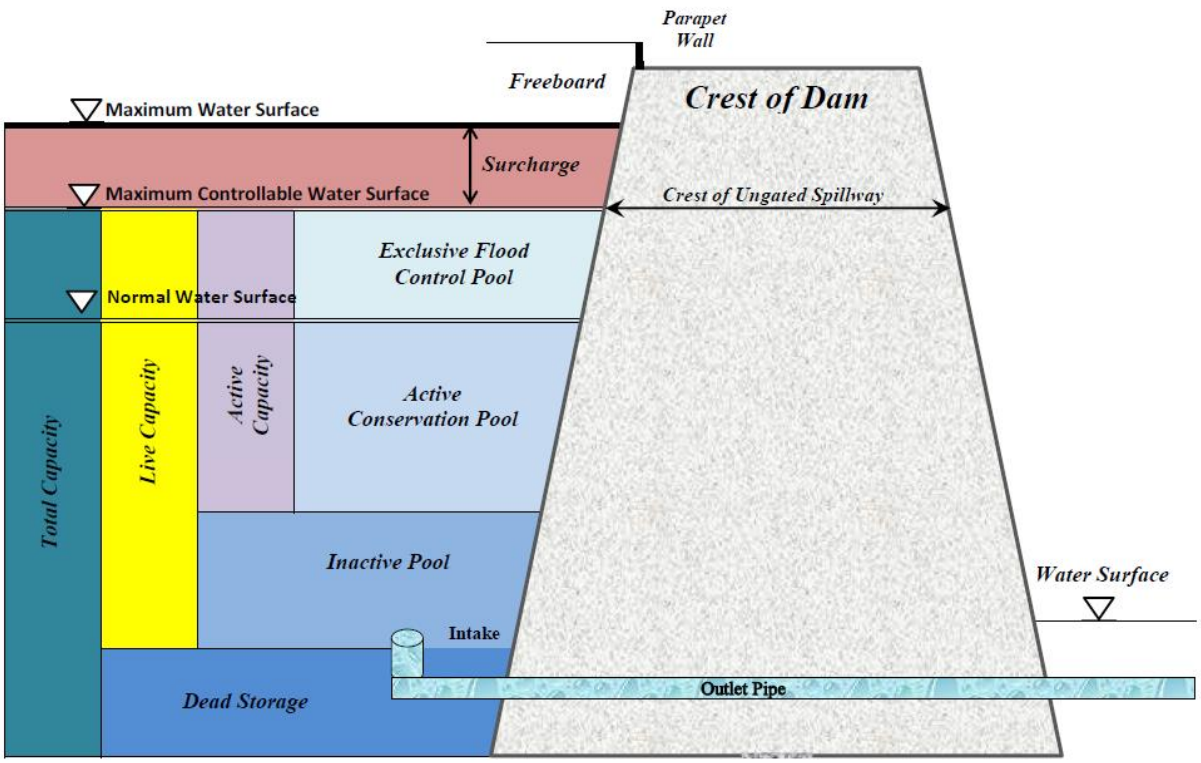
The control of water volume to meet allocation requirements can have positive and/or negative impacts on dredging operations. Unlike navigation dredging, where sediment is required to be removed from a dredging template, in most reservoir dredging (aside from areas around structures), the main objective is to simply recover volume within the active pool. Areas with adverse sediment (or other conditions such as debris), to a certain degree, could potentially be avoided. But, limited water volume releases downstream to maintain allocation requirements could, if the sediment placement involves passing to the downstream side, impose smaller allowable levels of solids concentrations.

The volume of water in storage and flood control reservoirs is managed by reservoir operators to meet the operational requirements for the dam. Large reservoirs use area-capacity curves that provide a unique reservoir surface area and volume (i.e. capacity, usually measured in acre-ft) for specific reservoir water surface elevations. Additionally, operators may store or release water to meet recreation, cultural, or environmental needs. As an example, the U.S. Bureau of Reclamation uses specific terms for these various levels that are incorporated in dam design and day to day operations (Figure 5).

Total capacity is tied to the maximum controllable water surface and is used to express the total quantity of water which can be impounded. The elevation corresponding to the top of total capacity is typically the same as the uncontrolled spillway crest elevation or the top of the spillway gates. The surcharge capacity is additional capacity provided for use in passing the inflow design flood through the reservoir. Most reservoir dredging operations do not aim to recover or maintain the total capacity within a reservoir. Instead, sediment management would focus on recovering or maintaining “live capacity”, which is the volume of water that can be withdrawn by gravity and needed to continue the operational goals of the dam. The live capacity is composed of active and inactive storage. Active capacity is the most used storage area for regulating reservoir inflow for irrigation, power, municipal and industrial use, fish and wildlife, navigation, recreation, water quality, and other purposes.

Inactive reservoir capacity is normally not available because of operating agreements or physical restrictions. The U.S. Bureau of Reclamation "requires that provisions be made for sediment storage space whenever the anticipated sediment accumulation during the period of project economic analysis exceeds 5 percent of the total reservoir capacity" (U.S. Bureau of Reclamation, 1987). This area of expected sediment deposition is referred to as the "dead storage" in Figure 5, and in most cases any outlets or gates are set above the top of dead storage.

Figure 5
Reservoir Water Allocation Definitions



Source: U.S. Bureau of Reclamation, Asset Management Division, April 2021

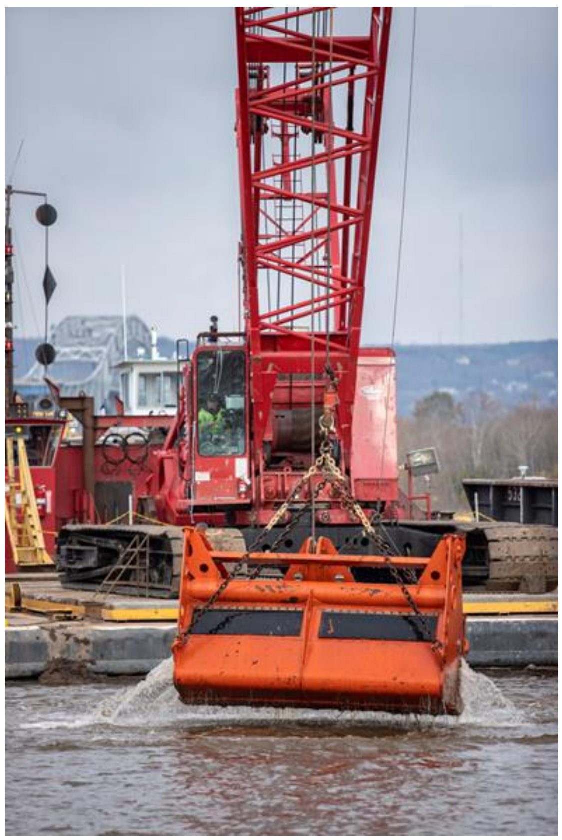
3.5 Mechanical Dredging Operations for Removal of Reservoir Sediment

For reservoir projects, mechanical dredging typically takes the form of land excavation equipment positioned on portable barges utilizing either a clamshell or hydraulic excavator (a.k.a. backhoe, trackhoe, etc.) bucket to remove sediment. Attendant plant with the dredge includes portable tugs and small material handling barges. The typical mechanical dredging operation includes:

- A mechanical dredge is moved on station by a portable tug and is held in stationary position by spuds in shallow water or anchors in deep water.
- A material barge is positioned along the hull of the dredge barge.

- Digging patterns, as well as the bucket type and size, are planned based on the width of cut, depth of water, and type of sediment to be dredged. The clamshell bucket (Figure 6) is held in an open position above the water and lowered through the water column to penetrate into the sediment to the designed depth before closing to capture the sediment. After closing the bucket at the required digging depth, it is raised through the water surface and swung to a point over the material barge for release.
- The hydraulic excavator usually uses either an open-faced bucket or one that is hydraulically closable (Figure 7).
- After completing the designed digging pattern, the mechanical dredge can move forward either by spuds or by anchoring system or with the support of a portable tug.
- When a material barge is loaded the portable tug or launch will be repositioned for offloading.
- These operations are repeated until the dredging is completed.

Figure 6
Mechanical Dredge Consisting of a Crane Using a Clamshell Bucket



Source: J.F. Brennan

Figure 7
Mechanical Dredge Consisting of a Hydraulic Excavator Using a Hydraulically Activated Bucket

Source: J.F. Brennan

Production is determined by the number of cycles per hour, the estimated volume (in cubic yards [CY] or m^3) that the bucket will capture, and loss time for equipment maintenance and waiting on availability of material barges.

The effective digging depth will vary by equipment type. A hydraulic excavator will be limited to a maximum of a 50-foot (15-meter) depth, whereas a crane can effectively dig to depths up to 150 feet (45 meters). Excavating below 150 feet (45 meters) will require specialized equipment.

The actual excavating bucket design will vary in order to maximize digging efficiency based on material types to be dredged and depth of sediment to be excavated.

Operational notes that should be considered during design for mechanical dredging include:

- Collect key data needs prior to design, including material types to be dredged, as discussed in the previous section
- A high level of accuracy to provide grade when employing a backhoe dredge
- Road access in and out of the reservoir area needed to mobilize dredging equipment
- Proper landside staging areas to receive all the needed equipment for staging and placement and/or launch into the reservoir
- Offloading area of sufficient size to match the proposed work

- Depth of water from the landside staging area to the area to be dredged

3.6 Hydraulic Dredging Operations for Removal of Reservoir Sediment

Hydraulic dredging is the most commonly used method to remove sediments from reservoirs, utilizing suction to lift material off the bottom to be pumped through a pipeline to the placement area. Some small, specialized projects are more efficiently dredged using mechanical means using barge-mounted cranes or backhoes to excavate material for loading into barges that will be transported to an offloading site for upland placement.

The benefits offered by hydraulic dredges are continuous dredging, direct pump into the placement area, ability to efficiently remove different material types, and capability of achieving relatively high production rates compared to other dredging methods. As listed in Table 1, hydraulic dredges have been used frequently for reservoir dredging projects in the United States and are often the lower overall cost option to remove sediments from operational reservoirs. They generally involve removal with the least interference with reservoir operations and can conveniently transport sediment through a slurry pipeline. Limits include challenging and expensive mobilizations to move over land all the needed equipment and pipeline to the site, restrictions to where placement areas can be constructed, discharge and management of effluent water, and possible long-term management of sediment in placement areas.

Table 1
Examples of Reservoir Dredging Projects in the USA

Reservoir	Location (State)	Dredge Volume (Cubic Yards)	Discharge Pipeline Size*	Material Types	Placement Area (PA)	Pipeline Length
San Jacinto	Texas	2,420,000	Large CSD	Sand and debris	Fill Old Sand Quarries	Up to 50,000 LF
John Redmond[1]	Kansas	3,000,000	Large CSD	Sediments	Beneficial Reuse Placement	>30,000 LF
Lake Decatur 2nd Phase[1]	Illinois	10,770,000	Large CSD	Silts, clays, and sand	Confined Placement	>45,000 LF
Lake Decatur 1st Phase[1]	Illinois	1,520,000	Large CSD	Sediments and debris	Confined Placement	>18,000 LF
Lake Worth	Texas	1,490,000	Large CSD	Sands/clays/silts	Confined Placement	>15,000 LF
Mission Lake	Kansas	1,100,000	Large CSD	Sediments	Confined Placement	>10,000 LF
Loíza (Carraízo)	Puerto Rico	7,800,000	Large CSD	Gravels, sand, silt, clay	3 Confined Placement Areas	Up to 35,000 LF
Oahe Dam Spillway Inlet Channel	South Dakota	167,000	Small CSD	Sands/clays/silts	Confined Placement	>10,000 LF
Cedar Lake	Iowa	1,065,000	Medium CSD	Sediments	Confined Placement	<10,000 LF
Lake Mauvaiterre	Illinois	550,000	Medium CSD	Sediments	Confined Placement	<10,000 LF

Strontia Springs[1]	Colorado	228,000	Medium CSD	Medium to coarse granite sediment	Confined Placement (Material Reuse)	>30,000 LF
Wonder Lake	Illinois	470,000	Medium to Small CSD	Sediments	Confined Placement	<15,000 LF
Muskingum Watershed	Ohio	200,000	Small CSD	Sediments	Confined Placement	<5,000 LF
Fountain Lake	Minnesota	620,000	Small CSD	Sediments	Confined Placement	>17,000 LF
Waurika Inlet Channel	Oklahoma	75,000	Small CSD	Fine to medium sand	Confined Placement	<5,000 LF

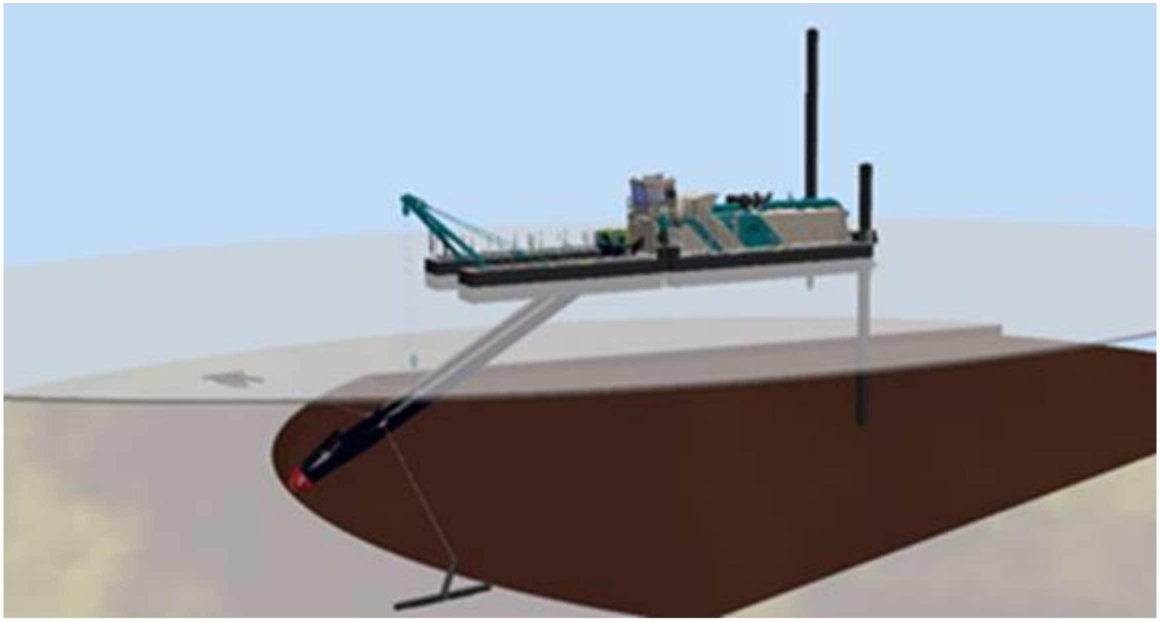
Notes:
Examples of hydraulic dredging projects (using portable cutter suction dredge [CSD] equipment) conducted in reservoirs in the United States over the past 15 years
* The size of CSD is referenced by the Discharge ID:
Large CSD > 20 inches or larger (500 millimeters [mm])
Medium CSD => 14 inches, <20 inches (>= 350 mm, <500 mm)
Small CSD =/< 14 inches (350 mm)

1. Further detail is provided for selected projects in Appendix A.
LF: linear feet

If it is determined that a hydraulic dredge is the best and most cost-effective means to excavate sediments for a specific reservoir, the characteristics of the project will define the size and type of dredging equipment employed. The two types of hydraulic dredges employed most frequently to remove sediments from reservoirs are conventional swinging dredges and swinging ladder cutterhead dredges. These hydraulic pipeline dredges are classified by the size of the diameter of their discharge pipeline (e.g., a 12-inch dredge [300 millimeters (mm)]). Hydraulic dredges are also defined by the depths to which they can dredge, dredging speed, width of cut, cutting power needed to dislodge or break up material, the pipeline discharge size, the size of solids that can pass through the pump(s), the volume of discharge slurry, and the number of truck loads needed to mobilize to a reservoir project. All these features help define the benefits and limits to determine the most cost-effective hydraulic dredge that will be employed. Production rate is defined as the number of CY (or m^3) of in-situ sediments dredged during a given period and is usually expressed in CY/hour (or cubic meter/hour [m^3/hr]). Production rates of dredges vary according to the factors listed above and site conditions of the dredge area.

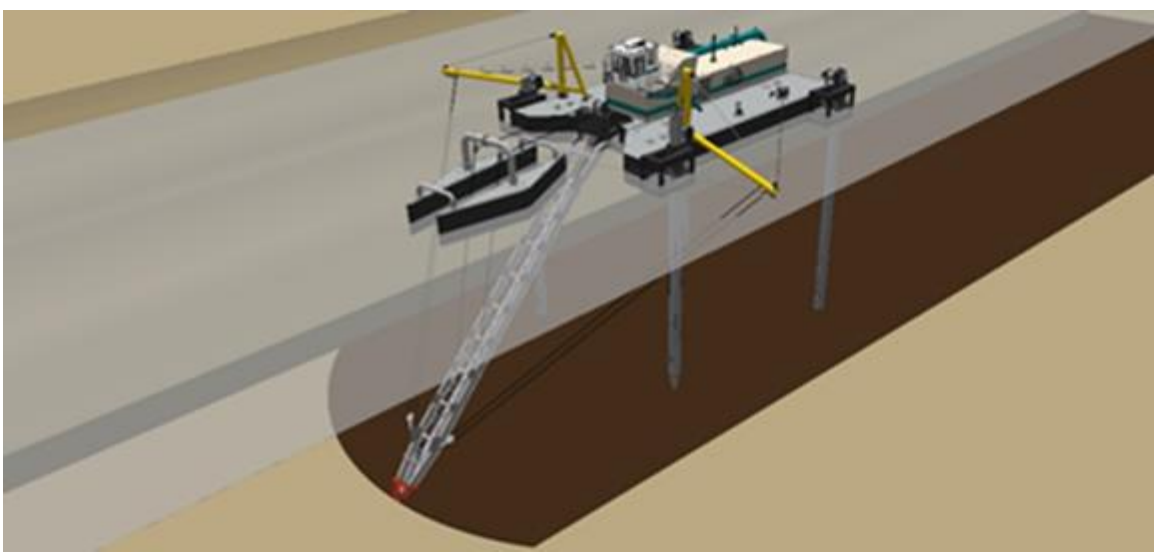
During operations, a conventional hydraulic cutterhead suction dredge is equipped with two spuds, one being used to hold the plant in a working position and another to advance the vessel into the excavation area (Figure 8). Both the conventional and swinging ladder dredges move the cutterhead from side to side while being held in position by spuds. The swinging ladder cutterhead suction dredge employs a hydraulic system to sweep the ladder from side to side while the hull remains stationary (Figure 9). This allows it to work in narrow waterways, as little as the width of the dredge. The conventional swinging dredge employs anchors and swing cables to sweep the entire dredge from side to side, allowing it to efficiently swing wide cuts.

Figure 8
Conventional Cutterhead Suction Dredge



Source: DSC Dredge

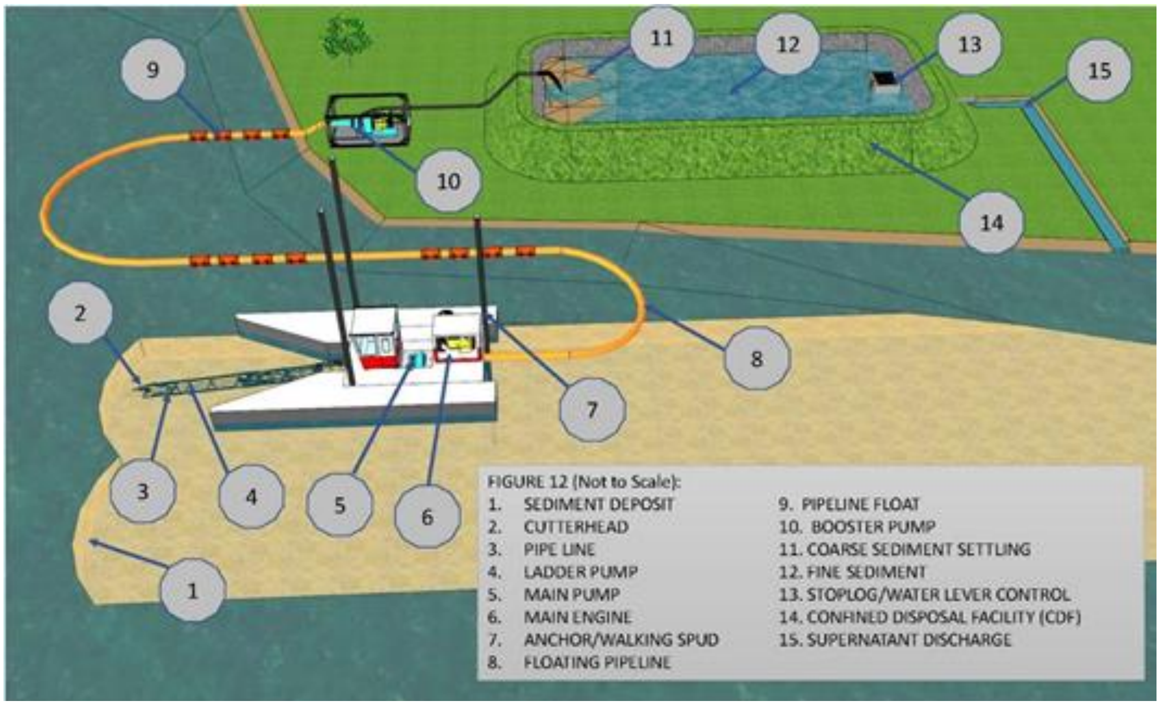
Figure 9
Swinging Ladder Cutterhead Suction Dredge



Source: DSC Dredge

Hydraulic dredges are characterized by their use of centrifugal pumps to remove bottom material by entraining it with water at the dredge suction mouth to create a slurry (solids and water mixture) that is discharged through a pipeline. A rotating cutterhead is equipped to dig and direct the loosened material to the suction mouth. Figure 10 shows various components of a swinging ladder cutterhead dredge discharging slurry into a confined disposal facility.

Figure 10
System Components of a Swinging Ladder Cutterhead Suction Dredge Depositing Slurry in a Confined Disposal Facility



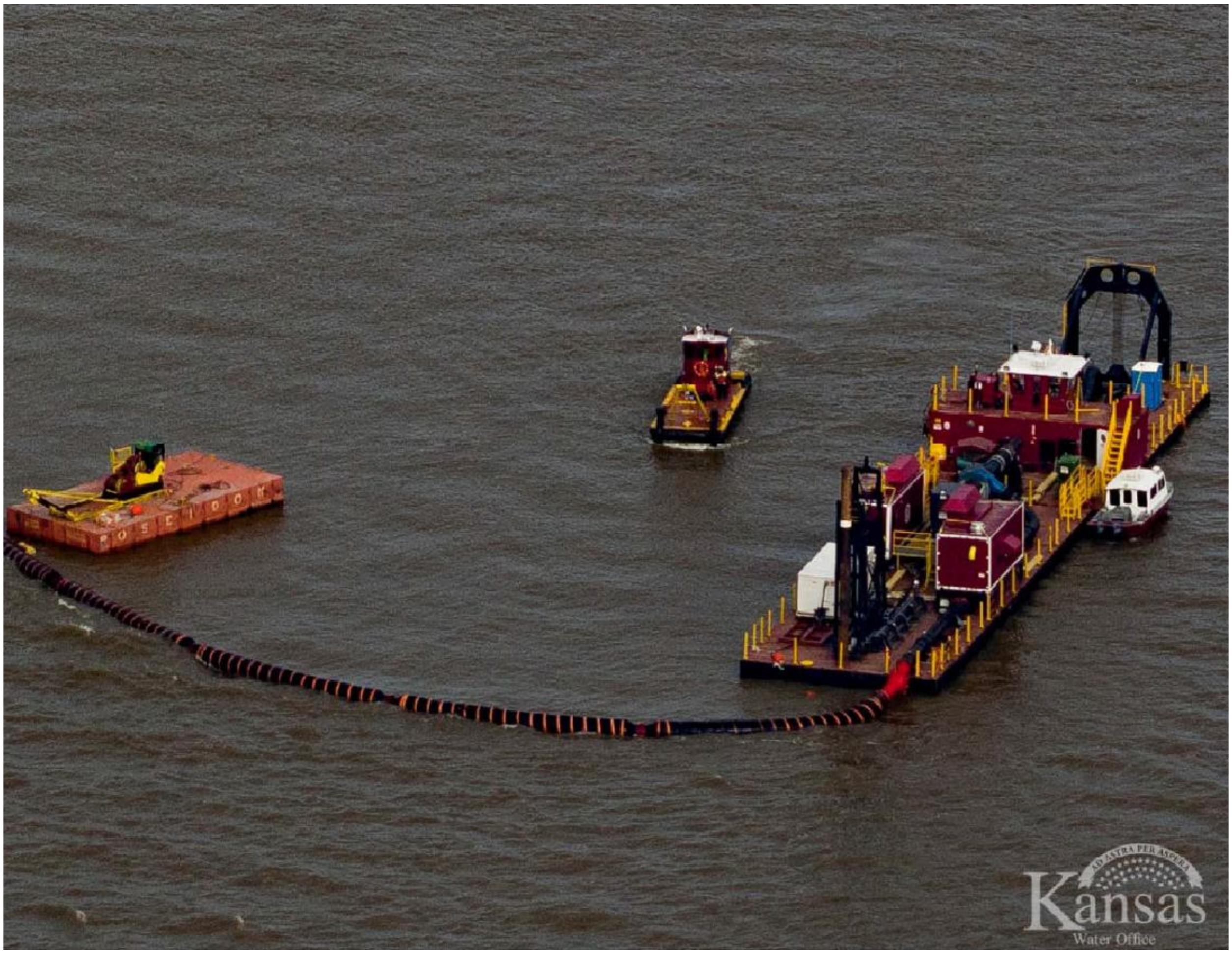
Source: J.F. Brennan

Operational notes that should be considered during design for hydraulic dredging include:

- Collect key data needs prior to design, including material types to be dredged, as discussed in the previous section.
- A hydraulic dredge's accuracy to provide grade is limited by several factors, ranging from type of dredged material, hydrodynamic conditions, to size of the cutterhead and suction piece and more. Dredge accuracy can be especially relevant when dredging close to the dam, whether embankment dam or other type, and can also be a key design parameter to consider in case of dredging to clear intake or bypass structures. Due to size and weight limits to transport a portable hydraulic dredge (in one piece or in modules) over the road, the cutting power of the dredge is limited, so these dredges can only economically dredge silts, sands, and soft-medium clays, which are common in reservoirs.
- Slurries of 10% to 20% solids (by dry weight) are typical, depending upon the material being dredged, dredging depth, horsepower of dredge pumps, and pumping distance to the placement area.

- It is imperative that upland placement areas are properly designed to account for the bulking of sediment (above its in-situ volume) because it is mixed with water (see further discussion in Section 4).
- Hydraulic dredges, in conjunction with booster stations, have the capability of pumping dredged material long distances past the dam to the downstream river channel or to upland disposal areas.
- Digging depths are limited by the size of the hydraulic dredge. Most portable dredges in the United States will effectively dig to 35 feet (10.5 meters) below the water level. Conventional hydraulic dredges can be modified to dig to depths of 100 feet (30 meters). Depths below 100 feet (30 meters) will require specialized equipment.
- When dredging coarse-grained sediment, slurry pipelines must operate at high flow velocities (e.g., >10 feet/second [>3 m/sec]) with correspondingly high friction loss and energy cost for pumping, together with high pipeline abrasion rates.
- Road access in and out of the reservoir area is needed to mobilize dredging equipment.
- Proper landside staging areas to receive all the needed equipment and pipeline for assembly and placement and/or launch into the reservoir
- Pipeline routes from the dredge area to the downstream river channel or confined placement site(s)
- Depth of water from the landside staging area to the area to be dredged

Figure 11
22-Inch Electric Cutter Suction Dredge LP at John Redmond Reservoir in Kansas



Source: Photograph courtesy of Kansas Water Office

Figure 12
Booster Pump Station at Lake Decatur, Illinois

Source: Great Lakes Dredge & Dock

For deep-water applications, as may be encountered in reservoirs, additional considerations will likely apply. As water depth increases, the hydraulic efficiency of a hull-mounted centrifugal pump decreases due to increasing suction lift requirements. Submersible pumps (supported via cables, as shown in Figure 13, or structurally via ladder, as shown in Figure 14) reduce these inefficiencies and have been used for reservoir dredging projects involving deeper operating depths. Submersible pumps are typically vertical pumps that have prime movers integrated into a singular unit and differ from conventional hydraulic dredges in that the submersible pump is placed directly in the material to be removed. (Figure 21 in Section 6.3 illustrates a dredging system based on pontoon-mounted submersible pumps developed for deep-water applications.)

Figure 13
Hydraulic Dredging with Cable-Supported Submersible Pump

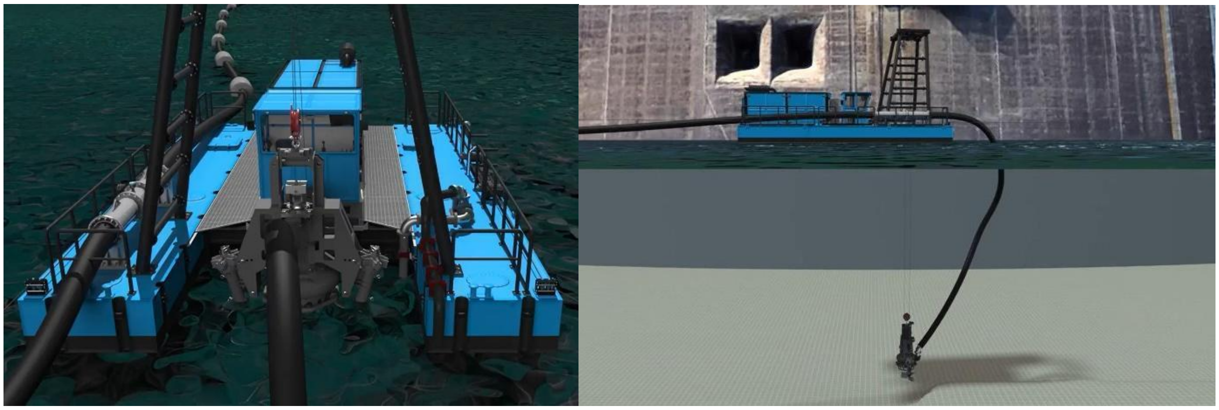
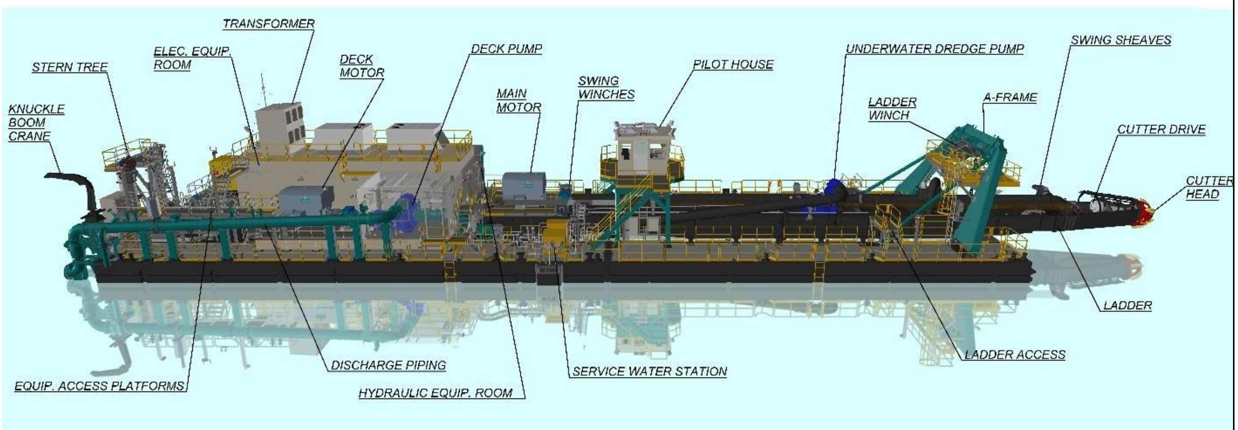


Illustration of the dredging system based on submersible pumps developed for deep-water applications
Source: Dragflow

Figure 14
Example of Dredge with Ladder-Supported Submersible Pump

Source: Great Lakes Dredge & Dock

Figure 15
Dredge with Ladder-Supported Submersible Pump and Other Components



Source: DSC Dredge

For example, some specialized dredges are specifically designed for deep depth applications such as those encountered in hydroelectric dams and other reservoirs. Such arrangements employ a submersible dredge pump suspended from a steel cable that can be lowered vertically into the material. Because there is no ladder to hold the pump, it is possible to achieve working depths up to 160 feet (49 meters) using a pontoon that is only 40 feet (12 meters) long. This significantly reduces the cost of the system and provides a simple solution to the issue of dredging silt traps and other critical deep-water reservoir areas.

The dredges can be either diesel-driven or fully electric to adapt to the site requirements and use mooring winches to cover a set dredging area. Once that area has been finished, the operator can use a propeller to move to a different set of anchoring points.

While the dredges are compact, the pumps can manage up to 17,000 gallons per minute (77 m^3/minute) and can be equipped with mechanical cutters or jetting systems to deal with different types of material. Turbidity being a major concern during reservoir dredging is also taken care of through the use of a turbidity shroud that prevents suspended material from drifting away from the pump suction.

The dredge can also be equipped with different control packages to keep track of the most relevant parameters of the project and even automate certain parts of the operation. Some of the aspects that can be automated in these dredges include maintaining a constant density in the discharge without intervention from the operator, leaving a flat surface by automatically regulating the pump depth and mooring winches or following a certain path using GPS tracking while dredging to the preset target depth. These control packages are designed based on the project needs and integrated into the dredges.

3.7 Water Management for Hydraulic Dredging Operations

Hydraulic dredging produces a sediment-and-water slurry, typically containing between 5% and 20% sediment (by dry weight) depending on material types, and in cases of an upland placement area needs to be pumped to a relatively large on-land repository area when pumping fine materials in which the water can be managed as it is separated from the sediment load through passive dewatering. When pumping sand and/or gravel, the upland fill area can be more limited in size because of the relatively higher solids fraction in the slurry, the faster settling-out rate of the larger granular particles, and the fact that coarser material can rapidly dewater if placed above water level. Of course, those restrictions do not apply in cases where the dredged sediments are directly delivered to the downstream channel.

Dewatering equipment can be used to aid in the dewatering process. Coarse grained materials can be dewatered with sand wheels, hyrdo-cyclones and vibratory screens. If the material is fine-grained belt filter presses, centrifuges, and geotubes can be used. At times these processes will be combined. Hydraulic dredging slurry can also be pumped into or a large bermed enclosure with weir(s) set at specific heights to allow for controlled water outflow. In some locations thin layer disposal may be the best option. This is where the dredge slurry is “sprayed” over land/marsh to deposit the material in thin lifts.

4 Options for Placement or Disposal of Removed Sediment

Whereas Section 3 discussed the process of sediment removal by dredging, this section deals with the equally fundamental question of where the material will get placed, permanently disposed, or even beneficially used after it has been removed from the reservoir. This question can have cost implications equal to, or exceeding, the costs of the dredging work.

Determining a final location for the dredged sediment is dictated in large part by the following fundamental questions:

- How much **material volume of sediment** will be produced by the dredging and over how long a period of time?
- What is the **moisture condition** of the sediment as it is dredged? In other words, will it be removed as a high-water-content slurry produced by a hydraulic dredging operation, or as a largely solid material produced by mechanical dredging?
- What is the **physical nature** of the sediment? For example, what is its proportion of fine silts and clays as compared to sands, gravel, and larger stone sizes? Will it contain larger gravels, cobbles, or boulders? Will it contain debris (wood, concrete, or other non-sediment materials)? Will it be organics-rich?
- What is the **chemical nature** of the sediment? In other words, does it contain chemicals at concentration levels above background levels that could affect the surrounding environment after it is placed or that might impact its potential for reuse? Sediments that have accumulated from industrialized, agricultural, or residential watersheds, for example, may contain chemicals that are a byproduct of human activity in these upstream areas. At sufficiently high concentrations, some of the resulting chemicals could be considered as threats to the environment and to biological and human health, both within the reservoir and after their removal.

The sediment material types involved will help determine the most efficient dredging and placement methods to be employed. Silts and soft clays are cheaper to dredge but have very little commercial value and have a higher placement cost. If, on the other hand, a reservoir is near a major metro area and it contains a high percent of sand, it is possible that there is commercial value to the sand being removed, which could help offset the entire project cost.

In certain hydraulic operations where the sediments to be dredged are well-graded, mechanical separation equipment can be designed to match the dredge production. This additional effort to separate out materials can provide an opportunity to develop commercial material for resale and reduce the volume of material in an upland place area. Both the creation of commercial materials and reduction in the size of the placement area will reduce the overall cost of the project.

The main sediment placement or disposal options are as follows:

1. **Upland confined placement**: Commonly used approach; requires sufficient available land space nearby (typically not feasible for reservoirs on rivers with large sediment loads)

2. **Downstream placement**: May present significant environmental benefits, in that it can restore sediment and habitat to downstream areas that have been cut off from sediment supply by original dam construction
3. **Beneficial use**: Can be a means of offsetting project costs, if the removed sediment has potential commercial value (e.g., aggregate or construction fill)
4. **Haul to landfill**: Hauling and disposal of dredged sediment at commercial waste disposal facilities (landfills) is an expensive proposition but may be the only viable option if the sediment is chemically contaminated or if the other disposal options are unavailable.

These options are described in more detail in the following subsections. Even more specific information on planning, designing, developing, and managing dredged material for beneficial uses while incorporating ecological concepts and engineering designs with environmental, economic, and social feasibility is available in the USACE Engineering Manual 1110-2-5025.

4.1 Upland Confined Placement

Upland confined placement is currently the most commonly employed method to capture and retain sediment removed from a reservoir for one-time projects. It involves the preparation and use of a sufficiently sized land parcel to serve as a potentially permanent and controlled repository for the dredged sediment (Figures 16 and 17).

Such an upland area is referred to by a variety of possible terms, one of which (used here) is a confined placement area (CPA). Typically, the preparation of a CPA requires land grading and the construction of containment dikes to hold the sediment and (if hydraulically dredged) to contain and help manage the water that is introduced. The initial design considerations for a CPA include:

- Planned life of the facility: Is it for a single event or planned to be used over multiple projects?
- Use of area after use as a CPA: Once no longer used as a CPA, how will the site be reclaimed?
- Final destination or use of the material: Can the material placed in the CPA also be excavated for possible future beneficial use of the sediments?
- Type of dredging to be employed: If hydraulic dredging is the method to be used, the CPA needs to account for bulking (increase of volume due to stirring up, mixing with water, etc.) and be designed to hold a multiple of 1.35 to 1.60 over the in-situ volume to be excavated, and water management needs to be addressed during design as well.
- Available resources for construction: Is there sufficient and suitable material on site to construct the needed earthen berms to develop containment cell(s)?
- The amount of dredging: The total volume of material to be placed
- The material types to be dredged: Whether the CPA will be filled with sand, clay, silts, other, or a mixture of those.
- Effluent water management: Especially for hydraulic dredging, the effluent or return water from the site can be significant and will have to be managed. In those cases, dikes can provide a settling basin system allowing for the consolidation of the material with the resulting effluent being drained via strategically positioned weir structure(s).

The big hurdle for upland placement areas is securing the needed properties to retain the dredge sediment. Consequently, it is questionable if upland placement areas can provide a long-term sustainable solution for reservoirs where sediment inflow volumes are large.

Figure 16
Example of Confined Upland Placement Area for Sediments

Sediment disposal ponds for Fountain Lake, Minnesota
Source: J.F. Brennan

Figure 17
Example Confined Upland Placement Area for Sediments

John Redmond Reservoir, Kansas
Source: Great Lakes Dredge & Dock

4.2 Downstream Placement

Downstream placement involves placement of dredged sediment in the stream or river channel below the reservoir's impoundment dam. Geologic processes naturally transport eroded materials downstream along rivers, and downstream placement can restore this downstream movement of eroded materials.

Rivers downstream of dams become sediment-starved (Kondolf, G. M. (1997). "Hungry Water: Effects of Dams and Gravel Mining on River Channels." *Environmental Management*, 21(4), 533–551.). The lack of coarse sediment will typically result in incision of the river bed, producing higher bank heights and increased bank erosion as the river bed lowers due interruption of the supply of coarse bed sediment by the dam, and can include ecological impacts such as coarsening of the downstream river bed resulting in substrates that are no longer suitable for spawning. On the other hand, fine sediments and natural organic material can constitute an important source of food and nutrients for the downstream aquatic ecosystem, and when the reservoir traps these materials it alters the natural flow of nutrients and organic materials to downstream ecosystems. In regions with high nutrient loads from fertilizers or other sources this trapping may be considered beneficial. In either case, the effect of the reservoir on the downstream river can be a relevant factor to consider.

Several advantages may be realized by downstream placement:

- The downstream placement approach presents a potentially significant environmental benefit by restoring sediment to otherwise sediment-starved downstream streambed and riparian areas. The environmental benefits of such an approach can be an important consideration for regulatory agencies during the permitting and environmental review process. In this sense, it could be reasonably considered "sediment augmentation" for the downstream reach.
- If a balance can be achieved between reservoir sediment inflow and outflow, downstream placement could effectively mimic the downstream sediment transport process that existed before the dam was constructed, thus presenting a long-term and theoretically inexhaustible sediment placement strategy.
- For navigation dredging on major waterways, in-water placement is an established low-cost method to keep channels open and allow the sediment to remain in the river systems. For this method, dredged sediments are released in a location of the waterway where they do not create any hindrance to navigation, and are typically moved along again by natural processes.
- Given that the sites for upland disposal are ultimately limited, restoration of sediment movement along rivers may ultimately be driven by the exhaustion of viable upland disposal options.

Several key practical considerations apply to planning and implementing downstream placement:

- **Selecting appropriate location(s) for downstream sediment placement.** Location(s) could be immediately downstream of the impoundment dam, and/or in locations that are strategically selected for their habitat (or fishing) value. Hydraulic characteristics may also come into play in terms of how the placed sediment will be redistributed or carried downstream gradually after it has been initially placed. Natural riffle or rapids, bends in the stream thalweg, sandbars, and natural mixing areas could be important considerations.
- **Method of moving sediment to downstream locations.** As discussed in the previous section, sediment could be hydraulically dredged and transported via a slurry pipeline, or by mechanical earth-moving equipment. Hydraulic placement by slurry may require a movable outfall point, and an energy dissipation or spreading mechanism at the point of outflow.
- **Timing of sediment placement.** It may be most appropriate to match dredge production to reservoir sediment inflow, with its seasonal variability, if an ongoing method of sediment removal and delivery can be fashioned. Temporary storage of dredged material followed by a strategically timed downstream placement may also be warranted. If additional dredging is needed to restore reservoir capacity, then the discharge rate downstream will have to exceed the annual sediment inflow rate into the reservoir. In that case, it might be wise to schedule dredging events to match seasons of high flow when the stream's sediment-carrying capacity is seasonally high. Alternatively, some consideration could be given to design and construction of shallow diked areas along the riverbank downstream from the dam, where the dredged sediments can be placed. During high river flows, the sediment placed in the shallow dike areas will erode, mimicking the natural sediment load of high-flow events.
- **Monitoring** may be required by environment permits for downstream placement, potentially including:

- Upstream reservoir inflow (discharge, sediment load, concentration, and quality)
- Downstream sediment outflow (total discharge, sediment load, mixed concentration, and mixed water quality)
- Downstream channel sediment deposition (location, thickness, and bed material grain size)

In evaluating the alternative of returning sediment to the river below a dam, recognize that the downstream river has been operating for decades under a sediment-starved regime. When evaluating the environmental impact of re-introducing sediment into the river several concepts may be relevant:

- First, the “natural” condition for the river may be represented by the river reach upstream of the dam which still contains its natural load of sediment. This implies that the impact of sediment addition should be compared to conditions in the river upstream of the dam, rather than the unnatural sediment-starved condition in the river below the dam, adjusting for the decreased sediment transport capacity below the reservoir due to its impact on flood flows.

- Second, it may be relevant to consider that if the reservoir is simply allowed to fill with sediment, it will no longer act as a trap and the downstream river reach will again receive the sediment load generated by the watershed. The sediment-starved condition that currently occurs in rivers below dams is ultimately a temporary human-induced condition. It may be useful to examine options for downstream sediment placement against the context of a do-nothing alternative, with the corresponding downstream sediment load.

- Third, rivers downstream of dams frequently experience negative impacts from interruption of the downstream flow of coarse sediments. In some cases, it may be desirable to excavate coarse sediment from the reservoir delta and place this into the river below the dam, even though the fine material dredged from further downstream in the reservoir is discharged to a confined disposal area.

While downstream placement offers a number of potential benefits both to cost and to the downstream environment, it has not seen widespread use as compared to upland confined placement. The industry would seem to benefit from the implementation of one or more pilot programs, by which the implementation methods can be applied and monitored, providing performance data for other reservoir projects.

4.3 Beneficial Use

Sediment with the right physical and chemical characteristics could potentially be used as a beneficial resource, being used to augment farm fields, improve and expand wetlands, as cover material for a solid waste site, or as commercial applications for the sand and gravel market. Downstream placement, or “downstream sediment augmentation” as discussed previously, is a prime example of beneficial use. Other beneficial uses include:

- **Wetland restoration or habitat development:** Along the coastal areas of the United States, dredged sediment is commonly used to restore existing wetlands. Using reservoir sediment for such application has been limited but could be a feasible alternative to upland placement areas and for restoring habitat and riverbanks downstream. Many upland wildlife habitats have resulted from dredged containment areas that are no longer being used.

- **Shoreline stabilization and erosion control:** Use of dredged material for shoreline stabilization and erosion control typically consists of the placement of dewatered sediments along eroded embankments and shorelines to replace lost material. Use of dredged material for erosion control is generally limited to sediments containing primarily coarse-grained sand and/or sand-sized materials.
- **Pumping into geo-tubes for shoreline stabilization and erosion control:** Geo-tubes can be used as shoreline protection, erosion control, breakwaters, jetties, groins, and berms. They are filled with a slurry by hydraulic dredge and have the ability to filter water and provide for dewatering of the material. The water draining from the container can be held within a containment basin or allowed to flow back into the waterway.
- **Farm field augmentation:** Dredge sediment can either be delivered by hydraulic or mechanical means as a method to improve the quality of the agricultural land or to raise the land's elevation. This practice has been a constant method of placement of dredged sediment along the Yazoo River in Mississippi and has been used as one of the placements methods for the John Redmond Reservoir Dredging Project.
- **Beach Nourishment/Island Creation:** It is a common practice to place dredged sand onto beaches or to reinforce habitat islands using material removed as part of maintaining ship and/or barge channels along the coastal United States. This method of placement was employed in South Dakota as a means to develop habitat islands in reservoirs and reduce dredging cost by limiting the pipeline discharge distance. The most suitable means to excavate sandy material for placing it on a beach or for creating/nourishing habitat islands is by hydraulic dredging.

4.4 Management and Disposal of Chemically Impacted Sediment

As part of a sediment management plan, reservoir owners and operators should conduct a due diligence review of available data and upstream watershed conditions to determine if there is "reason to believe" contaminants may be present. If the potential for contaminants exist or local regulatory procedures require testing before handing reservoir sediment, chemical sampling analyses are conducted to compare with sediment quality criteria and background levels. A sediment analysis guideline for dam removal walks through the due diligence step along with how many samples to collect and what types of chemical analysis to conduct (Randle and Bountry 2017). The guidance is based on federal recommendations for evaluating contaminants in sediment proposed to be dredged and disposed or released to inland waters (USEPA and USACE 1998). Sediment testing should also adhere to any regional sediment management standards developed by state or county agencies. Coordination with fisheries agencies, landowners, and resource managers should also be considered when developing sediment testing plans. Early communication with permitting agencies and stakeholders can help streamline the permitting process. Agencies that have not previously permitted sediment management would benefit from talking with other agencies who have granted sediment management permits.

When materials are not suitable for use or conventional placement due to the presence of potential contaminants, options for downstream placement and beneficial use likely become unavailable, and a specially designed and approved upland disposal site is required. These could take the form of existing commercial landfills (potentially at a significant distance away from the reservoir site) or specially designed and lined containment facilities. The nature and degree of chemical contamination would dictate what level of containment measures would be needed for the containment, possibly including a bottom liner and underlayer, careful controls on permanent cap and cover, and long-term monitoring, etc.

Chemically impacted sediment could also undergo certain treatment steps to help offset its level of contamination. Addition of organic binding agents, for example, can help decrease the leachability of organic chemicals; other techniques can be available for certain metals. This approach adds cost and effort to the sediment management process, but the disposal savings could more than offset the additional management costs, if the processed material can be accepted as a less stringently controlled waste category.

In some cases, projects can take special advantage of the tendency of chemical contaminants to concentrate disproportionately in the finer grain size fraction (silts and clays) of the material. Mechanical screening techniques, hydrocyclones, and similar measures can separate the fine-grained fraction of sediment from the coarser sand and gravel load. In some project examples, this approach has significantly lessened the volume of “contaminated” material requiring landfill disposal, while simultaneously producing a sizable volume of clean, coarser sand and gravel that can be used elsewhere. The end result is a tremendous cost savings to the project, compared to treating the entire sediment load as “contaminated.”

5 Costs of Reservoir Dredging

Any evaluation of potential dredging operations requires a reasonable understanding of the likely costs involved with the operation. Although it would be convenient to apply simple “rule-of-thumb” cost values to dredging projects, the key cost drivers are numerous and varied enough to require an understanding of the unique properties associated with any given project. Estimating costs for reservoir dredging, in other words, is not a simple process, and there is no single “typical” unit cost rate that can be applied. Still, it is helpful to explore the key cost drivers for reservoir dredging projects and their implications on overall budgeting, as is presented in the following discussion.

5.1 General Cost Drivers

The cost estimating process can be subdivided into a series of key, general cost drivers, each of which affects likely cost ranges in ways that are often interrelated. Understanding these drivers is essential to developing realistic project cost ranges for dredging projects under consideration. Key cost drivers include:

- Costs of **dredging equipment and associated labor**, including mobilizing and demobilizing the equipment to the site, and running and maintaining the equipment for the duration of the work. Pipelines and booster pumps would accompany hydraulic dredging work, one or more support scows would accompany in-water mechanical dredging, and various types of earthmoving equipment would be needed for any work done over exposed land area.
- Costs associated with **site usage,** including achieving access for the dredging equipment. In confined or high-relief settings (such as reservoirs in narrow canyons), equipment access may require the construction of new roadways, ramps, platforms, or other means of facilitating the work.
- In the event that reservoir sediments are not delivered to the downstream river channel, costs associated with **managing, stockpiling, transporting, disposing, and/or reusing the dredged material**. This may include the application of dewatering or screening methods to make the dredged material better suited to its final placement or use. In some cases, a significant amount of land space may be required for management or placement of the dredged material, which could involve negotiated land lease or purchase costs.
- Costs associated with implementing required and appropriate protocols for **safety and environmental protection** (including any permit requirements).
- Costs associated with **quality control and assurance**, including owner oversight and surveys.

Most of these cost drivers are affected by the overall duration of the project, itself a product of mobilization time, dredging production rate, processing and disposal rates for the dredged material, and demobilization. For long-term sustainable reservoir sediment management, the mobilization cost will be less significant than for navigation dredging projects. In addition, costs for the work are affected by factors that extend beyond the work itself and can be subject to unpredictable variations over time, including market conditions (size and availability of qualified contractors), availability of materials, and changing regulatory requirements.

5.2 Cost Management (in different stages of the process)

The best approaches for managing costs on reservoir dredging projects are much the same as those applicable to other types of construction. Namely, costs can be controlled through the use of several key management steps, such as:

- Performing a thorough up-front investigation of reservoir and sediment conditions (incl. geotechnical study) so that the designer and contractor have as accurate an expectation as possible regarding the conditions that will be faced, and the material types encountered. A geotechnical or sediment baseline report should be provided to clearly document the expected conditions that will be encountered. Such report should describe the sediment grain size distributions of samples collected from the reservoir and other pertinent information. The objective of a geotechnical site investigation is to obtain the most complete and accurate estimate of the location and character of the materials to be dredged within the limits of practicality and available time and money (EM 1110-2-5025). This information must be communicated in a readily understood manner to all parties involved in the design, planning, cost estimation, contracting and construction for a project. Due to the nature of dredging and location of work, lack of or poor site/geotechnical studies is one of the most significant areas during a dredging contract that will create a "change of conditions" with a potential for major cost increases. Providing clear and comprehensive design drawings and technical specifications to minimize uncertainties during bidding and during the construction itself.
- Assuring a well-planned and executed program of quality control and quality assurance on the part of both the contractor as well as the oversight engineer and owner's representative. This facilitates mutual agreement on satisfactory completion of the work and overall payment.

As a primary objective for reservoir dredging is typically to maintain reservoir storage capacity, the exact locations and depths to which sediment is dredged may not be as important as the total volume dredged or removed during a given year or season. If problems with rock or debris are encountered in one area of the reservoir, it may be acceptable to dredge the required volume from a different area.

The economic costs of reservoir dredging alternatives should be compared with the costs of reduced reservoir storage capacity over time, sediment burial of dam and reservoir facilities, impacts along upstream and downstream river channels, and eventual dam decommissioning. Lifecycle dredging costs need to be considered because periodic sediment removal is needed to sustain storage capacity over the long term. The life-cycle costs include the initial mobilization and capital equipment costs, annual operating and maintenance costs, and replacement costs to keep the project functioning over the long term. The mobilization cost will become less important for long-term dredging projects than for short-term projects. The years that these various costs are incurred is important for economic analysis. Costs that are incurred in future years are discounted at an exponential rate. An alternative with an initially high capital equipment cost may be cost-effective if the annual operation and maintenance costs are low or if the equipment can last a long time before replacement is needed.

5.3 Example Cost Ranges from Recent Reservoir Dredging Projects in the United States

Although project costs are dependent on the unique circumstances that apply, when planning a new project, it is helpful to understand reservoir dredging costs from other projects completed across the United States. As discussed in Section 3, most reservoir dredging projects in the United States have been completed by hydraulic means, so that is where most of the available comparative cost information originates.

A review of publicly available bid information for hydraulic reservoir dredging projects accomplished for public entities is listed in Table 1. For projects ranging in size from 75,000 to 1.5 million CY (55,000 m^3 to 1 million m^3), an overall bid cost range of as little as \$2 million to as much as \$17 million covered construction costs (excluding the costs for permitting, design, and project management). Larger projects (3 million to more than 10 million CY [2 to 7 million m^3]) were fewer and varied from \$20 million to more than \$80 million in construction cost. The most typical dredging price over the last decade has been in the range of \$5 to \$8 per CY (\$3.5 to \$5.8/m^3) for hydraulic dredging into a nearby confined placement site. Higher-priced exceptions apply to projects where access was particularly difficult or the containment area required a significantly higher amount of preparation, among other factors as discussed in this section. Costs are expected to be lower if reservoir sediments are delivered to the downstream channel and more natural sediment transport conditions restored to the environment.

6 New Technologies for Reservoir Dredging

Many dams and reservoirs were designed and built over a half-century ago, and some go back as far as the late 1800s. Dredging technology advanced substantially during the past century with a focus on navigation, marine construction, and coastal protection. The topic of reservoir dredging is comparatively new, and additional innovations are needed to reduce cost, readily provide power, reach depths deeper than 100 feet (30 meters), provide real-time monitoring of dredge excavation position, reduce abrasion problems, and provide a smaller footprint for equipment that can be transported on roads and other areas.

An innovation can be defined as an idea, practice, or project that is perceived as new by an individual or other unit of adoption (Rogers 2003). Innovations can generally be considered as falling into two broad categories: incremental and groundbreaking. Incremental innovation focuses on relatively smaller cost and/or feature improvements to existing technology, as opposed to groundbreaking innovation that produces significantly larger improvements by introduction of a radically novel technology.

Of course, adoption of innovative sediment management technologies does not happen overnight. It often requires years or decades, with equipment development, environmental permitting, funding, and stakeholders involved. Most innovations, regardless of the belief that the advantageous ones will sell themselves, are adopted at a disappointingly slow rate (Rogers 2003). This is true for reservoir dredging just as it is for other areas of technology, although reservoir dredging innovation does not, at this point, benefit from the market-based funding sources that apply to such fast-growing technologies as electronic communication, for example.

As previously discussed, ideally a sustainable dredging technique should incorporate the strategy to maintain sediment continuity through the reservoir, meaning the amount of sediment coming into the reservoir equals the amount of flow out of the reservoir (in the same time frame). Sediment is important in river systems; if sediment is trapped in a reservoir, then the downstream water does not have that sediment and is, from an environmental perspective, “sediment-depleted.”

6.1 Anticipated Key Areas for Innovation Focus

To provide solutions to advance more sustainable reservoir sediment management practices, dredging technology innovations will need to address the social, environmental, and/or economic factors, in conjunction with the site-specific conditions involved in these types of projects. As described in Section 3.2, reservoirs pose unique conditions and challenges to dredging. Some of the main aspects where innovation is required to improve the overall efficiency and sustainability of reservoir dredging projects include:

- **Cost of dredging and disposal and/or placement of dredged sediments:** While funding for dredged navigation channels is usually limited for the respective volume of shoaled sediment requiring removal, the funding for dredging reservoirs is even more limited because (as previously described) costs associated with sustainable sediment management were not considered when the reservoir was built.
- **Deep depth dredging:** For the dredging of silt and clay located close to dam walls, underwater intake structures, or other high-depth applications, conventional portable hydraulic dredges have limited

digging depth. Conventional cutter suction dredges can be adapted to large depths applications and provide a more constant production regardless of depth, but the size of the system increases considerably with the depth as longer ladders with ladder pumps are needed. Mechanical dredges have been used for these applications, but lower production rates inherent in this dredging methodology are further reduced because of the longer cycle time caused by increased depth.

- **Monitoring of dredging operations:** When dredging around underwater structures such as intakes and galleries, it is necessary to have a high degree of excavation point (e.g., cutterhead) positioning control. Improved positioning and monitoring systems that allow the operator to see the dredge's cutterhead relative to the reservoirs infrastructure regardless of water visibility is critical for higher precision dredging and associated production rates.
- **Reduce component abrasion:** The wear on critical dredge components such as pump impellers, wear plates, casings, and discharge pipelines have a direct impact on the cost of a project as replacement unit costs and maintenance time increases. In reservoirs, the coarser sediments settle first in the shallower areas, while finer sediments (silt and clay) deposit closer to the dam. Given that sand and gravel will wear out system components faster than finer-grained sediment, if coarse-grained material is to be bypassed downstream of the dam, the longer transportation distance exacerbates abrasion impacts.
- **Reduced site footprint:** Due to particularly difficult access to certain reservoirs and the complications to bring in large equipment, the size of the dredge plant and its footprint (including transport and placement machinery) on the reservoir itself should be as contained as possible, which is pushing manufacturers to innovate on new dredging methods and arrangements. A smaller footprint is desired especially when implementing sediment management solutions for long-term, sustainable sediment management operations.
- **Surgical dredging:** While dredging in close proximity to dam infrastructure such as in front of trash grates, stop log guides, etc., the possibility exists of damaging these components with the dredge's excavation point (cutterhead, bucket, etc.). Technology innovation that increases positional accuracy and control (while maintaining practical production rates) would reduce the degree of this risk.

Dredging technologies will keep evolving as new demands arise and reservoir sediment management moves toward a more sustainable approach that includes more funding source(s). Section 2.2 discussed the three current reservoir sediment management methods:

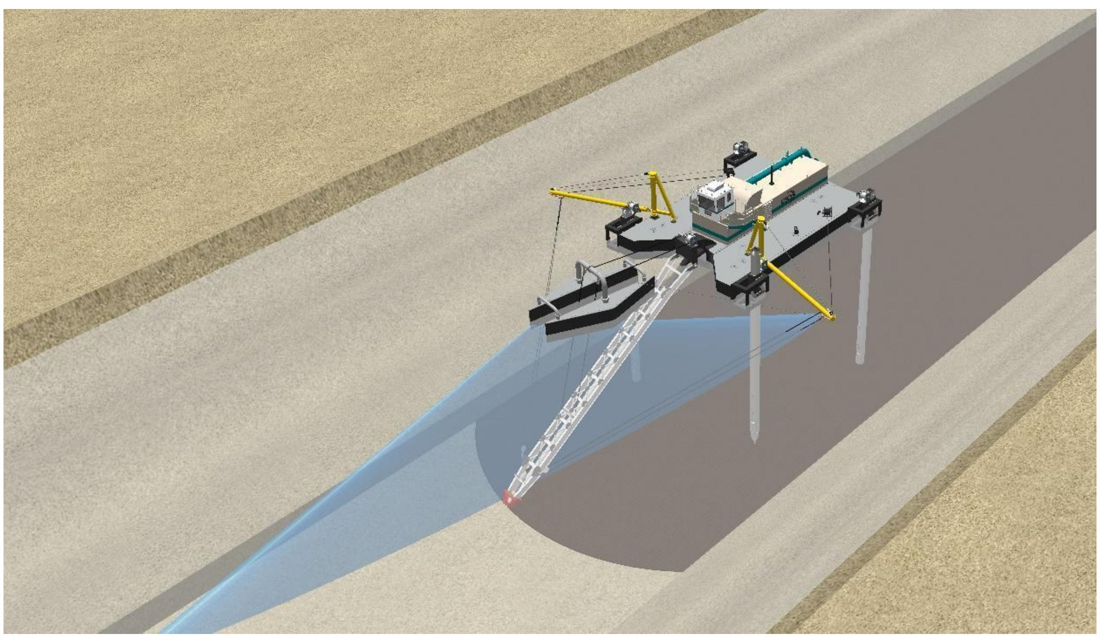
1. Reduce sediment yield entering the reservoir (watershed management practices)
2. Route incoming sediments around or through the reservoir, to minimize sediment deposition within the reservoir (sediment bypassing or pass-through)
3. Remove or redistribute sediments already deposited in the reservoir (e.g., empty flushing and dredging)

Incremental innovation of traditional dredging technologies will involve aspects related to the third method listed: sediment removal or redistribution method. While groundbreaking innovation of dredging technologies could be included in this method as well, it is not necessarily limited to just this one. A truly novel innovation that radically changes the existing paradigm could include one of the other two methods or a combination of any of these three methods. Several examples of technological innovations that have been made or proposed in recent years that focus on solving some of the issues mentioned above are presented in Section 6.2.

6.2 Innovative Approach to Dredging Controls

One example of an innovative dredging control system improves dredge positioning accuracy by allowing an operator to see underwater infrastructure in turbid water with the use of multibeam sonar imaging. This system is illustrated in Figures 16 and 17 and uses remote connectivity to integrate multiple variables simultaneously: geographical dredge cutterhead position and heading, multibeam sonar imaging and mapping of the lake bed, and dredge navigation and instrumentation, all through a user graphical display and software interface that depicts the current dredge location, depth of the cutterhead, and topography of the bottom. With this technology, the operator can see the entire bottom around the dredge, and these data are stored into a comprehensive map of the dredging area or mine site for computation, historical documentation, and future planning. This high-precision dredging control is especially useful when dredging around dam outlets, reservoir water intakes, or boat ramps and marinas. The position accuracy is not as important in more open areas of the reservoir because the volume of sediment removed is more important than the bathymetry created by the dredge.

Figure 18
Illustration of a Hydraulic Dredge Using Multibeam Sonar Imaging



DSC Vision
Source: DSC Dredge, LLC

Figure 19
Multibeam Sonar Imaging Underwater Infrastructure to Improve Dredging Accuracy and Production.

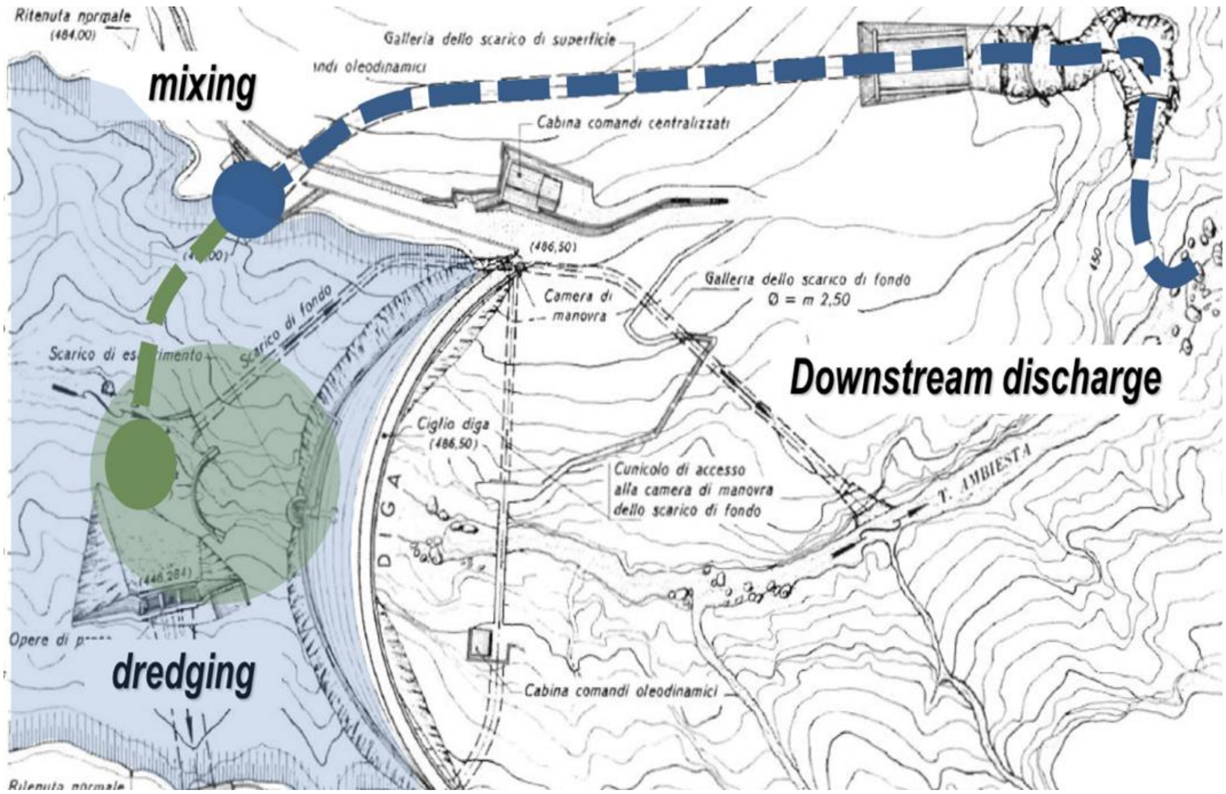
DSC Vision
Source: DSC Dredge, LLC

6.3 Innovative Approach to Deep Reservoir Dredging and Material Pumping

An innovative approach to achieve deep depth reservoir dredging while controlling slurry solids concentration to meet downstream placement environmental requirements was used on a case study in fall 2016 at the Ambiesta Reservoir in Italy. The total area of the dredge prism was 48,500 square feet (4,500 m^2), and the sediment located at water depths ranged between 65 feet (20 meters) and 120 feet (37 meters) depending on the variable surface water level in the reservoir. A sediment volume of 36,600 CY (28,000 m^3) had to be removed to ensure a correct efficiency of the ancillary structures. Sediment consisted of 95% fine-grained (74% silt and 21% clay) with remaining 5% coarse-grained. Because the Ambiesta Reservoir feeds the Somplago power plant, turbidity generated by the dredging operations had to be kept at a minimum.

Figure 20 illustrates the layout of the reservoir, the dredging and material pumping lines, and the downstream discharge point. Considering the characteristics of the sediment to be dredged, and a total project time of 100 calendar days including mobilization operations, an average slurry discharge was fixed at 654 CY/hr (500 m^3/hr). The material was to be pumped downstream through the surface outlet located on the left side of the dam, where it would mix with a clear water flow of 5.2 CY/sec (4 m^3/sec). Solid concentrations in the downstream discharge could not exceed 9,000 ppm (parts per million) in order to meet water quality requirements.

Figure 20
Ambiesta Dam Dredging Concept



Dredging concept showing the material being mixed and diluted prior to its discharge downstream
Source: Dragflow

As illustrated in Figure 21, the dredge consisted of a submersible dredging pump deployed through a modular pontoon. The pontoon was equipped with four mooring winches driven by individual electric motors and a hoist to handle the dredging pump. The dredge was equipped with density and flow meters to ensure that solid concentrations in the downstream discharge did not exceed the limit set by water quality requirements.

A special anti-turbidity shroud was installed on the dredge's submersible pump to minimize sediment resuspension (see photographs in Figure 21), avoiding the movement of fine sediment to the right side water intake, and the ingestion of fine sediment by turbines installed at the Somplago power plant.

Slurry solids concentration were continuously monitored and always available to the reservoir operator and contractor. Dredging productivity, evaluated on daily basis, has been the following:

- Minimum productivity: 261 CY/day (200 m^3/day)
- Average productivity: 523 CY/day (400 m^3/day)
- Maximum productivity: 1,046 CY/day (800 m^3/day)

Average capacity for this type of dredge ranges from 130 CY per hour (100 m^3/hr) for 10-inch (250-mm) dredges to 1,300 CY per hour (1,000 m^3/hr) for larger 20-inch (500-mm) dredges, depending on the type of material. The entire dredging equipment is easily controlled and operated from the central cabin where the operator manages all necessary controls with indicators of working depth, flow, and density measurements as well as a bathymetric survey system.

Figure 21
Ambiesta Reservoir Dredging Design

Dredging system used at Ambiesta Reservoir; photographs of the complete dredge and submersible dredging pump anti-turbidity shroud
Source: Dragflow

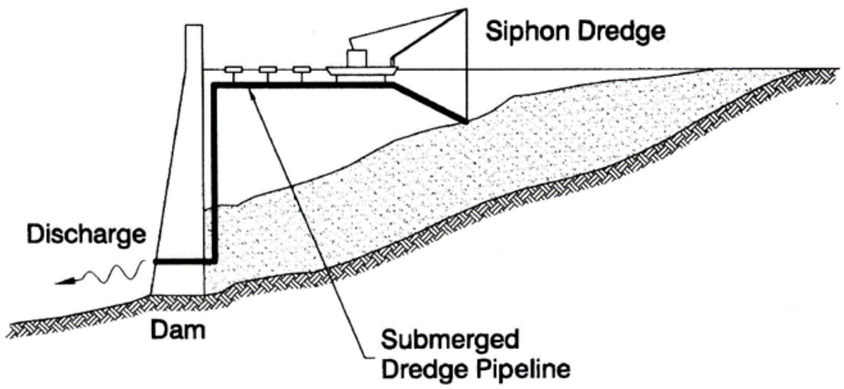
Dredging was done in three shifts per day, 24 hours per day, with a cost of approximately $27/CY ($35/m^3) and noise levels under the limits set due to surrounding residential areas.

6.4 Innovative Approaches to Sediment Removal and Transport from Lakebed

The desire for a low-cost method to remove consolidated fine sediment from a reservoir bottom has driven development of innovative approaches like hydrosuction and water-injection dredging, particularly for cases when there is a low-level dam outlet. The following sections feature examples of such recent or ongoing innovations, which have either been successfully deployed or are actively in the process of being developed and tested in reservoir settings.

Hydrosuction (or Siphon) Dredge: Hotchkiss and Huang (1995) described a hydrosuction sediment removal system that involves entraining bottom sediment with water into a suction pipe and transporting this slurry downstream through a pipeline by utilizing energy from the siphon effect due to the differential static head between the reservoir water surface and lower elevation pipeline discharge. In more recent years, this approach have been successfully implemented. A key challenge of siphon dredging is posed by the need for a significant available head differential to entrain and force slurry through the pipeline, effectively limiting its use to the near vicinity of the dam. Figure 22 illustrates a physical configuration that generates the necessary differential head. Sediment consolidation also has a pronounced impact on the solids concentrations that are erodible and entrained by this type of dredge (Ke et al. 2016).

Figure 22
Differential Head Operating Principal of a Siphon Dredge



Source: Morris and Fan 1998

Innovations to the siphon dredge have reduced the severity of these impacts. One example of these modified siphon (hydrosuction) dredges is shown in Figure 23, in which a specially designed (and patented) suction head reportedly ensures continuous high sediment removal capacity and low water consumption. This dredge uses a water jetting array (Figure 24) to reportedly dredge a wide range of sediments, from cohesive clay and organic material to gravel and stones up to 14 inches (350 mm). A demonstration project in Guatemala showed successful removal of reservoir sediments ranging from silt to pieces of wood and stones up to 11 inches (280 mm) in size. The calculated capacity of the dredge was verified, as was the ability to produce a continuous high production with high suction capacity and low water consumption.

The typical average capacity for this type of dredge ranges from 65 CY/hr (50 m^3/hr) cohesive sediments for 8-inch (200-mm) dredges to up to 1,300 CY/hr (1,000 m^3/hr) for sandy materials dredged with a 20-inch (500-mm) dredge. For more details on this demonstration project, refer to SediCon (2016).

Figure 23
Modified Hydrosuction Dredge in Operation

Source: SediCon, available at: https://sedicon.no/wp-content/uploads/2017/09/01-Sedicon-Brochure-2016.pdf

Figure 24
Modified Hydrosuction Water Jetting Array

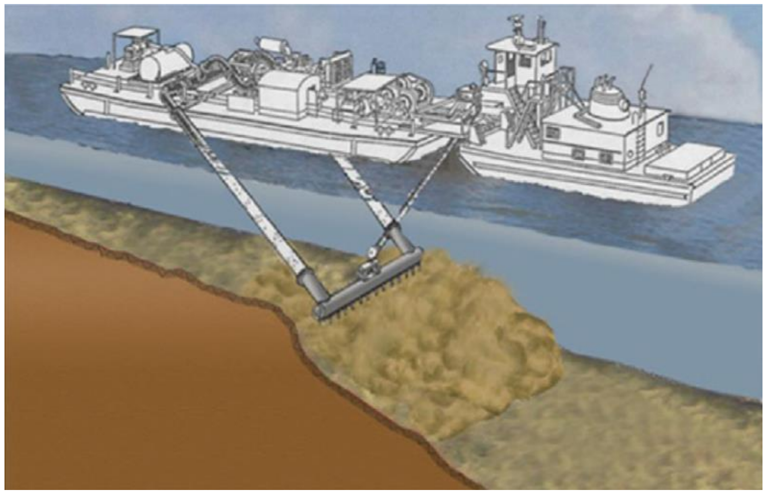
Source: SediCon, available at: https://sedicon.no/wp-content/uploads/2017/09/01-Sedicon-Brochure-2016.pdf

Water Injection Dredge: The water injection dredge (WID) is a dredging technique primarily used in navigation dredging in which a dredge vessel pumps water into channel bottom sediments at low pressure and relatively high-volume flow rates. This dilutes and fluidizes the sediments, creating a near-bottom layer (density current) with higher density than the surrounding water. This layer is then transported downslope by gravity to deeper water. In suitable conditions, the created density current remains relatively close to the waterbody bottom. The WID density current does not absolutely require a sloping bottom to flow, but a slope can assist the density current in a manner that can be likened to an underwater avalanche. Figure 25 presents an illustration of the WID concept.

Under the right conditions, WID can be a cost-effective alternative for removing fine-grained (soft) sediments without requiring dredged material transport equipment or a placement site. Compared to cutterhead and hopper dredges, the WID requires less personnel and with the right conditions is capable of achieving extremely high production rates (Welp et al. 2017). Bronsvoort (2013) investigated reservoir sedimentation management options and the possibility of implementing WID to generate a density current and thereby transport sediment to the dead storage of a reservoir or pass through an opened low-elevation discharge conduit (outlet).

Although WID has not seen large-scale application to reservoir projects, the Kansas Water Office (KWO), in partnership with the USACE Kansas City District and the Engineer Research and Development Center (ERDC) Dredging Operations and Environmental Research (DOER) program, are currently conducting planning to implement a WID demonstration project at Tuttle Creek Lake (Kansas) to promote sustainable long-term reservoir sediment management. With a historical sedimentation rate of nearly 3,800 ac-ft/yr (4.7 million m^3/year), Tuttle Creek Lake has lost approximately 48% of its original multi-purpose pool storage to sedimentation and created a significant sediment deficit downstream. Tuttle Creek Lake is the primary source of water supply to a variety of users in the Kansas River Basin, including three major municipal water suppliers with direct surface water intakes in the Kansas River. Water quality in the Kansas River is highly variable due to periodic high runoff events from large, unregulated tributary flows. Water suppliers employ sophisticated water treatment processes to deal with solids and nutrients present in the system under regular reservoir operations. These treatment processes, as well as ecological impacts, have been a focus in the planning and monitoring considerations for the demonstration. For more information on this initiative, see KWO (2018).

Figure 25
Illustration of Sediment Being Transported in a Density Current Generated by a WID



Source: Welp et al. 2017

6.5 Innovative Approaches for Dredge Portability and Footprint Reduction

Another area where technical innovation stands to provide significant benefits to reservoir dredging is the development of portable dredging equipment, which can be readily transported to the project site and set up for operation—particularly for remote or difficult to access locations. Some dredging equipment has been developed for increased portability, utilizing a self-launching or "amphibious" capability (see example in Figure 26), although these tend to be limited in capacity.

Figure 26
Example of Self-Launching "Portable" Dredge Equipment

Source: Amphibex/Normrock

6.6 Innovative Approaches for Sediment Capture (before entering reservoir)

There is also value in developing methods to reduce sediment entry into reservoirs before the material needs to be dredged at all. As an example, bedload interceptor technologies (BI-T) are emerging as alternative sediment management methods that are being installed in an increasing number of sediment management applications to reduce dredging requirements, restore flood carrying capacity, and harvest sand commercially.

BI-T systems use a structure of some configuration (hopper, bin, pit, trough, etc.) installed directly on the bottom of a waterbody to intercept and collect bed load sediment (sand, gravel, and cobble) as it is being transported by the river's current. The collected sediment is transported in various manners either to a deposition location or a re-handling facility.

Figure 27 shows an example of a BI-T sediment collector installed in Fountain Creek in Pueblo, Colorado, that was pumped ashore, at the natural transport rate for bedload sediment, to a sediment re-handling plant (Thomas et al. 2017). BI-T could potentially be used to address the coarse-grained fraction of sediment that forms in the reservoir's delta by being located either upstream in the river or in the lake's delta proper. bedload removal rates between 0.2 and 1 yd^3/hr (0.1 and 0.9 m^3/hr) were demonstrated with a 2-ft wide (0.6-m wide) collector with potential removal rates between 3 and 17 yd^3/hr (2 and 13 m3/hr) for a 30-ft wide (9-m wide) collector.

A small-scale BI-T was installed in the South Platte River in Colorado, located upstream of the Strontia Springs Reservoir and operated in a proof-of-concept demonstration in September 2019. Figure 28 shows photographs of a 2-foot (60-cm) collector deployed in the South Platte River illustrating how sand and gravel is intercepted and collected prior to being pumped ashore and measured in time trials to estimate production rates relative to the river's flow rate. Based on a two day sample collection period with the river discharge averaging 139 ft^3/s (3.9 m^3/s) , it was estimated that a 30 ft (9 m) long collector could harvest 0.75 CY/hr (0.6 m^3/hr).

Figure 27
BI-T Collector Installed in Fountain Creek, Pueblo, Colorado, and Shore Sediment Re-Handling Plant

Source: Streamside Systems LLC

Figure 28
Small-Scale BI-T Deployed in a Proof-of-Concept Demonstration Upstream of the Strontia Springs Reservoir

Sand and gravel being deposited into a collector prior to being pumped to shore and volumetrically measured in production time trials
Source: Streamside Systems LLC

6.7 Opportunities for Development of New Technologies

The U.S. Bureau of Reclamation and USACE have a high level of interest in encouraging further technological innovation toward sustainable approaches to reservoir sediment removal. In 2018, stage 1 of a research prize competition was held, seeking ideas for the collection of sediment from the reservoir bottom, moving sediment from the collection site to the disposal site, and delivering sediments to the downstream channel. Of the 40 potential solutions received, six winners shared $75,000 in prize money.

The four top winning solutions are as follows:

- Transport of coarse sediments through a hydraulic capsule pipeline
- Transport of cohesive sediments as compressed sediment logs through a pressurized pipeline
- Submersible robotic “Sediment Snake” for collecting reservoir sediments
- Use of flexible augers to transport coarse sediment

The two second-tier winning solutions are as follows:

- CryoDredger utilizing inert liquid nitrogen
- Collect reservoir sediments using adapted electro-coagulation methods

Beginning in 2020, a second and larger prize competition was initiated called Guardians of the Reservoir Challenge. The goal of this challenge is to develop and demonstrate new processes and technologies that will collect and transport sediment from reservoirs at a rate that sustains their current capacity. The authors of the most compelling submissions have the opportunity to develop and demonstrate their technologies at increasing scales with up to $550,000 in prize money shared among the winners. The U.S. Bureau of Reclamation is conducting this prize competition in partnership with the USACE, NASA Tournament Lab, and HeroX.

In December 2020, five projects each received $75,000 through phase one of the Guardians of the Reservoir Challenge. The five winning projects move to phase two, where solvers continue developing their solutions and perform a laboratory-scale demonstration of their ideas.

The winning submissions are as follows:

- Wing Marine Team composed of Doug Thompson, John Crowson, Mel Friedman, Peter Crossland, Bryan Longhurst, James Coats, and Joel Friedman, Texas, A Cure for Ailing Reservoirs
- Nicholas LaBry and Kenneth LaBry of Prometheus Innovations, LLC, and Bartolomeo Mongiardino of Hydro Maintenance Service, Louisiana, The 3 D DREDGER™: Complete Sediment Management
- Dr. Peter Murdoch and Dr. John Newport, Pennsylvania, Air Bubble Suction Pipe with Water Recirculation
- Baha Abulnaga, Washington, High Volume Deep Dredging for Low Water De-silting
- Dr. Michael Detering, Laura Backes, and Joana Kueppers, Germany, Sediment Continuity and Restoration

For more details on both innovation prize competitions and their results, consult U.S. Bureau of Reclamation (2019 and 2020).

7 Conclusions and Final Take-Away Message

The ongoing accumulation of sediment in reservoirs is a problem that is continuing to develop across the United States and at a worldwide scale. Although the issue has been long recognized, agencies and water managers have often not been in position to apply the necessary energy and funding to successfully address it.

Furthermore, while many potential means exist for managing or reducing sediment in reservoirs, dredging (either mechanically or hydraulically) remains a well-established and practical technology, whose role in sediment management is integral to attempts to manage the issue. While dredging is perceived by some as a costly option, a comparison with other alternatives may very well show that dredging is cost-competitive.

This report has presented detail on the nature of available dredging technologies, both those that have been used for decades and some newer improvements and innovations. The dredging industry is encouraged to continue advancing toward further optimization of the dredging and sediment transport processes, as market conditions are likely to demand and implicitly drive such innovation as the need for sediment removal increases in the future.

Another challenge that dredging faces is the navigation of a host of federal, state, and local permits. While the permit process is complex, it represents environmental necessities and protections that have a rightful place in project planning within the nation's waterways. It may be that regulations can be streamlined in the future, but the dredging industry is of course best of to work diligently in a timely fashion, within existing mandates and constraints to develop more efficient and economic techniques that will deliver more comprehensive, economic and environmentally beneficial methodologies/solutions to this concern.

The challenges of dredging are offset by the critical and urgent nature of the endeavor, and the fundamental role that healthy reservoirs play in the nation's water supply and power-generating infrastructure. Just as comprehensive national efforts are needed to address the problem of deteriorating roads, bridges, pipelines, and other infrastructure, so too must the growing problem of sediment accumulation in reservoirs become an important priority at the national, state, and regional levels. This will require a commitment not only to fund and permit the necessary work, but the political initiative to rally support for the hard work of reservoir dredging and sediment management. Ultimately, reservoir sedimentation and its solutions are a regional issue with broader implications at the state and national levels. Comprehensive plans to strategize dredging efforts and manage sediment (in both inland reservoirs and in coastal settings) include such collaborative efforts as the State of Kansas Reservoir Sustainability Initiative (KWO 2009), the Verde Reservoirs Sediment Mitigation Study (USBR and SRP, 2020), and the Los Angeles County Regional Dredged Material Management Plan (USACE et al., 2002). It is the hope of the authors that this report will not only inform others on the current state of dredging as applied to reservoirs but also help spur interest, urgency, innovation, and optimization in terms of dredging cost, environmental effectiveness, and overall public benefit.

8 References

ACWI and SOS (Advisory Committee on Water Information and Subcommittee on Sedimentation), 2014. *Resolution on Reservoir Sustainability.* Accessed January 11, 2021. Available at: https://acwi.gov/sos/.

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.

ASDSO (Association of State Dam Safety Officials), 2020. *Spencer Dam Failure Investigation Report*. April 2020.

Bronsvoort, K., 2013. *Sedimentation in Reservoirs: Investigating Reservoir Preservation options and the Possibility of Implementing water Injection Dredging in Reservoirs.* Master's thesis, Delft University of Technology.

Brune, G.N., 1953. *Trap Efficiency of Reservoirs.* Transactions of the American Geophysical Union, vol. 34, no. 3.

Graf, W. L., E. Wohl, T. Sinha, and J. L. Sabo, 2010. *Sedimentation and Sustainability of Wwestern American Reservoirs.* Water Resources Research., 46, W12535, doi:10.1029/2009WR008836.

Hotchkiss, R.H., and X. Huang, 1995. *Hydrosuction sediment-removal systems (HSRS): Principles and field test.* Journal of Hydraulic Engineering, American Society of Civil Engineers (ASCE). 10.1061/(ASCE)0733-9429(1995)121:6(479), 479–489.

Ke, W., Chen, Y., Hsu, H., Toigo, K., Weng, W., Capart, H., 2016. *Influence of sediment consolidation on hydrosuction performance.* Journal of Hydraulic Engineering, ASCE. 04016037-1.

KWO (Kansas Water Office), 2009. *Reservoir Sustainability Initiative*, presented to U.S. Army Corps of Engineers Institute for Water Resources, Water Supply Workshop. June 2-4, 2009. Available at https://www.iwr.usace.army.mil/Portals/70/docs/CleanWaterSupplyWorkshop/Kansas%20WaterSupplyWorkshop_060309_sm.pdf.

KWO, 2018. *Water Injection Dredging Study & Demonstration at Tuttle Creek Lake.* Available at https://kwo.ks.gov/projects/water-injection-dredging-(wid)-study-demonstration-at-tuttle-creek-lake.

Kawashima, S., 2007. *Conserving reservoir water storage: An economic appraisal.* Water Resources Research 43, WO5417. Available at: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2006WR005090#:~:text=Under%20the%20scale%20economy%20dredging,of%20sediment%20removed%20per%20event.

Kondolf, G.M., Y. Gao, G.W. Annandale, G.L. Morris, E. Jiang, J. Zhang, Y. Cao, P. Carling, K. Fu, Q. Guo, R. Hotchkiss, C. Peteuil, T. Sumi, H.W. Wang, Z. Wang, Z. Wei, B. Wu, C. Wu, and C.T. Yang, 2014. *Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents*. Earth's Future 2(5). DOI:10.1002/2013EF000184.

Kondolf, G. M., 1997. Hungry Water: Effects of Dams and Gravel Mining on River Channels. Environmental Management, 21(4), 533–551.

Leech, J. R., and Biedenharn, D., 2012. *Sediment Management at the Watershed Level*. ERDC/CHL CHETN-VII-12, U.S. Army Corps of Engineers, Engineer Research Development Center (ERDC), Vicksburg, MS.

Morris, G.L., and J. Fan, 1998. *Reservoir Sedimentation Handbook*. Available at: https://reservoirsedimentation.com/. New York: McGraw-Hill Book Co.

Morris, G. L. , 2020. Classification of Management Alternatives to Combat Reservoir Sedimentation. Water, 12(3), 861.

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. Available at: https://acwi.gov/sos/pubs/dam_removal_analysis_guidelines_for_sos_final_vote_2017_12_22_508.pdf.

Randle, T., Bountry, J., Ritchie, A., Wille, K., 2015. *Large-Scale Dam Removal on the Elwha River, Washington, USA: Erosion of Reservoir Sediment. Geomorphology*. 246.10.1016/j.geomorph.2014.12.045.

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

Randle, T., G. Morris, M. Whelan, B. Baker, G. Annandale, R. Hotchkiss, P. Boyd, J.T. Minear, S. Ekren, K. Collins, M. Altinakar, J. Fripp, M. Jonas, S. Kimbrel, M. Kondolf, D. Raitt, F. Weirich, D. Eidson, J. Shelley, R. Vermeeren, D. Wegner, P. Nelson, K. Jensen, and D. Tullow, 2019. *Reservoir Sediment Management: Building a Legacy of Sustainable Water Storage Reservoirs, National Reservoir Sedimentation and Sustainability Team White Paper.* June 12, 2019. Available at: https://www.sedhyd.org/reservoir-sedimentation

Rogers, E.M., 2003. *Diffusion of Innovations, 5th Edition.* New York: Simon and Schuster.

SediCon, 2016. *Dredging product brochure*. Available at: https://sedicon.no/wp-content/uploads/2017/09/01-Sedicon-Brochure-2016.pdf.

Thomas, R., J. McArthur, D. Braatz, and T. Welp, 2017. *Sediment management methods to reduce dredging: Part 2, sediment collector technology*. DOER Technical Notes Collection. ERDC TN-DOER-T13.

Vicksburg, MS: U.S. Army Engineer Research and Development Center. Available at: https://erdc-library.erdc.dren.mil/jspui/handle/11681/22150.

USACE (U.S. Army Corps of Engineers), 1983. *Survey of Portable Hydraulic Dredges*. Technical Report HL-83-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg MS 39180

USACE, 1987a. Engineer Manual EM 1110-2-5026, *Beneficial Uses of Dredged Material*, Washington DC, June 1987. Available at: https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-5026.pdf.

USACE, 1987b. Engineer Manual EM 1110-2-5027, *Confined Disposal of Dredged Material*, Washington DC, September 1987. Available at: https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-5027.pdf.

USACE, 2015. Engineer Manual EM-1110-2-5025, *Dredging and Dredge Material Management.* Washington DC, July 2015. Available at: https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-5025.pdf.

USACE-ERDC (Engineer Research and Development Center), 2003. EL TR-03-1, *Evaluation of Dredged Material Proposed for Disposal at Island, Nearshore, or Upland Confined Disposal Facilities – Testing Manual*. Vicksburg, MS, January 2003. Available at: https://www.spn.usace.army.mil/Portals/68/docs/Dredging/guidance/trel03-1.pdf.

USACE, Anchor Environmental, and Everest International Consultants, 2002. *Los Angeles County Regional Dredged Material Management Plan Pilot Studies, Los Angeles County, California, Evaluation Report.* November 2002.

U.S. Bureau of Reclamation (USBR), 1987. *Design of Small Dams: A Water Resources Technical Publication.* Available at: https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/SmallDams.pdf.

USBR, 2019. *Reclamation selects winners of competition to develop solutions for removing sediment from reservoirs.* July 2019. Available at: https://www.usbr.gov/newsroom/stories/detail.cfm?RecordID=66923.

USBR, 2020. *Guardians of the Reservoir: Reclamation moves five ideas forward in prize competition to help improve sediment removal in reservoirs.* December 2020. Available at: https://www.usbr.gov/research/challenges/sediment-removal.html.

USBR and Salt River Project (SRP), 2020. *Salt and Verde River Reservoir System, SECURE Reservoir Operations Pilot Study, Study Report*. Available at: https://www.usbr.gov/watersmart/pilots/docs/reports/Final_Reservoir_Operations_Pilot_Report-Salt_and_Verde_Az.pdf

USEPA and USACE (U.S. Environmental Protection Agency and U.S. Army Corps of Engineers), 1998. *Evaluation of Dredged Material Proposed for Discharge in Waters of the U.S.: Testing Manual* (Inland Testing Manual), EPA-823-B-98-004, Washington DC. Available at: https://www.epa.gov/sites/production/files/2015-08/documents/inland_testing_manual_0.pdf.

USSD (U.S. Society of Dams), 2018. *USSD Resolution on Reservoir Sustainability*. Available at: Sustainable-Reservoir-Sediment-Management-Plan.pdf.

USSD, 2020. *Benefits of Dams and Levees.* June 25, 2020. Available at: https://www.ussdams.org/dam-levee-education/overview/benefits-of-dams-levees.

Welp, T.L., M.W. Tubman, D.A. Wilson, and C.E. Pollock, 2017. *Water Injection Dredging.* ERDC TN-DOER-T14. Vicksburg, MS: U.S. Army Engineer Research and Development Center. Available at: https://erdc-library.erdc.dren.mil/jspui/handle/11681/22822?mode=full.

Appendix A
Case Studies of Recent Sediment Removal Projects for Reservoirs

Case Studies of Recent Sediment Removal Projects for Reservoirs

The following sections provide an overview of selected projects involving sediment removal from U.S. reservoirs. The projects featured range greatly in size, region, ease of access, and regulatory context, so they provide a good overview of how reservoir dredging projects are typically approached. Technical details of the design and construction methods are provided, along with an overview of key elements of the permitting process required. Several other project examples are listed in Table 1 of the main text.

A.1 Strontia Springs Reservoir, Colorado

In 2011, more than 200,000 CY (more than 153,000 m^3) of sediment were dredged hydraulically from the Strontia Springs Reservoir in Waterton Canyon (South Platte River) by Denver Water. Sediment was pumped via pipelines over the dam and to a grain-size splitting area in Waterton Canyon where finer particles were scalped (physically separated) from gravels and coarse sand. Several dredging and material disposal alternatives had been studied prior to starting the dredging project; delivering the sediment directly to the river downstream of Strontia Springs Dam was viewed as unfavorable because it would require a USACE dredge and fill (Section 404) permit for impacts to the South Platte River. Similarly, development of improvements to the river upstream of the reservoir were not undertaken as they would have required a lengthy process for developing an Environmental Assessment (EA) or Environmental Impact Statement (EIS).

In the end, an EA process was not necessary, nor was an Individual Permit from the USACE. Denver Water obtained a Nationwide Permit (NWP)-16 for return water from upland contained disposal area. Other permits, including an industrial wastewater discharge permit and a certificate of disposal from the Colorado Department of Public Health and the Environment, were obtained for water being discharged at the endpoint of the pumping and treatment process. Denver Water also needed to maintain 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.

A.2 Wilde Lake, Maryland

This project involved hydraulic dredging of approximately 20,000 CY (approximately 15,000 m^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 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 Maryland Department of the Environment, its Dam Safety division, and the USACE (Baltimore Division). 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.

A.3 Lake Decatur, Illinois

The City of Decatur, Illinois, led this project involving hydraulic dredging of 10.5 million CY (8 million m^3) of sediment to increase the overall water holding capacity of Lake Decatur the lake 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 (more than 800 meters) away, with discharge of return water from the Oakley Basin contained disposal area.

A 404 permit application was submitted to the USACE, as well as 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 (61-meter) wide buffer area for mapped forested wetlands areas. Elsewhere, dredging was kept 25 feet (7.5 meters) away from the shoreline and was required to avoid any emergent wetlands areas. Temporary impacts to water quality were anticipated due to resuspended 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 submitted July 21, 2014.

No additional biological characterization was required for the downstream (un-named) tributary.

A.4 Conestoga Reservoir, Nebraska

Consistent with National Environmental Policy Act (NEPA), the USACE (Omaha District) completed an EA of this project, which involved a number of improvements to the Conestoga Reservoir, including removal of more than 500,000 CY (more than 380,000 m^3) of sediment, in-lake regrading, 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 NEPA EA/Finding of No Significant Impact (FONSI) was prepared, and an EIS was not required.

The project qualified for Nationwide Permit 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.

A.5 John Redmond Reservoir, Kansas

The John Redmond Reservoir is in the process of a multi-phase effort involving the removal and disposal of 3 million CY (2.3 million m^3) of sediment, along with shoreline and streambank improvements. The purpose of the sediment removal is to restore water supply capacity in the reservoir while also improving related aquatic habitat.

Permitting sediment removal for this reservoir was unique because it required a Section 408 USACE permit because the project is being implemented within a federal reservoir by a non-federal party (the KWO). This project was, in fact, the largest Section 408 request for an inland waterbody to date and was influential in the USACE's efforts to streamline the Section 408 permitting process.

The NEPA process, involving development of a programmatic EIS covering the project over several phases, was carried out 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 dredge.

As part of the first phase of work, sediment disposal took place via hydraulic pumping to various upland confined disposal sites (CDFs), intended to be returned to farmland after sediment placement. Creation of the upland disposal areas 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 encompasses approximately 600,000 CY (460,000 m^3) of sediment removal.

Future phases will be advanced as funding is available. Further consideration of approval for additional sediment removal, and use of additional CDFs, will be evaluated in future and tiered environmental analyses under NEPA, consistent with the programmatic EIS.

A.6 Devil's Gate and Pacoima Reservoirs (among others) – Los Angeles, California

The Los Angeles County Public Works and Flood Control District conducts regular sediment removal operations at a number of dammed reservoirs and retention basins in order 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 input events (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 County as "flow-assisted sediment transport" [FAST]).

The Flood Control District's sediment management operations are authorized by a Section 401 permit from the California Regional Water Quality Control Board, 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 a burst 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 EIR 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 public and between agencies. Formulation of the joint document typically required approximately 1 year, followed by a 60-day public comment period and final certification and decision.