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Coastal and Hydraulics Laboratory

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Sustainable Sediment Management at US Army Corps of Engineers Reservoirs

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Abstract

The US Army Corps of Engineers (USACE) maintains and operates 419 reservoirs nationwide for diverse purposes. This infrastructure is essential to the nation's continued economic progress and provides numerous benefits. Sedimentation in reservoirs causes the loss of storage capacity, leading to interference with operations, reduction of project benefits, and eventual rendering of project operation technically infeasible or uneconomical. All reservoirs trap sediment, and sustainable long-term operation can be achieved only if sedimentation is managed. With many of the USACE reservoirs now reaching 50 years of age, sedimentation is starting to encroach on the beneficial pools. Under the paradigm of sustainable use, it is important to identify and implement strategies to sustain reservoir operation in the long term, beyond the period contemplated in the original project design life.

This report outlines the major types of sediment management strategies available for reservoirs. Because the rate of new reservoir construction by USACE is very low, this report focuses on remedial strategies at existing reservoirs and presents a general methodology for the preliminary analysis of such sites. This report examines four example USACE reservoirs with known sedimentation issues to highlight the types of problems encountered and the development of strategies that can lead to sustainable use.

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Preface

This study was conducted for the US Army Corps of Engineers under Funding Account Code U4381209; AMSCO Code 031398.

The work was performed by GLM Engineering COOP and the River and Estuarine Engineering Branch of the Flood and Storm Protection Division, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory (ERDC-CHL). At the time of publication of this report, Mr. Casey Mayne was acting chief, River and Estuarine Engineering Branch; Dr. Cary A. Talbot was chief, Flood and Storm Protection Division; and Dr. Julie D. Rosati was the technical director for Flood and Coastal Storm Protection. The deputy director of ERDC-CHL was Mr. Keith Flowers, and Dr. Ty V. Wamsley was the director.

Mr. Chris Shultz and Ms. Cara Hendricks of the Kansas Water Office and Mr. Greg Estep of the US Army Corps of Engineers (USACE), Tulsa District, provided feedback on the John Redmond Reservoir case study. Ms. Kim Gilbert and Dr. Moosub Eom of the USACE Los Angeles District reviewed the Prado Reservoir case study and provided updated information. Ms. Julia Fritz of the USACE Baltimore District provided feedback on the Jennings Randolph case study. Mr. Dan Pridal and Dr. Paul Boyd of the USACE Omaha District and Mr. Jon Remus of the USACE Northwestern Division reviewed and updated the Lewis and Clark Lake and Gavins Point Dam case study. Dr. Heidi Wadman provided information on the use of sub-bottom profilers.

The commander of ERDC was COL Christian Patterson, and the director was Dr. David W. Pittman.

1 Introduction

1.1 Background

Dams interrupt the flow of both water and sediment along a river. Flow velocity drops when flow enters the impoundment, allowing sediments to settle and displace storage capacity. In contrast, the channel below the dam becomes sediment starved, which can produce impacts including channel incision, bank erosion, and loss of ecological habitat.

The fluvial system will eventually restore the sediment balance across the impounded reach after the reservoir becomes completely filled. Active sediment management seeks to bring sediment inflow and discharge into balance while maximizing storage long-term capacity and other benefits and minimizing environmental harm. This concept is illustrated in Figure 1.

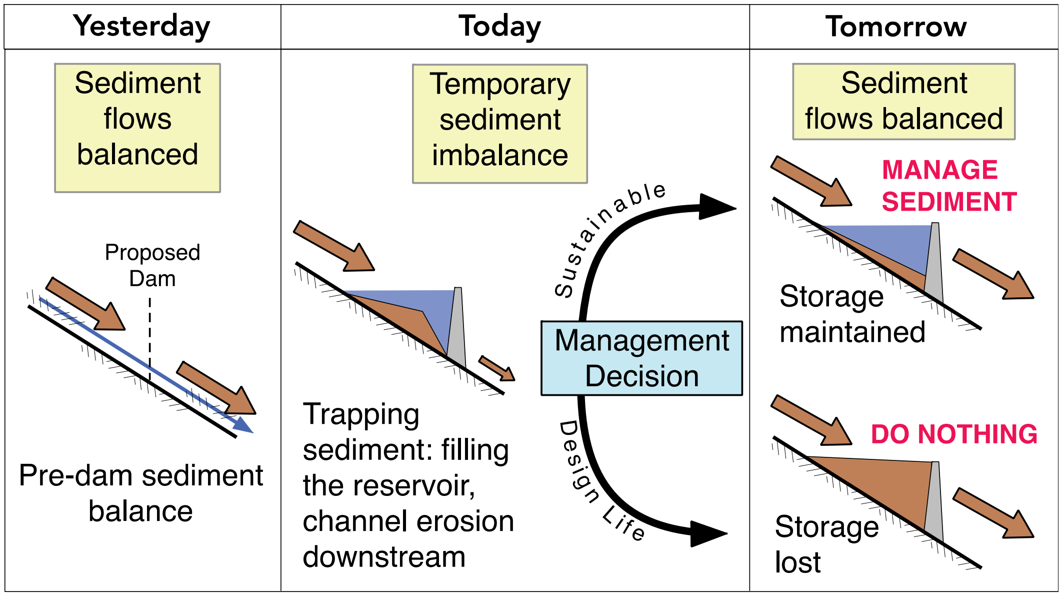

Figure 1. Reservoir construction creates a temporary sediment imbalance along a river. Absent management, that balance will be restored by natural processes after the reservoir fills with sediment. The sustainable use paradigm seeks to manage the reservoir in a way that re-establishes the sediment balance while preserving usable storage.

The US Army Corps of Engineers (USACE) manages and operates 419 dams and reservoirs with active water storage requirements[1], including 24% of the nation's hydropower capacity. These facilities represent critical infrastructure needed to sustain a wide range of economic and social benefits nationwide. USACE projects have an assigned *design life*, an artificial time frame established during project planning that serves as a boundary for certain contractual obligations and management objectives. Consistent with twentieth century engineering practice, most USACE storage reservoirs were designed to include a sediment storage (or inactive) pool sufficient for, typically, 50 to 100 yr[2] of sediment storage.

However, most of the USACE dam and reservoir projects have passed their original 50 yr planning lives and are entering a phase of long-term maintenance and modification (USACE-IWR 2016). USACE reservoirs have generally functioned as planned, and relatively few sites are experiencing problems due to greatly accelerated sedimentation rates. However, project age and continuing sediment inflows, increasingly focused in beneficial pools as the designated sediment pools fill, make it necessary to address the challenge of long-term sediment management. Many reservoirs are starting to experience significant displacement of beneficial pool capacity and other sedimentation impacts not addressed by the original designers but which must now be resolved to sustain long-term operations and limit adverse impacts to third parties and the environment, both upstream and downstream of the reservoir.

To transition from the design-life to the sustainable-use paradigm requires a shift in design and operational strategies for dams and reservoirs and will require the development and application of active sediment management strategies not previously employed in US reservoirs. This report outlines design and operational strategies that can support the transition of existing infrastructure to long-term sustainable use.

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[1] There are 419 Water Control Manuals for projects owned and operated by the USACE with active storage management requirements.

[2] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

1.1.1 Sedimentation problems at US Army Corps of Engineers (USACE) reservoirs

Many regions in the country have come to depend on USACE reservoir projects to manage the risks of flooding, ensure reliable supplies of water for public health and economic production, generate clean and affordable electricity, provide safe and enriching opportunities for water-based recreation to the public, and maintain adequate levels of streamflow to support navigation and commerce on the inland waterways, aquatic and wildlife habitat, and water quality.

In 2016, the USACE Institute of Water Resources submitted questionnaires to ascertain the current status and identify challenges potentially impairing the ability of reservoirs to consistently and sustainably deliver their vital services to the nation. With respect to sedimentation, the following conclusions were obtained:

- Only 15 of the 353 positive responses showed the gross pool or the conservation pool as having a sediment accumulation of greater than 25% of original volume.
- Overall, 97 of the 378 projects surveyed (26%) indicated that project operations for one or more purposes were restricted by some degree due to sedimentation.
- 60% of the operating restrictions reported were submitted by two districts: Tulsa and Omaha.

Clearly, sedimentation is not yet considered a severe problem at most USACE reservoirs, but the fact that 26% of the projects already report some degree of impact is indicative of a problem that is already present, is growing, and can be expected to become severe. Some reservoirs can expect severe consequences during upcoming decades, while others may escape severe problems until beyond the twenty-first century. This underscores the need to better quantify the problem, to identify sites with the most critical emerging problems and consequences, and to start addressing this emerging problem on a proactive basis.

1.1.2 Concepts of sustainable reservoir use

The concept of sustainability was popularized in the 1987 report to the United Nations by the World Commission on Environment and Development, which focused on long-term rights of and our obligations to future generations by stating the following: "Humanity has the ability to make development sustainable—to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs." The USACE considers sustainability one of its missions (USACE 2020). The USACE "strives to protect, sustain, and improve the natural and man-made environment of our Nation…Sustainability is not only a natural part of the Corps' decision processes, it is part of the culture."

Unlike other engineering infrastructure that can be rebuilt when they suffer from obsolescence, once a reservoir fills with sediment, the site loses its utility, even if the dam remains fully functional. Although the hydrologic cycle is renewable, reservoir storage capacity is not renewable. Morris and Fan (1998) described this unique non-renewable nature of dams and reservoirs and predicted "Whereas the twentieth century focused on the construction of new dams, the twenty-first century will necessarily focus on combating sedimentation to extend the life of existing infrastructure."

Absent sediment management, all reservoirs are subject to obsolescence by sedimentation. The need to change the paradigm for reservoir management from the traditional design life approach to a long-term sustainability approach is increasingly being recognized. The August 2014 resolution adopted by the Federal Advisory Committee on Water Information

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

> activities should also be identified. (Advisory Committee on Water Information 2014)
>
> In this instance, the term *retirement* means either leaving the dam in a safe condition or removing it outright. A similar resolution was adopted in 2017 by the US Society on Dams, which "encourages all dam owners to develop long-term reservoir sediment-management plans for the reservoirs that they own or manage by 2030." (USSD 2018)

Although 50 to 100 yr of sediment accumulation are considered at the design stage, there is currently no policy to periodically update sediment management plans. Sustained use requires that project plans and operations be regularly updated to reflect the long-term perspective needed to manage essential hydraulic infrastructure. Sustainable long-term benefits may differ in both type and magnitude from the project's original purpose because at many sites it may not be feasible to sustain the full original capacity. However, long-term operation will not always be economically and environmentally feasible; in some cases, decommissioning will be the appropriate action, and this option should always be considered as an alternative. In some cases, decommissioning may in fact be a viable alternative, but in other cases the consequences of project loss (decommissioning) may be so dire that it will highlight the need to undertake aggressive action to preserve reservoir capacity.

1.2 Study objective

The objective of this study is to outline the types of sedimentation problems that may be expected to impact USACE reservoirs, identifying management strategies and data needs that can help sustain long-term benefits.

1.3 Approach

This study addresses four main topic areas:

1. Problem description. Describe the types of sediment problems affecting USACE reservoirs today and anticipated in the future.
2. Management options. Outline sediment management strategies for reservoirs.

3. Data availability and needs. Discuss data needed to evaluate and monitor conditions at existing reservoirs and to develop sustainable management strategies.
4. Example reservoirs. Four reservoirs were selected for site visits by reference to data received in the 2008 reservoir sedimentation data call for USACE reservoirs, selecting sites representative of different geographic regions and hydrologic environments and reported to have significant sedimentation issues. Data from each of these sites have been used in preparing a preliminary analysis and recommendations, identifying sediment management strategies and limitations relevant to each site. Recommendations given at each specific site should be understood as conceptual in nature until supported by more detailed data and analysis.

Sediment management is a complex topic, and this document provides only an overview of basic concepts. There is today a large and growing literature on reservoir sedimentation, consequences, and management that is readily accessible via the internet. Publications giving an overview of management strategies include Morris and Fan (1998), Basson and Rooseboom (1999), Annandale et al. (2016), Morris (2020), and Xiaoqing (2003). Publications cited elsewhere in this text provide greater detail on specific topics.

2 Reservoir Sedimentation Processes

2.1 Sediment concepts

Most sediment that accumulates in reservoirs is transported by water. Contributions from landslides around the sides of the reservoir, plus airborne sediment, are almost always negligible in comparison to fluvial sediment inputs. Rivers transport a wide range of particle sizes into reservoirs, mostly during floods. In steep mountain rivers, the sediments are normally coarse, and the bed material may consist of gravel and cobbles while farther downstream, the river slope flattens and the sediment size being transported diminishes. An understanding of sediment transport and characteristics particular to each reservoir and its watershed and fluvial environment is the starting point for identifying potential management strategies.

The sediment that comprises the bed of the river is termed *bed material*. Sediment may be transported as *bed load*, consisting of particles that move along the stream bed by a rolling or jumping motion. However, in most rivers, the main transport process is *suspended load*, consisting of sand or fines sustained in the water column by turbulence, without depending on bouncing or other interactions with the river bed. Sand-sized bed material may be transported as either bed load or suspended load, depending on the flow velocity. The *total load* includes all sediment transported by the river, including both bed and suspended load. Due to measurement difficulties, field data for bed load transport rates are rarely available and are therefore typically estimated as a percentage of the suspended load. Sediment grain sizes and nomenclature are given in Table 1.

Table 1. Sediment size classification.

Size Class	Description	Diameter (microns/µ)	Diameter (mm)
Clay	Fine, cohesive	0.24–2 µ	0.00024–0.002
Silt	Fine, non-cohesive	2–62 µ	0.002–0.062
Sand	Coarse, retained on #230 ASTM Sieve	62–2000 µ	0.062–2
Gravel	Coarse		2–64
Cobble	Coarse		64–256
Boulder	Coarse		256–4096

Sediment particles larger than clay may be conceptualized as rocks that have been broken down into successively smaller particles. The behavior of individual grains is controlled by gravitational forces. However, clays consist of flattened mineral platelets created from the chemical weathering of rock, individual particles being typically smaller than 2 µ. Their small size and geometry give clays a very large surface area in relation to their mass. As a result, their behavior is controlled by electrostatic and van der Waals surface forces rather than gravitational forces.

Surface forces cause clay particles to stick together, making it a *cohesive sediment*. In water, this cohesion causes clays to act differently than the larger, noncohesive sediments. For example, a sand particle may stop moving along a streambed when the flow velocity decreases, but when the original velocity is reestablished, the particle will begin moving again. In contrast, once a clay particle drops out of suspension and adheres to the bottom, it may be necessary for the flow velocity to increase by an order of magnitude to strip the clay particle away from the bed to reinitiate motion. In suspension, clay particles will normally adhere to one another when brought together by turbulence, agglomerating into larger flocs that settle at velocities characteristic of much larger silt particles. These differences in particle behavior have implications for sedimentation behavior, and sampling and management strategies.

2.2 Delta deposits

A highly generalized longitudinal diagram of reservoir sedimentation patterns is shown in Figure 2. Based on hundreds of reservoir surveys, Ferrari (2006a) noted that most sediment inflow tends to deposit either in the delta (coarse sediment) or along the reservoir thalweg (fine sediment). This typically creates a flat bottom within each cross section, filling the reservoir with sediment from the bottom up while the amount of sediment deposited on submerged side slopes is typically very limited, as seen in Figure 3.

Figure 2. Generalized longitudinal pattern of reservoir sedimentation. Deposition patterns in individual reservoirs vary considerably, and some of the features shown here may be absent.

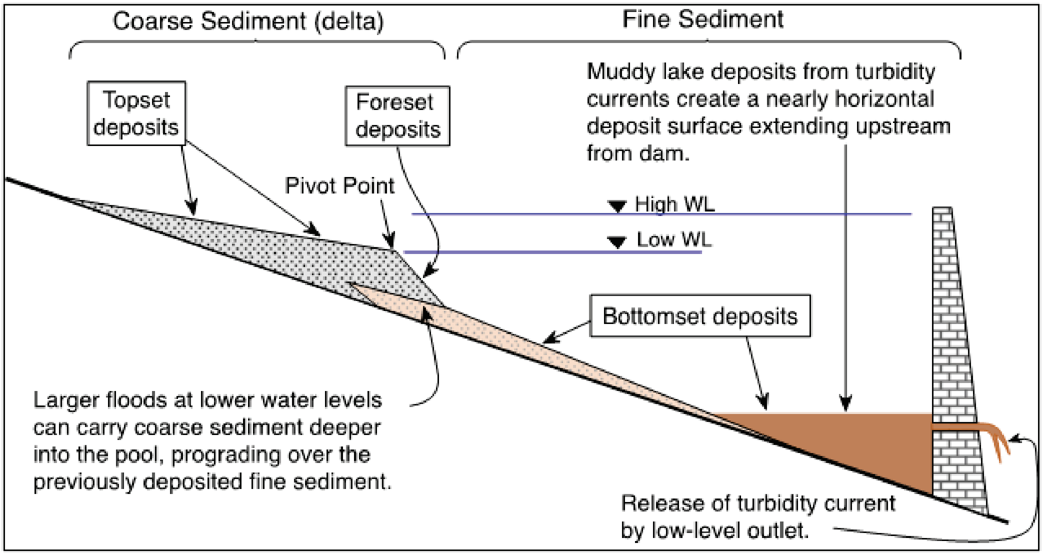
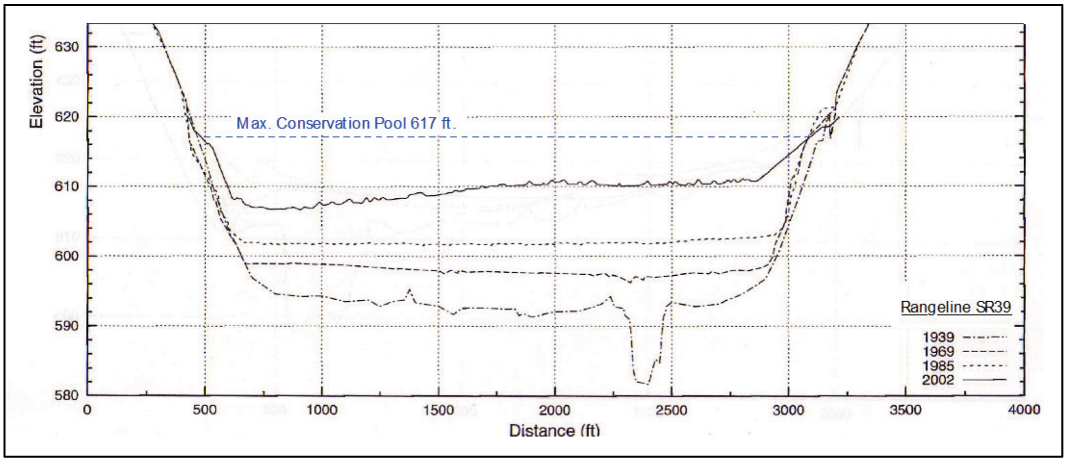


Figure 3. Successive cross-section plots in Texoma reservoir showing infilling to create essentially level sediment surfaces (Austin et al. 2003).



Coarser sediments settle rapidly as soon as they enter the reservoir to create delta deposits. On steep mountain streams, delta deposits may be dominated by coarse gravels, but on low-gradient streams, deltas may consist of fine sands and coarse silts. The downstream limit of the delta is distinguished by a rapid change in grain size, and it is also usually associated with a change in slope. However, not all reservoirs will have readily identifiable deltas (Fan and Morris 1992).

In some reservoirs, most sediment is deposited in the delta, though more typically the delta, with its coarse sediment, represents only a small fraction of the total sediment volume. The delta is typically the first visible sign of sedimentation as it emerges into plain sight during reservoir drawdown. Fine sediment is deposited into the deeper pool beyond the delta, underwater and out of sight.

During reservoir drawdown, delta deposits can also be scoured and transported deeper into the reservoir, accelerating delta advance toward the dam and intake. When the reservoir is drawn down to a similar level each year, most deposition will occur on the face of the delta, moving it toward the outlet with very little vertical growth. However, if the minimum drawdown level is progressively raised over the years, forward motion will be retarded, or can even be stopped, and the delta will grow vertically.

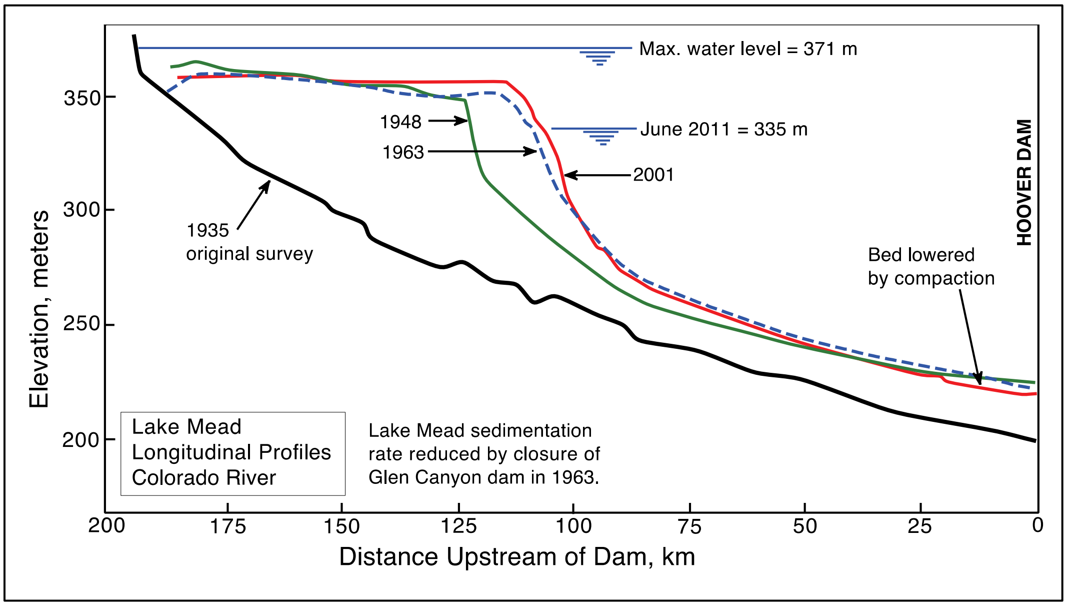
Deltas rarely extend uniformly across the entire cross section of a reservoir, and sedimentation can be focused along a meandering main channel that runs through the reservoir, similar to the way a finger of the Mississippi delta extends into the Gulf of Mexico. Even in narrower reservoirs, the tendency for more sediment to deposit along the main channel may often be observed.

Coarse delta sediment will prograde across previously deposited finer sediment as the delta extends deeper into the reservoir, as shown in Figure 2. For this reason, sediments on the top of a delta will tend to be coarser than the deeper sediments, but there is considerable local variability created over the course of multiple deposition and scour events. Delta deposits can exhibit alternating lenses of coarse and fine sediment, responding to alternating periods of flood that transport larger sediment and low flow periods that deposit only fines and organic detritus.

Deltas typically have a high sand content, creating a variety of problems when the delta face reaches the dam or intake. Sediment may be entrained into hydropower or other intake structures, causing severe abrasion damage to turbines, pumps, and valves. At sites where outlet works are not designed to pass abrasive sediment, this can cause abrasion of structure components such as low level outlets and spillway flip buckets. To the extent that fine sediments can be released downstream by venting turbidity currents or by sluicing, this will create more room for the delta and will retard arrival of the delta and its abrasive sediment at the dam or intake.

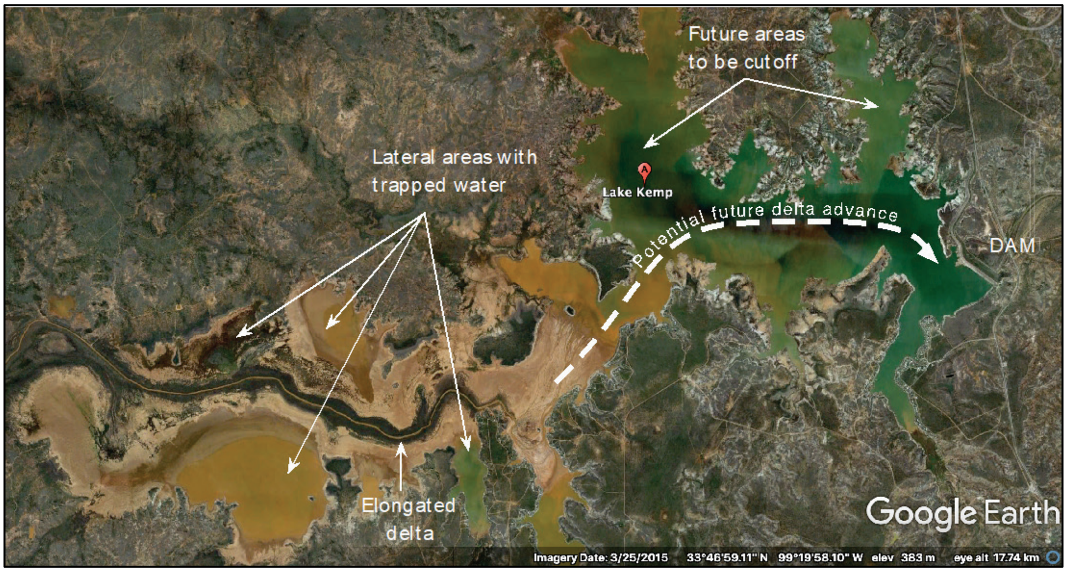
The upstream reach of reservoirs is narrow and shallow, and longitudinal profiles will initially show rapid delta advancement. However, the rate of advance will decline as the delta encroaches into progressively deeper areas of the reservoir having greater volume, and the rate of delta advance will decline even though the rate of volume loss is unchanged. This is apparent in the profiles for Lake Mead (Figure 4) showing rapid advance in the delta during the first 13 yr of impounding, but a much slower advance during the next 15 yr. Turbidity current inflows were also important in Lake Mead, carrying fine sediment all the way to the dam. Most of the sediment supply was cut off after 1963 due to construction of Glenn Canyon dam upstream, which trapped the sediment, largely halting both delta growth and turbidity current formation in Lake Mead. Looking again at Figure 4, it can be seen that a very small advance in the delta has occurred since 1963, but the surface elevation of the fine sediment deposits closer to the dam has declined, despite inputs from lateral tributaries, indicating compaction of the fine sediments.

Figure 4. Longitudinal sedimentation profiles in Lake Mead, Colorado River, showing advancement of delta deposits and compaction of fine sediment near the dam. The closure of Glen Canyon Dam in 1963 upstream dramatically reduced sedimentation and curtailed turbidity current flows to the area near Hoover Dam, resulting in a net lowering of the sediment beds near the dam by compaction (profiles from Ferrari 2006a).



The delta advancing into a reservoir can take many shapes. At the hydrologically small Lewis and Clark reservoir, subsequently described as a case study and shown in Figure 59 and Figure 60, the delta extends across the full width of the reservoir. In contrast, in hydrologically large reservoirs the delta can grow in an elongated form, advancing toward the dam and cutting off but not infilling, lateral embayments. This pattern occurs in Lake Kemp, shown in Figure 5. When the lake level drops, the delta disconnects upstream areas of the lake from the main part of the lake, eliminating these areas for usable water supply storage even though they have not filled with sediment (Texas Water Development Board 2006).

Figure 5. Elongated delta advancing through Lake Kemp on the Wichita River, Texas, and cutting off lateral storage lobes during reservoir drawdown (Google Earth 33°44′ N lat, 99°14′ W long, dated 3/25/2015).



Other examples of delta deposition patterns that can be seen on Google Earth are listed in Table 2, illustrating the variety of shapes that can be taken by a delta as it advances toward the dam. Different delta views can be seen by looking at images on different dates, and the table lists dates with images at lower water levels that expose more of the delta.

Table 2. Reservoir delta geometries.

Name (began operation)	Location	Latitude	Longitude	Best Photo Dates
Tuttle Creek (1962)	Kansas R., USA	39°25′N	36°43′W	12/2012
Lewis & Clark (1955)	Missouri R., USA	42°51′N	97°49′W	Today*
Texoma (1944)	Texas/Oklahoma, USA	36°57′N	96°56′W	12/2014
Peligre (1956)	Artibonite R., Haiti	18°53′N	71°57′W	3/29/18 vs. 12/1985
Bhakara (1963)	Sutlej R., India	31°17′N	76°41′E	3/4/2017
Camaré (Pedregal)	Venezuela	10°52′40″N	70°09′10″W	Today **
Tarbela (1976)	Indus R., Pakistan	34°15′N	72°49′E	12/2014
Mrica (1988)	Java, Indonesia	7°23′N	109°37′E	10/4/2019
Denadai Dam	Eritrea	15°26′10″N	39°4′30″E	Fully sedimented
Guanting (1954)	Beijing, China	40°18′N	115°37′E	2/22/2013 ***

* Lewis & Clark reservoir (Gavins Point Dam), water level is maintained at nearly a constant level.

** Reservoir had filled completely with sediment before year 2000, spillway failed, and now you can see the breached dam and eroding deposits.

*** Delta deposits separate the larger upstream reservoir pool from the dam.

It is important to understand that even though the overall reservoir geometry may be complex, delta advance is typically a 1D (linear) process that transports coarse sediment toward the outlet, without infilling lateral embayments or tributaries. These lateral branches may be infilled by sediment from their own drainages, plus fine sediments that flow into deeper areas of the reservoir. As a result, the delta may reach an intake even before half of the conservation storage volume has been lost. If the reservoir is subject to extensive seasonal drawdown, sediment may reach the intake much earlier. For example, the Paonia irrigation reservoir in Colorado experienced complete intake blockage by sediment and debris before 25% of the gross capacity had been lost.

Deltas can also grow in the upstream direction as a result of reduced bed slope and backwater effects causing coarse sediment to be deposited above the maximum reservoir level. Generally, the longitudinal slope of the delta is approximately half the slope of the original river channel, but sediment transport modeling should always form the basis for any engineering opinion concerning delta evolution.

2.3 Bottomset deposits and turbidity currents

Most sediment transported by rivers and trapped in reservoirs consists of fines (silts and clays, <0.062 mm). Fine sediments are deposited downstream of the delta and tend to first infill the original stream channel, converting the reservoir floor into relatively flat sediment beds (recall Figure 3).

Large water bodies are typically stratified due to temperature differences created by solar heating of the surface layer, or by differences in temperature and sediment concentration between the inflowing and previously impounded water. With sufficient density difference, the inflowing water will remain separate from the impounded water. Temperature-induced differences can cause warm inflowing water to run along the surface of a cold water reservoir, to flow along the top of the thermocline, or for denser cold water to run along the bottom of warmer water in the reservoir (Figure 6). However, when the suspended sediment concentration is high, the density will be determined primarily by the sediment concentration. With enough sediment, even warm water will plunge and run along the bottom of a cold-water reservoir. Water density as a function of both temperature and suspended sediment concentration is given in Table 3.

Figure 6. Density currents can flow through a reservoir at different levels, but if the inflow has a high sediment concentration, with adequate reservoir depth, the density imparted by the sediment will create a turbid density current that runs along the bottom of the reservoir.

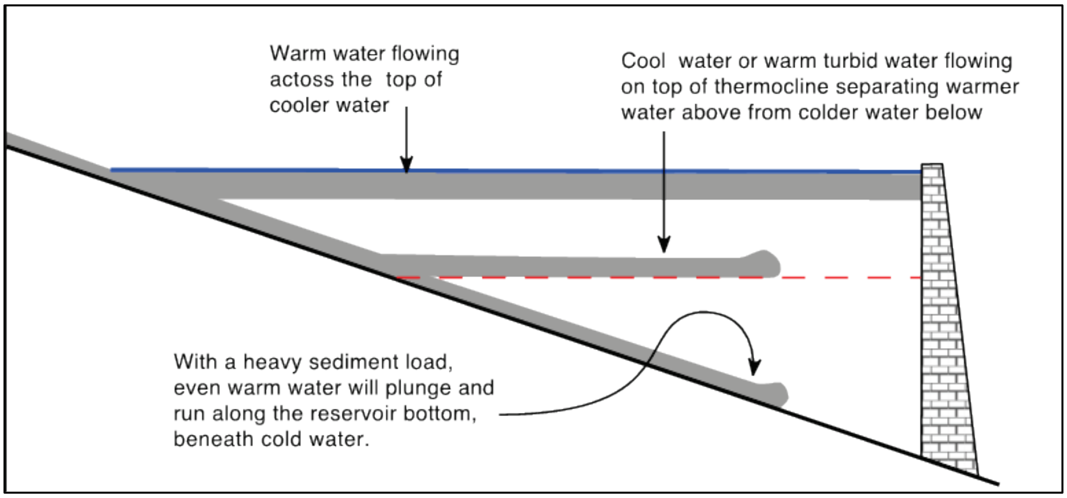


Table 3. Density of water and sediment mixtures as a function of temperature.

Temperature		Density of Pure Water, g/cm^3	Density of Water and Sediment, g/cm^3		
°C	°F		1 g/L	10 g/L	100 g/L
0	32	0.999868	1.000491	1.006095	1.062137
4	39.2	1.000000	1.000623	1.006226	1.062264
10	50	0.999728	1.000351	1.005955	1.062002
20	68	0.998232	0.998855	1.004465	1.060562
30	86	0.995676	0.996300	1.001919	1.058103

Source: Washburn (1928)

A turbid density current that plunges beneath the reservoir surface is illustrated in Figure 7. The plunge point is characterized by a change in water color, as seen in Figure 8*A*. If the inflowing river carries floating debris, the debris will become trapped at the plunge point, as seen in Figure 8*B*. The debris becomes trapped because of the upstream-flowing surface that is created by the plunging flow, as schematically shown in Figure 7.

Figure 7. Passage of turbidity current through a reservoir and release through a low-level outlet such as a power intake.

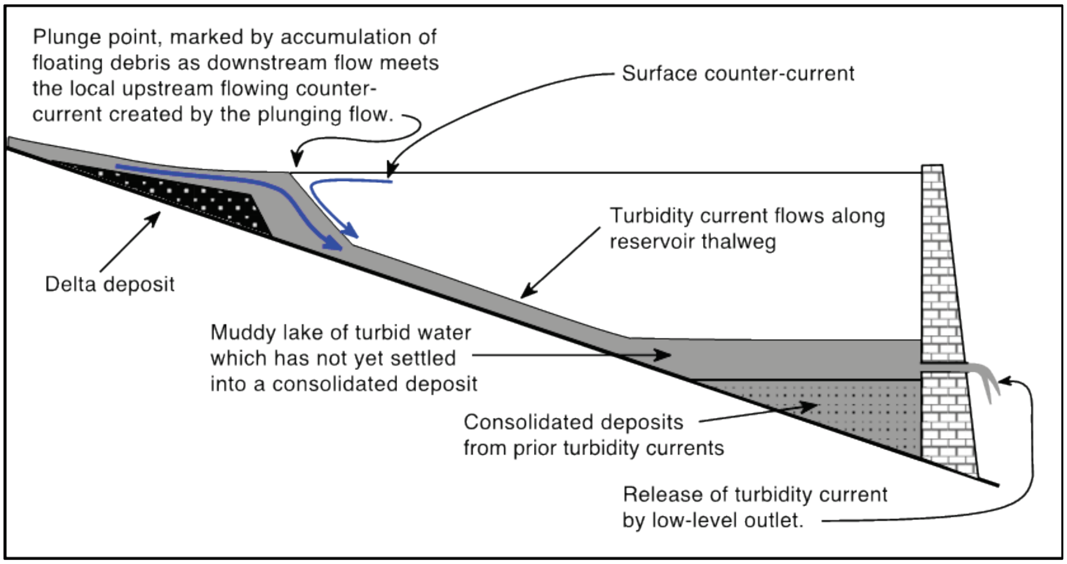
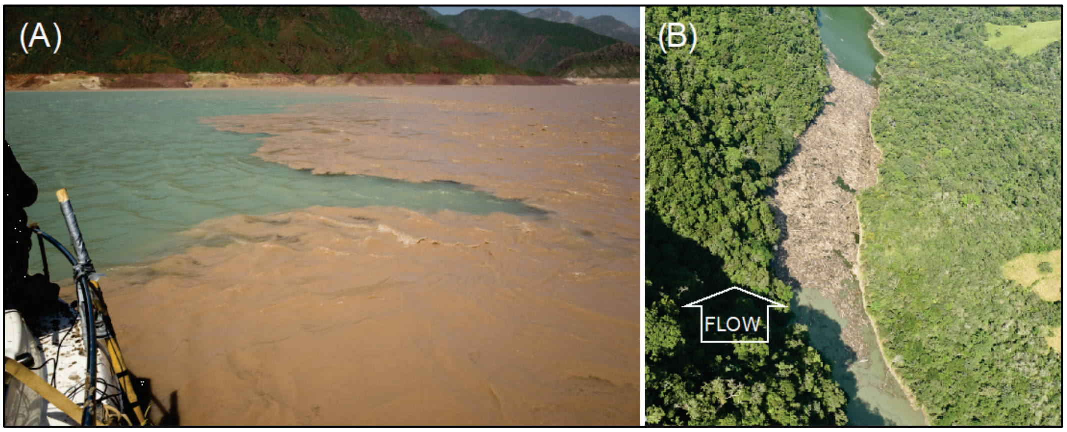
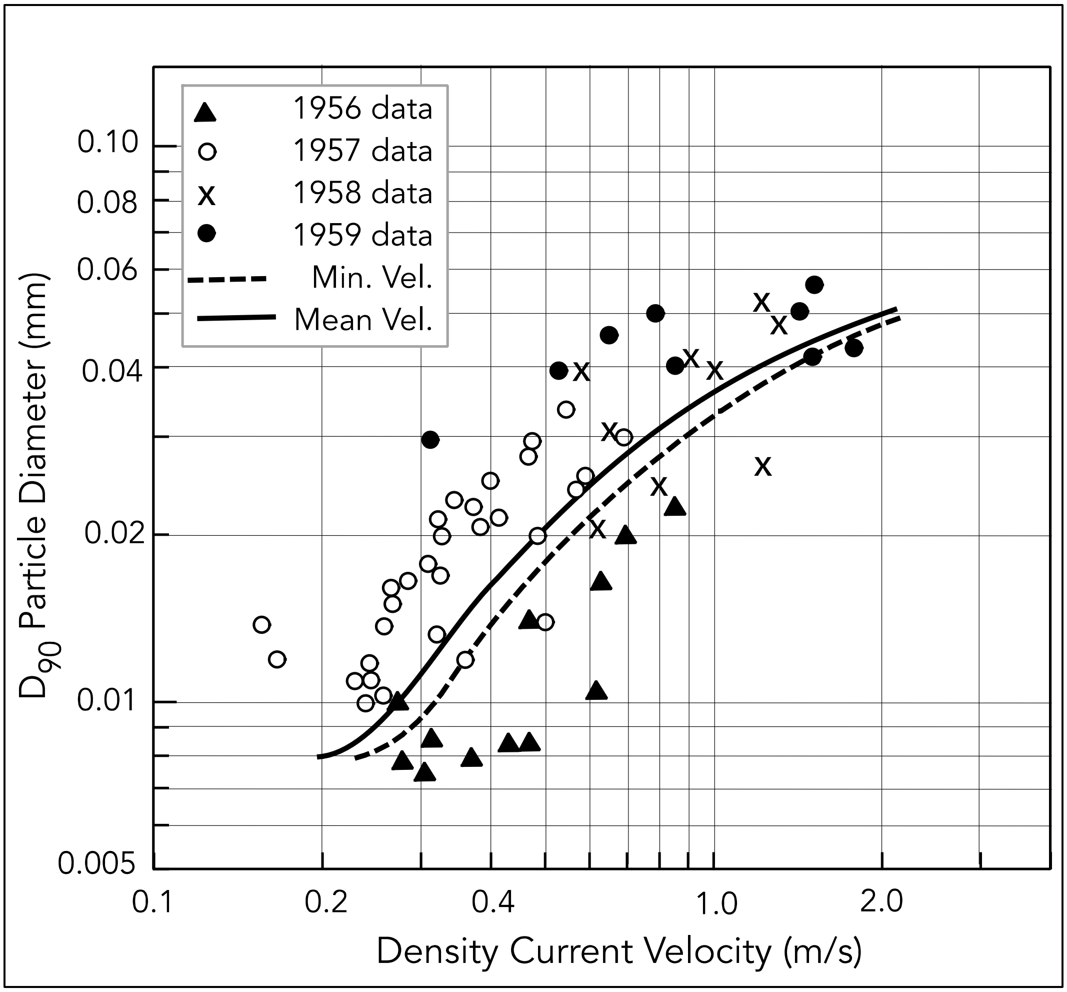


Figure 8. (A) Turbid water plunging into Nurek reservoir, Tajikistan. (B) Accumulation of floating debris at the density current plunge point in Miel-1 reservoir, Colombia (photos G. Morris).



The submerged turbidity current can transport fine sediments to the area of the dam, or if conditions are less than optimal, the current will dissipate as the sediment settles along its flow path. Fine sediments often comprise over 90% of the sediment load entering a reservoir, and turbid density currents are particularly important in explaining both the depositional patterns and transport processes for fine sediment in deeper reservoirs. Under favorable conditions, turbid density currents can travel tens of kilometers to the dam and be released downstream via a low-level outlet or power intake. Turbid density currents traveled 129 km along the bottom of Lake Mead prior to construction of Glenn Canyon Dam upstream (Grover and Howard 1938). Turbidity current velocities as high as 2.5 m/s have been documented in the Luzzone reservoir, Switzerland (Althaus and De Cesare 2006), though velocities under 1 m/s are more typical. The size of sediment that can be transported by a turbidity current, as a function of the turbidity current velocity, can be estimated from Figure 9. Except on very steep slopes, the sediment that can be transported by turbidity currents is limited to silt and clay. In shallow reservoirs, turbid density currents may not form.

Figure 9. Size of sediment that can be transported by a turbidity current as a function of current velocity (data from Fan 1986).



If the turbidity current reaches the dam and is released through a low-level outlet or turbines, water exiting the dam (or power station) will be muddy even though the surface water in the reservoir is clear. Turbidity currents reaching the dam that are not released will accumulate as a submerged muddy lake, and sedimentation from repeated events will create nearly horizontal sediment beds extending upstream from the dam as was illustrated in Figure 7. These horizontal sediment beds indicate that significant amounts of sediment are being transported to the dam by turbidity currents.

Turbulence created by the forward motion of the gravity-driven turbidity current sustains sediment in suspension. However, as the transported sediment settles out of the current, this diminishes the gravitational force driving the current, causing it to slow down. The reduced velocity and turbulence will allow more sediment to settle, further diminishing the density difference between the current and the surrounding water. Continued deposition and the resultant decline in velocity and turbulence will cause the current to dissipate. Flood discharge, suspended-sediment grain size, and concentration all vary over the duration of a flood. Consequently, the flow of turbid density currents is unsteady due to variability in the inflowing discharge, sediment concentration, and grain size distribution. Current velocity within the reservoir is also affected by the variable geometry and slope of the reservoir bottom.

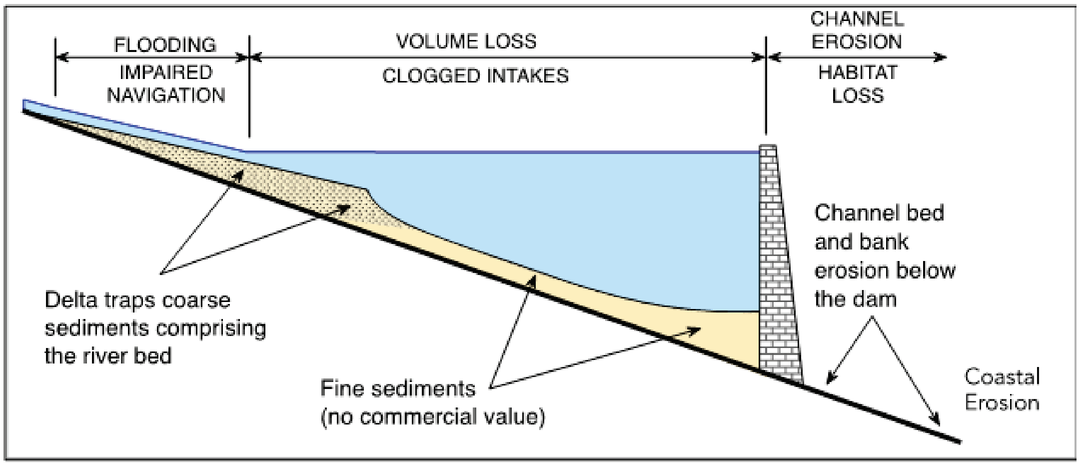
Propagation of turbidity currents along the bottom of a reservoir will be greatly influenced by changes in subsurface reservoir geometry which occur over time due to sedimentation, or modification of the subsurface geometry by reservoir flushing, dredging, or structures. When the reservoir is newly impounded, the turbidity current can flow along the original river channel producing a thick and compact current with a low wetted perimeter. However, as the original channel is filled, the reservoir bottom becomes wide and flat, and the turbidity current itself becomes wide and thin, greatly increasing the frictional effects and the potential for dilution with clear water across the upper boundary. This effect was noted as early as 1954 by Lane, who observed that turbidity currents reached the Elephant Butte Dam on the Río Grande in New Mexico during the initial years of impounding but thereafter dissipated before reaching the dam (Lane 1954).

3 Problems Associated with Sedimentation

3.1 Overview of sedimentation impacts

Sedimentation impacts not only the reservoir pool but also areas upstream and downstream of the reservoir (Figure 10). Significant impacts can be experienced when only a small fraction of the reservoir volume has been lost.

Figure 10. Sedimentation impacts can occur above the pool, within the pool, and downstream of the dam.



Potential sedimentation impacts are listed in Table 4. The available information indicates that some level of sedimentation impacts are now occurring at about 25% of USACE reservoirs (USACE-IWR 2016). Given the age of USACE reservoirs and the progressive nature of sedimentation, both the number of affected sites and the severity of the problem will accelerate over time.

Table 4. Sedimentation impacts to beneficial management activities at US Army Corps of Engineers (USACE) reservoirs.

Beneficial Activities	Impact Description
Water supply and low-flow augmentation	Loss of storage capacity causing decline in firm yield and reliability. Reduced ability to augment downstream flows.
Flood Control	Loss of storage capacity causing decline in level of flood protection. Sedimentation can raise flood levels and cause soil water logging in areas upstream of a reservoir delta.
Recreation	Impaired access (boat ramps), reduced open water surface, in some cases partially offset by gains in activities related to wetlands (e.g., hunting).

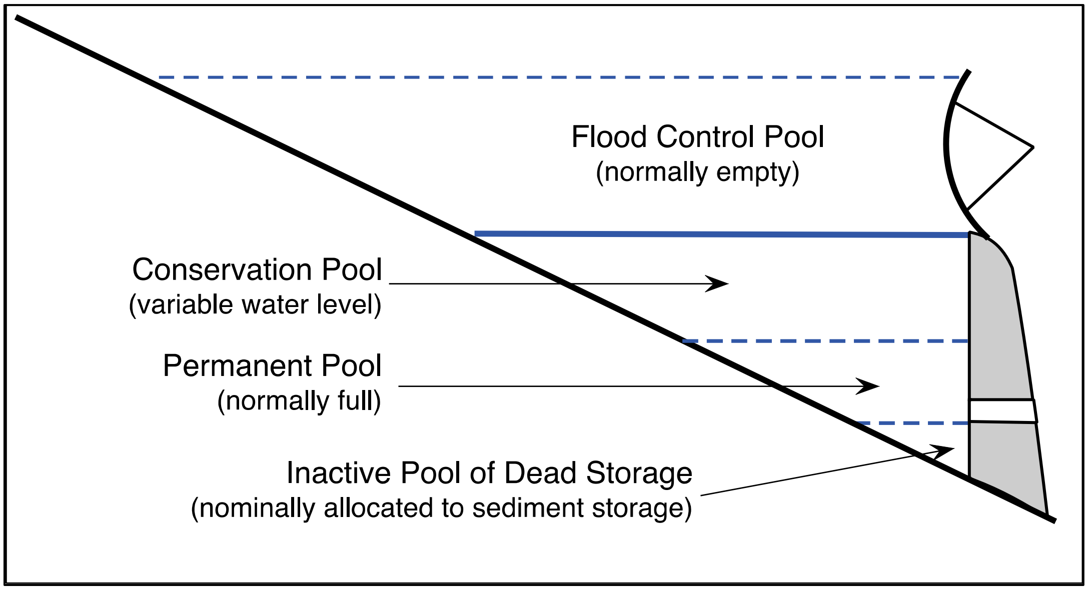
Table 4. (cont.). Sedimentation impacts to beneficial management activities at US Army Corps of Engineers (USACE) reservoirs.

Beneficial Activities	Impact Description
Hydropower	Loss of regulating storage, sediment entrainment by intakes causing turbine abrasion, restricted pool operating levels to retard delta advancement toward the intake.
Fish and Wildlife	Change in above-dam habitat, reduced ability to control downstream releases as regulating storage volume is lost. Below dam: channel incision, loss of sandbars and other habitat, bed armoring, clogging of spawning gravels by fine sediment absent flushing flows.
Navigation	Sedimentation within navigation channels, decreased clearance beneath bridges by sedimentation above the pool.
Water Quality	Reduced pool volume available for water quality control including cold water releases. Reduced ability to trap contaminants associated with sediments.

3.2 Sedimentation impacts within storage pools

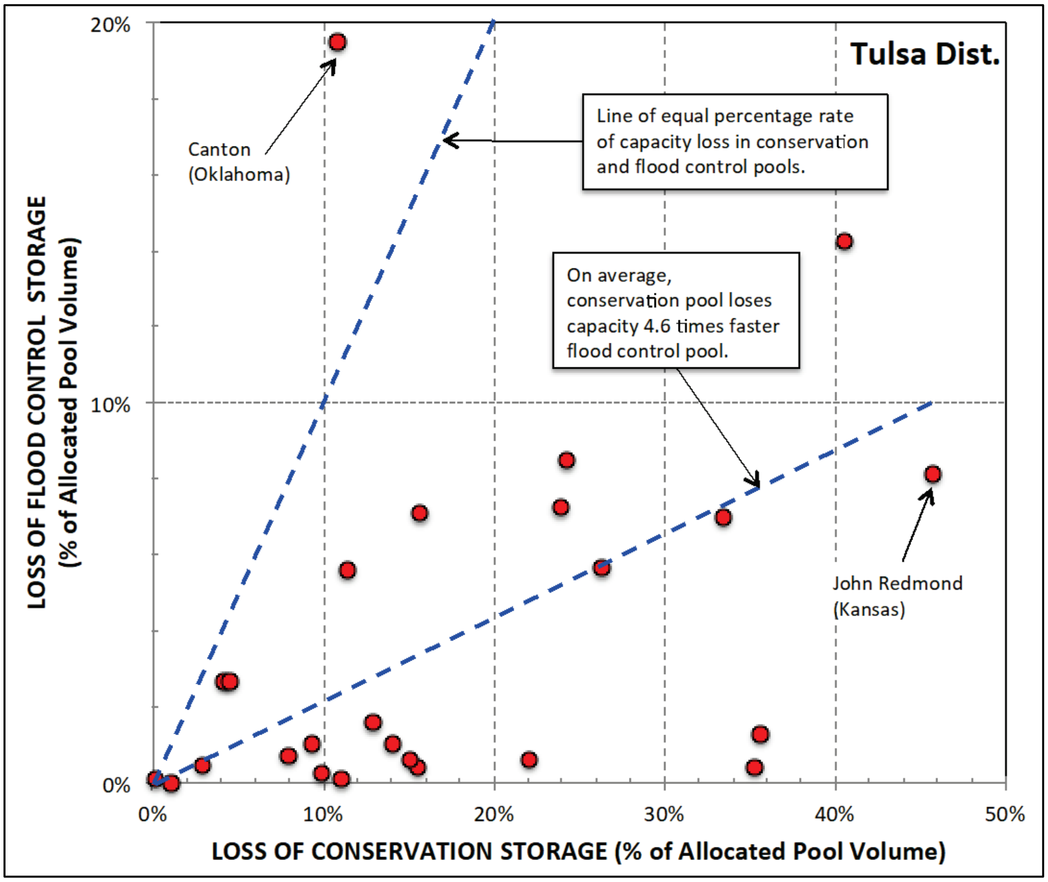
Many USACE reservoirs have a large, normally empty flood control pool overlying a significantly smaller conservation pool for water supply storage and related uses. A typical pool arrangement is illustrated in Figure 11. Sedimentation will adversely impact all beneficial uses associated with reservoirs, but some impacts may be felt earlier than others depending on pool size and location.

Figure 11. Arrangement of pools characteristic of USACE reservoirs. Not all pools are found in all reservoirs.



Conservation pools, which are normally ponded and smaller than the flood control pool, typically lose capacity much faster than the flood control pool. Although the total sedimentation rate at USACE reservoirs indicates that the rate of total capacity loss is relatively low, significant sedimentation problems are increasingly being experienced in many conservation pools. Available data suggest that conservation pools are losing capacity approximately five times faster than flood control pools, and at a number of reservoirs essentially all of the sedimentation impact is accruing in the conservation pool (Figure 12).

Figure 12. Rate of storage loss, flood control pool vs. conservation pool, for reservoirs in Tulsa District as of 2012.



As water supply pools are lost, there will be growing pressure for storage reallocation. The USACE may reallocate up to 15% of the pool volume[3] from one use to another to compensate for sedimentation. Larger reallocations may be authorized by the Secretary of the Army; however,

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[3] Or 50,000 acre feet, whichever is less (USACE 2000).

Congressional authorization is required if the reallocation requires significant structural or operational modifications (USACE 2000). Maintaining water supply storage poses serious challenge to communities that have come to rely on reservoirs for municipal supply.

Impacts to water supply will accelerate once the inactive pool underlying the conservation pool becomes filled with sediment. All the sediment previously collecting in the inactive pool will now be displacing capacity in the conservation pool, accelerating the loss of conservation storage.

At the national level, the problem of volume loss in the conservation pool is probably the most severe sedimentation issue with the most immediate impacts. Loss of storage volume will affect water supply benefits of all types, including low-flow augmentation to sustain water quality in rivers delivering raw water to municipal water filtration plants and for ecological protection.

3.3 Downstream sediment deficit

The trapping of sediment by a dam eliminates the supply of sand and gravels to the downstream channel. Deprived of its normal load, the water is now clear and sediment hungry, accelerating erosion of bed and banks in the downstream channel. Sediment trapping by dams, together with the impacts of instream sand and gravel mining, can have severe geomorphic and ecological impacts on rivers (Kondolf 1997). Consequences of the river's sediment deficit can extend to the coast, accelerating shoreline erosion due to the reduction in sediment inputs.

Problems related to the trapping of sediment can also affect the river reach extending tens or hundreds of miles downstream. For example, on the Trinity River in Texas, Smith and Mohrig (2017) documented 7 m of bed incision 40 yr after dam construction, with measurable impacts to the river profile extending over 30 mi downstream. The sediment load reaching the coastline can also be impacted with resultant coastal erosion impacts. For example, dams in southern California currently trap an estimated 50% of the sand that previously nourished beaches (Slagel and Griggs 2006). On the Pacific coast of Mexico, the interruption of sediment supply to the coast by two rivers dammed for hydroelectricity initiated a process of rapid coastal recession in what should otherwise be an accretional coastline (Ezcurra et al. 2019). Even major river deltas such as the Mississippi, Ebro (Spain), and Mekong (Vietnam) Rivers are affected by sediment trapping in upstream dams.

Channel incision below the dam and the coarsening and armoring of downstream channels can produce an array of related secondary impacts including incision of tributary streams, accelerated bank erosion, loss of aquatic habitat, desiccation of riparian wetlands, reduced recreational opportunity, plus the environmental and economic costs of mitigation measures. Hydropower peaking operations that produce large fluctuations in streamflow can further destabilize channel banks. The scope and nature of these problems vary widely and reflect location-specific conditions.

The river channel below the dam can also be impacted by the reduction in flood flows, which reduces sediment transport capacity below the dam. This can partially offset the erosive impact of sediment-hungry water, but if too much water is diverted away from the river by the dam, or flood pulses are completely eliminated, tributaries below the dam delivering a heavy sediment load into the river can cause the downstream channel to aggrade, as occurs along the Río Grande downstream of Elephant Butte Reservoir in New Mexico (Colleir et al. 1995). However, the more common situation is channel degradation.

3.4 Sedimentation and backwater impacts above pool elevation

Sands settle rapidly at the upstream limit of the pool, initiating the process of delta building and raising the level of the river bed as well as the flood level. Delta deposits will cause flood levels to rise above the backwater profile computed in the absence of sedimentation, and sediment deposits can extend well upstream of the reservoir's normal pool level. This can produce the following: (1) upstream flooding; (2) water logging of adjacent soils; (3) burial of upstream intakes and stream diversions beneath sediment; (4) increased tailwater elevations at upstream hydropower plants; (5) reduced freeboard beneath bridges affecting both flood hazard and navigational clearance; and (6) avulsion of the upstream channel. Recreational access by boaters is a beneficial use that may be impacted early on by sedimentation because boat ramps are often located near the upstream end of reservoirs, in areas impacted by delta deposition.

Sedimentation of the main channel will also affect tributaries. In the case of Niobrara, Nebraska, for example, a delta was created by the sand-laden Niobrara River where it discharged into Lewis and Clark Reservoir (Gavins

Point Dam) on the Missouri River. This delta increased backwater flood levels to the extent that it became necessary to relocate the entire town to higher ground (Carter 1991). A current example of delta sedimentation increasing flood levels in an urban area occurs at Clarkston, Washington, and Lewiston, Idaho. This area is affected by sediment deposition at the upstream limit of Lower Granite Reservoir near the confluence of the Snake and Clearwater Rivers.

3.5 Sediment abrasion of hydromechanical equipment

Coarse sediment is very damaging to water supply pumps and hydropower machinery such as turbine runners, wicket gates, and valves. The alloys used for hydropower turbine manufacture have a Mohs hardness of approximately 5, which is softer than many of the minerals commonly transported by water, the hardest of these common minerals being quartz with a Mohs value of 7. As sediment advances into hydropower reservoirs, hydropower machinery that operated for decades without problems may start to experience abrasion problems. When angular quartz particles are present at high concentrations, even silt-size particles cause severe abrasion damage.

The abrasive impact of sediment against hydro-machinery can be related to a variety of factors including hydraulic head (velocity of impact), sediment concentration (number of particles impacting), sediment diameter (which influences the momentum of particle impact), particle shape (angularity), sediment mineralogy (percentage of quartz), and characteristics of the metal including the presence or absence of a hard protective coating. The Nozaki equation (Nozaki 1990) has been used to estimate the repair cycle for hydropower components subject to sediment abrasion.

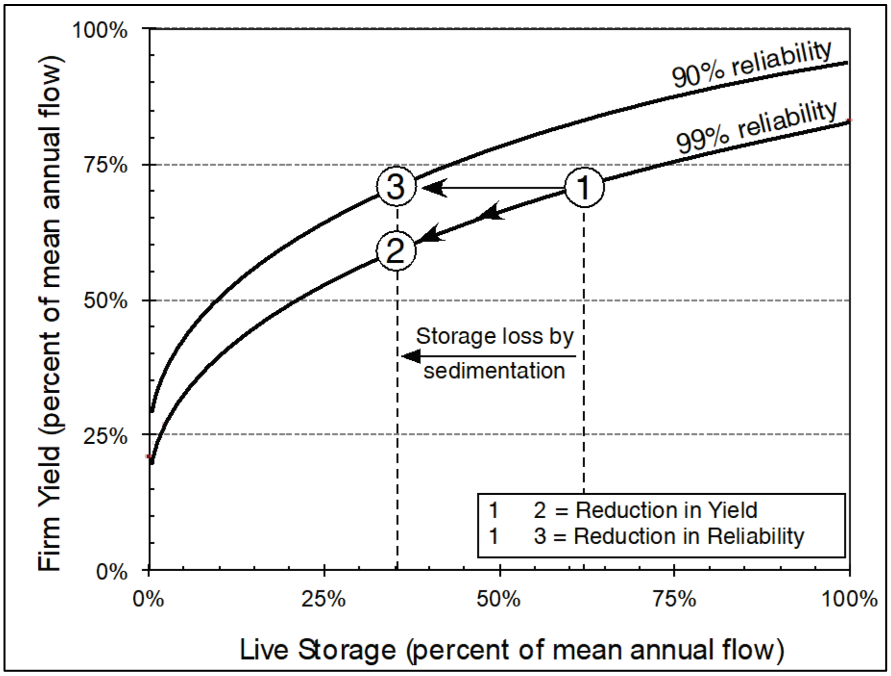
To avoid extensive turbine damage, exclusion of coarse sediment particles will be required at reservoirs when the delta approaches the intake. As sandy deltas approach the area of the intake, it may be necessary to increase the minimum operational level of the reservoir (reducing live storage capacity) to re-focus delta deposition farther upstream. Although this will not reduce the rate of capacity loss, it will delay the arrival time of the delta at the intake.

Another potentially important strategy for retarding the arrival of the delta at the dam is to release turbid density currents whenever possible, including their release through turbines. This will maximize the volume available to store delta sediment thereby delaying delta arrival to the intake.

3.6 Sedimentation impact thresholds

Some types of sedimentation impacts have discernible thresholds. Sediment can accumulate for many decades without causing a problem, but when a threshold is reached, the impacts become apparent and may increase rapidly. Distinguishable impact thresholds may include (1) the filling of the inactive pool meaning that all future sedimentation now displaces beneficial pools; (2) sediment encroachment which, when combined with debris, blocks an intake; (3) critical flood levels below a flood control reservoir or upstream of delta deposits, especially in communities protected by levees; (4) required navigational depths; and (5) the characteristic non-linear shape of water supply storage-yield relationships (Figure 13). Not only does firm yield decline in a non-linear manner, but when sedimentation produces a progressively shallower reservoir, this increases the surface-to-volume ratio and thus the relative importance of evaporative losses to the reservoir's water budget (De Araújo et al. 2006).

Figure 13. Characteristic pattern of a reservoir storage-yield curve. Loss of storage can produce diminished yield, diminished reliability, or some combination of the two. Storage-yield curves are nonlinear, and yield diminishes more rapidly as volume declines.



3.7 Future rates of capacity loss

Sediment yield—the sediment reaching a reservoir—reflects both the erosional processes within the watershed and the sediment trapping opportunities between erosion sources and the downstream reservoir or other measurement point.

There is a lag between the implementation of soil conservation measures and measurable changes in the rate of sediment delivery to downstream reservoirs. This lag occurs because between the initial point of soil detachment and the reservoir located many miles downstream, there are multiple opportunities for sediment to be deposited. A single sediment particle may experience multiple erosion-deposition-erosion sequences before reaching the dam. As a result, the *sediment delivery ratio*, the ratio of sediment delivered to sediment eroded, plays a significant role in the dynamics of reservoir sedimentation (de Vente et al. 2007; Walling 1983).

Sediment yield can be reduced by practices including contour farming, no-till farming, reducing grazing pressure, treatment of drainage channels, and other measures. Also, upstream impoundments and farm ponds act as sediment traps. An inventory based on 30 m satellite imagery revealed approximately 2.6 million ponds in the conterminous United States while extrapolation from a sample of 1:24,000 topographic quadrangles suggests the total may be as large as 8–9 million ponds. These ponds capture runoff from an estimated 21% of the total drainage area of the conterminous United States, representing 25% of total sheet and rill erosion (Renwick et al. 2005).

When looking over longer timeframes, it is characteristic to see trends of declining yield from watersheds in the United States. Reviewing data showing a dramatic decline in sedimentation rate in a study of eight flood control reservoirs in central Texas, comparing pre-1963 and post-1963 periods, Berg et al. (2016) showed that the watersheds had reduced both grazing and cropping areas and increased the number of farm ponds, which act as effective sediment traps. In central Oklahoma, Garbrecht and Starks (2009) compared sediment gauging data above Fort Cobb Reservoir and concluded that, even though it is generally difficult to identify impacts of upstream conservation practices on sediment yield at the watershed outlet during the short timespan of a particular conservation project, targeted and widespread conservation efforts in the Fort Cobb Reservoir watershed have led, over 60 yr, to a sizable and measurable reduction in watershed sediment yield. An extensive data analysis project by the US Geological Survey (USGS) (Oelsner et al. 2017) compiled water quality data across the country. The analysis of 137 gages (Murphy and Sprague 2019) showed that suspended sediment concentrations were declining in over 50% of the stream sites and were increasing at less than 25% of the stations.

4 Data Needs and Reporting Formats

Successful sediment management to sustain long-term reservoir capacity requires a significant enhancement in data collection frequency, scope, and presentation format. At present, sedimentation appears almost an afterthought. For example, Pinson et al. (2016) reported that approximately 200 USACE reservoirs lack recent surveys. This situation is not remarkable; the US Bureau of Reclamation (USBR) also has a large backlog of unsurveyed reservoirs. Graf et al. (2010) noted that the number of reservoir sedimentation surveys peaked in the 1960s and 1970s and declined to negligible numbers by the 1990s while at the same time, federal agencies greatly reduced support for sediment transport studies.

At the sites surveyed by the USACE, data collection and analysis related to sedimentation have traditionally been limited to periodically updating the elevation-storage curve, without publishing a formal report and without any more detailed analysis or the sediment data collection that is needed to develop a comprehensive sediment management plan.

This section outlines the types of survey data and presentation formats that are useful for analyzing sedimentation patterns and potential mitigation approaches.

4.1 Reservoir survey data

To develop a sustainable sediment management plan, reservoir capacity data are needed to support multiple types of analysis:

1. Track capacity loss, including the impacts of any management activities such as watershed management, upstream dam construction, sluicing, flushing, etc., that may reduce the sedimentation rate.
2. Observe sedimentation patterns and changes in these patterns over time in response to changes in reservoir geometry as sediments accumulate or in response to management activities.
3. Provide data to calibrate models, such as numerical or physical sediment transport models used to predict future sedimentation patterns and test management alternatives.
4. Determine sediment yield, as reservoir sediment surveys, corrected for trap efficiency and bulk density of the deposits, are considered the best measure of sediment yield as they capture sediment from all events

since dam construction, including extreme events that are difficult to measure directly and that may be so large that measurement equipment is swept away.

5. Observe the sedimentation impact of extreme flood events.

Survey data may also be required to determine volumes for payment of excavation work, such as dredging, but such surveys may only cover a specific area of the reservoir.

Better information on the extent of the sedimentation problem and its patterns can be achieved by improving the reporting formats for existing data and by increased data collection. There are several areas where improvements can be made.

- Much of the data required to make a quantitative system-wide evaluation of the extent of sedimentation are available, but these data have not been compiled into a format suitable for system-wide assessment or management. This situation can be rectified rapidly and at low cost by summarizing key data from existing reservoir surveys into a common format, such as the USACE Reservoir Sedimentation Inventory (RSI) database.
- Technology changes that result in more accurate survey data often point to lack of precision in older survey data, including problems with the original pre-impoundment volume estimate. In some cases, newer and more accurate data contradict the older data, resulting in considerable uncertainty as to the true rate of sedimentation even in 50 yr old reservoirs. To resolve uncertainties of this type requires complementary data such as fluvial sediment gaging, sediment cores, and in some cases a dual-frequency sediment survey (e.g., 200 and 25 MHz) to obtain sub-bottom profiles to detect the pre-impoundment bottom and determine deposit thickness.
- The available survey data are not being analyzed to predict future sedimentation patterns and impacts. Although 50 to 100 yr sediment impacts were projected and designed for in the initial project plan, there is no ongoing policy to reassess and project capacity loss beyond the horizon of the project’s original design life. The regular updating of long-term, forward-looking projections and sediment management plans is essential to achieve sustainable use.

Although sedimentation is the principal threat to the long-term functioning of reservoirs, there is relatively poor information on reservoir sedimentation, and the available information has not been organized to maximize the value of existing data. Yet, the cost of this data collection and analysis is miniscule compared to the replacement cost of the reservoir infrastructure.

4.2 Accuracy of reservoir survey data

Although reservoir survey data represent the most essential dataset for monitoring and predicting rates of future storage loss, these data have important limitations. One critical weakness is that pre-impoundment survey data are often inaccurate. Pre-impoundment volumes in older reservoirs were calculated from a variety of sources including ground survey, photogrammetric survey, and USGS topographic maps, each with its own error characteristics. Subsequent capacity estimates based on range-line surveys are themselves of limited accuracy; not only are they based on limited geometric data, but selection of the volume computation method (e.g., end-area versus surface-area-end-area) can give substantially different results from the same dataset. Range line techniques are described by Strand and Pemberton (1987) and by Morris and Fan (1998).

Modern data-intense digital terrain mapping or contour surveys using lidar and sonar/GPS are much more accurate than older survey methods, but these too are subject to error. Transitioning from range-line to contour survey methods can introduce a change in volume attributable solely to the changed methodology, especially when the data collection for the digital terrain model generates large additional amounts of geometric data. When comparing the two methods with a dense dataset, computed volume differences may not be large. For example, FMSM Engineers[4] used closely spaced range lines (spaced at approximately 0.20 to 0.25 times reservoir width) to compute the volume of Dillon Lake, OH, by constructing a digital terrain map, and this result was compared to the volume computed by the range-line end-area method using the same dataset. In this case, the difference was only approximately 3%. However, in most cases, range lines are not so tightly spaced, and the contour mapping produces a much more comprehensive geometric database for capacity computations. Even with a

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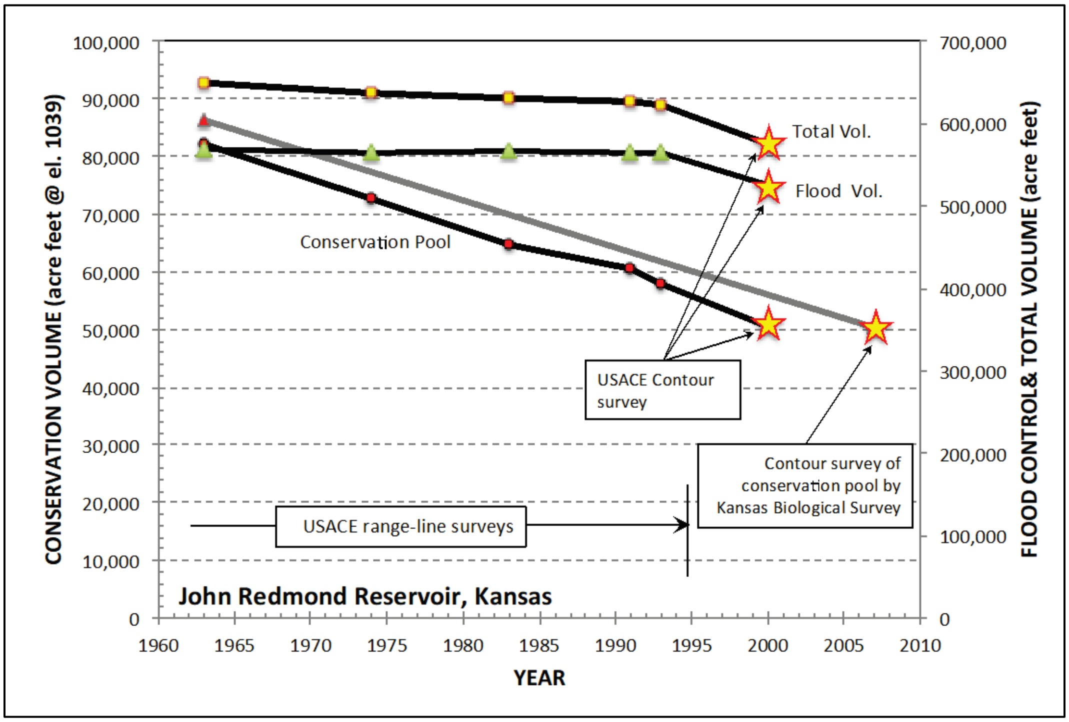
[4] FMSM (Fuller, Mossbarter, Scott and May) Engineers. 2000. *Computations for 1997 Sedimentation Survey and Comparison of Computation Methods for Sedimentation Survey at Dillon Lake, Ohio*. Report to USACE, Huntington Dist.

comprehensive digital dataset, selection of different computational algorithms can produce volume differences on the order of 1% to 2% (Ortt et al. 2000).

As an example of the types of problems that can occur with reservoir survey data, consider the data from multiple surveys of John Redmond Reservoir in Kansas shown in Figure 14. While survey data from the USACE indicate that the rate of storage loss within the conservation pool has been consistent over time, the rate of storage loss reported for the flood control pool saw a sudden change when the survey methodology was changed from range-line to contour survey. However, there was no corresponding shift in the capacity estimate for the conservation pool. Does this 40,000 acre-ft departure from the historical trend in the flood control pool mean it is losing capacity twice as fast as previously thought, or is there a corresponding undetected error in the original capacity estimate? This volume adjustment is not trivial; it is equivalent to 80% of the conservation pool capacity.

Figure 14. Reservoir survey data for John Redmond Reservoir. Contour survey data are shown as stars; other survey data are by range-line. Data from Tulsa District and Kansas Biological Survey (2010).



The Kansas Biological Survey (KBS), which conducts surveys at reservoirs throughout the state, also surveyed the John Redmond conservation pool by the contour method, resulting in a data point for conservation pool capacity that is inconsistent with the storage value extrapolated from the USACE data (Kansas Biological Survey 2010). The KBS also re-computed the original capacity of the conservation pool by digitizing the original pre-impoundment topographic survey (which had 5 ft contour intervals) and obtained a larger value for initial capacity than used by the USACE. Nevertheless, both the USACE and the KBS datasets agree on the rate of storage loss (the slopes of the curves are identical), and both datasets also concur that conservation storage is being lost much faster than flood control.

To cite another example, in the Baltimore district there are 13 reservoirs with survey data. As of 2012, four of these reservoirs were reported to have increased their total volume (negative sedimentation) by 0.4% to 4.4% after 20 to 30 yr of impounding, obviously reflecting inaccuracies in either the pre-impoundment volumes, subsequent volume surveys, or both (Table 5). At the remaining reservoirs, the surveys reported total volume losses ranging from 0.1% to 8.5% over periods ranging from 16 to 55 yr. These data should also be expected to contain similar inaccuracies, resulting in overestimation of the sedimentation rate. Jennings Randolph, subject of one of the case studies in this report, had the highest reported sedimentation rate, approximately 20 times higher than the original sedimentation rate estimate. The reservoir resurvey in 2013 confirmed that the 1997 survey was in error. Capacity measurement issues and alternative capacity checks at the Jennings Randolph reservoir are discussed as a case study in this report. An examination of similar data from other districts can be expected to reveal similar problems and points to the need for repeated surveys and use of consistent survey methodology.

Table 5. Capacity loss by sedimentation determined by reservoir surveys, as reported in 2012, Baltimore District.

Reservoir	Completion	Last Survey	Percentage Volume Loss to Top of Pool	
			Conservation	Flood Control
Aylesworth	1970	2000	3.1%	−4.4%
Sayers	1969	1997	1.4%	−1.5%
Hammond	1978	1999	2.5%	−0.8%
Tioga	1978	1999	−4.7%	−0.5%
Bush	1962	1999	−7.1%	0.1%
East Sidney	1950	2000	15.2%	2.4%
Whitney Point	1942	1997	6.5%	2.6%
Savage	1952	1996	3.3%	3.0%
Curwensville	1965	1965	19.9%	3.7%
Stillwater	1960	2000	28.0%	3.7%
Cowanesque	1980	1997	7.8%	4.6%
Jennings Randolph	1981	1997	6.8%	6.3%
Almond	1949	1997	48.8%	8.5%

Inaccuracies in reservoir survey data are widespread, and every organization that collects reservoir survey data faces similar problems. These examples do not imply that USACE procedures have deviated from accepted practices and standards of care. Rather, it reflects the limitations inherent in measurement technology, coupled with the effects of changes from older to newer techniques. It also underscores the need to document the degree to which volume changes are attributable to use of more accurate survey techniques. This can be performed by including the historical reservoir range lines in the survey tracks for a new contour survey and processing the data by both methods to determine the volume difference attributable to changed methodology. The use of additional types of sediment data may be required to resolve uncertainties and establish a more accurate estimate of sedimentation rates and patterns.

Bathymetric survey techniques are outlined in Engineer Manual (EM) 1110-2-1003 *Hydrographic Surveying* (USACE 2013a) and elsewhere (Ferrari and Collins 2006; Ferrari 2006a). Many USACE reservoirs have large, normally dry flood pools that cannot be surveyed by bathymetric methods. Recommendations on lidar survey techniques suitable for normally dry pools is presented by Baker et al. (2016).

With many reservoirs to survey, both survey time and cost are issues of concern. Given the computational ability to process huge amounts of field data, there is a temptation to collect more data than are necessary, but the collection and processing of field data involve both time and cost. To prevent cavitation on the sonar equipment, boat speed during a survey will typically be limited to under approximately 5 mph, and in large reservoirs with tightly spaced transects, the amount of boat time can be very large. Even with the advent of autonomous survey vessels, the running cost is not zero, and there are many reservoirs that need to be surveyed. For example, the survey of Texoma reservoir involved 1,812 mi of closely spaced transects due to an excessively tight spacing of 15 transects for a distance along the reservoir equal to one reservoir width.

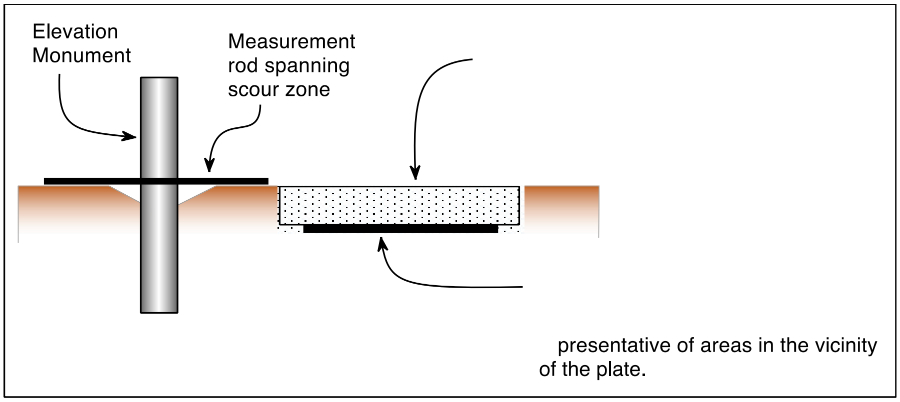
It is more important to have repeated data using a consistent methodology than it is to have infrequent but highly precise data, for two reasons:

1. It is important to observe changing sedimentation rates that are documented by repeated surveys (e.g., every 10 yr), and this requires data at regular intervals.
2. Highly precise data are of questionable value because, as the delta advances, it will cut off the lateral branches, and as a result, the effective elevation-storage relationship may differ from the measured values.

4.3 Sedimentation monuments

Many USACE reservoirs have a large and normally empty flood pool, typically with vegetated or forested conditions that can create measurement difficulties for photogrammetric or lidar surveys. Also, as previously illustrated at John Redmond Reservoir, it may not be possible to determine the long-term sedimentation rate in these areas due to uncertainties in the accuracy of the original survey data. In these cases, the rate of sediment deposition in the flood pool can be measured over short periods of time (a year or two, for example) using monuments or sedimentation plates. If the monument extends above the soil surface, it can create a localized scour pattern if there is significant flow velocity, and the soil surface should be measured using a rod that extends across the scour zone. The change in sediment level is measured over time from the top of the monument. A sediment plate does not have the problem of scour, but if it is on a dry part of the reservoir, there is the potential for rain splash erosion to remove sediment. One possible way of avoiding this problem is to bury the plates and cover them with a uniform depth of clean sand. Both options are conceptually presented in Figure 15.

Figure 15. Reference points for measurement of sediment depth in a normally dry area of a reservoir.

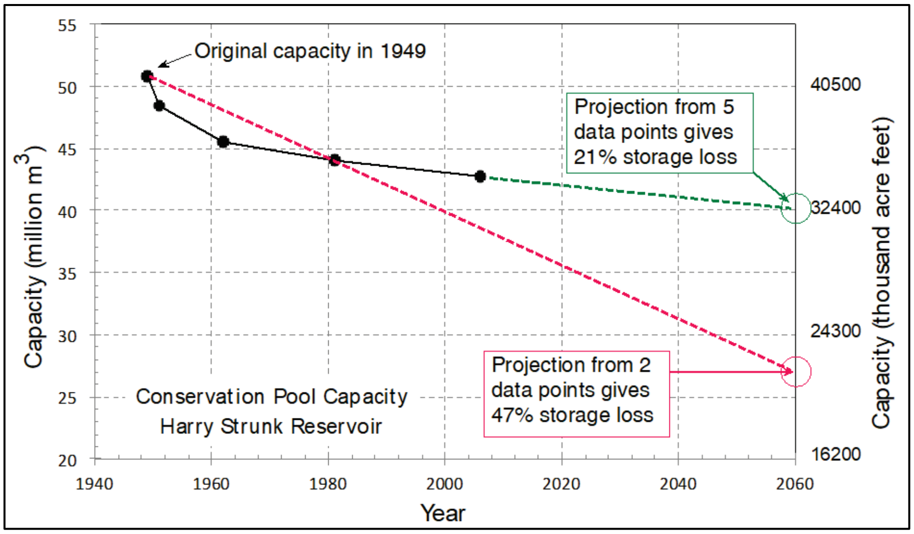


4.4 Survey frequency and predicting capacity loss

To provide data for determining the rate of volume loss, an initial reservoir survey should be performed soon after impounding to compute volume by the methodology to be used in subsequent surveys, and the next survey might be made at an interval of perhaps 10 yr. Some water supply agreements state that a survey will be conducted every 15 yr unless the district engineer deems it unnecessary. Thereafter, reservoir surveys should document each 5% loss in volume, or at intervals otherwise not exceeding about 20 yr. Given the error inherent in surveys and volume computations, surveys closely spaced in time may generate data of uncertain utility. However, resurvey intervals of a few years may be useful at sites with a high sedimentation rate, where sediments are affecting critical uses or infrastructure, or following an extreme inflow event or a sediment removal operation that may significantly affect reservoir volume.

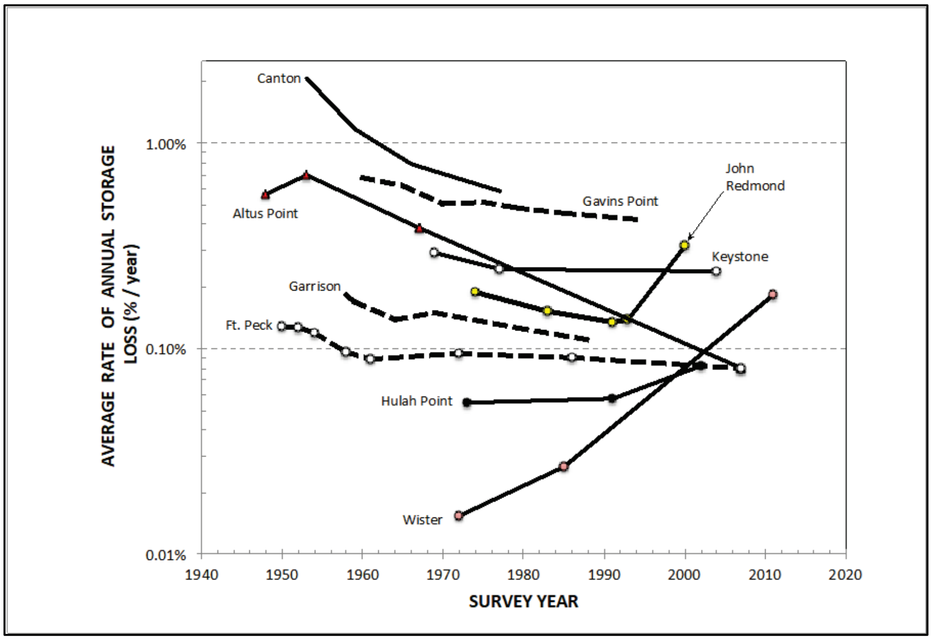
To estimate future reservoir capacity by extrapolating the observed rate of capacity loss from reservoir surveys requires a series of data points. A pre-impoundment survey followed by a bathymetric survey many years later can give very inaccurate results. As an example, look at the data from Harry Strunk reservoir shown in Figure 16. The projected rate of storage loss determined by comparing the original capacity against the survey volume after 30 yr of impounding is very different from the value obtained from a series of surveys which demonstrate a reduction in the rate of storage loss over time. Also note the importance of having a survey immediately following the initial impounding as the basis for future measurements.

Figure 16. Repeated survey data are essential to detect changes in the rate of capacity loss and predict future storage capacity (survey data from Ferrari 2006b).



Rates of capacity loss that change over time are actually not an unusual phenomenon. To illustrate, consider the rates of annual storage loss plotted over time for several reservoirs from the Tulsa District plus several main stem Missouri reservoirs in the Omaha District (Figure 17). In some cases, the rate of storage loss is relatively constant over time, but in many reservoirs the rate of capacity loss changes over time, many decreasing but some increasing.

Figure 17. Examples of the time-wise variation in the average annual rate of storage loss as reported by reservoir surveys, Tulsa and Omaha Districts. (Storage loss is computed as cumulative rate from date of initial impounding).



The fraction of the total sediment load deposited within each pool also varies over time. Most important, once the inactive pool at the bottom of the reservoir is filled with sediment, the sedimentation that previously occurred in the inactive pool will now start depositing in the conservation pool, increasing the depletion rate of conservation storage.

Long-term prediction of future storage loss and of depositional patterns is best performed by sediment transport modeling using tools such as HEC-RAS, Adaptive Hydraulics (AdH), and the USBR models SRH-1D and SRH-2D.

4.5 Complementary sediment data

Reservoirs trap sediment from all storm events, thereby avoiding two common problems that affect fluvial sediment datasets: unsampled events and the limited data available from extreme events. However, reservoir survey data do not show the time-wise variation in sediment delivery, information essential for developing a sediment rating curve and to analyze management alternatives such as sediment pass-through.

Sub-bottom profiles. In some situations, it is useful to employ a shallow acoustic reflection (chirp) sub-bottom profiler. Depending on the model, acoustic chirp profilers use a range of frequencies (chirped at one or more frequencies) to create a sub-bottom profile. Generally, the higher frequencies (e.g., 200 kHz) will reflect from the initial surface while the lower frequencies (e.g., 4–24 kHz) will penetrate sediment deposits and reflect off the more dense original reservoir surface, thereby enabling the sediment thickness to be computed by difference. These estimates of sediment thickness must still be ground-truthed because of variations between reservoirs in the character of the deposited sediment (e.g., composition and consolidation). An additional complicating factor is the presence of methane and other gas bubbles produced by microbial activity in the reservoir sediment. The sharp gas-water interfaces associated with these bubbles reflect acoustic energy and limit the effectiveness of sub-bottom profilers. Gas tends to be patchy, so it may be possible to work around these areas.

Sediment cores. One factor that can influence the rate of volume loss over time is sediment compaction. Sediment cores can be used to determine total sediment thickness, grain size distribution, sediment dry bulk density, and the change in bulk density with depth, which reflects the effect of sediment compaction. For instance, data from fine sediment deposits in John Redmond showed a 30% reduction in volume with depth due to compaction. These types of data are needed for the calibration of sediment transport models to predict future patterns of sedimentation and volume loss and analyze management alternatives.

Fluvial gage data. Sediments are delivered into reservoirs by fluvial processes, and a key to more efficient and effective sediment management is to have a good understanding of the sediment delivery process based on reliable data. The data from reservoir surveys provide a cumulative measure of the total sediment trapped, but it does not provide information on the timewise variation in sediment concentration or grain size, information essential to the evaluation and development of sediment management techniques such as the routing of sediments through or around the storage pool. These data require the operation of suspended sediment gage stations. Unfortunately, the collection of fluvial sediment data has declined over the past decades.

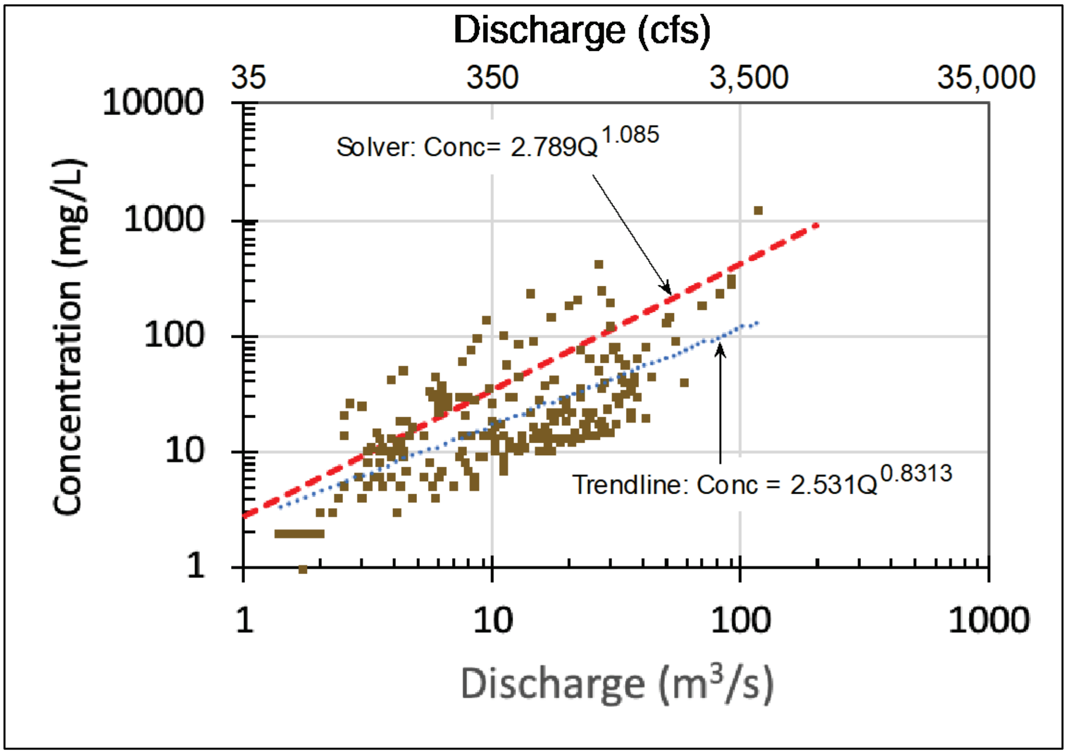
One of the most persistent errors in the analysis of fluvial gage data is the practice of using an Excel spreadsheet to perform a trendline (least squares) analysis of sediment data to construct a sediment rating curve (sediment concentration vs. discharge). These graphs often show both the regression equation as well as the R^2 (goodness of fit) value. However, this is not a reliable procedure to produce a rating curve. The objective of the rating curve is not to produce a high R^2 value; rather, it is desired to accurately reproduce the overall sediment load in the river. Rating curve data will always have a significant amount of scatter because many factors other than discharge influence sediment concentration, but discharge is the best parameter available. If the rating curve can accurately reproduce the load over a sampling period covering a few years, then this rating equation can be applied to the multidecade discharge time series to estimate long term sediment yield, year-to-year variability, the influence of large events, and to generate the daily sediment inflow dataset needed for long-term sediment transport modeling of reservoir sedimentation and sediment management alternatives.

Rating curves are usually expressed as a power function of the form

$$\text{Concentration} = aQ^{b},$$

where *a* and *b* are coefficient values and *Q* is the discharge, typically in cubic feet per second or cubic meters per second. This plots as a straight line on log-log coordinates, as shown in Figure 18 using data from the Randolph Jennings case study. The suspended sediment data for the North Branch of the Potomac River at Kitzmiller, MD (USGS gage 1595500), is a good example of the large error that can occur. This graph shows the trendline equation, and it also shows the equation developed by Excel Solver using the trendline equation coefficients as the initial seed values and the total sediment load from the original dataset as the solver objective function.

Figure 18. Comparison of rating equations developed using trendline least squares regression vs. Solver to reproduce total load, based on suspended sediment data from the Kitzmiller gage (USGS 1595500). The trendline accounts for only 35% of the measured load whereas the Solver equation accounts for 100% of the load.



To check that the rating equation does indeed accurately reproduce the measured load, perform a mass balance check. Sum the daily loads in the field data and compare this to the sum of the daily loads computed by the rating equation. This mass balance comparison has been made in Table 6, showing that the trendline equation accounted for only 35% of the actual load. If the sediment load entering the reservoir were calculated using the trendline equation, the result would be a 65% undercounting of the suspended sediment load! Most datasets do not have errors this large, but without performing the mass balance analysis shown in Table 6, it will not be possible to know the extent of the error.

One of the reasons for the potentially large errors is that the least square method equally weights each data point whereas in sediment transport, the high discharge events (floods) are much more important because of the extreme sediment load they can carry. Notice that the solver equation in Figure 18 reflects the influence of the sediment-laden floods much better than the trendline.

This mass balance computation is an essential check that must be made on rating equations, yet virtually all rating equations are developed using least square analysis and without this check. (For further information refer to Annandale et al. (2016, Chap. 6), Ferguson (1986), Glysson (1987), Gray and Simões (2008), and Morris and Fan 1998.)

Table 6. Comparison of trendline vs. Solver for mass balance for development of sediment rating relationship.

Parameter	Load in Ton	Percentage Accounted For
Load in Dataset	45,420	100%
Load by Trendline Equation	15,955	35.1%
Load by Solver Equation	45,343	99.7%

4.6 Advances in technology for suspended sediment monitoring

Given the high variability in suspended sediment concentration and the rapid changes in concentration that can occur, the limited data coverage offered by conventional sampling techniques can result in significant under-reporting of suspended sediment transport, and in smaller watersheds the timewise variation in sediment concentration may be poorly documented. Active management techniques at reservoirs, such as sediment bypass and pass-through, require more information on variations in sediment concentration to optimize the storage of water having low sediment concentration and release of water with high sediment concentration. Activities such as reservoir flushing may require real-time sediment monitoring to help manage sediment releases to mitigate downstream impacts.

Suspended sediment is one of the most difficult of all parameters to measure in water. Both concentration and grain size distribution change with discharge, and there are wide variations in total concentration and grain size distribution both vertically and horizontally within the stream's cross section. Sediment with a higher settling velocity, such as sands, will be found at higher concentrations near the bed. A fixed sampling point may be above the water surface at low flow, at the correct relative depth at bankfull discharge, but too close to the bottom for an extreme flood. As a result, the fixed sampling point may oversample sands during extreme flood events. This is a disadvantage inherent in all measurement systems that rely on fixed-point sampling. Regardless of the technology used to measure the sediment, when fixed-point sampling is used, it should be calibrated against conventional depth-integrated sampling across the full river width.

Sediment sampling has traditionally required the laborious collection and analysis of multiple water samples for each suspended sediment measurement, a costly and time-consuming procedure. There has been a long search for surrogate technologies to measure suspended sediment concentration and grain size distribution inexpensively and in real time. Three types of proven technologies are now commercially available and offer varying degrees of capability.

Optical methods based on turbidity measurement have been widely used to measure water pumped from a fixed sampling point but suffer from several important limitations, perhaps the most important being the problem posed by the different optical response of sediment particles of different colors and diameters. For example, the turbidity response of clay is much greater than sand, and turbidity vs. solids concentration calibration achieved for one grain size distribution will not be valid at a larger discharge if the grain size distribution changes significantly. These instruments are also subject to biological fouling of the optical surfaces and have maximum concentration thresholds that they can measure. As an advantage they are relatively robust and inexpensive.

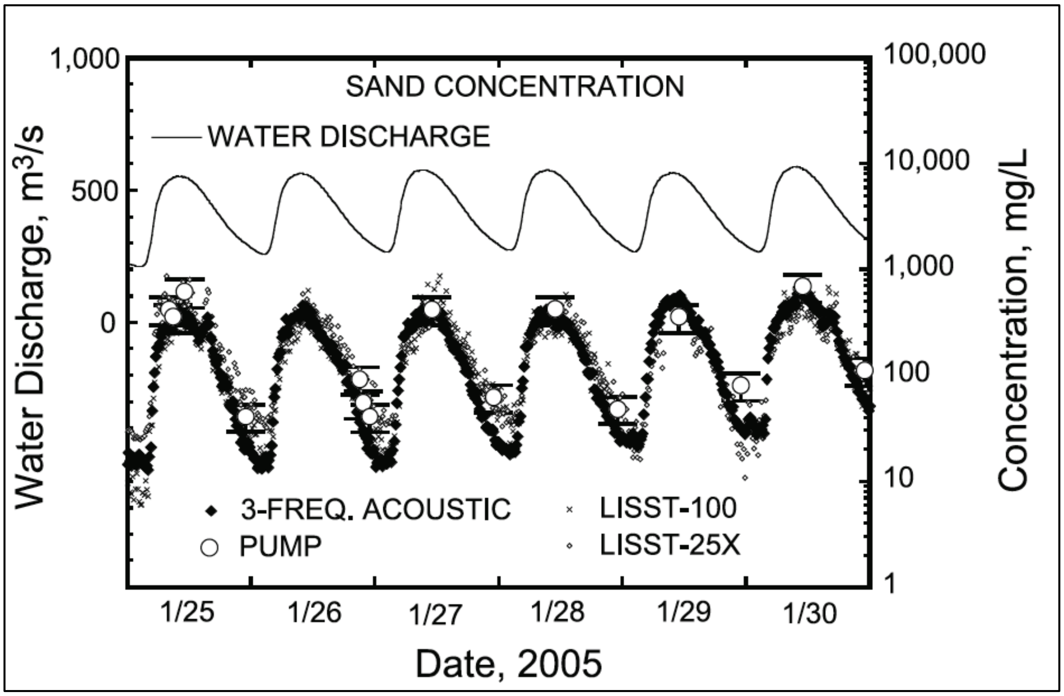
Laser diffraction technology is also applied to water pumped from a point sampler. It projects a laser beam into a flow-through test cell and a sensor consisting of concentric ring detectors placed behind a receiving lens registers discrete cones of scattered light. Each ring detector determines the concentration of sediment grains for different grain size classes, and the total suspended sediment concentration is derived by summation.

(Currently available instruments can sample over 30 grain size classes with grain diameters from 1 to 500 microns). High concentrations are handled by a dilution procedure. Laser diffraction instruments can also be subject to biological fouling, have the limitations inherent in point sampling instruments, and are currently several times more costly than turbidimeters. However, portable units are available, including a streamlined, submersible, bridge-deployable model that can replace conventional depth-integrated samplers using bottles, providing virtually instantaneous data on both concentration and grain size distribution.

Acoustic Doppler profilers use acoustic backscatter to measure suspended sediment concentrations through the entire water column rather than at a single point, though they do not measure the entire cross section. Therefore, they monitor a much larger sample of water and partially address the limitations inherent in point sampling. A single-frequency array cannot differentiate between a change in concentration and a change in grain size distribution, but a multifrequency array properly calibrated to the site can overcome this limitation and provide the potential to approximately resolve concentrations by fine versus coarse fractions (clay-silt versus sand size), but without providing details on the grain size distribution. This technology is generally immune to biological fouling, and the cost can be lower than laser diffraction instruments.

An example of comparative data obtained by different methodologies is presented in Figure 19, showing how variations in suspended sediment concentration can be tracked using different methodologies. Broad application of these surrogate technologies has the potential to revolutionize fluvial sediment monitoring to provide safer, near-continuous, consistent, arguably more accurate, and less expensive stream sediment data as compared to conventional methods (Gray and Gartner 2009).

Figure 19. Variation in concentration of sand in the Colorado River in the Grand Canyon as measured by different instruments (Topping et al. 2007). LISST refers to laser diffraction instruments.



4.7 Reservoir half-life

Sedimentation rates may be expressed as the annual percentage loss of the total original storage volume. The computation of *reservoir life*, taken as the time required to completely fill the reservoir and typically computed by linear extrapolation of the observed sedimentation rate, is not a relevant concept because most reservoir benefits are largely lost well before the entire volume is lost. Furthermore, as the volume declines, the capacity/inflow ratio and trap efficiency decline resulting in a declining rate of storage depletion over time. A better indicator of the period of effective reservoir operation under conditions similar to the original project plan is the *reservoir half-life*, the time required for the loss of half of the original capacity.

Half-life computations for the main stem reservoirs on the Missouri River are shown in Table 7. These data illustrate a characteristic of US reservoirs, previously noted in the nationwide sedimentation survey reported by Dendy and Champion (1978), that sedimentation rates tend to be very low in the large federal reservoirs because they have a large storage volume in relation to the inflow. In contrast to the relatively lower rates of storage loss in US reservoirs, the average rate of storage loss worldwide has been estimated to range from 0.5% to 1% annually (White 2001 and Mahmood 1987, respectively).

Table 7. Sedimentation rates in main stem Missouri River reservoirs.

Dam	Year Closed	Total Original Volume (acre-ft)	Total Storage Loss by 2019, %	Annual % Loss	Year of 50% Storage Loss
Ft. Peck	1937	19,557,000	6.6	0.08	2562
Garrison	1953	24,728,000	6.0	0.09	2508
Oahe	1958	23,751,000	3.7	0.06	2786
Big Bend	1963	1,980,000	10.1	0.18	2240
Ft. Randall	1953	6,208,000	16.5	0.25	2152
Gavins Point	1955	575,000	30.1	0.47	2061

Note: Storage loss by 2019 is extrapolated from the most recent survey based on long-term rate of storage depletion.

4.8 Sediment yield

Sediment delivery into reservoirs is highly variable over time, with most sediment being delivered by large floods. The sediments trapped in reservoirs present a cumulative record of all the sediment delivered to the reservoir from upstream but must be adjusted for sediment bulk density and for reservoir trap efficiency before the accumulated sediment volume can be converted into sediment yield from the watershed. Long-term data on sediment yield are useful for projecting the average rate of sedimentation and to identify changes in sediment yield that can significantly influence reservoir life.

Sediment transport is the most difficult parameter to measure in the fluvial environment since both concentration and grain size change over time and with respect to both the horizontal and vertical location of the sampling site within the river cross section. Furthermore, much of the transport occurs during large events, which may be difficult or impossible to measure accurately. In mountainous areas, episodic events such as landslides, debris flows, and fire also play a significant role in sediment transport, and channels may accumulate sediment over a period of decades and have this load washed out and delivered downstream by an extreme flood.

Reservoir survey data may also be subject to significant error, as already discussed. For this reason, it can be useful to plot data on storage loss from multiple sources within the same physiographic environment on a graph of annual storage loss vs. drainage area to detect data that appear to be suspect (an example is given in Figure 74 as part of the Jennings Randolph case study).

Sediment yield is the amount of sediment transported by a stream past a specific point and is expressed in units of mass/year. The *specific sediment yield* is derived by dividing sediment yield by the area of the contributing watershed. In some regions, the specific sediment yield will tend to decline as watershed area increases due to sediment redeposition, onto river floodplains for example. However, in other regions there is no clear relationship between these two parameters (De Vente et al. 2005).

Sediment yield is based on sediment mass, but reservoir sedimentation rate is typically measured in terms of volume loss. Because of the paucity of data from sediment cores, published values are frequently used to convert between one and the other. When there is uncertainty concerning existing and future rates of volume loss by sedimentation, it is useful to compare data from multiple sources within the same physiographic region, converting sediment yield data into an equivalent sediment volume. An example of a plot of sedimentation rate vs. drainage area and developed for Jennings Randolph reservoir by Burns and MacArthur (1996) is shown in the case study for that reservoir (Figure 74).

When determining the grain size distribution of sediment containing clays, it is important to measure the sedimentation velocity using native water and without the aid of a deflocculant. Use of standard geotechnical laboratory techniques (deflocculant and distilled water) will determine the clay fraction of the sample, but not the sedimentation velocity, because sample preparation destroys the flocculation that occurs in natural waters. Nevertheless, differentiation between the silt and clay fraction is needed to estimate parameters such as future compaction and cohesion so, when significant amounts of clay are present, tests with and without deflocculant are recommended.

4.9 Sediment bulk density

The dry weight per unit of submerged sediment volume is the *specific weight* or *dry bulk density* (pounds per cubic foot, grams per cubic centimeter, ton per cubic meter). To estimate volume loss from fluvial sediment gage data, which reports sediment yield in units of mass, a mass-volume conversion is required. The dry bulk density can be determined by analysis of sediment cores, being careful not to compact soft sediment during the sampling and spacing cores such that each represents a known fraction of the total deposit volume to enable the overall volume-weighted dry bulk density to be computed. In soft sediment, piston-type coring devices should be considered without core-catchers as the latter device may actually prevent sediment from entering the core. Sediment compaction should be documented by cores that penetrate to the original reservoir bottom. Compaction is primarily a problem with predominantly soft sediment, as coarse sediments experience little compaction after the first year. The volume-to-mass conversion can also be estimated by empirical methods. Lara and Pemberton (1963) presented a method to compute initial bulk density, and the Lane and Koelzer (1953) method adjusts for compaction of fine sediment over time. These methods are described in EM-111—2-4000 (USACE 1995), Morris and Fan (1998) and Strand and Pemberton (1987). Representative values of bulk density are summarized in Table 8. In fine sediment, the bulk density changes with depth, as described subsequently in the John Redmond example.

Table 8. Representative values of specific weights for reservoir sediments in ton per cubic meter or grams per cubic centimeter.

Dominant Grain Size	Always Submerged	Aerated
Clay	0.64 to 0.96	0.96 to 1.28
Silt	0.88 to 1.20	1.20 to 1.36
Clay-silt mixture	0.64 to 1.04	1.04 to 1.36
Sand-silt mixture	1.20 to 1.52	1.52 to 1.76
Sand	1.36 to 1.60	1.36 to 1.60
Gravel	1.36 to 2.00	1.36 to 2.00
Poorly sorted sand and gravel	1.52 to 2.08	1.52 to 2.08

Source: Geiger (1963)

5 Visualizing and Quantifying Sedimentation

To achieve sustainable long-term utilization of reservoirs requires development of a workable mental model of the sedimentation process, which will serve as the basis for all stages of decision-making, including the design of field studies; the scope and focus of mathematical or physical modeling; and the analysis of engineering and operational alternatives. The importance of proper *conceptual modeling* of the system cannot be overstated because even the most sophisticated modeling study can address the wrong problem or be undertaken under constraints that do not allow feasible solutions to be identified. Time spent in the field is particularly important in developing a workable conceptual model (Morris and Fan 1998).

This section outlines several formats that can prove useful for the presentation of data to better conceptualize the sedimentation problem and that can help identify management options and develop criteria and strategies for more detailed analysis.

5.1 Analysis of existing data

Existing data for USACE reservoirs are typically reported on Form 1787, which provides general characteristics of the reservoir, plus elevation-area-capacity curves for different survey dates. These existing data can be reported and displayed in several ways to extract information that can be helpful in assessing future sedimentation trends.

Elevation-capacity data for each top-of-pool elevation can be reported in the summary format shown in Table 9, a format that requires little effort to extract. Although the table shows only the elevation-capacity data, the top-of-pool area data should also be reported. Pool volumes are computed by difference and then plotted against time to better visualize the sedimentation trends impacting each pool plus any data irregularities that may be attributed to modified survey techniques or other causes (Figure 14). These same data can also be used to compute trends in the rate of volume loss (see Figure 17). It is recommended that these data be reported and analyzed for all reservoirs, since they can be tabulated, graphed, and analyzed to provide a quantitative picture of the sedimentation situation nationwide.

Table 9. Sample of format for summarizing elevation-capacity and elevation-area data.

Reservoir Identification		Survey Date	Survey Type	Cumulative Pool Volume (acre-ft)			Notes
				Inactive (1020')	Conservation (1039')	Flood Pool (1068')	
Reservoir:	John Redmond	Sep-63	Range (D)	3,479	54,630	650,260	
State:	Kansas	May-74	Range (D)	745	46,032	636,820	
Lat:	38° 14′ 32″ N	Sep-83	Range (D)	273	38,244	630,538	
Long:	95° 45′ 20″ W	Aug-91	Range (R)	188	34,757	626,007	
District:	Tulsa	Aug-93	Range (R)	190	33,386	623,138	
		Jul-00	Contour	0	27,726	574,918	

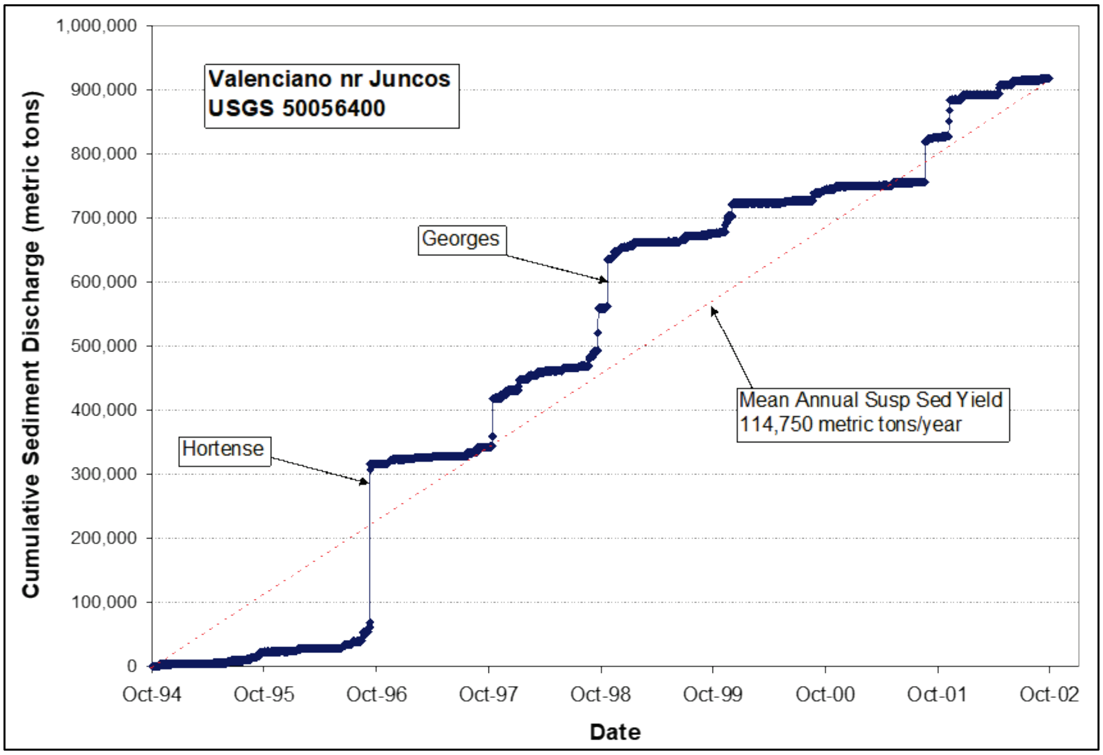
The complete elevation-area-capacity dataset can be analyzed to compute the average sediment deposition thickness by elevation increment and plotted in the format shown in Figure 71. This graph format illustrates the depth zones within the reservoir most affected by sedimentation much more clearly than an elevation-capacity curve such as that shown in Figure 48.

5.2 Hydrology and sediment supply

Plotting of daily inflow over time will provide a general picture of the reservoir inflow characteristics and seasonality. It will also give a general picture of the extent of inflow variability and the general relationship between base flow and flood events. For the analysis of sediment transport, a daily time-step is typically the longest time-step that should be used, and because concentration can vary greatly over the duration of an individual storm, data at shorter time-steps (e.g., 15 min) should be reviewed for significant inflow events insofar as these data are available. A plot of sediment concentration vs. time (rather than sediment load vs. time) will help identify opportunities for implementing management strategies based on bypassing or pass-through of high concentration flows.

Cumulative mass plots are particularly useful for identifying changes in trends and can also show variability over time. A plot of cumulative sediment load vs. time, such as presented in Figure 20, can illustrate the significance of major events with respect to the overall sediment load. At this site, a significant reduction in sediment load could be achieved by routing sediments on only 6 days over an 8 yr period.

Figure 20. Cumulative daily sediment load with time, Río Valenciano River in Puerto Rico, showing the importance of Hurricanes Hortense and Georges in sediment transport.



A graph of cumulative sediment load vs. cumulative water discharge can also be used to analyze trends in sediment concentration. If this plot curves upward, it indicates increasing average suspended sediment concentration, and a downward curve indicates declining concentration over time. However, if suspended sediment measurement techniques are modified (e.g., by increasing the sampling frequency during flood events or use of continuous sampling), this may produce an apparent change in concentrations, the result of having better data rather than a consequence of changed load from the watershed.

Sorting the data by ascending discharge, and plotting cumulative load vs. discharge, will provide the basis for identifying the range of discharges most important from the standpoint of sediment delivery.

5.3 Presentation of bathymetric data

Bathymetric data should ideally be collected using GPS with either single or multibeam sonar for underwater areas and lidar for dry areas of the reservoir and used to prepare a digital terrain map (DTM). A pre-impoundment DTM should also be prepared from original topographic data so that data such as sediment thickness can be mapped by comparing graphic information system (GIS) data layers. Bathymetric data may be presented in a variety of formats:

- Longitudinal profiles of the original reservoir bottom and the new bottom corresponding to each survey, showing also the elevation of the outlets at the dam and the normal operational range (Figure 4, Figure 61, Figure 72), to help understand the sedimentation process in a reservoir
- Time-wise plot of gross and conservation volumes, to provide information on rate of storage loss, changing rate of storage loss, and data uncertainties (Figure 14, Figure 17, Figure 70)
- Elevation-area-capacity curves showing the curves corresponding to each bathymetric dataset, to track volume changes in each pool (Figure 48)
- Representative cross-section plots showing the pattern of sediment deposition at different transects along the reservoir, located at range lines to incorporate data from early surveys (Figure 3, Figure 62)
- Longitudinal profile of cumulative reservoir volume for the original condition and the sediment condition (Figure 21)
- Contour map showing reservoir depth (or bottom elevation) for the current condition
- Contour map showing thickness of sediment deposits (Figure 47)
- Sediment thickness as a function of elevation computed by difference using the elevation-area-capacity curves, dividing each increment in cumulative capacity by the corresponding area increment (Figure 71)
- Map showing the track lines in the bathymetric survey (Figure 22)
- Aerial photography of delta advance patterns, while not part of the bathymetric dataset, can also be very useful to help visualize processes (Figure 5, Table 2).

The amount of available data will vary considerably between reservoir sites, and the data needs and format for data presentation will also vary depending on the characteristics of each site.

Figure 21. Plot of cumulative volume as a function of distance above the dam.

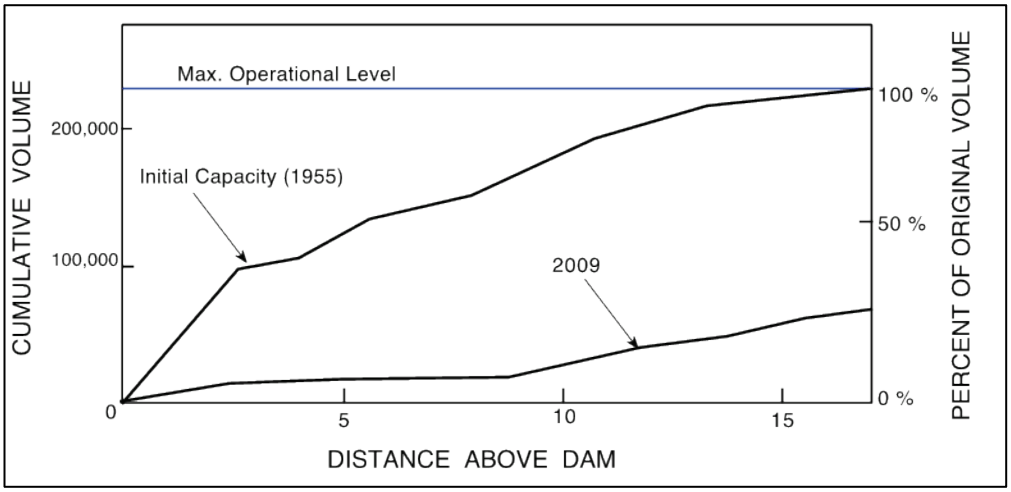
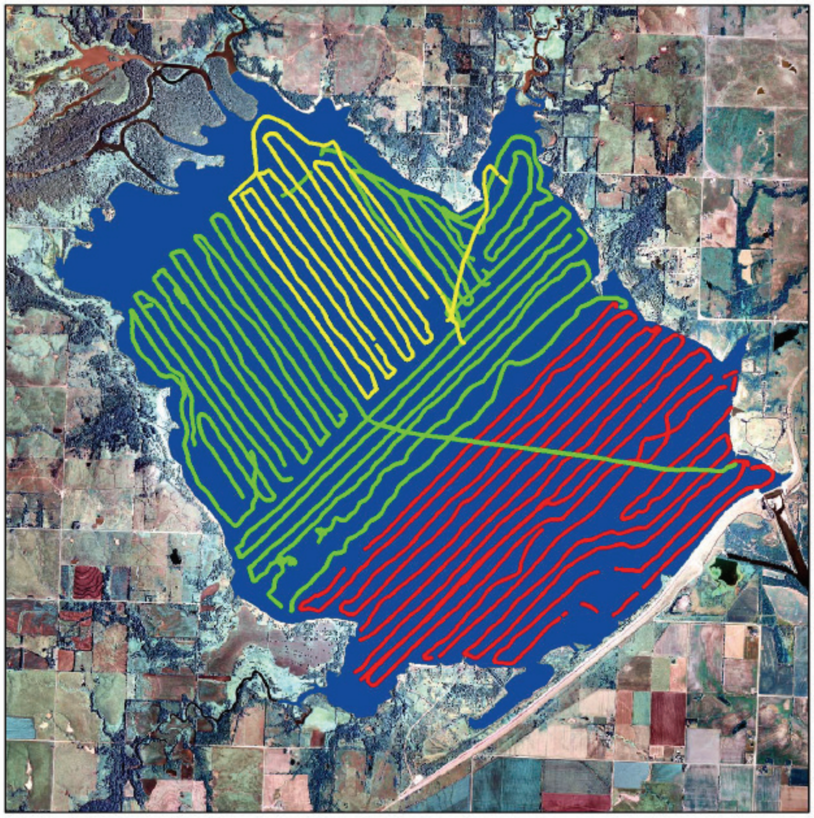


Figure 22. Map of bathymetric survey track lines in John Redmond Reservoir (Kansas Biological Survey 2010).



5.4 Data from sediment cores

Sediment core locations should be presented in plan view or on the longitudinal profile, and the data from the individual cores may be plotted either individually or collectively. For example, collective data on dry bulk density as a function of depth are presented for John Redmond Reservoir in Figure 49. In presenting density profiles, never group data from cores in different parts of the reservoir as the delta sediments will be very different from the finer bottomset sediments.

Grain size data can also be plotted as a function of distance above the dam, such as the example at Lewis and Clark reservoir shown in Figure 63. It is the upper layer of sediment that is typically most important because that is part of the sediment that can be mobilized. Fine sediment buried 30 ft deep under delta deposits will probably have very little opportunity for remobilization and for this reason is of limited relevance in the preparation of a longitudinal grain size profile.

5.5 Regional or national summary reports

To facilitate the quantitative analysis of basic sedimentation data from reservoirs regionally or nationwide, a standardized electronic reporting format should be utilized. The minimum recommended data are summarized in Table 10, which also indicates the fields that were included in the 2008 USACE data call. These data can be analyzed to compute the percentage of capacity loss by pool for each reservoir and an initial projection of the half-life of each pool. This information can then be summarized at the regional or national level to better quantify storage loss status and trends.

Table 10. Minimum reservoir data needed for nationwide database to quantify sedimentation conditions.

Item	Description	In Data Call?
1	Name: dam, reservoir	Yes
2	Identification number(s)	Yes
3	Dam location: latitude/longitude, USACE district, river	Yes
4	Authorized uses	Yes
5	Dam location: state, other political jurisdiction	No
6	Current allocations: name and top-of-pool elevation for each	No
7	Elevation-area-capacity data (following format of Table 9)	No
8	Inflow: mean annual inflow (to compute trap efficiency)	No
9	Watershed area: total and unregulated	No
10	Hydropower: installed capacity	No
11	Data reporter: name, date of report	Yes

5.5.1 Reservoir sedimentation (RESSED) database

The Advisory Committee on Water Information Subcommittee on Sedimentation developed a reservoir sedimentation (RESSED) database that incorporated reservoir-capacity data from the USACE, the USBR, and other entities. This database includes data provided through 2013 and was based on a previous database, RESIS-II (Ackerman et al. 2009). The database is still available from the USGS (USGS 2014). RESSED includes a relational database, interactive maps for viewing the reservoir locations, a list of reservoirs, and individual data sheets for the reservoir. The database includes fields for all of the information suggested in Table 10, except for the installed hydropower capacity. Although the database was last updated in 2013, the data for many of the reservoirs have not been updated since the 1970s or earlier.

5.5.2 Reservoir Sedimentation Inventory (RSI)

The USACE developed the Reservoir Sedimentation Inventory (RSI) as a successor to the RESSED database (Jonas et al. 2010; Cooper 2015; Pinson 2016). The RSI includes a web portal for data entry and reporting, storing the data in the USACE CorpsMap Oracle database. The web portal can calculate annual storage loss rates and estimated reservoir storage loss rates. The RSI was initially populated with the contents of the RESSED database and was subsequently updated by both the USBR and USACE with more recent survey information (Pinson et al. 2016; Kimbrel 2017). It now contains over 60 updated surveys that were not present in the RESSED database. As of 2020, access to the RSI database is available to credentialed users upon request.

6 Sedimentation Management Options

Multiple strategies are available to address reservoir sedimentation. Three broad types of strategies focus on actively managing sediment while the fourth strategy is *adaptive* in that it does not modify the sediment but rather modifies infrastructure or patterns of use to adapt to the accumulating sediment. These strategies, summarized in Table 11, are (1) reduce sediment inflow from upstream, (2) pass sediment through or around the impoundment to minimize sediment trapping, (3) remove sediment after it has been deposited, and (4) structural and operational modifications to adapt to sediment accumulation. Figure 23 lists specific techniques within each strategy.

The physical and end-user environment varies considerably from one reservoir to another, and each has its unique set of constraints and opportunities. Within this complexity, a variety of different specific techniques may be considered, including multiple methods to implement any particular strategy. It will typically be most effective to employ a combination of management strategies, and the techniques suitable for implementation can change over time and as reservoir volume diminishes. For example, it may be feasible to release turbid density currents in the initial period following initial impounding, but these currents may no longer reach the dam when sedimentation alters the bottom geometry of the reservoir. Conversely, strategies such as sediment pass-through by drawdown may be infeasible when the reservoir capacity is large but may become more attractive as sedimentation reduces reservoir volume.

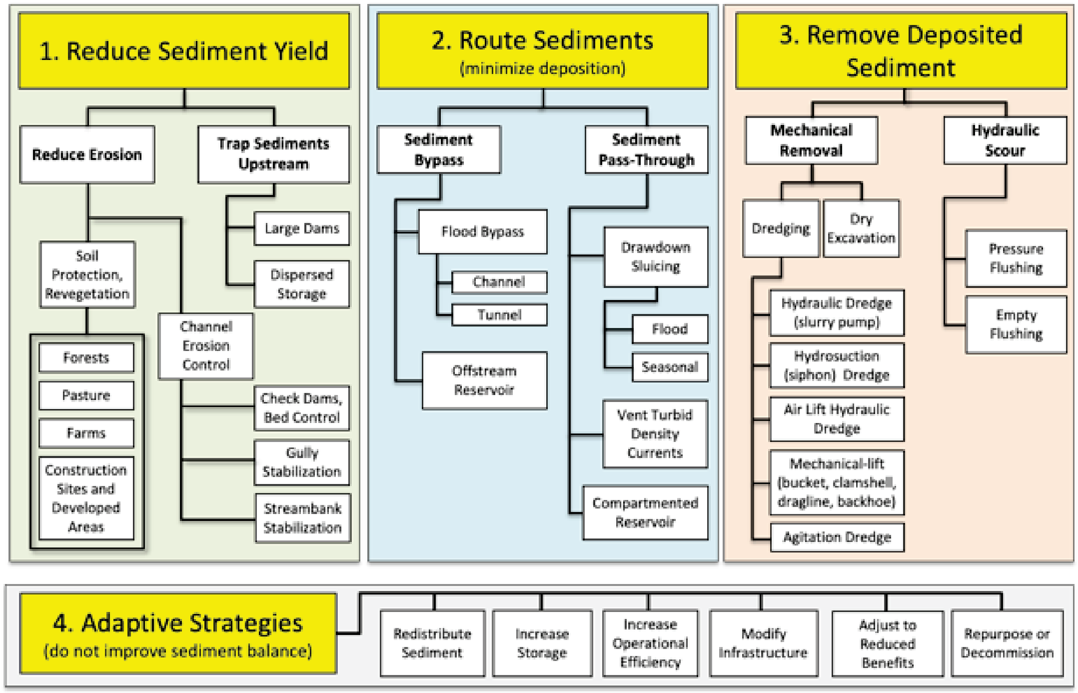
Table 11. Classification of sediment management strategies.

Strategy	Description
Reduce sediment input	Watershed Sediment Management to reduce sediment yield entering the reservoir. This may include a wide variety of practices such as reduced grazing intensity and on-farm practices to reduce erosion, improved forestry practices, erosion controls in channels, and low impact development techniques in urban areas. Upstream Trapping of eroded sediment in structures ranging from small check dams and farm ponds to major reservoirs.
Sediment routing	Sediment Bypass. Sediment is passed around the storage zone, for example, by constructing an off-stream reservoir or sediment bypass channel, tunnel, or pipeline. Sediment Pass-through. Route sediment through the impounded reach by either short-duration or seasonal reservoir drawdown. The lowered water level accelerates flow velocity, transporting sediment to the dam.

Table 11 (cont.). Classification of sediment management strategies.

Strategy	Description
Sediment removal	Flushing. Use hydraulic action to scour previously deposited sediment. Flushing requires full reservoir drawdown to be effective. Pressure flushing occurs with water ponded in the reservoir and only removes a scour cone in front of the flushing outlet. Dredging. Remove sediment from underwater by mechanical means. Excavation. Remove sediment from an empty reservoir.
Adaptive Strategies	Raise the Dam. Increase storage volume. Relocate Structures. Move or modify intakes or other structures to avoid sedimentation impacts. Operational Efficiency. Increase operational efficiency to achieve better utilization of the available storage. User Adaptation. Users adapt to reduced water supply or flood control by increasing the efficiency of water utilization, alternative flood control strategies and investments, etc. Pool Re-allocation. Reallocate pools to better apportion sedimentation impacts between the flood control and conservation pools. Retire Infrastructure. Retire infrastructure or abandon beneficial uses which can no longer be sustained in the face of sedimentation.

Figure 23. Classification of sediment management alternatives.



7 Reduce Sediment Yield

7.1 Overview

Watershed sediment management can reduce sediment yields significantly in many instances and should be evaluated as a long-term strategy for reservoir sustainability.

Watersheds have a characteristic *natural* rate of sediment delivery. Human interventions, vegetation removal being the most important, can greatly accelerate rates of erosion and sediment delivery downstream. Watershed management seeks to reduce erosion and sediment yield but may also have a variety of other corollary objectives and benefits such as improving soil infiltration to enhance vegetative growth and recharge aquifers and to produce overall improvements in water quality.

To have a measurable impact on sediment yield, watershed management needs to be applied across large areas of land and will typically require a coordinated effort by multiple organizations working with many landowners, both private and public. Each may engage in management activities having different objectives in mind. While the dam owner will seek to reduce the sedimentation rate, others may seek to improve water quality for fishing; farmers may want to retain topsoil and nutrients on their fields to improve their yields; the city council may see landscape and water quality enhancements as supporting tourism; etc. No one organization may have the wherewithal to achieve the desired level of change, which makes working together to achieve multiple benefits a key to successful management at the watershed scale.

7.2 Sediment sources

Sediment delivery into a reservoir is a two-stage process: (1) erosion involves the detachment of sediment from the soil or stream boundary to initiate its motion and (2) the transport of sediment from the erosion site to the reservoir which may be many miles downstream. There are multiple opportunities for sediment to be redeposited along the way, and as a result, erosion rates are characteristically much higher than sediment yield. This ratio is termed the *sediment delivery ratio*:

$$\text{Sediment Delivery Ratio} = \frac{\text{Sediment Eroded}}{\text{Sediment Yield}},$$

Erosion rates are estimated by models using data from small erosion plots tested on different soils, slopes, and cropping systems. These plots measure transport over relatively short distances; the erosion plots used for the universal soil loss equation are 22 ft long.

Both upland areas and the channels that transport sediment can contribute to the sediment yield, and the relationship between these two types of sources will vary from one watershed to another. This makes it essential to understand the sources of sediment, to properly focus control efforts. Also, the primary source of sediment can change over time in response to human activities, as demonstrated by the experience in the Yazoo Basin of Mississippi described further below.

There are many potential sources of sediment, and watersheds vary considerably with respect to the dominant erosional and sediment delivery processes. Measures that were successful in one watershed may be ineffective in another. Floodplains and channels downstream of eroding landscapes may capture sediment causing channels to aggrade. If upstream erosion rates decline, the channels may start to degrade, releasing the accumulated sediments. Increased flood peaks due to upstream activities that increase runoff peaks (e.g., loss of vegetation, channel straightening, or urbanization) can initiate aggressive channel erosion, especially in highly erodible, silty soils.

Spatial information on sediment source areas, sediment yield per area, and probable delivery ratio from different types of erosional features, is essential to evaluating the potential for reducing sediment yield by erosion control. Spatial data can also be very helpful in identifying areas of potentially high sediment yield. However, spatial data are typically developed within a GIS environment primarily for land surface erosion, which may not have a high sediment delivery ratio. Sediment yield from channel incision, streambank erosion and gullying are normally expected to have higher delivery ratios because they supply sediment directly to the river but are much more difficult to address through GIS techniques. Be careful that sediment sources are not prioritized based on the limitations of the analysis system, rather than the reality expressed in the field.

The Yazoo Basin in the Lower Mississippi Valley is an area long known for its highly erodible soils. The 1901 soils survey (Bonsteel 1902) provides the following text on one of the photographic plates demonstrating extreme gullying: “Memphis silt loam in the cane hills region, showing the excessive erosion in nearly level land. The soil washes or seems to melt away, even on gentle slopes, and it appears impossible to prevent this with ordinary cultivated crops.”

The USACE has demonstrated a watershed systems approach to reducing sediment yield in the Delta Headwaters Project (DHP), formerly known as the Demonstration Erosion Control Project. The DHP activities targeted 16 watersheds comprising 2,625 mi^2 in the Yazoo Basin and achieved reductions in sediment yield of up to 60%. The DHP resulted in significant advances in the state-of-the-knowledge with respect to watershed rehabilitation and sediment yield reduction. This knowledge is documented in multiple publications, including a report by Biedenharn and Watson[5].

The effectiveness of watershed sediment management in reducing downstream sediment delivery is addressed in *Sediment Management at the Watershed Level* (Leech and Biedenharn 2012). They showed that the nature of sediment yield changed over the period of nearly 200 yr. Forest clearing for crop production occurred during the period 1830–1910 in the Yazoo Basin. Without erosion controls, the fragile soils of the area produced massive amounts of sediment that infilled natural stream channels, causing flooding. The flooding problem was addressed by channelization, which in turn initiated an aggressive phase of channel incision, thus moving the dominant erosion problem into the channels.

Today the Yazoo Basin is a pathway dominated system that is very efficient in delivering sediment downstream, and in which the channels themselves are eroding through both incision and widening and represent a major contributor of sediment. In this case, a very small percentage of the landscape can contribute the majority of the sediment. Responding to the nature of sediment delivery in the Yazoo Basin, the DHP focused on stabilization of stream channels rather than upland erosion sources. For additional information refer to Leech and Biedenharn (2012) and the Federal Stream Corridor Restoration Handbook (NEH-653), developed with input from 15 federal agencies. Of critical importance in any stream restoration project is understanding the scour forces that will be present

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[5] Biedenharn, D. S., and C. C. Watson. 2011. *Delta Headwaters Project: A Review*. Report to the Vicksburg District, US Army Corps of Engineers.

during floods and ensuring that either the geometry is modified to disperse these forces or that any structural measures are capable of withstanding these forces.

7.3 Trends in rate of volume loss

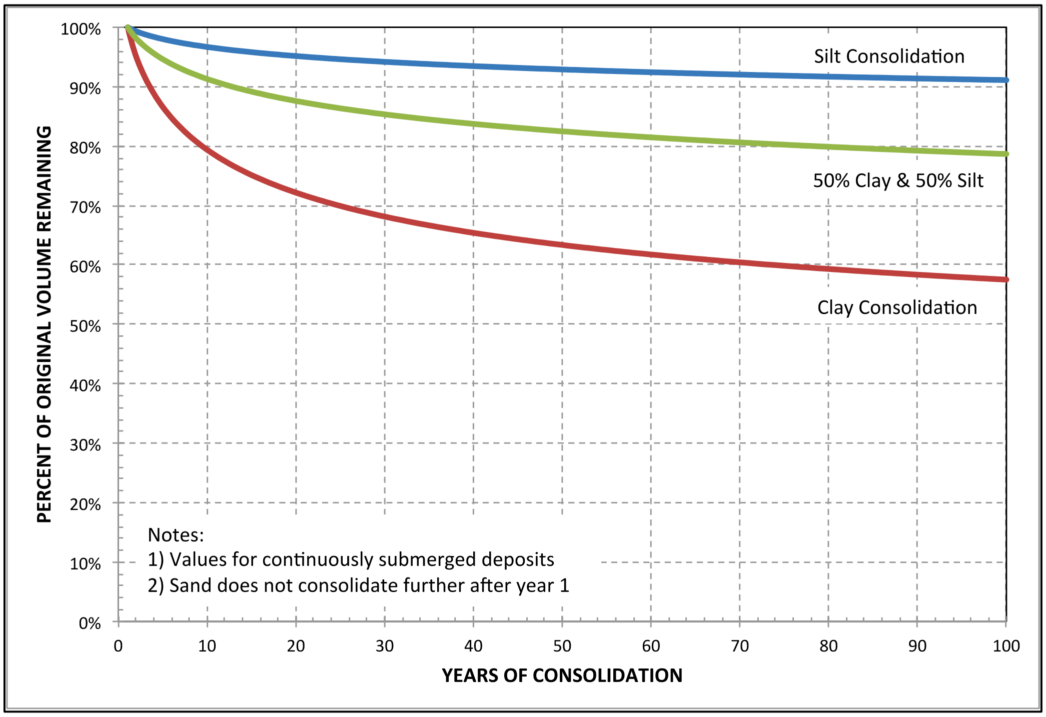
When plotting data on the rate of annual storage loss from reservoirs, the rate of volume loss usually declines over time (Figure 17). Three principal factors may contribute to this observed decline in the rate of volume loss over time: (1) reduced rate of erosion due to land use controls, (2) reduction in sediment yield from upstream by trapping in artificial ponds and impoundments, and (3) consolidation of the sediment deposits. At present, there is no clear information on the relative contribution of each of these potential factors.

7.4 Sediment consolidation

Reservoir sediment will consolidate under self-weight, and based on the analysis of the bulk density of sediments from reservoirs, Lara and Pemberton (1963) developed an empirical equation for estimating the initial bulk density of deposits at the end of the first year after settling. These values have been supported by subsequent reservoir resurveys (Strand and Pemberton 1987). The method to estimate compaction by self-weight was presented by Lane and Koelzer (1953) and Miller (1953). These procedures differentiate among three types of reservoir operations: *continuously submerged*, *periodic drawdown* and *normally empty*. These procedures are outlined in Strand and Pemberton (1987) and Morris and Fan (1998).

These methods have been used to generate the graph of compaction over time shown in Figure 24. Under the continuously submerged condition, the sediment’s initial bulk density is low, and this initial condition allows the greatest consolidation over time. Clays exhibit the lowest initial weight and also the greatest degree of consolidation as they are compressed by additional sediment deposits whereas sands do not exhibit appreciable consolidation and are not graphed.

Figure 24. Decrease over time in the volume of sediment deposits under self-weight consolidation calculated for continuously submerged conditions, which is the condition that will generate the greatest reduction in sediment volume.



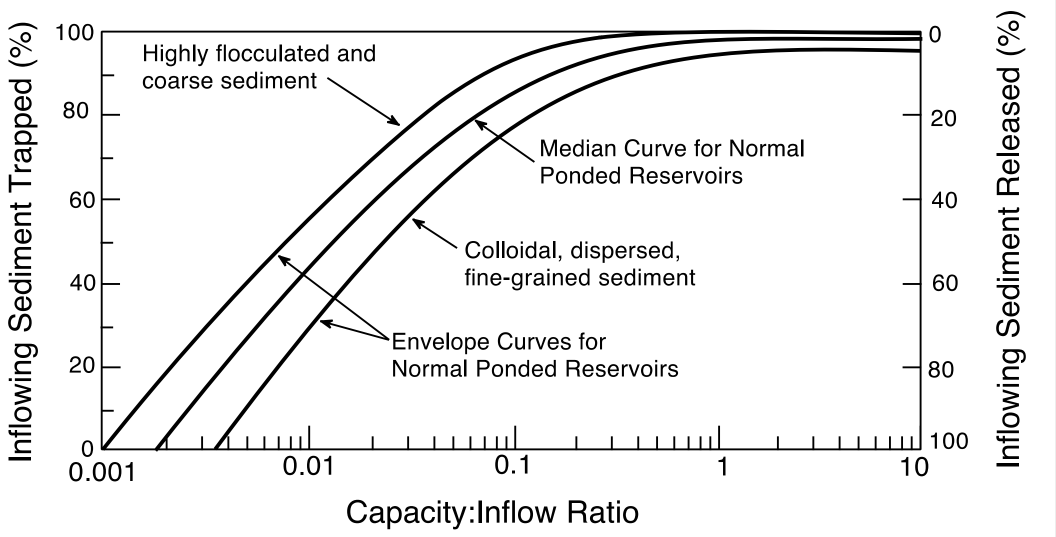
The problem of computing consolidation in an entire reservoir is complicated by the different sediment composition and operational modes in each pool. Sediment deposited into the flood control pool will consolidate under a different operating rule than sediment in the conservation pool, and the grain size distribution may also be different. Nevertheless, in reservoirs with significant clay content the process of sediment consolidation may be a significant factor in explaining the general trend of declining rate of storage loss.

7.5 Yield reduction by upstream impoundments

The most effective measure to reduce sediment inflow to a reservoir is by constructing storage reservoirs farther upstream that act as sediment traps. A large number of reservoirs have been constructed in the United States, and these can have a substantial effect on sediment delivery to downstream impoundments. For example, the California state database lists 57 dams above Folsom Dam on the American River (Minear and Kondolf 2009). The gradual construction of upstream reservoirs will be reflected in a corresponding decline in sediment yield, until such time as the upstream reservoirs fill with sediment or initiate management procedures to release sediment downstream.

Sediment *trap efficiency* is the percentage of the inflowing sediment load retained within a reservoir, and it varies greatly from one event to another. Whereas all sediment from a small inflow event may be captured, a significant percentage of fine sediment from a large flood having a short hydraulic residence time may pass through the impoundment and beyond the dam producing relatively low trap efficiency. The long-term trap efficiency as a function of a reservoir's hydrologic size, expressed as ratio of total reservoir capacity to mean annual inflow (the capacity:inflow or C:I ratio) is approximated by the Brune (1953) relationship shown in Figure 25. The three curves represent an envelope of conditions ranging from reservoirs having a lower average trap efficiency (reservoir emptied annually, slowly settling sediment) to reservoirs having a higher average trap efficiency (continuously impounding, coarser sediment inflow). In normally impounded reservoirs, a significant decline in trap efficiency does not occur until a reservoir's C:I ratio becomes quite small. Virtually all coarse sediment will be trapped until the delta approaches the dam.

Figure 25. Trap efficiency as a function of reservoir capacity:inflow ratio (Brune 1953).



A sediment transport model, properly calibrated against the entire historical impounding period, is the preferred tool for predicting future sedimentation patterns and trap efficiency, particularly as reservoir volume diminishes and trap efficiency declines. A properly validated model can simulate the contribution of major discharge events to the sedimentation process, as well as the sediment management benefits of alternative operational measures such as the routing of sediment-laden floods through the reservoir-by-reservoir drawdown.

The important role of considering sediment trapping by upstream reservoirs and sediment trap efficiency was illustrated by the work of Minear and Kondolf (2009) in predicting the future rate of storage loss at the 1,382 reservoirs registered within the State of California. This methodology requires (1) estimates of specific sediment yield by physiographic region, (2) the location of each reservoir and its watershed limits overlain on the physiographic regions to estimate sediment load from the unregulated watershed above each dam, (3) a hierarchy of reservoirs within each watershed and construction dates and volume for each site to account for changes in sediment trapping over time, and (4) a procedure to estimate sediment trapping efficiency at each reservoir, since trap efficiency declines as reservoir capacity diminishes. To facilitate computation of watershed areas and sediment loads, the data were organized in a GIS database, locating each dam on a digital elevation map with an overlay for physiographic regions. This facilitated computation of watershed areas and sediment loads. Because the Brune relationship (Figure 25) requires data on annual inflow, which was not available for approximately 80% of the reservoirs, it was necessary to use Brown's equation (Brown 1944) to estimate trap efficiency from watershed area:

$$T_{a,t} = 1 - 1/[\,1 + 0.00021 * K_{a,t-1}/A)],$$

where $T_{a,t}$ is the decimal trap efficiency of reservoir a at time-step t, A is the watershed area, and $K_{a,t-1}$ is the capacity of reservoir a at time-step $t-1$. This analysis (Table 12) demonstrates the importance of accounting for both trap efficiency and upstream dams when assessing long-term sedimentation impacts.

Table 12. Cumulative loss of existing reservoir volume computed by alternative methodologies (adapted from Minear and Kondolf 2009).

Methodology to Estimate Sedimentation	Cumulative Percentage Storage Loss	
	Year 2000	Year 2100
Using Total Basin Area and 100% Trap Efficiency	16%	70%
Correcting for Trap Efficiency and Upstream Dams	4%	15%

Although often overlooked, even small structures such as stock watering ponds can act as efficient sediment traps, and if abundant, can have a significant impact on sediment yield. In the conterminous United States, Renwick et al. (2005) estimated there are at least 2.6 million, and possibly as many as 8 or 9 million, small impoundments that capture runoff from approximately 21% of the total drainage area. Total sediment capture in these ponds was estimated at 25% to 100% of the total sedimentation in the 43,000 reservoirs listed in the US National Inventory of Dams. Over time, the trap efficiency of upstream reservoirs may be diminished as it fills with sediment, if this is not achieved earlier by implementing active sediment management practices.

7.6 Climate change and future sedimentation rates

Sediment yield will be influenced by climate change, but the magnitude and direction of climate change impacts may not be clear because of offsetting factors. For example, increasing aridity in some regions will reduce vegetative cover and make the soil more susceptible to erosion, but the decreased precipitation will reduce runoff and thus sediment transport capacity (Huang and Makar 2013), unless the smaller precipitation depth is focused into more intense rainstorms (another anticipated impact of climate change). Because climate change will produce a variety of responses at the land surface, including changes in land management techniques by humans, future changes in sediment yield associated with climate change cannot be accurately predicted at this point, but the combination of climate change plus land use impacts from population increase is expected to sustain or increase sediment yields over time in many parts of the world (Walling 2009). Most studies show climate change to be associated with increasing sediment yield.

Wildfire accelerates erosion rates and fires are increasing worldwide, from the Siberian tundra to tropical forests. In the United States, the increase in wildfire is most dramatic in the western forests, but very large fires are projected to also increase in frequency in other regions such as northern forests and the southern coastal plain, including much of Florida (Barbero et al. 2015). In the western United States, an ensemble of climate, fire, and erosion models projected post-fire sediment yield to increase in nearly all watersheds and more than double in over one-third of watersheds by mid-century (Sankey et al. 2017). Littell et al. (2018) modeled change in ecosystem productivity and fire in response to climate change in the western United States. They found that, in moist areas, warmer and drier conditions will extend the fire season and make more fuel available, increasing fire frequency and area burned. Three to five decades may be required for the climate-fire regime to reset to a new regime characterized by reduced fuel production. In contrast, in ecosystems that are already relatively dry, fire frequency may diminish as drying further limits the supply of available fuel.

The effects of climate change on reservoir sedimentation will vary regionally (Pinson et al. 2016). The USACE has conducted multiple studies looking at climate change impacts on sedimentation. At Coralville Lake in Iowa, 30% of the modeled climate scenarios resulted in increased sedimentation (Karlovits and Landwehr 2014). A study of the potential impacts of climate change at Garrison Dam showed that all scenarios resulted in increased sediment loading to the reservoir, but the additional sediment would have little impact on pool elevations and releases (USACE 2012a). Cochiti Lake, on the Rio Grande in New Mexico, is expected to experience decreased spring peak flows, resulting in a reduction of the transport of coarse-grained sediments into the reservoir (USACE 2012b). T. A. Dahl and Kendall (2017) examined projected climate change impact in two adjacent watersheds in the Great Lakes and observed differing impacts, with average sediment outflows at the river mouth increasing in one case and decreasing in the other, although there was a wide range of results.

There is a widespread concurrence among climate change models that precipitation will become more variable and, in particular, that extreme events will become more frequent. For example, the consensus results of multiple global climate models across multiple scenarios projects that the 20 yr, 24 hr extreme precipitation event will increase approximately 6% for each 1°C (1.8°F) increase in warming (Viatcheslav et al. 2007). Studies of the Midwestern United States indicate that increased precipitation coupled with a bias toward more intense storms, trends already being observed, will increase both runoff volume and soil erosion (Soil and Water Cons. Society 2003; Pinson 2016). Because the most intense 10% of storms account for about half the increased precipitation, erosion rates will increase more rapidly than total precipitation (Nearing et al. 2005). However, farmers are expected to respond to climate modification by changing cropping patterns and management techniques, which will affect erosion rates (T. A. Dahl et al., 2018). Modeling studies for 11 regions within five Midwestern states of the United States (O’Neal et al. 2005) took these factors into consideration and concluded that soil loss might increase by a factor ranging from 33% to 274% in 10 of the regions and would decrease slightly in the eleventh. However, as pointed out by Walling (2009), because of low sediment delivery ratios, only a small percentage of the erosion may actually find its way into downstream reservoirs due to sediment re-deposition near the point of erosion, at the base of slopes, in upstream ponds or impoundments, in channels and wetlands or on floodplains. It may also be possible that increased high flows will cause more erosion from in-channel sources, increasing the efficiency of the channel network and the sediment yield delivered to reservoirs downstream.

Reservoirs are constructed to reduce variability in water flows, taking the peaks off floods and increasing low flows either downstream or in diverted water. The ability of reservoirs to provide these services diminishes as reservoir volume is reduced by sedimentation and also as the variability of hydrologic inputs are increased by climate change. Thus, climate change may cause two simultaneous effects that impact the ability of reservoirs to control floods and sustain water supplies: increased sedimentation and increased hydrologic variability.

When conducting climate change analyses for USACE reservoirs, it is recommended to consult with the Climate Preparedness and Resilience (CPR) Community of Practice (https://www.usace.army.mil/corpsclimate/). The USACE has formal guidance about incorporating climate change into studies (USACE 2018) and looking for trends in streamflow (USACE 2017). The USACE CPR group has created a number of tools to make climate change analyses easier, including regional syntheses of recent climate change and hydrology; a non-stationarity detection tool; and a climate hydrology assessment tool.

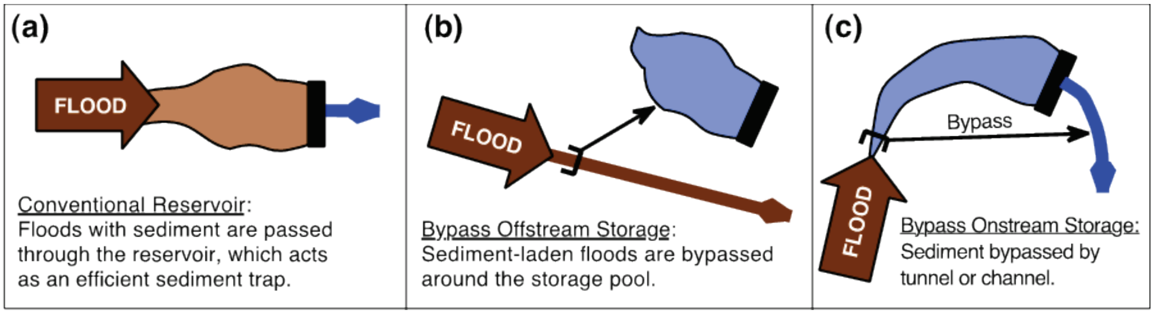
8 Sediment Bypass

8.1 Overview

Suspended sediment concentration is positively related to discharge, and consequently the variation in sediment load over time is much greater than the variability of streamflow itself. Based on a review of data from gaging stations in the United States, Meade and Parker (1984) noted that more than half of the annual sediment load is characteristically discharged within a period of 5 to 10 days, and that over a period of years, a large proportion of the long-term sediment yield may be transported by a few large but infrequent storm events. Sediment management is necessarily focused on the management of high discharge events, and management strategies such as sediment pass-through or sediment bypass are based on taking advantage of this variability to develop procedures to impound the clear water and avoid sediment-laden flow.

Sediment bypass seeks to capture clear water in the storage pool and bypass sediment-laden flows around the pool. As conceptually illustrated in Figure 26, bypass can be achieved by diverting flow with low sediment concentration into an *offstream* or *off-channel* reservoir or by diverting sediment-laden flows around an instream reservoir. Offstream reservoirs may be fed by gravity or by pumping. Both techniques can be highly efficient at excluding sediment under appropriate hydrologic conditions.

Figure 26. Comparison of (a) conventional reservoir that receives the total sediment load from floods, against strategies to bypass sediment-laden flood waters by (b) an offstream reservoir or (c) bypass around an instream reservoir.



8.2 Time-wise variation in sediment yield

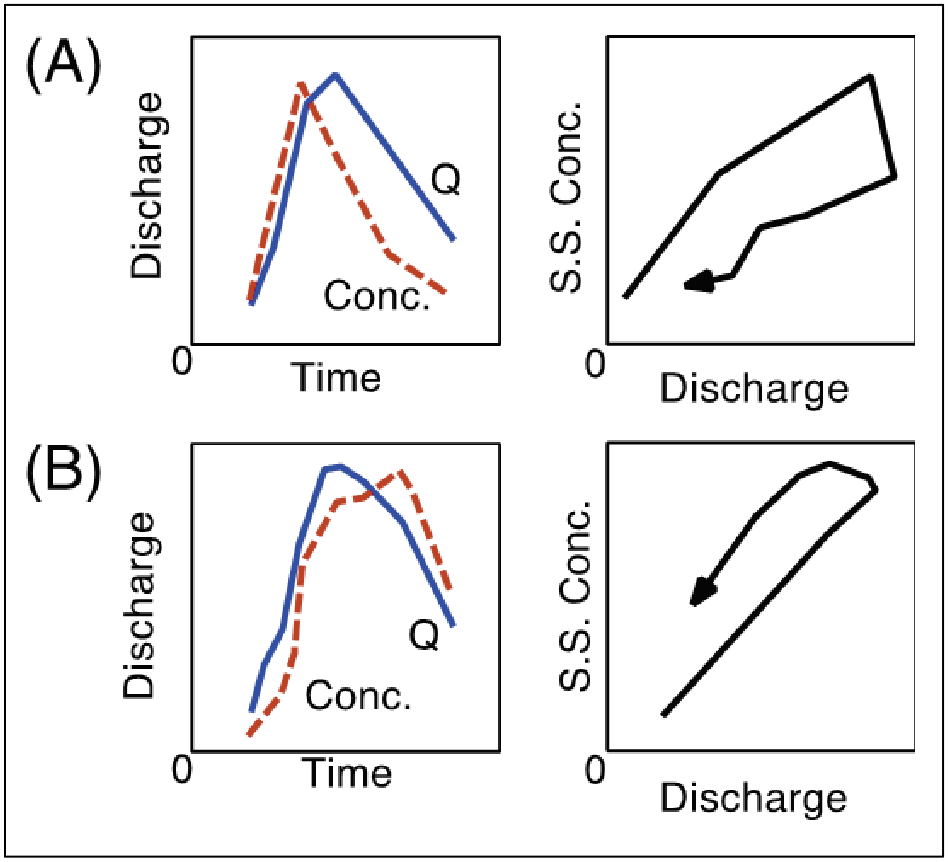
Sediment yield is highly variable over all time frames, and it is necessary to understand this variability to properly interpret sediment data and devise efficient management strategies. For example, some management strategies take advantage of the time-wise variation in suspended sediment concentration to capture and impound flows having relatively low suspended load while passing high-concentration flows through or around the impoundment.

Because so much sediment can be discharged by large floods, sediment yield can vary dramatically from year to year reflecting variation in hydrologic conditions and time-wise variations in sediment availability within the watershed. In mountainous areas, landslides can contribute over half the sediment load during extreme events, and the onset of widespread landslide activity may be associated with an intensity-duration threshold (Larsen and Simon 1993). In climates characterized by infrequent extreme events (e.g., hurricanes), these floods can generate sediment loads equivalent to many years of sediment inflow. Such events may not be captured even in decades of gage record (Kirchner et al. 2001).

The finer fraction of the total sediment load, the *wash load*, is delivered to the stream primarily by the erosion of the land surface, and the delivery rate of this material to the stream is dependent on rainfall-runoff processes in the watershed. However, transport of the coarser bed material that composes the predominant fraction of the stream bed, the *bed material load*, is driven primarily by stream hydraulics rather than the delivery rate from the watershed. Thus, in a sand- or gravel-bed stream, a storm early in the flood season may have a high total suspended load with a high component of fine wash load while a late-season storm having the same discharge may have a much lower suspended sediment concentration of fines, although the rate of bed material transport remains unaltered. The late-season suspended sediment yield may be reduced by factors such as increased ground cover as vegetation grows during the wet season and the exhaustion of readily mobilized sediment. Where a consistent time-wise sediment delivery pattern exists, it may be possible to bypass sediment-laden water at the start of the season and fill the reservoir with late-season discharge.

If suspended sediment concentration and discharge are measured continuously for the duration of a flood event, when these data pairs are plotted, they rarely produce a straight line relationship. Rather, there is typically a systematic variation within the duration of a single runoff event, producing hysteresis effects in concentration-discharge (C-Q) graphs (Williams 1989). The more common pattern is for sediment concentration to peak before discharge peaks, producing a clockwise C-Q hysteresis loop (Figure 27*A*). This can occur when the first part of the flood washes out readily mobilized sediment, leaving the latter portion of the hydrograph relatively deficient in sediment. Counter-clockwise loops (Figure 27*B*) can occur when more distant areas of the watershed have more erodible soils or when landslides develop as soils become oversaturated as the storm progresses. The hysteresis pattern is not necessarily a fixed watershed characteristic, and different storms can produce different time-wise patterns in the same watershed.

Figure 27. The left-hand graphs show the variation in concentration and discharge over time, and the right-hand graphs show the hysteresis effect when these data are plotted as concentration-discharge (C-Q) graphs. (A) Clockwise loop with concentration peaking before discharge; (B) counter-clockwise loop with concentration peaking after discharge.



8.3 Offstream reservoir to bypass sediment

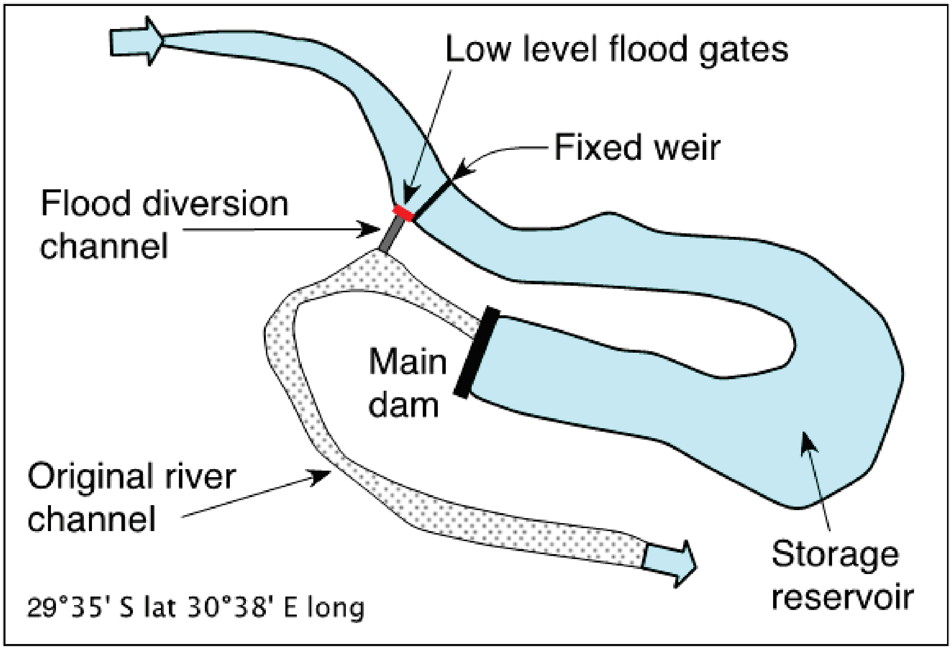
Offstream, gravity-fed, water supply reservoirs have been constructed for sediment management in Taiwan (Wu 1991) and Puerto Rico (Morris 2010). Sediment enters an offstream reservoir either as suspended sediment in the streamflow diverted into the impoundment or by erosion from the watershed tributary to the dam. Because an offstream dam should normally not need to spill water, its trap efficiency will be essentially 100%. Simulations for the Río Fajardo offstream reservoir in Puerto Rico showed that 26% of the mean annual streamflow can be diverted into the reservoir with only 6% of the annual suspended sediment load, and the intake design excludes 100% of the bed material load. This strategy produces a reservoir half-life in excess of 1000 years. Dredging will eventually be required to recover reservoir capacity, but given the small sediment load, the reservoir capacity can be maintained by relatively small dredging projects at intervals of centuries. This strategy was particularly useful for water supply in moist areas of Puerto Rico where sediment yield is both high and very episodic with over half the sediment load coming from heavy rains and floods associated with tropical depressions and hurricanes. Because rather unique topographic configurations are required for a gravity-fed, offstream reservoir, the number of potential offstream sites is quite limited, but pumping can also be used to deliver water into offstream storage.

In addition to sediment management benefits, the exclusion of floods greatly diminishes spillway size, offsetting the cost of the intake and diversion works, and because the sedimentation rate is dramatically reduced, the size of the sediment storage pool is correspondingly diminished, which again reduces the size of the structure. Offstream reservoirs also avoid environmental problems associated with the construction of onstream dams by minimizing impacts to channel morphology because bed material is not trapped by the dam, impacts to riparian wetlands can be minimized, the only barrier to the migration of aquatic species is the intake, instream water quality is not modified by the reservoir other than effects related to flow reduction, and water quality in the reservoir is also improved for users such as water filtration plants.

8.4 Sediment bypass at onstream reservoirs

Under favorable conditions sediment may be passed around an onstream reservoir using a bypass channel or tunnel which discharges below the dam. For example, the Nagle reservoir in South Africa (Figure 28) passes sediment-laden floods around the storage pool using an upstream gated dam to divert floods through a bypass channel (Annandale et al. 2016).

Figure 28. Configuration of Nagle Dam and reservoir in South Africa showing the normally impounded area and flood bypass channel.



Most sediment bypass tunnel projects to date are located in Japan and Switzerland. The Japanese have several projects in mountainous areas that incorporate a flood bypass tunnel to transport sediment-laden flow including bed material load from the upstream limit of the pool to below the dam. A small diversion dam at the upstream limit of the pool directs bed material into the bypass tunnel (Figure 29). A primary objective of these systems is to maintain bed material transport below the dam to preserve aquatic habitat and offset streambed incision. Bypass tunnels have been used primarily on mountain reservoirs that allow for tunnel slopes of at least 1%, and the maximum tunnel length reported to date is 4.3 km (Sumi and Kantoush 2011). At the Solis reservoir in Switzerland, a physical model study was used to support the design of a 900 m bypass tunnel that included a skimming barrier at the tunnel entrance to exclude floating logs (Auel et al. 2010).

The entrance to the sediment bypass tunnel may be located either above or below the normal pool level. If it is located in the river before it reaches the pool, the tunnel entrance sill is set slightly below riverbed elevation, followed by a short steep entrance reach to accelerate flow before transitioning to a long reach at constant slope. If the tunnel entrance is located within the reservoir pool, the entrance may be set below the normal reservoir level, and water is diverted during a sediment-bypassing flood event by opening a normally closed gate. These tunnels are characteristically designed for super-critical flow to maximize hydraulic capacity and minimize construction costs, but the combination of coarse sediment and high velocity can produce substantial scour damage to the tunnel floor (Sumi et al. 2004).

Figure 29. Upstream area of Asahi reservoir, Japan, shows entrance to gravel bypass tunnel on the right and cofferdam that directs flood flows into the tunnel entrance (photo G. Morris).

9 Sediment Pass-Through

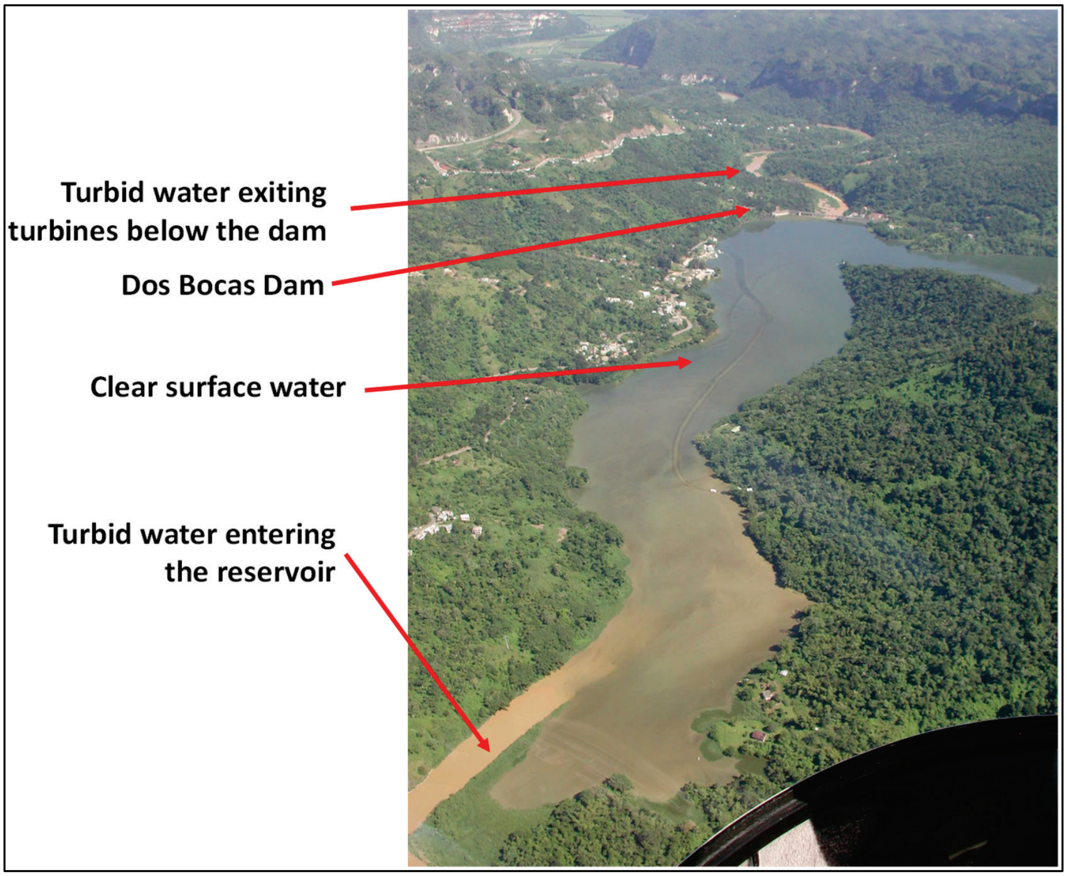
Sediment pass-through strategies route sediment-laden flows through the reservoir in a manner that minimizes sediment trapping. Pass-through strategies include (1) release of turbid density currents, (2) reservoir drawdown to pass sediment-laden floods through an onstream reservoir at a high velocity to minimize deposition, and (3) use of within-reservoir structures to reduce sediment trap efficiency. Although some previously deposited sediment may be scoured and released, the primary objective is to adopt reservoir operation to the natural sediment inflow events to minimize deposition.

Pass-through is distinct from reservoir emptying and flushing in that pass-through must be timed to coincide with natural inflow events having the highest discharge and sediment load, which requires a correspondingly large gate capacity. Emptying and flushing may be performed during lower discharge events if there is limited low-level gate capacity or during high-discharge events if gate capacity is available. The solids concentration of water released by pass-through has a suspended concentration similar to the inflowing river. In contrast, flushing is designed to achieve a large net export of sediment and can have very high peak suspended sediment concentration, with short-duration concentrations reaching 100,000 mg/L or even higher.

9.1 Turbid density currents

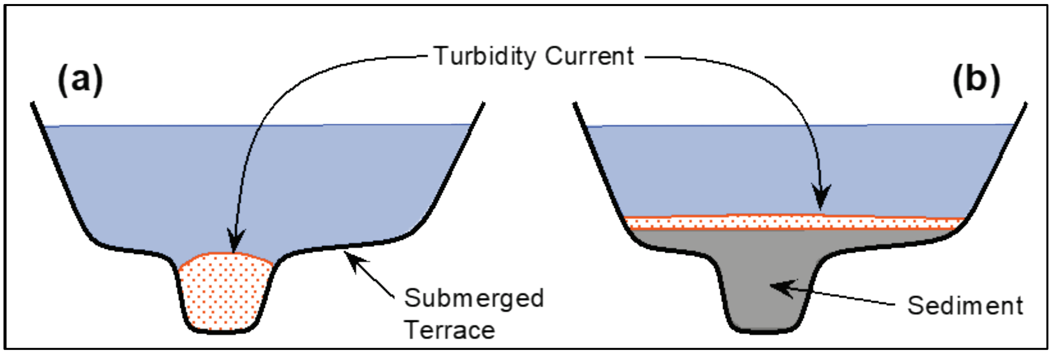
Sediment can be passed through a reservoir in the form of a turbidity current when sediment-laden flow enters the impoundment, plunges beneath the clear water, and travels downstream to the dam where it is released, as previously illustrated in Figure 7. Not infrequently, turbidity currents are released through a low-level intake as part of normal hydropower operations. The release of a turbidity current during normal hydropower operations is illustrated in the photograph in Figure 30.

Figure 30. Passage of turbidity current through Dos Bocas hydropower reservoir in Puerto Rico, showing muddy water entering the reservoir and exiting the powerhouse below the dam while surface water in the reservoir remains clear (photo G. Morris).



Turbidity current movement along the bottom of a reservoir is facilitated where a thick current can flow along a defined channel, but as the submerged channel is infilled with sediment, the geometry of the reservoir bottom becomes flat and wide. This causes the turbidity current to spread out, increasing frictional resistance, lowering velocity, and facilitating the deposition of the transported sediment (Figure 31). For this reason, turbidity currents that reach the dam soon after initial impounding may dissipate before reaching the dam once the bottom configuration is modified by deposition of sediment from the turbidity current. The submerged channel can be maintained by either flushing or dredging.

Figure 31. Schematic reservoir cross section of reservoir showing (a) propagation of turbidity current along the original river channel and (b) modification of geometry by sedimentation, which affects the configuration and hydraulic radius of turbidity current and retards its forward motion.



A detailed sediment balance at the Cachí hydroelectric reservoir in Costa Rica (Table 13) illustrates the impact of turbidity current releases in reducing the rate of sedimentation. This reservoir was being flushed each year, thereby maintaining a normally submerged channel along the reservoir, which facilitated the flow of turbidity currents to the low-level power intake at the dam where the turbidity was vented with the turbine flow. Because the turbidity current deposits its sediment load along the submerged flushing channel (which follows the original stream channel), each subsequent flushing event will scour the fine sediments deposited in this channel by the turbidity current.

Table 13.Sediment balance for Cachí Reservoir, Costa Rica, during an average hydrologic year (Morris and Fan 1998; Sunborg and Jansson 1992).

Sediment Distribution	Ton/year	Percentage of Total
Through flow (power tunnel and spillway)	148,000	18
Deposited on submerged river terraces	167,000	21
Bed load trapped in reservoir	60,000	7
Turbidity current deposits removed by flushing	432,000	54
Total	807,000	100

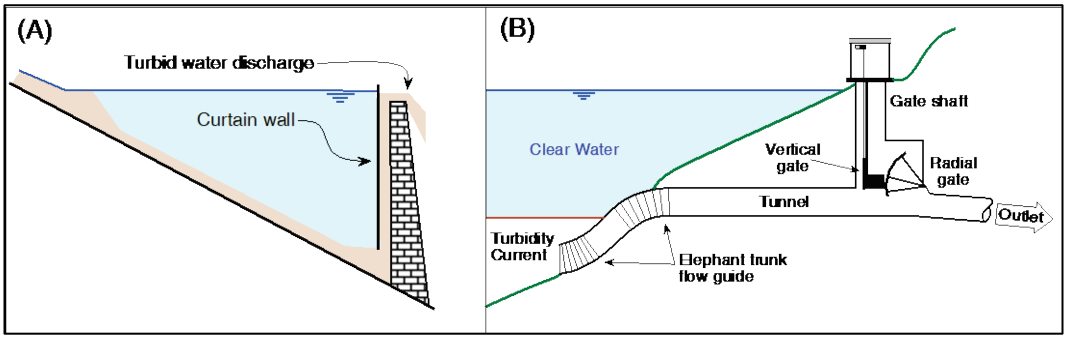
The most favorable conditions for reducing sedimentation by releasing turbidity currents occurs when most of the sediment inflow consists of silts and clays, grain sizes capable of being transported long distances by turbidity currents. These conditions occur in China’s Yellow River basin, an area of severely eroded loess (silty) soils. Some Chinese reservoirs have documented individual flood events that discharged a greater amount of sediment from the dam as turbid density currents than entered the reservoir. This occurs when the arriving current scours unconsolidated deposits from a prior event. For example, at the narrow Liujiaxia hydropower and flood control reservoir on China's upper Yellow River, over a 10 yr period, 37% of the inflowing Taohe sediment was vented (IRTCES 2005).

To release turbidity current sediments with a minimum of water release, it is necessary to know the arrival time at the dam and operate outlets to minimize the settling period in the muddy lake. Hydropower facilities with low-level power intakes may be well suited to release these currents, and a multilevel outlet structure may be used to selectively release turbidity currents. This may include the use of an intake structure designed to suction water from a deeper level to enable turbid water to be discharged through a higher-level power or other intake.

Because turbidity currents can deposit sediment in front of low-level intakes and other locations, it may be desirable to reduce the opportunity for these currents to reach the dam by trapping them farther upstream, to direct them into an outlet tunnel, or to focus their deposition into another area of the reservoir. This can be performed using either solid or permeable underwater obstacles that intercept the current, causing sedimentation to occur farther upstream in the reservoir or by orienting the barrier so that the current is diverted into a discharge tunnel or a tributary arm of the reservoir where deposition has less adverse impacts, or to trap sediments from a sediment-laden tributary.

It is not necessary to install a low-level outlet to extract a turbidity current. At the Katagiri Dam on Japan's Tenryu River, Kantoush and Sumi (2010a) have described the installation of a curtain wall in front of an ungated spillway to preferentially draw turbid water from deep in the reservoir. In Taiwan, an elephant trunk intake with a design discharge of 35,000 ft^3/s (995 m^3/s) was installed at Zengwen reservoir in 2018 to withdraw deeper turbidity currents for discharge through a higher-level outlet (Figure 32). This configuration minimized construction difficulties as the elephant trunk was pre-fabricated on land.

Figure 32. (A) Use of curtain wall or similar riser to selectively draw deep, sediment-laden water over a fixed spillway. (B) Elephant trunk intake to aspirate turbidity current through a higher level gate.



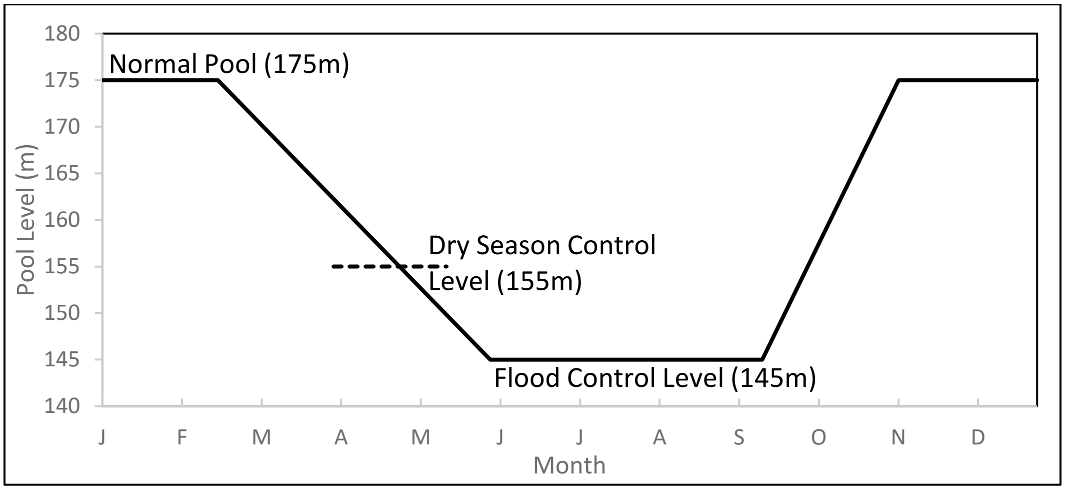
9.2 Sediment routing by reservoir drawdown

Sediment pass-through seeks to route sediment-laden inflows through the impounded reach at the highest velocity possible to maintain sediment in suspension, minimizing deposition in the reservoir. Prevention of sediment deposition is particularly important for cohesive sediment, since the velocity required to maintain cohesive fines in suspension may be an order of magnitude less than that required to scour these sediments following deposition.

High velocity flows are achieved by reservoir drawdown, lowering the water level in anticipation of arrival of the flood, passing the flood through the reservoir at the highest possible velocity (lowest possible water level), and refilling the reservoir with water having lower sediment concentration toward the end of the flood. This is essentially the method used to sustain the capacity of river barrages. Because this strategy entails drawdown and refilling of the reservoir, this strategy is most suitable for reservoirs with a small storage capacity in relation to annual streamflow. It also requires large-capacity low-level outlets or tall crest gates as the velocity through the reservoir will be determined by water level at the dam, which is a function of gate capacity. In the case of tall gates that require substantial upstream backwater to achieve high discharges, a smaller flow that produces lower water levels may generate higher velocities and be more efficient in passing sediment than a large flow which generates deeper backwater.

Seasonal operation for sediment pass-through was first documented at a large storage reservoir at the Sanmenxia Dam in China, which regulates flow from the upper 165,800 mi^2 of the Yellow River watershed. Serious sedimentation problems became evident within the first 18 months of operation. To achieve the low-level outlet capacity required to facilitate riverine flow along the entire reservoir during the initial part of the wet season required reopening of low-level river diversion works through the dam, two new outlet tunnels around the dam, and dedication of several power penstocks for sediment sluicing instead of power production. This enabled riverine flow to be achieved along the length of the reservoir, not only passing inflowing sediment but also scouring out sediment accumulated from the prior year's impounding (Morris and Fan 1998; IRTCES 2005). The Three Gorges Reservoir on the Yangtze River in China also employs seasonal drawdown to control sedimentation (Morris and Fan 1998). This operation takes advantage of the fact that from July through September, the Yangtze carries approximately 90% of the annual sediment load but only 61% of the runoff. The reservoir is over 600 km long but has a maximum width of only approximately 1.5 km, making it possible to generate high velocities along its entire length by drawdown. The operating rule for the Three Gorges Reservoir is given in Figure 33. The essence of pass-through at Three Gorges is to sluice as much sediment load out of the reservoir as possible during the flood season by drawdown. It is estimated that approximately 150 yr will be required for the reservoir to achieve equilibrium between sediment inflow and outflow (Zhou 2007).

Figure 33. Seasonal operating rule at Three Gorges Reservoir (redrawn from Zhou 2007).

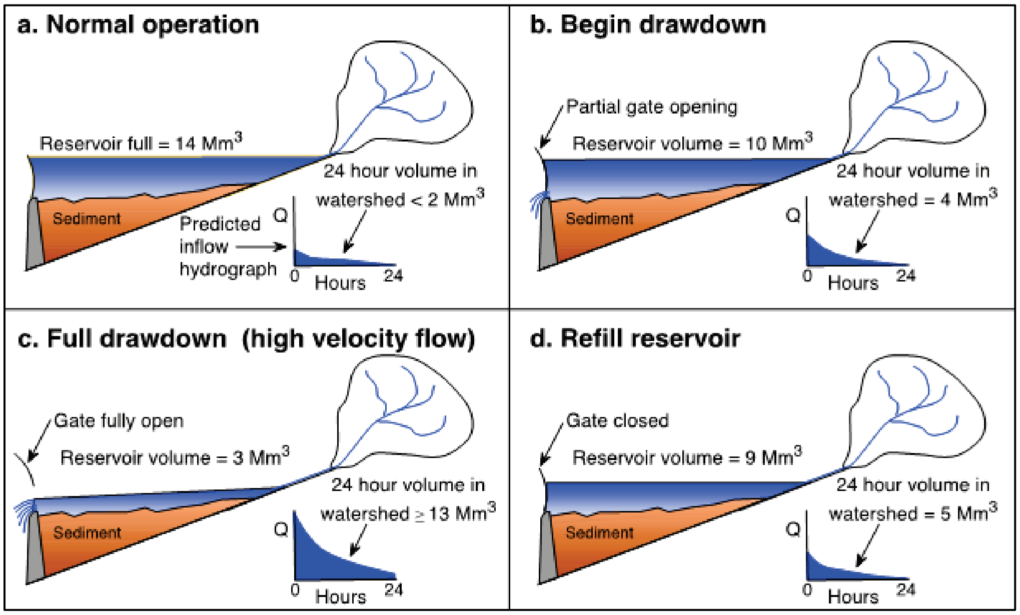


At smaller reservoirs, instead of a seasonal operating rule, the cycle of drawdown, pass-through, and refill may be associated with individual flood events. A sediment routing strategy suitable for a reservoir with a smaller watershed is schematically illustrated in Figure 34. It requires real-time rain and stream gage stations with attendant software to continuously monitor stored water volume in the reservoir and the inflow rate and to predict the volume under the recession curve of the storm hydrograph. This strategy is implemented in a sequence of four steps.

1. During periods of normal weather, the reservoir operates in a conventional water supply mode, and the hydrologic forecast system uses received (not predicted) rainfall to continuously update the forecast of inflow for the next 24 hr or other period relevant to the watershed in question.
2. At the beginning of a forecast flood, event reservoir gates are opened to draw down the storage pool to match the increase in the forecast inflow volume; in this way, there is always enough water to refill the reservoir if forecast rainfall does not occur. During this period, the reservoir will be discharging at a rate exceeding inflow, which may require that releases be limited to bankfull capacity.
3. As early as possible during the event, the reservoir gates are fully opened, and riverine flow occurs through the impoundment, transporting flood-laden water through the reservoir and beyond the dam at the highest possible velocity.
4. As the storm declines, when the sums of volume in the reservoir plus the forecast inflow volume drop to the full reservoir capacity, gates are closed and the reservoir is refilled.

Implementation parameters for this strategy will obviously vary from site to site.

Figure 34. Conceptual operation of a reservoir for sediment pass-through during large flood events: (a) normal operation, (b) initiation of drawdown as precipitation is received in the watershed, (c) gates fully open and high-velocity flow developed through the length of the reservoir, and (d) when precipitation diminishes, gates are closed to refill the reservoir.



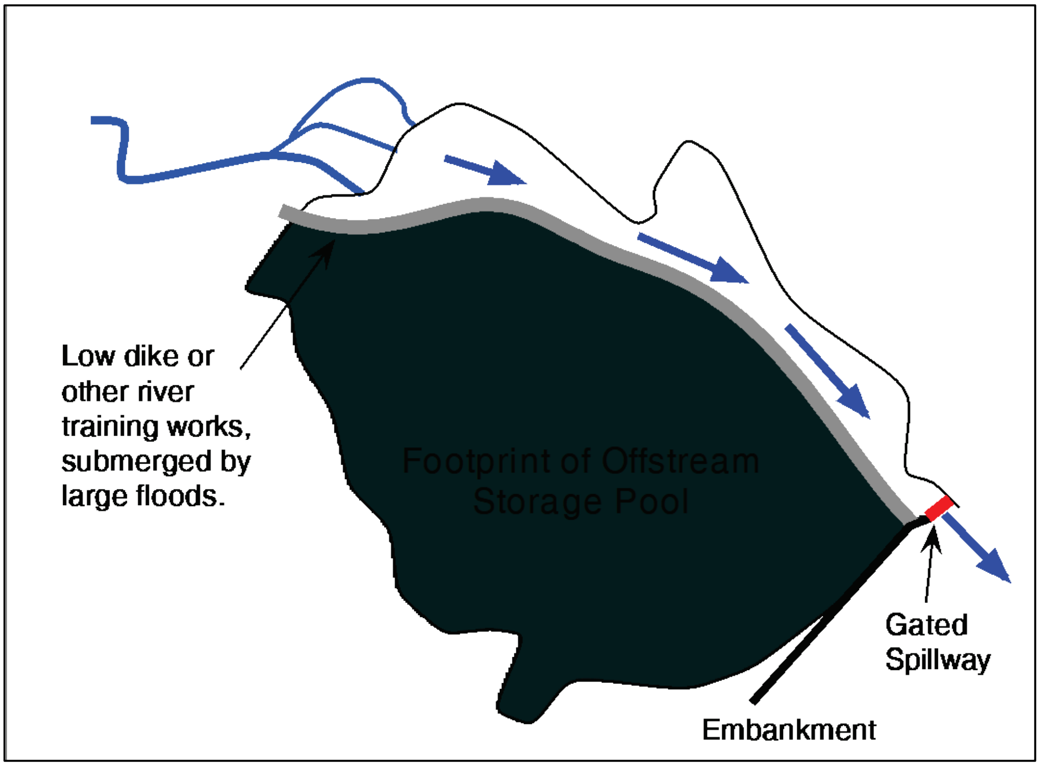
9.3 Modifying reservoir geometry to maximize pass-through

Many USACE reservoirs have a large flood control pool and a much smaller conservation pool, which in some cases can be quite shallow. For instance, the average conservation pool depth at John Redmond Reservoir is only 6.2 ft. When a flood enters a wide shallow pool, the flow velocity rapidly diminishes, and a large percentage of the inflowing sediment can be trapped.

In the case of a wide shallow reservoir, it may also be possible to establish a flood conveyance channel through the storage zone to direct as much of the flood flow as possible to the spillway area at the highest possible velocity. It would be equivalent to apportioning the reservoir footprint into a channel area for flood and sediment conveyance and an off-channel area for water storage. This configuration is conceptually illustrated in Figure 35, based on the geometry of John Redmond Reservoir conservation pool. A low dike separates the two pools and serves to guide flood flows through the reservoir with the highest possible velocity to minimize sediment deposition but would be submerged during the largest floods. The dike would be permeable or breached at planned locations so that water level on both sides of the dike would always be the same; in this manner when the dike is submerged by a flood this submergence will not occur as an erosive overtopping flow. It may not be necessary to construct a dike the complete length of the reservoir and other river training options exist. It may also be possible to apply this concept to the design of a dredging template that will increase the efficiency of sediment pass-through. The objective is not necessarily to create two separate water bodies but rather to focus flood flow within a restricted width to maximize velocity.

This configuration does not prevent sedimentation; the flood channel would continue to accumulate coarse sediment at its upstream end, which would require mechanical removal, and fine sediment deposition should also be anticipated. The storage pool would also continue to accumulate fine sediment but at a reduced rate. This strategy becomes attractive when the sedimentation rate can be substantially reduced based on site-specific characteristics. This strategy is presented as a concept as there are currently no known examples.

Figure 35. Conceptual diagram of reservoir geometry modification to bypass most flood flows around the storage pool.



10 Sediment Removal

Sediment can be removed by either hydraulic scour, termed *flushing*, or mechanically. *Pressure flushing* occurs when a low-level gate is opened while keeping the reservoir full and will scour only a limited area in front of the outlet. *Empty flushing* occurs when a low-level outlet is opened so that the reservoir is emptied and the river runs across and scours sediment deposits along the entire length of the impoundment. Sediment can also be removed mechanically from beneath the water while the reservoir is inundated (dredging) or with the reservoir empty (dry excavation). Having high costs and energy requirements, mechanical management should normally be considered as an addition to, rather than as a substitute for, hydraulic strategies.

10.1 Pressure flushing for localized sediment scour

Pressure flushing is performed by opening a low-level outlet while the reservoir pool is held at a high level. Periodic pressure flushing is useful to maintain the area in front of an intake located immediately above or adjacent to the low-level outlet. This will release only the sediment contained within a scour cone that forms in the immediate vicinity of the outlet, but it will not remove sediment from other areas of the reservoir (Figure 36).

Figure 36. Definition sketch of pressure flushing.

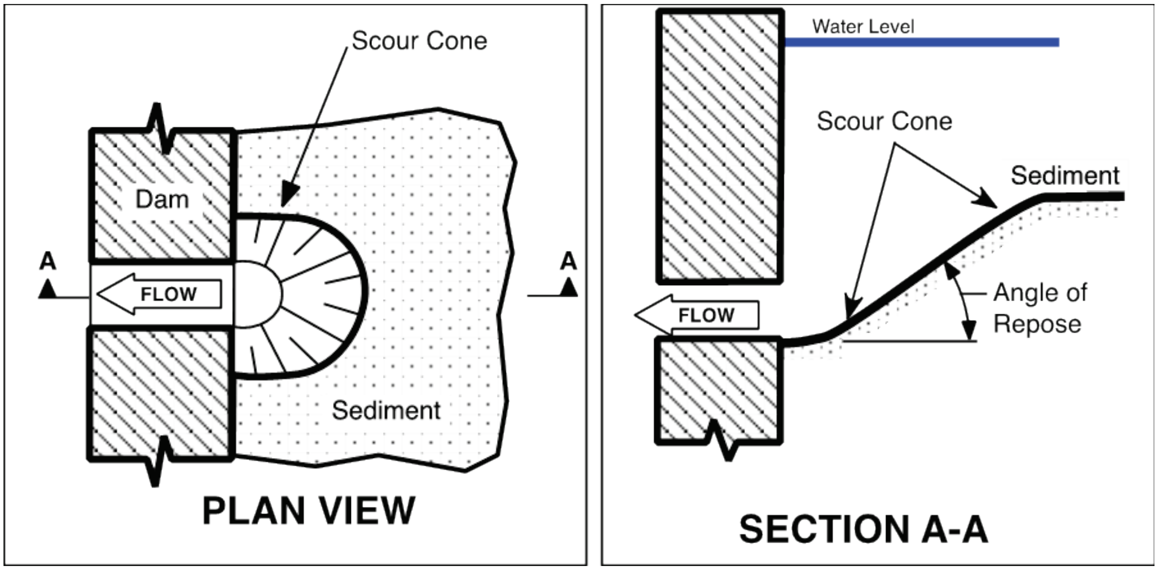
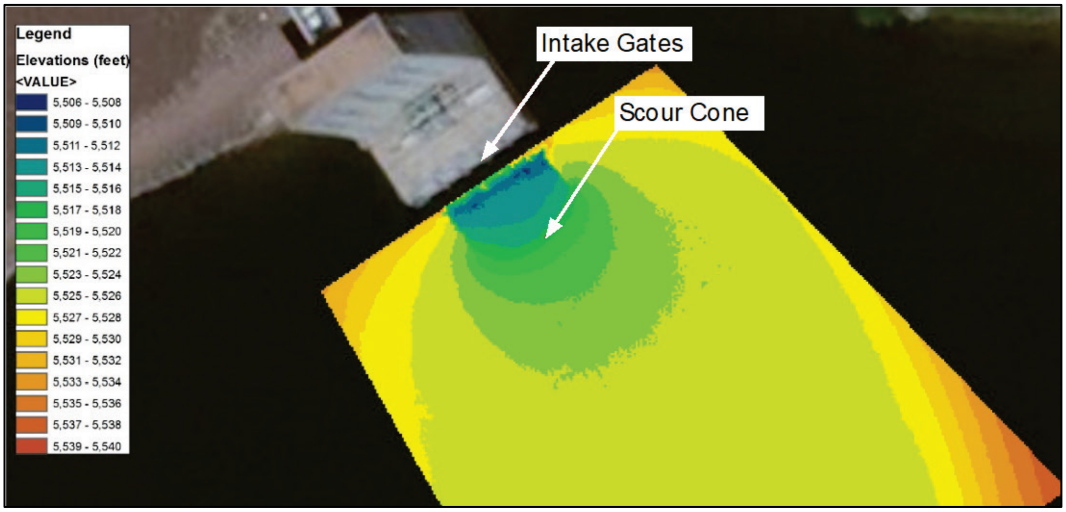


Figure 37 shows the scour cone geometry at the USACE Cherry Creek Reservoir, where annual pressure flushing maintains the intake free of sediment and debris (Collins et al. 2019). Every year, the five radial gates are individually opened and closed, using either a low-flow flush (250 ft^3/s per gate for 10 min duration) or a high-flow flush (1,300 ft^3/s per gate for 15 min) in alternating years.

Figure 37. Scour cone at Cherry Creek reservoir, Colorado (Collins et al. 2019).



In granular sediment, the side angle of the scour cone will be approximately the submerged angle of repose of the sediment, approximately 30°. However, this angle can be much steeper in the case of cohesive sediment, and operators at some sites have found it necessary to dredge cohesive sediment from the intake area to reduce clogging despite continuous hydropower releases. When the reservoir is emptied, sediments will normally slump, and the angle of repose can be less than half of the submerged value. When a low-level outlet is buried in consolidated sediment, it may be necessary to sink a small shaft (e.g., by water jet) to create a piping channel to initiate flow through the outlet.

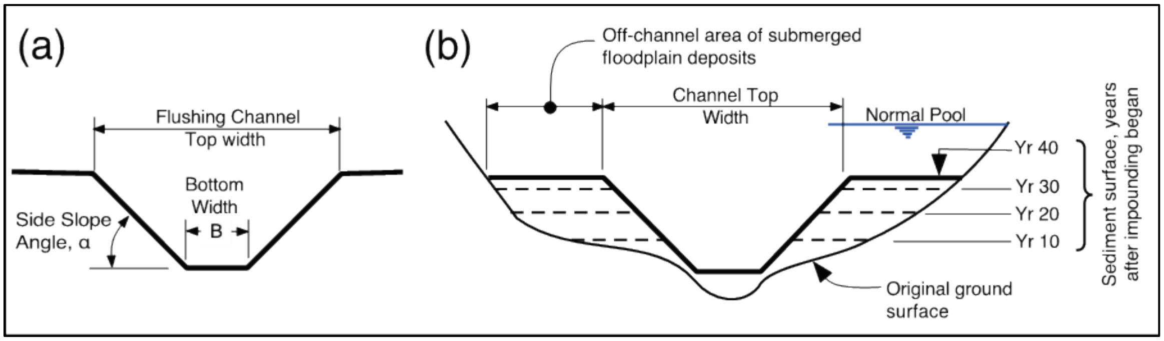
Based on laboratory experiments on scour cone formation using cohensionless sediment, Meshkati et al. (2010) reported that the half-cone created centered on the outlet at the wall of the dam was nearly symmetrical and that the volume of the scour cone is increased (angle of repose decreased) by increased discharge, increased outlet diameter, or decreased water depth over the sediment deposit.

10.2 Empty flushing

Empty flushing, or drawdown flushing, is performed by opening a low-level outlet to empty the reservoir and initiate sediment scouring along the full length of the impoundment. Over 500 yr ago, the storage capacity of irrigation reservoirs in Moorish Spain was sustained by emptying and flushing scheduled at intervals of 4 yr (Brown 1943). Today, empty flushing is more commonly performed annually for a period of several days and is generally used at smaller reservoirs on steep slopes. Empty flushing has been documented at over 30 reservoirs in the past 100 yr (T. A. Dahl and Ramos-Villanueva 2019). Only one USACE reservoir, Fall Creek in Oregon, is known to be completely emptied annually, in this case to facilitate the downstream migration of juvenile salmon (Gibson and Crain 2019).

Flushing creates a channel through the deposits, typically following the original pre-impoundment stream channel. The storage capacity that can be maintained by flushing is defined by the flushing channel's bottom width and side slopes (Figure 38). To maximize the channel width and thus the storage capacity, flushing should be performed using the highest flow rate that can be accommodated by the bottom outlet without creating significant backwater. In narrow reservoirs, flushing can preserve most of the original reservoir capacity. However, in wider reservoirs, sediments deposited on either side of the flushing channel during impounding will not be removed, instead creating a submerged terrace that will continuously accumulate sediment and increase in elevation over time. The channel created and maintained by flushing can conduct turbid density currents and sedimentation from turbidity currents will be focused therein. This will greatly reduce the sedimentation rate on the submerged terraces. The data previously presented for Cachí Reservoir in Table 13, which showed high rates of sediment removal, reflect the beneficial effects of the flushing channel, which conducts turbidity currents to the power intake at the dam. The submerged flushing channel also focuses deposition of fine sediment from turbidity currents where it is easily removed during each annual flushing event.

Figure 38. Effect of flushing on reservoir geometry showing (a) definitional cross section of flushing channel in reservoir deposits and (b) conceptual sequence of deposit configuration over time. This geometry is applicable only to deposits of fine sediment beyond the area of the reservoir delta.



Sediment deposits on the submerged terraces can be removed mechanically. They can also be removed hydraulically by diverting a flow from upstream into a diversion channel that is discharged at multiple points to create erosional channels across these deposits from the side of the reservoir toward the center. This hydraulic method was initially employed at Heisonglin Reservoir in China where sediments consist of readily erodible silts (Xia 1989; Morris and Fan 1998).

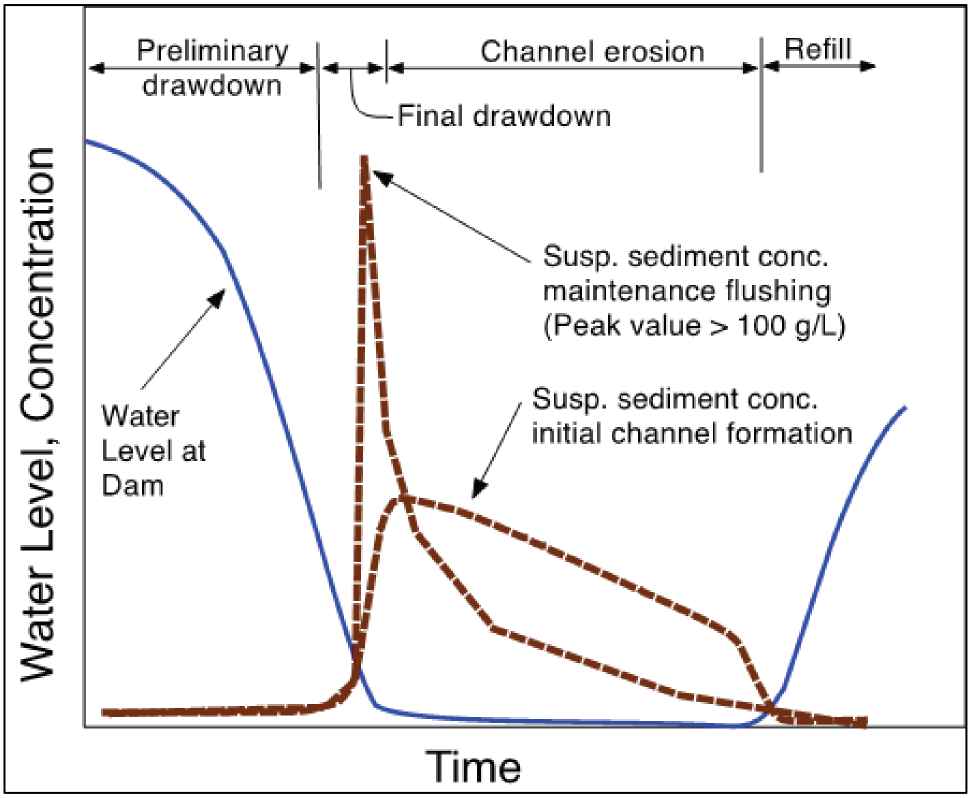
In addition to the restricted geometry that can be maintained by flushing, the ability to remove bed material sediment by flushing is also limited. Bed material is delivered into reservoir deltas by high discharge events whereas flushing flows may be limited to much smaller events by low-level outlet capacity. Consequently, coarse bed material can accumulate, as shown in the data from Cachí Reservoir (Table 13), which indicates that 7% of the total sediment inflow consists of bed material that remains trapped. At Cachí, it is not possible to schedule flushing to coincide with large inflows due to limited outlet capacity. Thus, while flushing may achieve a sediment balance for the fine fraction of the inflowing load, the coarse fraction may continue to accumulate in the reservoir. At the Unazuki Dam in Japan, Sumi and Kantoush (2010a) reported that flushing was effective in removing 73% of the total sediment inflow but removed only 10% of the annual load of coarse sediment >2 mm in diameter. In contrast, hydropower dams in the Nepal Himalaya are today being designed to incorporate large low-level outlets that can pass all inflowing bed load.

10.3 Water quality impacts

The principal impediments to sediment flushing are the downstream impacts to water quality and channel bed morphology. Variations in hydraulic parameters and suspended sediment concentration typically associated with flushing are illustrated in Figure 39. One characteristic of flushing is the occurrence of a large spike in suspended sediment concentration as the reservoir reaches the end of the emptying process and the eroded sediment begins to be discharged as a thick mud. Peak concentration typically occurs as soon as full drawdown is reached and loose mud is flushed out. High concentrations may be sustained by retrogressive erosion through highly erodible sediment deposited along the normally submerged river channel.

High sediment concentrations from flushing can produce the following impacts: consumption of dissolved oxygen; physical interference with gill function in fish or other organisms; reduced visibility and light penetration; and changes to channel morphology by infilling pools and clogging river gravels with fine sediment. Social and economic impacts include interference with water treatment processes; sediment accumulation in both navigation and irrigation canals; sediment accumulation in heat exchangers; reduced recreational quality; impacts to fisheries of economic importance; accumulation within navigational channels; and impacts to coastal areas. While the total amount of sediment released is not different from that which would have been transported downstream absent the dam, the combination of high sediment concentrations during flushing, changed downstream hydrology due to the dam, and the potential to release sediment-laden water out of sync with natural biological cycles can produce large adverse impacts.

Figure 39. Variation in water level and suspended sediment concentration characteristic of flushing events. When a reservoir is flushed for the first time and a flushing channel is gradually eroded, peak suspended sediment concentrations are lower than in the case of a reservoir flushed on a regular basis. In the latter case, poorly consolidated sediments in the flushing channel are rapidly mobilized when the reservoir first attains free-flow condition.



Flushing of alpine hydropower reservoirs has been conducted for many years in Europe. Management practices to minimize environmental impacts are summarized below based on Hartmann (2009), Eberstaller et al. (2008), Fruchart and Camenen (2012), Sumi et al. (2018), and Espa et al. (2019).

- *Timing of release*. The most important criteria for minimizing flushing impacts is the proper timing of the release. Flushing releases should be timed to coincide with natural high-flow events or releases from other reservoirs, thereby providing dilution flows, including dilution flows from tributaries downstream of the dam. Also, if flushing coincides with the beginning of the wet season, there is the opportunity for subsequent floods to cleanse the river channel and gravel beds of fine sediment deposited by the flushing release. If flushing releases sediment when fish are using gravels for spawning or the recently emerged weak-swimming larvae are using gravels for refuge, the juvenile population may be decimated, making it important to use biological as well as hydrologic criteria in selecting flushing dates. Because natural populations of juvenile fish can experience significant cyclic fluctuations, it is important to understand and document the fluctuations that occur due to natural or other impacts and separate them from the impact of reservoir management.

- *Duration of release*. At a number of sites, the volume of flow required to flush sediment from a reservoir was found to be significantly less than the volume required to transport the released sediment downstream in a manner which minimizes excessive localized sediment accumulation. The availability of tributary inflow and the ability to release clear water downstream to further transport the released sediment soon after the low-level outlet is closed are additional factors which require consideration and analysis.
- *Frequency of release*. More frequent releases can result in smaller sediment releases during each event, which would normally be considered favorable. This is particularly true of pressure flushing, which can be performed frequently without affecting the reservoir level, thereby releasing relatively small volumes of sediment in each event. For example, review of data from flushing at the Dashidaira and Unazuki Dams on the Kurobe River in Japan, indicates that downstream impacts to the river channel were limited due to the high slope and short distance (<30 km) to the sea. To minimize water quality problems, the reservoirs were flushed as frequently as possible during periods of high flow to provide high dilution volumes; this reduces the peak suspended sediment concentration and sustains higher oxygen levels in the water below the dam. Studies of reservoir flushing ecological impacts in Italy (Crosa et al. 2010) also emphasized the positive effect of frequent (annual) flushing which minimizes the amount of sediment release during any single event, in combination with the adequate release of clear water for dilution and cleaning the bed after the sediment release. Fish were impacted by both the hydraulic flow and elevated sediment concentration, with juveniles being particularly susceptible.
- *Controlling drawdown level*. Because a flushing release depends on the water level in the reservoir, the rate of sediment release can be controlled by limiting the drawdown rate or partially closing the flushing outlets to slightly raise the water if critical concentration thresholds are reached.

Sumi et al. (2018) described the following procedure at Unazuki Dam. When the suspended sediment concentration approaches the upper limit of 30,000 mg/L, the low-level flushing outlet is closed to reduce discharge and limit scour of the river bed in the reservoir. When a lower limit of 20,000 mg/L is reached, the gate opening is increased to intensify discharge and sediment scour. Multiple gate operations are performed over the course of the flushing event to maintain the sediment concentrations within the permitted range.

- *Post-flushing flows*. Clear water releases can be important at the end of a flushing event to mobilize and move sediments downstream, clear sediments out of pools, re-establish channel morphology, etc. If flushing is scheduled at the beginning of the wet season, these flows may be provided naturally. Otherwise, high-flow releases from reservoirs may be used to mobilize and flush sediments downstream. High flows are needed to mobilize bed material to wash out fines released during the flushing event (Doretto et al. 2019).

Note that critical concentrations may be best defined based on both concentration and duration. For example, for flushing of the Genissiat Dam on the Rhone River in the French Alps (Fruchart and Camenen 2012), downstream concentration limits were set at: 5,000 mg/L average during the operation, 10,000 mg/L during any 6 hr, and 15,000 mg/L for a maximum of 30 min. In China's Yellow River, where natural sediment concentrations are much higher, Baoligao et al. (2016) recommended upper limits as: 55,000 mg/L as maximum at any time and 32,000 mg/L for the average over the entire flushing event. At the other end of the spectrum, in the Cancano Reservoir on the Adda River, the main tributary of Lake Como in northern Italy, the limited capacity of the low level outlet prevented discharge during flood events. This required the slow release of sediment over 40–50 days for each of 3 yr, including use of an instream settling basin, to flush 120,000 ton. This was achieved with a peak flushing concentration of only 100 mg/L and average values in the range of 8–10 mg/L.

Although there is almost no experience with reservoir flushing in the United States, it is a strategy that is gradually becoming more common internationally, and if undertaken with care, the downstream environmental impacts can be made acceptable.

10.4 Dredging

10.4.1 Dredging costs

Dredging is often considered as a means to address sedimentation issues. However, its applicability as the principal long-term management approach is limited by high costs and the lack of adequate disposal sites. At most locations in the United States, it is not feasible to dispose of fine-grained dredged material to the downstream river due to water quality impacts. However, in some situations, as described at the Prado Reservoir example, the deposition of coarse material below the dam as a result of reservoir dredging is recognized as important to re-establishing the continuity of the transport of coarse sediment along the river system. The cost of sediment dewatering and placement, including land acquisition, engineering, permitting and environmental mitigation costs, are generally higher than the cost of dredge operation. The unit cost of reservoir dredging is typically higher than navigational dredging because dredges must be transported to the reservoir by land, are typically much smaller than the equipment available for navigational dredging, and upland dredged material containment area costs may also be higher than in navigational dredging.

The Texas Water Development Board commissioned a cost-benefit analysis to evaluate the costs of dredging existing reservoirs as a means of developing additional water supply versus constructing new reservoirs for water supply purposes. That study indicated that while dredging is a viable option of water supply augmentation, the cost per unit of storage volume for dredging, under favorable cost conditions, may be twice that of developing a new reservoir. In this case, it estimated the cost of new reservoir capacity at approximately \$1/yd^3 and the cost of dredging at \$2/yd^3. Depending on site-specific conditions, dredging costs can escalate several fold. However, the Board pointed out that the feasibility of dredging should not be based on cost alone since it may be useful as a temporary measure to forestall construction of a new reservoir, and it may be more cost effective than other alternatives such as advanced treatment technologies, including desalination. Dredging may compare favorably when measured against other project criteria such as time, permit requirements, and public acceptance (Alan Plummer Assoc. et al. 2005).

Morris and Fan (1998) described dredging operations at the Carraízo (Loíza) Reservoir in Puerto Rico during 1996–1997, which removed 6M m^3

of sand and fines, with disposal to three separate containment areas and pumping distances up to approximately 4.5 mi upstream of the dredging area. The unit cost of this operation, including land acquisition for containment plus all engineering and permitting activities, was approximately \$10/m^3 (\$7.65 yd^3). As subsequently described in the John Redmond Reservoir example, at that site, the USACE[6] estimated dredging costs of \$8–\$10/yd^3, but adding the cost of material placement, engineering and other costs approximately doubles the project cost. When the Kansas Water Office dredged at John Redmond in 2016, it ultimately cost \$6.67/yd^3, but future dredging efforts would cost significantly more due to the lack of available disposal areas. At Prado Reservoir, also described subsequently, the unit cost of dredging and re-introducing 500,000 yd^3 of sandy sediment to the river below the dam was estimated at \$17.40/yd^3. At the Rivanna water supply reservoir constructed in 1966 on a tributary to the James River in Virginia, the hydraulic dredging cost for a 1,126,010 yd^3 excavation project was estimated at \$8.84 to \$9.40/yd^3, without dewatering and placement. The total unit cost was between \$31 to \$36/yd^3 with the addition of mechanical dewatering, separation of sand for commercial sale, and haulage to a placement site (HDR Engineering 2010).

10.4.2 Dredging technology

Dredging refers to the excavation of material from beneath the water. There are broadly two types of dredging: (1) wet mechanical dredging in which the dredged material is removed from underwater by buckets such as a clamshell, dragline, or bucket ladder dredge and (2) hydraulic dredging in which sediment is excavated and transported as slurry. Mechanical dredging is generally used in low-volume applications that focus on dredging of smaller areas and the removal of woody debris, such as the area around an intake, or for the removal of gravels and cobbles, which are inefficient to dredge hydraulically. The dredged material will typically consist of a wet mud that is placed into a barge and transported to a shoreside location where it is removed and hauled to a placement site.

Most sediment is removed from reservoirs by hydraulic cutterhead dredges. Hydraulic dredges can achieve high rates of production, handle a wide range of grain sizes, and do not interfere with normal reservoir

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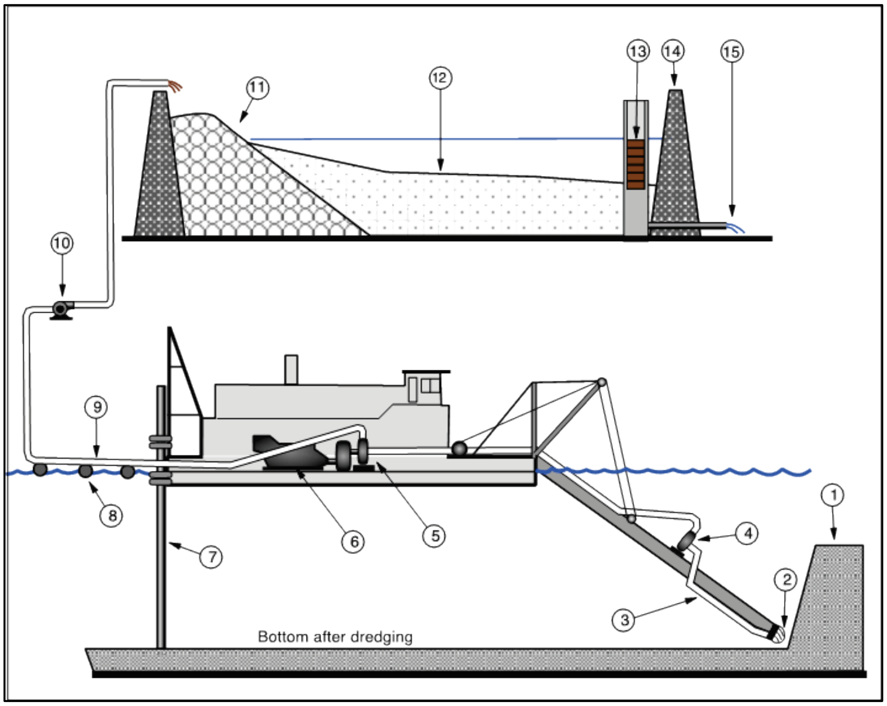
[6] USACE. 2009. Draft report. *Dredging Assessment John Redmond Dam and Reservoir, Kansas.*

operation. Turbidity production can be minimized when using hydraulic dredges, and the slurry pipeline is a clean and low-impact means to convey dredged material to the disposal site. However, an important disadvantage is the high water content of the dredged slurry, which requires costly dewatering facilities.

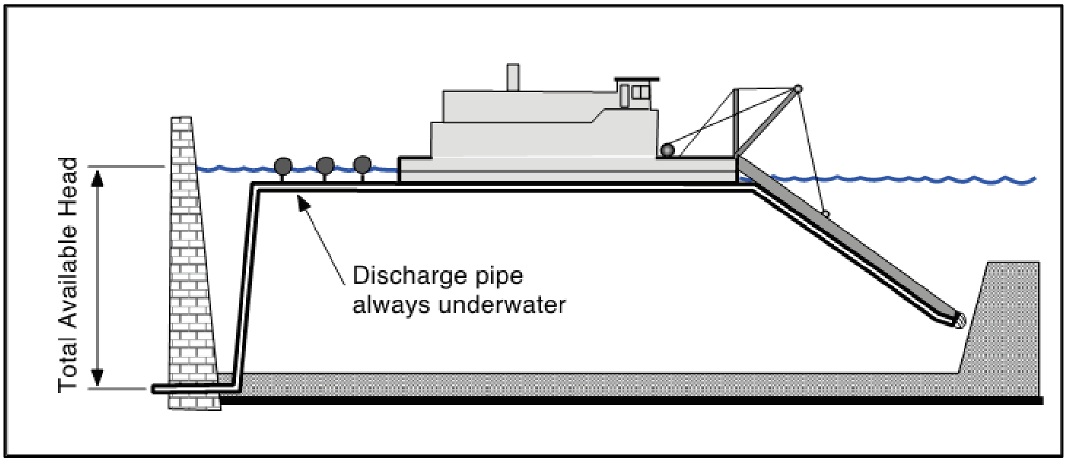
The principal components of a hydraulic dredging system are illustrated in Figure 40. The components are as follows: (1) sediment to be dredged; (2) rotating cutterhead; (3) suction line connected to the *ladder* onto which the cutterhead is mounted; (4) ladder pump, which may not be used for shallow dredging but is required for deeper or high-elevation dredging; (5) main pump; (6) main drive, either diesel or electric; (7) spud, which serves as a pivot point on which the dredge rotates to run the cutterhead back and forth across the cutting surface; (8) pontoons to support discharge pipe; (9) discharge pipeline; (10) one or more booster pumps, not always required; (11) coarser material deposited near the discharge point; (12) fine sediment; (13) discharge weir with flashboards to allow elevation to be raised as the containment area is filled; (14) containment area dike; and (15) discharge of clarified water back to the reservoir or to other receiving body.

Figure 40. Principal components of a hydraulic dredge and dredged material containment area. The containment area may serve as the permanent placement location, or it may be hauled to another location following dewatering, allowing the containment site to be reused. The numbered components are described in the body of this report.



The *siphon* or *hydrosuction* dredge (Hotchkiss and Xi 1995) can be used in reservoirs. It does not use a pump but instead uses the difference in water surface elevation between the water surface and a discharge point at the base of the dam to provide the hydraulic head needed to transport the slurry (Figure 41). The amount of hydraulic energy available is fixed by the dam height and reservoir level, the latter of which may vary over the year. Friction losses in the slurry pipeline typically limit the use of these dredges to the removal of fine sediment within approximately 2 km of the dam. The high velocity required to sustain sand or coarser material in suspension generates high friction loss, making it less feasible to transport coarse material a long distance without energy input by pumping, and the pipeline must be designed to transport the largest grain sizes in the material to be dredged. Hydraulics of slurry pipeline transport of coarse materials as related to siphon dredging has been outlined by Eftekharzadeh (1987). The longest transport distances are achieved when uniformly fine materials are present as they can be transported at much lower velocities. Shelley (2019), building on an earlier analysis[7], determined that a hydrosuction sediment removal system could remove a large portion of the accumulating sediment from the USACE's Tuttle Creek Lake in Kansas.

Figure 41. Siphon or hydrosuction dredging configuration.



10.5 Dry excavation

Dry excavation has been employed extensively for the management of sediment in debris basins, which are normally dry, and it has also been

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[7] McFall, B., and T. Welp. 2015. *Tuttle Creek Siphon Dredging Investigation*. ERDC/CHL LR-15-6. Vicksburg, MS: US Army Engineer Research and Development Center.

used in Taiwan and at Paonia Reservoir in Colorado for removal of sediment from reservoirs. Unlike dredging, it requires that the reservoir level be lowered or emptied to allow access to deposits by earth moving equipment. At some sites with predictable seasonal water level variation, dry excavation can be undertaken on a seasonal basis. Disposal area limitations similar to those associated with dredging apply, the difference being that sediment transport is typically by truck haulage. Dry excavation is readily employed in the removal of coarse and easily dewatered material from the delta, but the removal of deep deposits of poorly consolidated fine sediment presents significant difficulties absent a prolonged period for dewatering and consolidation.

10.6 Sediment placement

10.6.1 Downstream sediment placement

The interruption of the transport of the bed material load along a river system by dam construction has adverse downstream consequences including channel incision, bed armoring, and loss of environmental habitat such as spawning gravels (Kondolf 1997). There is increasing recognition of this problem, including the development of strategies to return dredged material to the river downstream of the dam, the Prado example given later in this document being a case in point, and the Gavins Point example focuses on moving coarse sediment downstream by flushing.

The natural sediment transport system is pulsed, with most sediment being transported by infrequent high-flow events, but dredging removes sediment at a relatively constant rate given by the capacity of the dredging equipment. Within this limitation, dredging may be undertaken as a discrete project that removes several years or decades of sediment accumulation or as a continuously operating project removing material at the average long-term rate of sediment accumulation. However, the attenuation of peak flows by the dam will reduce sediment transport capacity below the dam as compared to the pre-dam condition, limiting the amount of coarse sediment that can be placed downstream and moved by the attenuated peak flows. Also, it is generally undesirable to discharge downstream the fine sediment, which usually (but not always) constitutes the bulk of reservoir sediments.

Environmental remediation efforts below a number of dams in the United States now include replenishment of bed material suitable for spawning gravel. In 1991, Kondolf reported that 13 gravel replenishment projects had been undertaken in California. Gravel addition was implemented on a wider scale after 1992 when the Central Valley Project Improvement Act of 1992 requested that all reasonable efforts be made to obtain a sustainable salmon population that would be doubled by 2002 (Bunte 2004). Most gravel augmentation studies are located in California and occur on dammed Central Valley streams, as well as on the Trinity River, and projects outside of California are documented at only a few locations (Table 14). In the case of the Green River in Washington State, the USACE has been augmenting the reach downstream from Howard Hanson Dam with gravel since 2003 to provide salmonid spawning habitat (Corum et al. 2022. Bunte (2004) reviewed the state-of-the-art practices and compiled a range of strategies for gravel replenishment. The gravels are typically free of fines, the volumes are extremely small compared to the sediment volume in the reservoir, and placement practices range from dumping into the river to targeted placement in specific habitat areas.

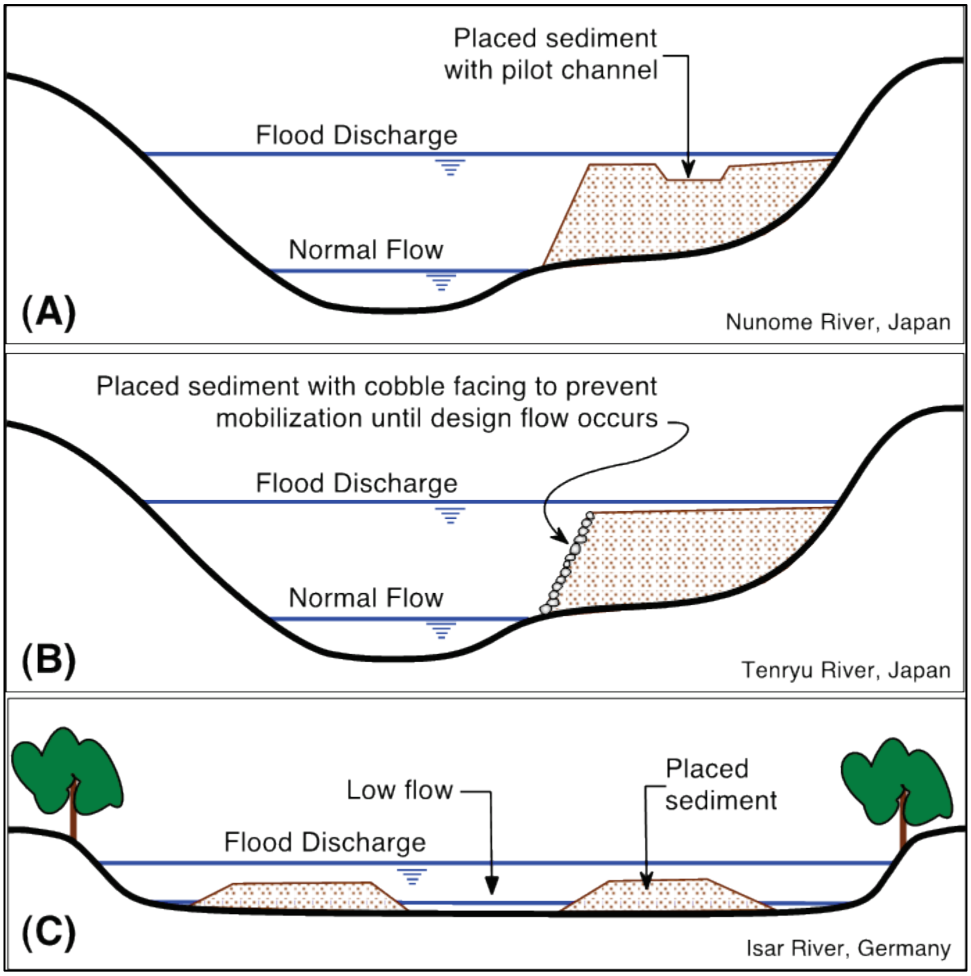
Table 14. Gravel replenishment projects in North America identified by Bunte (2004).

Jurisdiction	Streams
California*	Trinity River, Clear Creek, Upper Sacramento River, Stanislaus River, American River, Merced River, Big Chico Creek, Yuba River, Mokelumne River, Touhumne River
Montana	Madison River bypass reach below Madison Dam
Oregon	North Umpqua R., Slide Creek Boulder Enhancement Reach
North Carolina	Cheoah River
Washington	Cowlitz River
British Colombia	Campbell R. Spawning - Gravel Placement Project

*Projects reported for years 2002–2004.

Replenishment using dredged materials has been undertaken at a number of sites in Japan, where coarse sediment is removed from the reservoir by excavation and dredging, with placement below the dam to replenish the sediment supply, thereby making effective use of sediment removed from the reservoir. There are also examples in Europe. Because sediment is excavated more or less continuously, but transported episodically in response to floods, the procedure is to create a sediment stockpile along the side of the channel but which is outside of the low flow area. Appropriate deposition areas would be, for example, areas formerly occupied by point or lateral bars but which are now depleted of sediment. The deposited sediment will be eroded during a flood event and carried downstream in accordance with the transport capacity. In the case of the Nunome River in Japan (Kantoush and Sumi 2010a), the sediment deposit is gradually eroded laterally as the river rises, and when a high stage is reached, flow then runs along a pilot channel across the top of the deposit (similar to a meander cutoff), which accelerates erosion of the remaining material (Figure 42*A*). At the Tenryu River in Japan (Figure 42*B*), the side of the deposited sediment is covered with larger material to prevent erosion until the design flow has been reached and flood flow runs over the top of the deposited material (E & H 2009). In the Isar River in Germany, Hartmann (2009) indicates that 100,000 m^3 (81 acre-ft) of gravels have been relocated below the Oberfohringer Weir at Munich. In this case, the gravels are placed into the main river channel and then redistributed by the flow, as shown in Figure 42*C*. The placement technique will depend on local circumstances, including environmental considerations related to the river habitat. As an advantage, having the placement area below a dam provides a certain amount of control over the flow rates, and programmed releases can move the placed sediment into the stream channel in a more controlled manner.

Figure 42. Placement of sediment along a downstream channel to allow mobilization during flood events: (A) Nunome River, Japan (Kantoush and Sumi 2010a); Tenryu River, Japan (Kantoush and Sumi 2010a); and (C) Isar River in Germany (Hartmann 2009).



10.6.2 Upland placement

The availability of space for the disposal of dredged material is an important impediment to sustaining long-term reservoir capacity by dredging. Material removed by hydraulic dredging is subject to bulking, and if fines are present, the volume of the containment area must be proportionally larger than the in situ volume of the material to be dredged, as computed by the dimensionless *bulking* factor:

$$B = \frac{V_c}{V_i} = \frac{\gamma_c}{\gamma_i},$$

where, V = volume, γ = dry unit weight, and subscripts c and i refer respectively to containment area and in situ values. The value of the bulking factors is 1.0 for pure sands, in the range of 1.3 for silts, but can exceed 1.5 for clays. Their value depends on the amount of consolidation in the area being dredged as well as the settling characteristic of the material. Thus, the bulking factor for consolidated clays may be larger than for recent clay deposits having a lower in situ dry unit weight because they have not yet consolidated. Column settling tests run for at least 15 days can determine the anticipated settling characteristics of the material to be dredged. Over time, the dredged material will dewater and consolidate, particularly when the material is provided with good surface drainage by the construction of trenches (USACE 2015).

The major limitation imposed by upland disposal is the combination of high cost and the lack of available sites for long-term material placement. As a long-term management practice, it is not feasible to sustain the capacity of mainstem reservoirs by continuously dredging the sediment volume produced by the upstream watershed and place it into upland containment areas. For this reason, dredging with upland placement is more appropriate to support the tactical dredging of critical locations or as a complement to other long-term management practices to improve the sediment balance across the reservoir.

10.7 Reuse of reservoir sediments

Reservoir sediments will reflect conditions in the upstream watershed, including the contaminants generated by upstream activities. If there is extensive upstream agricultural activity including the historical application of persistent pesticides, these may be found in the reservoir sediments and must be taken into consideration. Similarly, upstream mining or industrial activity can result in sediment contamination. However, in general, reservoir sediments do not present special hazards and can be readily reused for activities such as agriculture, fill, or construction materials if sediments are sufficiently coarse. Testing protocols to ensure compatibility with intended uses will vary by jurisdiction and by use. USACE (2015) has an extensive section on beneficial uses of dredged material.

11 Adapting to Sedimentation

Several types of modifications to physical infrastructure and adaptations by project beneficiaries may be implemented to reduce or postpone the adverse impacts of sedimentation. As opposed to active management strategies that focus on modifying patterns of sediment transport, adaptive strategies focus on adjustments to patterns of use. These adaptive strategies may be used alone or in conjunction with strategies to actively manage sediments to reduce the rate of accumulation or to remove deposited sediment.

11.1 Increase or reallocate storage capacity

The most common method of increasing storage capacity at multipurpose reservoirs has been to reallocate the pool, typically enlarging the water conservation pool at the expense of one or more other pools. The impact of reallocation on other pools may be mitigated by optimizing operations so that a given portion of the reservoir capacity represents a shared pool.

Storage capacity may also be increased by raising the dam, by constructing a new and larger dam at the same location (possibly inundating the original dam), or by constructing a new storage facility at a new location. As previously mentioned, The Texas Water Board found that new reservoir capacity could be constructed at lower cost than dredging to recover capacity (Alan Plummer Assoc. et al. 2005).

When a dam is raised, because the additional storage is provided at the top of the pool with a large surface area, even a limited increase in elevation may produce a significant benefit in terms of extending storage benefits in time. However, it will also increase the evaporative surface. New projects to increase storage capacity may also provide an opportunity to incorporate, from the initial project planning stage, enhanced sediment management strategies to achieve a more favorable balance between sediment inflow and discharge. Without addressing sedimentation, the new investment will simply postpone the problem rather than move toward a more permanent solution, leaving a future generation to repeat the same problem with arguably fewer options.

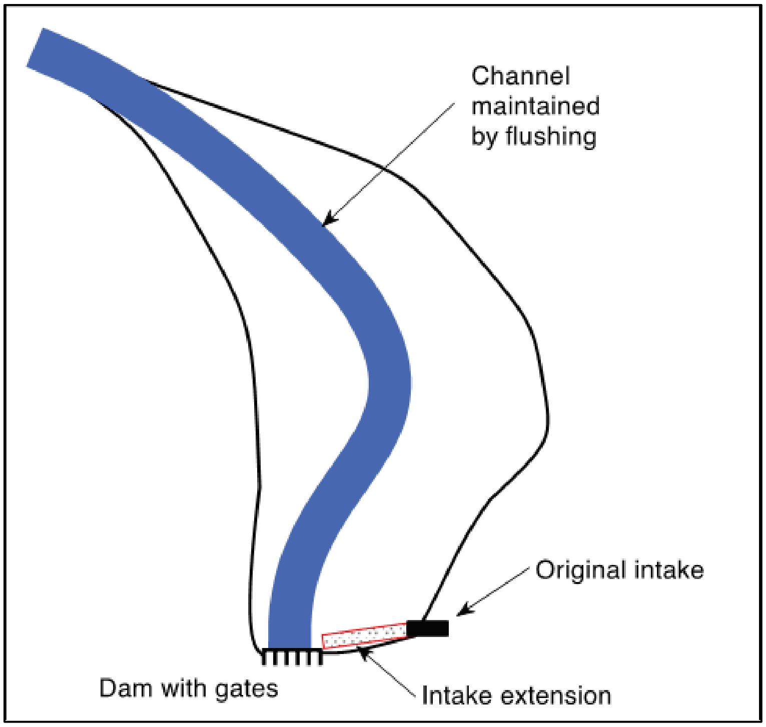
11.2 Intake modifications

Sediment can encroach into the area of intakes, requiring relocation or other modification to reduce sedimentation impacts. Deep power intakes may be subject to encroachment relatively soon following construction by finer sediment carried to the area of the dam by turbidity currents, and water supply intakes located along the side of the reservoir or farther upstream may be affected as sedimentation becomes more advanced.

When turbidity currents reach a hydropower dam, it is normally advantageous to pass as much fine sediment as possible through the turbines to retard the rate of storage loss and reserve space for storage of coarse material (delta deposits), which can be more difficult to manage. Raising the intake level to reduce the entrance of fine sediment will only increase the reservoir trap efficiency and accelerate movement of the delta toward the intake. As an exception, when sediments are removed by annual flushing, it may not be necessary to pass them through the turbines to sustain storage. This strategy was employed at the glacial-fed Gebidem hydropower reservoir in Switzerland, which maintains storage capacity by annual flushing and raised the elevation of the power intake by installing an intake tower to exclude abrasive fine sands and coarse silts that were causing turbine abrasion (Morris and Fan 1998). However, if turbine abrasion is insignificant, it may be advantageous to maximize the passage of fine sediment with turbine water. This will minimize the amount of sediment that needs to be released during subsequent flushing events and thereby also reduce downstream impacts during flushing.

Power intakes are often placed at locations prone to interference by sedimentation. In general, intakes should be placed above or immediately adjacent to a low-level outlet so that operation of the outlet for either pressure or empty flushing will clean out the area at the intake entrance. However, many intakes were designed with little thought to sustaining long-term operation, and many reservoirs have intakes located at the side of the pool at a distance from either the low-level outlet or the channel, which can be maintained by pressure or empty flushing (Figure 43). In these cases, it becomes necessary to relocate the entrance to the intake using a conveyance structure, such as a pipe, sized to generate the velocities needed to avoid sediment deposition within the structure. If sedimentation encroaches to the point that coarse sediment is being entrained, it may also be necessary to install desilting facilities where none was previously required.

Figure 43. Conceptual diagram of intake extension into an area of the reservoir sustained free of sediment by flushing.



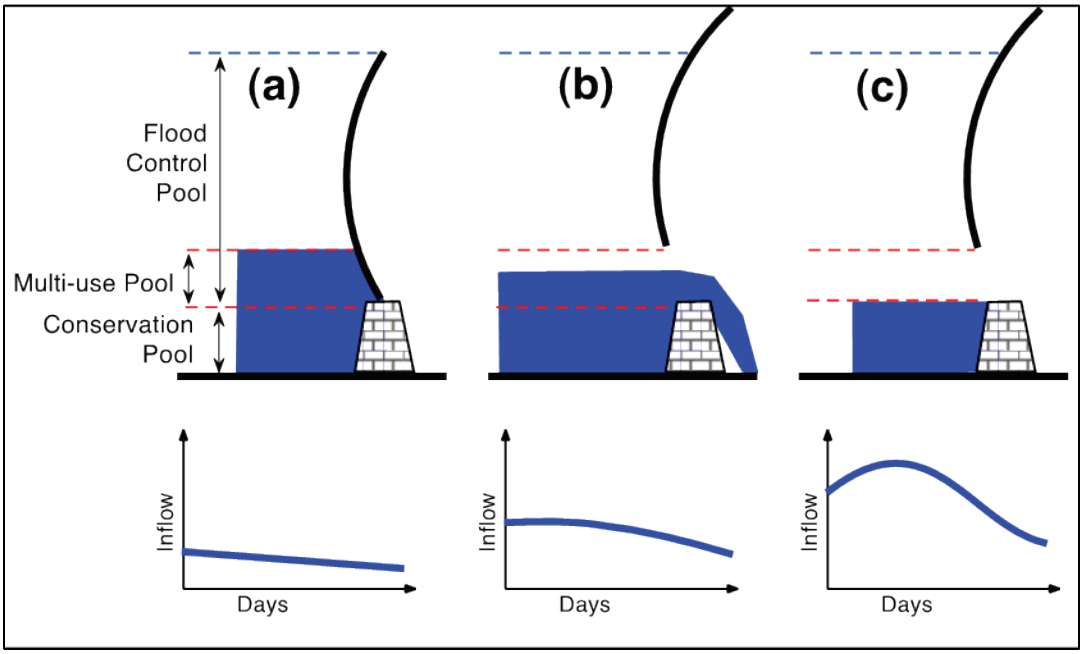
11.3 Shared storage in a multiuse pool

An emerging problem at USACE reservoirs is the growing need to reallocate conservation pools at the cost of flood-control capacity. A cost-effective method of increasing pool capacity and retarding the impacts of sedimentation is to optimize reservoir management to facilitate the creation of a multipurpose pool at the bottom of the flood-control pool, designating storage at the bottom of the flood pool as seasonal use or a multiuse pool. This pool would normally be used for water supply storage but would be emptied prior to the flood season or a specific flood event. Seasonal-use pools have been in use at some reservoirs for decades, but the hydrologic-hydraulic modeling tools now available make it possible to establish a shared pool operated not on a fixed seasonal basis but in real time on a storm-by-storm basis.

To undertake real-time management of the multiuse pool, modeling the water supply capacity is conceptualized to consist of both the water currently stored in the reservoir plus the water already in the watershed based on received rainfall or snowpack but which has not yet reached the reservoir. This future *firm* inflow is continuously predicted by the hydrologic-hydraulic model based on watershed and climatic conditions plus knowledge of upstream abstractions by other users. Thus, water supply consists of storage plus firm inflow. As the firm inflow is increased by rainfall, the volume held in storage can be reduced by an equivalent amount without affecting water supply availability. Thus, the multiuse pool will hold water as conservation storage during periods of normal or low streamflow but will be drawn down at the same rate as rainfall in the watershed increases firm inflow. By this means, the multiuse pool can be emptied prior to arrival of a flood event. The general sequences of events are illustrated in Figure 44. Meteorological forecasts can be used to augment system performance, but primary reliance would be placed on the amount of precipitation received and measured streamflow. Continued forecasting of inflows by the hydrologic-hydraulic model for the duration of the event may also enable optimization of reservoir operations to maximize flood control benefits.

While the potential for incursion into the flood control pool by this method may not be large, given that the flood control pools are typically many times larger than the conservation pool, dedicating even small percentage of the flood control pool to shared storage can have a significant positive impact in retarding storage loss by sedimentation.

Figure 44. Schematic of operational sequence for a shared buffer pool for both water conservation and flood control. (a) Normal operation. (b) As the firm inflow volume from the watershed increases by rainfall, water is released at the same rate to start emptying the multiuse pool to make its volume available for flood control. (c) Multiuse pool emptied prior to flood arrival.



12 Example: John Redmond Reservoir, Kansas

12.1 Problem statement

The 50 yr design project life for John Redmond Reservoir extended to 2013, by which time the reservoir had lost approximately 12.2% of its total capacity to sedimentation. Through its design life, the reservoir has operated largely as intended, but the conservation pool has been losing capacity much faster than the design rate. To make an equitable redistribution of the storage remaining between the flood control and conservation pools, reallocation was made in 1976, raising the conservation pool from elevation 1,036 to 1,039 ft (USACE 2013b). An additional reallocation of the water supply pool to 1,041 ft was completed in 2013. These reallocations did not guarantee the water storage capacity contracted to the Kansas Water Office per the 1975 agreement but redistributed the remaining storage between the pools.

The problem at John Redmond Reservoir is how to best manage this resource during the post-design life to maximize long-term project benefits in the face of continued sedimentation.

12.2 Setting

12.2.1 The reservoir

John Redmond Dam and Reservoir is used for flood control, water supply, and recreation. It impounds the Neosho River approximately 25 mi downstream (southeast) of Emporia, Kansas (38° 14′ 30″ N latitude, 95° 45′ 20″ W longitude). The dam consists of an earthfill embankment 3.9 mi long plus an ogee gated spillway on the left abutment equipped with fourteen 40 ft × 35 ft tall tainter gates having a discharge capacity of 428,000 ft^3/s at 1,068 ft, the top of the flood control pool, and a maximum discharge capacity of 578,000 ft^3/s at maximum pool elevation of 1,074.5 ft. The channel below the dam has a bankfull capacity of 12,000 ft^3/s. The embankment was closed in September 1963 and was completed for full flood control operation in September 1964. Flood control benefits are provided to multiple downstream communities in both Kansas and Oklahoma. It is among the least visited of all Kansas reservoirs, averaging 155,000 visitors/year for the period 1996–2007 (Nejadhashemi et al. 2008).

Only 10% of water supply yield serves municipal water supply. The remaining 90% of the water supply yield is allocated to make up water for the adjacent Wolf Creek Reservoir, a 113,000 acre-ft storage reservoir with a surface area of 4,800 acres and used for cooling the 1200 MW Wolf Creek nuclear power plant. Because the Wolf Creek Reservoir has insufficient inflow to offset evaporative losses, and its 1,088 ft pool level is higher than John Redmond, releases from John Redmond dam are picked up at a river intake and pump station immediately downstream of the spillway for delivery of water to the Wolf Creek Reservoir. Although John Redmond discharges seasonally large flows downstream, the 120 ft^3/s capacity of the Wolf Creek pump station limits the ability to take advantage of spills at John Redmond to refill the power plant's cooling reservoir. Also, the design of Wolf Creek Reservoir did not contemplate any variation in water level. This means it has virtually no live storage capacity and must be supplied make-up water on an as-needed basis.

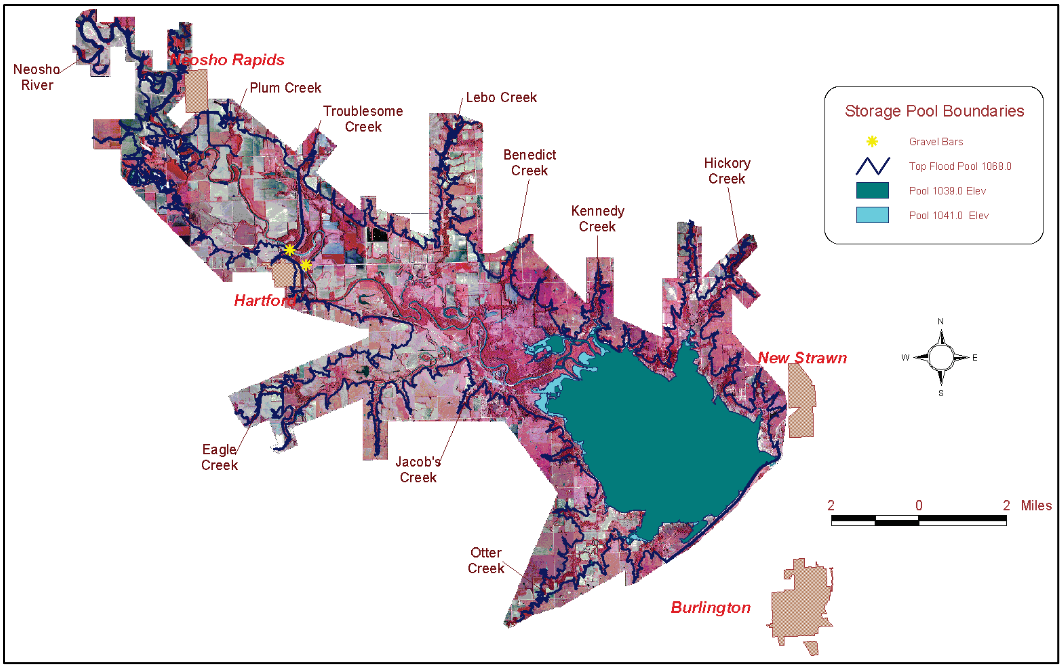
The John Redmond flood control pool capacity is nearly seven times larger than the conservation pool, and its surface area is approximately four times larger. The 2019 values are summarized in Table 15. Most of the reservoir area consists of the normally empty flood pool containing riparian forests and farmland. The relative pool areas are seen in Figure 45.

Table 15. John Redmond Reservoir pool characteristics in 2019 after dredging.

Measurement	Capacity (acre-ft)	Area (acres)	Average Depth (ft)
Top of flood pool, 1,068 ft	566,756	31,606	17.9
Top of conservation pool, 1,041 ft	62,607	9,181	6.8

There are uncertainties related to capacity measurements at John Redmond Reservoir, and the experience at this site provides an example of the differences in capacity measurements that can occur as a result of changing survey methods. The situation at John Redmond was discussed previously in Section 4.2 of this report, and differences in the results by different survey techniques and surveys were presented in Figure 14.

Figure 45. Comparison of the original conservation pool (1,039 ft), current conservation pool (1,041 ft), and flood pool (1,068 ft) boundaries for John Redmond Reservoir (USACE 2013b).



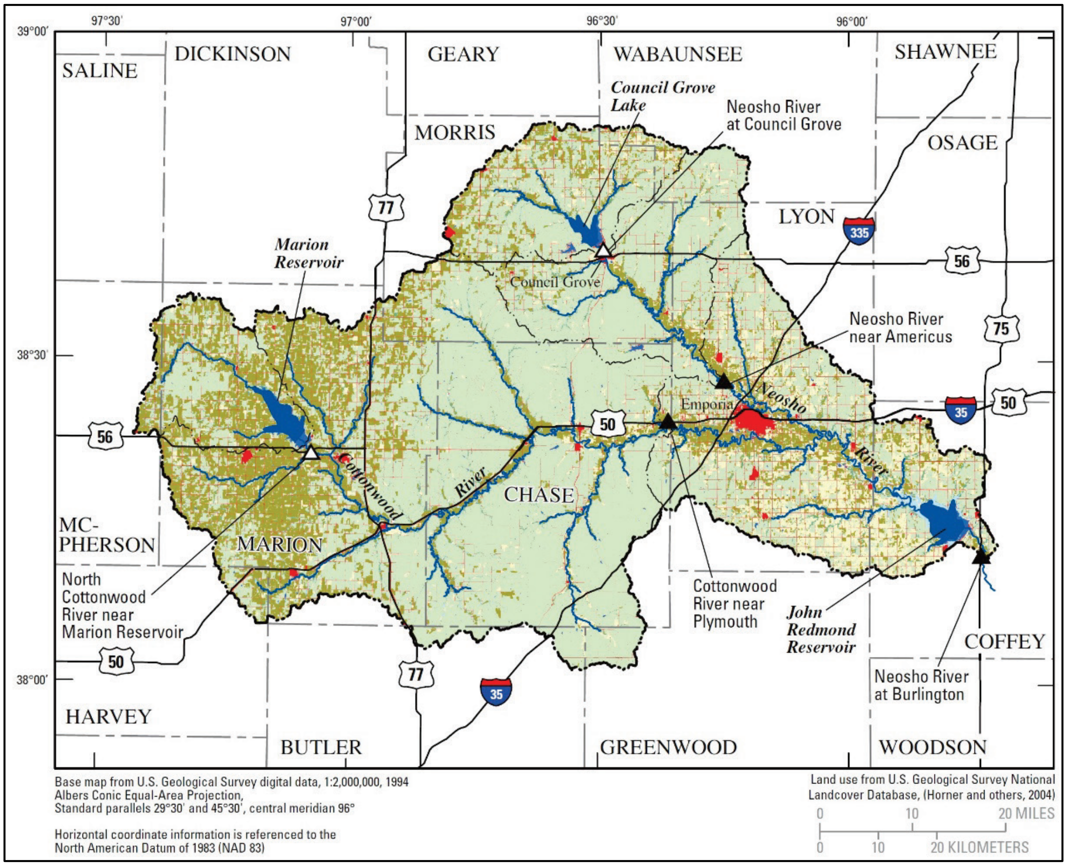
12.2.2 The watershed

The general configuration of the watershed and the location of upstream reservoirs are shown in Figure 46. Council Grove and Marion Reservoirs were constructed in 1963 and 1967 on the Neosho and Cottonwood Rivers, respectively. Several watershed parameters are listed below:

• Regulated watershed (Council Grove and Marion Dams)	446 mi^2
• Unregulated watershed	2,569 mi^2
• Total tributary watershed	3,015 mi^2
• Mean Annual Inflow to John Redmond Reservoir	1,054,800 acre-ft.

Grassland is the predominant land use, accounting for 61.2% of the area upstream of the dam. Crop production is the second largest land use at 28.4% and consists principally of rain-fed grains: wheat, milo, sorghum, maize, and soybeans. Woodland, water, and urban areas constitute the remaining 10.4% of land cover. Upper watershed soils are predominantly silty clay, and riparian areas are predominantly silty-clay loam with < 20% sand. John Redmond is considered an impaired water body due to organic enrichment, low dissolved oxygen, and siltation (Nejadhashemi et al. 2008). The dam operator reports that water in the reservoir is characteristically turbid all year as the shallow depth of the conservation pool (<7 ft) allows continual resuspension of bottom sediments by the windy climatic conditions.

Figure 46. Watershed tributary to John Redmond Reservoir (Lee et al. 2008).



Base map from U.S. Geological Survey digital data, 1:2,000,000, 1994
Albers Conic Equal-Area Projection,
Standard parallels 29°30' and 45°30', central meridian 96°

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Land use from U.S. Geological Survey National Landcover Database, (Horner and others, 2004)

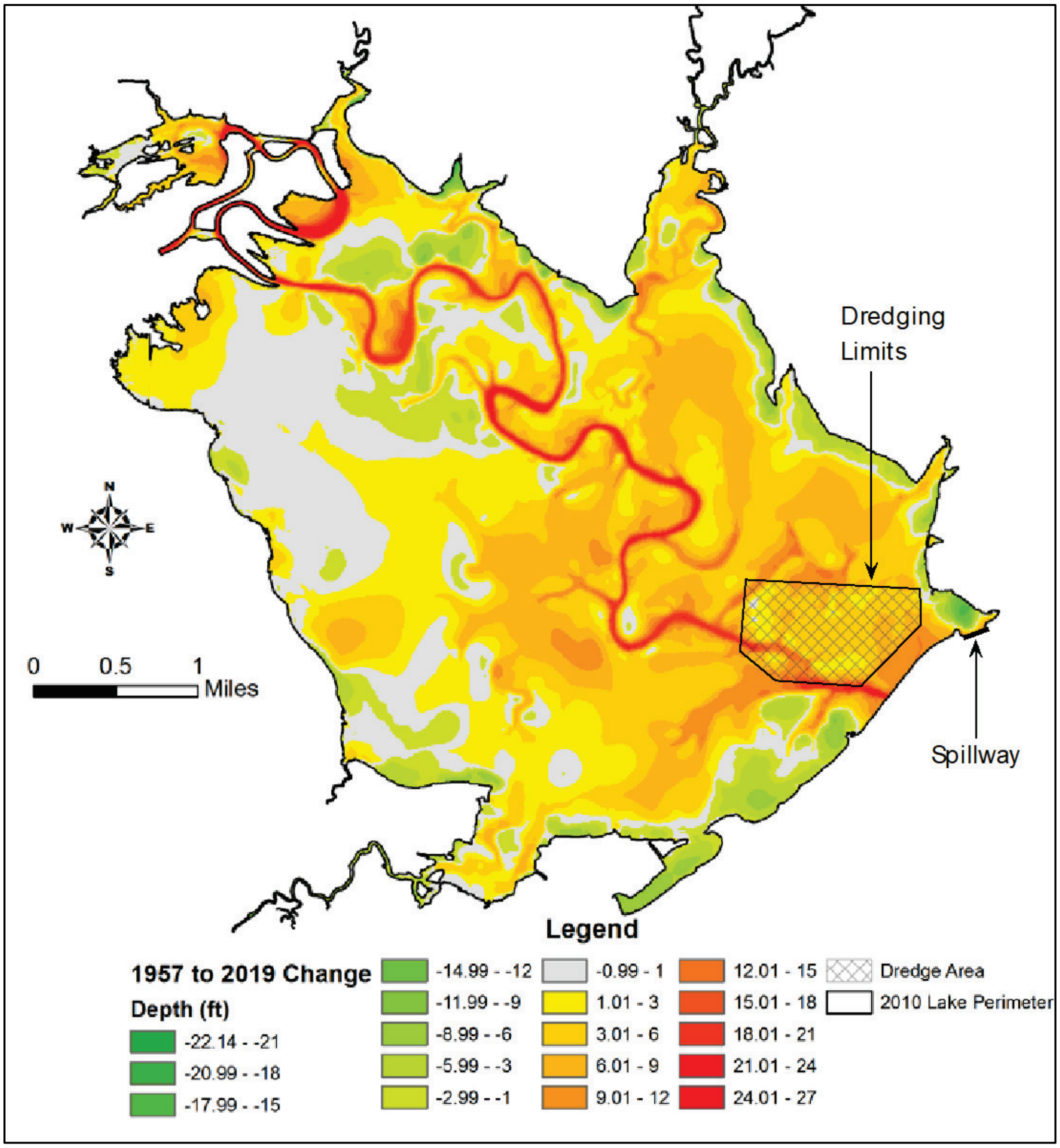
12.3 Sedimentation

12.3.1 Reservoir sedimentation patterns

The thickness of sediment deposits in the conservation pool is illustrated in Figure 47, prepared by digitizing the original 1957 pre-impoundment survey (5 ft contours) and comparing against the 2007 bathymetric survey. The original river channel has been completely filled in along with deeper portions of the reservoir, and the reservoir bottom has become increasingly flat and shallow.

The deposition pattern in the conservation pool, with sediment preferentially deposited in the deeper portions of the reservoir, is a pattern typically encountered in reservoirs. Wave action that resuspends sediment in shallow water can also cause sediment migration into deeper areas of the pool less prone to resuspension events.

Figure 47. Thickness of sediment deposits in John Redmond conservation pool in 2007 also showing the area of 2016 dredging.



Design and actual sedimentation rates at John Redmond Reservoir are summarized in Table 16. These data indicate that the rate of storage loss in all pools within the reservoir is nearly 50% higher than the original design estimate. Because the inactive pool is now essentially full of sediment, the prior storage loss rate for the "Conservation + Inactive" pools is now focused into the conservation pool. With the inactive pool filled, the sedimentation rate in the conservation pool will now be approximately 741 acre-ft/yr, 68% higher than the original design value.

The change in the elevation-area curve over time is given in Figure 48. The annual percentage of storage loss in the conservation pool is now nearly five times faster than the flood pool. However, because the last lidar survey of the flood pool was performed in 2000, flood storage loss is likely underreported. Current sedimentation concerns are focused primarily on the conservation pool, and loss of conservation storage by John Redmond and other reservoirs throughout Kansas is a problem of high concern to the government of the State of Kansas (Kansas Water Authority 2010; Kansas State University 2008).

Table 16. Rate of capacity loss by pool, John Redmond Reservoir.

1963 to 2007				1963 to 2019*			
	Design Sedimentation Rate (acre-ft/yr)	Capacity Loss (acre-ft)	Average Annual Capacity Loss (acre-ft/yr)	Capacity Loss (acre-ft)	Average Annual Capacity Loss (acre-ft/yr)	Average Annual % Loss	Rate of Capacity Loss as % of Design
Total Reservoir Capacity	1,020	77,103	1,752	85,366	1,524	0.23%	149%
Flood Control Pool	616	44,913	1,021	43,864	783	0.14%	127%
Conservation Pool	404	28,711	652	38,023	679	0.86%	168%
Conservation + Inactive Pools		32,190	732	41,503	741	0.90%	

* Includes effect of 2016 dredging and increase in conservation pool elevation.

Sources: Design sedimentation rate from USACE[8]. Other values from USACE Tulsa District and Kansas Water Office.

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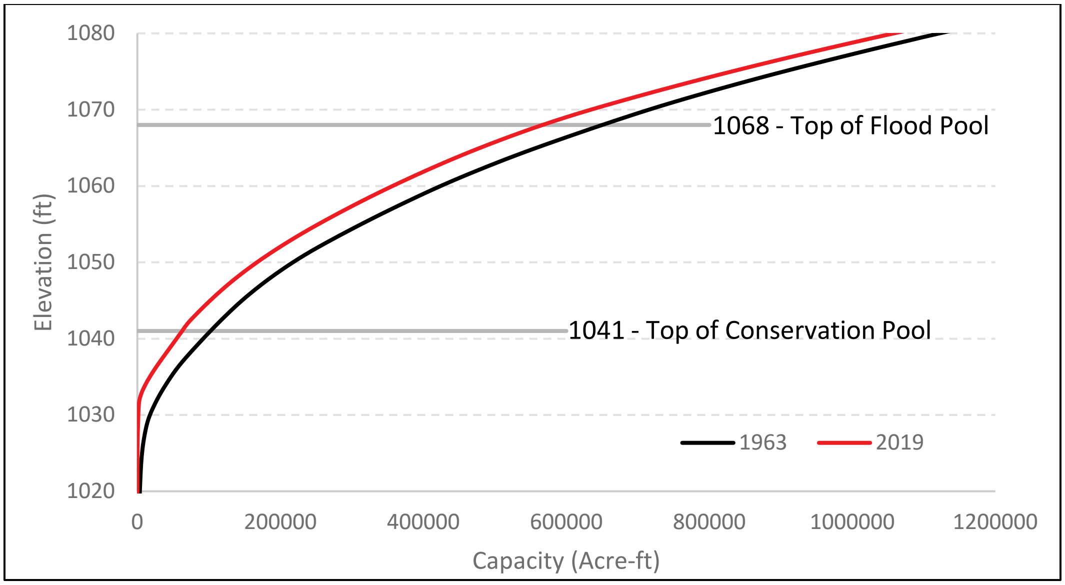
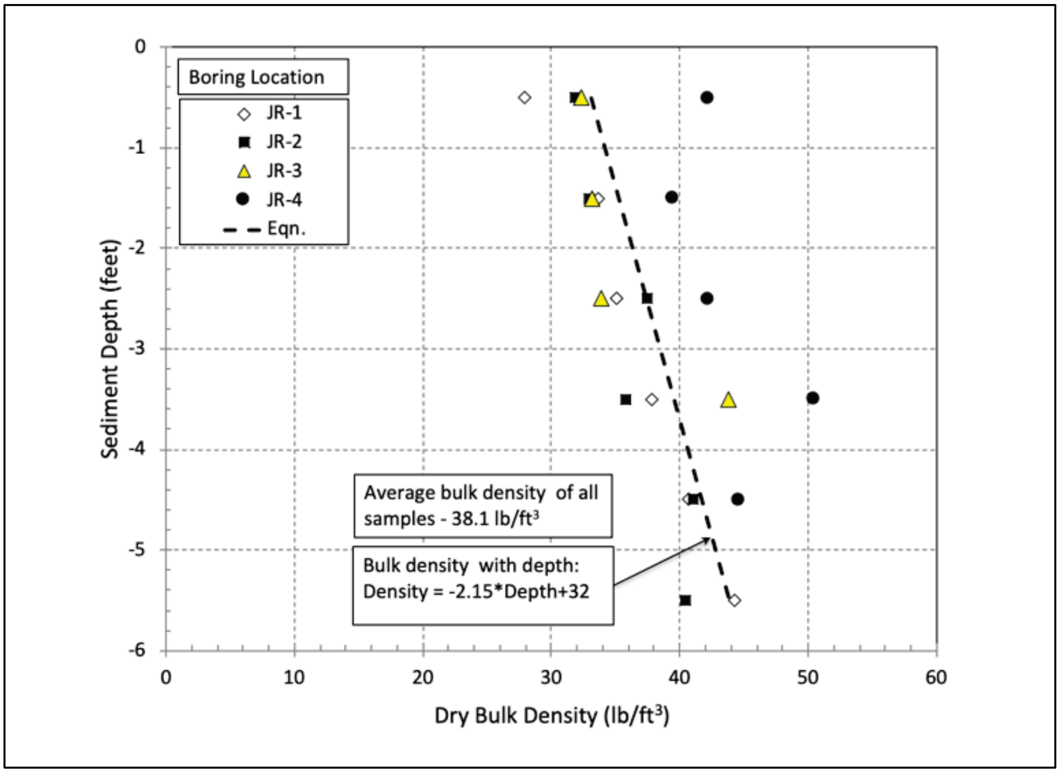
[8] USACE. 2009. Draft report. *Dredging Assessment John Redmond Dam and Reservoir, Kansas*.

Figure 48. Change in elevation-capacity curve with time due to sedimentation, John Redmond Reservoir, Kansas.



By comparing the year 2019 area of each pool against the reported capacity loss, the average sediment thickness in the conservation + inactive pool averages 4.5 ft while in the flood control pool (outside the perimeter of the conservation pool), thickness averages 2.0 ft. A portion of the difference in sediment depth between the conservation and flood pools is probably due to the greater density of sediment deposits in the flood control pool, which is normally dry, meaning sediment deposits are subject to desiccation and compaction. The bulk density of the submerged sediment in John Redmond Reservoir determined by four core samples is summarized in Figure 49, with an average value of approximately 38 lb/ft^3. In contrast, the dry bulk density of the aerated deposits (silt and clay) soil is estimated as 75 lb/ft^3 (Geiger 1963). On the basis of six cores taken in the area of the conservation pool by the Kansas Biological Survey (2010), the deposited sediment has the following average grain size: 3% fine sand, 43% silt, and 54% clay. Sand is largely absent in both suspended sediment samples and the bed material of the streams tributary to the reservoir.

Figure 49. Bulk density as a function of deposit depth in four sample cores in John Redmond Reservoir (graphed from data presented by Juracek 2010). Cores were taken along the reservoir centerline in areas not subject to desiccation during reservoir drawdown.



Given the ratio of dry bulk densities for aerated sediment (soil) and submerged sediment, 2.0 ft of sediment depth in the normally dry flood control pool is equivalent to 3.9 ft of submerged sediment depth. These data suggest that the bulk of the sediment inflow may not be focusing in the conservation pool, but rather the higher rate of storage loss is due to the lower density of the submerged sediments. However, the four core samples along the reservoir centerline are not representative of sediment density in the flood control pool or areas of the conservation pool subject to aeration and during drawdown.

12.3.2 Rate of storage loss

John Redmond has experienced accelerated sedimentation as compared to the pre-construction estimate and has also lost a greater percentage of its conservation pool compared to most other federal reservoirs in Kansas. Pool capacities are summarized in Table 17. The estimated conservation pool for 2019 is 62,607 acre-ft. The 2019 survey includes 1,860 acre-ft that were reclaimed due to dredging in 2016, which recovered 4 acre-ft of inactive storage, and the remaining 1,856 acre-ft was dredged from the conservation pool[9].

Table 17. John Redmond Reservoir pool capacities showing loss by sedimentation, including the effects of raising the conservation pool in 2013 and dredging in 2016.

		Original Capacity (1963)		2007 Capacity†		2019 Capacity‡	
Pool	Top of Pool Elevation (ft)	Acre-feet	% of Total Capacity	Acre-feet	% Capacity Loss	Acre-feet	% Capacity Loss
Total reservoir capacity	1068	650,262	100%	573,157	11.9%	566,756	12.8%
Flood control pool	1068	548,008	84.3%	523,117	7.9%	504,145	8.0%
Conservation pool	1039	78,751	12.1%	40,100	49.1%		
	1041	98,775	15.2%			62,607	36.6%
Inactive pool	1020	3,480	0.5%	0	100%	4	99.9%

† 2007 capacity estimated by Tulsa District as a combination of year 2000 lidar for the flood pool plus year 2007 bathymetry by Kansas Biological Survey.

‡ 2019 capacity estimated by Kansas Biological Survey as a combination of year 2000 lidar for the flood pool plus year 2019 bathymetry by Kansas Biological Survey.

The available data for the rate and pattern of sediment deposition in John Redmond Reservoir are not consistent. Given uncertainties in the original capacity estimate and changes in capacity estimates by different methodologies, the rate of sedimentation in the flood control pool is uncertain (Figure 14 and Figure 48). The impact of sediment compaction as a factor in explaining apparent differences in the observed sedimentation rate in the flood control and conservation pools is also unclear. In summary, the rate of capacity loss below elevation 1,041 ft has been well documented, but the capacity loss in the flood pool is much more uncertain.

12.4 Sediment delivery and trap efficiency

Inflow into the reservoir reflects the effect of intense rainstorms, as illustrated by 10 yr of inflow data presented in Figure 50. Most sediment is delivered by the high-flow periods.

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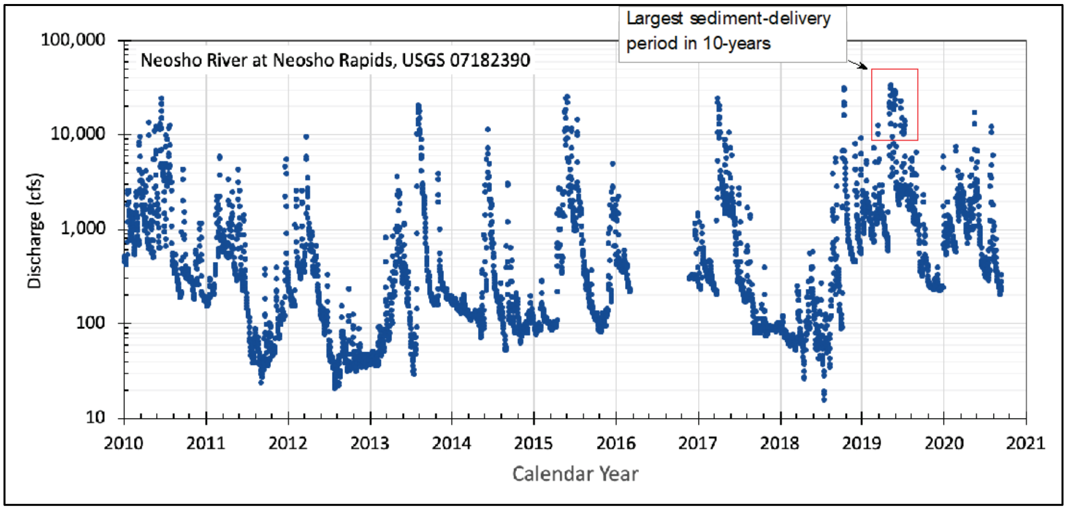
[9] Chris Shultz, Kansas Water Office, personal communication, 2 January 2020.

Figure 50. Daily flow at USGS gage upstream of John Redmond Reservoir highlighting large 2019 inflow.



To document the dynamics of sediment inflow, in a cooperative study with the USACE, the USGS characterized the suspended-sediment balance across the reservoir from February 21, 2007, through February 21, 2008 (Lee et al. 2008). Turbidity sensors were installed at two USGS stream gages above the reservoir (Neosho River near Americus and Cottonwood River near Plymouth) and one stream gage below the dam (Neosho River at Burlington) to compute continuous (15 min) measurements of suspended-sediment concentration and loading. Turbidity was found to be an accurate surrogate for suspended solids in this system due to the paucity of sand. Over 98% of the incoming sediment load was transported during nine storms that accounted for 25% to 27% of the study period. The largest storm during the study period, having a return interval of approximately 4.6–4.9 yr, accounted for 37% of the annual sediment inflow. Approximately 1,120,000 ton of suspended-sediment were transported into, and 100,700 ton were transported out of, John Redmond Reservoir during the study period, for a trap efficiency of 91%.

Another sediment balance study that included the May–July flood of 2015 found that this event deposited sediment equivalent to approximately 1.5 yr of delivery at the long-term average. This time compression of sediment delivery is characteristic of reservoirs throughout Kansas (Foster 2016).

The John Redmond conservation pool is hydrologically small with a capacity:inflow ratio of only 0.075, computed by comparing the 2019 conservation pool capacity to the mean annual inflow of 1,054,800 acre-ft.

As a result, for small inflows there is the potential to optimize operations to enhance sediment sluicing through the reservoir. However, during large inflows, water is retained in the flood control pool, as occurred in the 2015 flood, to prevent flooding downstream in Oklahoma, resulting in a high trap efficiency (Foster 2016).

12.5 Sediment management alternatives

This section summarizes measures that have been examined or which may be possible at John Redmond Reservoir to mitigate sedimentation.

12.5.1 Reduce sediment inflow

It has been estimated that just over half of the sediment entering the reservoir is derived from streambank erosion along the two principal rivers, and the remainder comes from upland erosion. To better understand bank erosion, studies were performed at 10 eroding sites by the Watershed Institute (2007). Deep silt loams were found consistently throughout all reaches. Most studied streams had a low bankfull width-to-depth ratio indicating a narrow and deep channel, conditions similar to equivalent stable reference reaches in the region. Most of the studied sites had riparian corridors that were narrow or entirely absent, coupled with excessive cattle grazing in the riparian corridor, and in some locations the herbaceous understory was in poor condition or missing due to grazing and hoof action. Sediment loading is greater from these disturbed riparian areas. Erosion rates were predicted to average 0.20 ton/ft/yr for 27 bank locations within the 10 study sites, and Pfankuch stream stability evaluations ranged from fair to poor. By comparing 1991 and 2006 aerial photographs, 13.4 mi of channel *erosion hotspots* were identified having significant bank recession over the 15 yr period, with an average streambank erosion rate of 2.54 ton/yr/ft. In comparison to healthy riparian corridors, survey reaches suffered from excessive cutting, mass wasting, and debris jam potential.

The Kansas Water Office (KWO) holds a statewide database of streambank sites and completed projects. Aerial photographs are compared, most recently using 2015 imagery, to past years to determine streambank *hotspots* and potential stabilization sites above reservoirs. KWO has found 37.5 mi of potential sites on the Cottonwood and Neosho rivers upstream of John Redmond Reservoir that produce an estimated 2.7 ton per linear foot per year of eroded sediment. With the watershed above John

Redmond being one of the focus areas of sediment reduction in the state, 41 sites representing 8.0 mi of hotspots have been addressed, producing an estimated reduction of 200,000 ton/yr of eroded sediment from the sites. However, further questions remain about the long-term effectiveness of the stabilization projects. The lag time required for sediment to move through the fluvial system also means that the benefits from reduced erosion may not be apparent in the reservoir until after a period of years.

By analyzing historical gage shift data at USGS stream gage sites, Juracek (2010) concluded that the streams tributary to John Redmond Reservoir were not incising. The exception was a period of incision, now stabilized, below Council Grove and Marion Dams. In contrast, there was widespread evidence of severe bank erosion. However, it is not clear to what extent the soil from eroding banks is redeposited farther downstream as point bar growth and what percentage reaches the reservoir. Since there was little evidence that the stream cross sections were changing (widening), the net transport of sediment to the reservoir from this source may be much lower than the 85% delivery ratio used by Kansas Water Authority (2010) to evaluate the benefits of streambank stabilization. Data presented by Juracek also show that sediment yield per unit of watershed area above John Redmond Dam is low compared to other Kansas reservoirs.

Modeling work by Kansas State University using the Soil and Water Assessment Tool model was not able to account for the suspended sediment concentrations reported in the Neosho and Cottonwood Rivers by the USGS. This work supported the conclusion that streambank erosion is the primary source of sediment delivered to the reservoir. Juracek (2010) also concluded that bank erosion was a more important source of sediment than the channel bed. As a result, particular attention has been given to streambank stabilization along the Neosho and Cottonwood Rivers, the reservoir’s two principal tributaries, since eroding streambanks deliver to the river sediment that has a high probability of being transported to the reservoir.

Measures recommended to mitigate bank instability problems include construction of rock vanes to reduce near-bank velocity and redirect flows at channel bends back toward the middle of the channel, plus riparian corridor restoration to include bank reshaping, riparian tree and shrub planting, native grass seeding, and maintenance until vegetation is established. Fencing would be used to restrict or limit cattle access to the riparian corridor.

Construction of proposed watershed structures are estimated to reduce current sediment yield by 56,610 ton/yr, at an implementation cost of $22M, or approximately $236/yd^3 of sediment deposited in the reservoir (Table 18). In contrast, streambank erosion projects focusing on 35 mi of eroding bank, and costing approximately $18M, were estimated to reduce reservoir sedimentation by 310,000 ton/yr. Converting to sediment volume at a bulk density of 45 lb/ft^3, considered appropriate for the overall conservation pool with compaction, sediment mitigation costs have been compared in Table 18. This table does not count any additional benefits of erosion control such as preservation of soil productivity and cropland against erosion or benefits to wildlife and recreation.

Table 18. Comparative costs of sediment management by alternative methods, John Redmond Reservoir.

	Annual Amount		Unit Cost	
Management Method	**ton/yr**	**acre-ft/yr**	**$/yd^3**	**$/acre-ft**
Erosion Control				
Watershed erosion	56,610	47	$289	$465,500
Mainstem riverbank erosion	310,000	259	$43	$69,600
Maintenance dredging		~650	$6.67	$10,760
Sediment Pass-through	50,000	51	$0.15	$245

Notes: Total storage loss rate in John Redmond Reservoir averages 1,752 acre-ft/yr.
Erosion control from Kansas Water Authority (2010).
Dredging unit cost is from the 2016 project and corresponds to maintenance dredging in conservation pool only.
Sediment pass-through from Lee and Foster (2011). Sediment pass-through cost is explained in Section 12.5.6.
All computations based on dry bulk density of 45 lb/ft3 for sediment deposits in the reservoir.

By comparison, if the original construction cost of the 650,262 acre-ft reservoir ($29.264 million in 1959) is brought forward to 2019 using the ENR construction cost index, today's cost for the total capacity would be $414.2 million, equivalent to an original construction cost of $637/acre-ft. This is lower than the cost of constructing a new reservoir today for the conservation pool only, estimated to exceed $500M (USACE 2014)

12.5.2 Pool reallocation

The conservation pool has been raised twice in the reservoir's history. First, the conservation pool was increased from 1,036 ft to 1,039 ft in 1976. Then in 2013, it was raised from 1,039 ft to 1,041 ft due to the higher than anticipated sedimentation rate in the conservation pool compared to the flood pool[10]. These reallocations are temporary rather than a long-term measure against sedimentation. Any additional reallocation above the 1,041 ft level is more likely to have a significant impact on flood control benefits.

12.5.3 Dredging

Dredging was analyzed at John Redmond Reservoir by the USACE[11], examining several dredging and placement alternatives. Dredging of John Redmond Reservoir was performed during the summer of 2016 at the expense of the State of Kansas. Three million cubic yards of sediment (1,860 acre-ft) was removed at a cost of $20 million ($6.67/yd^3 or $10,760/acre-ft). Dredged material was discharged to five containment areas for dewatering. The dredged material is mostly fine silt and will be mixed with local soils for subsequent use as farmland for crop production.

However, the 1,860 acre-ft of sediment removed represents only 2.5 yr of sediment accumulation in the conservation pool. The cost of offsetting 50 yr of sediment accumulation by this strategy would exceed $300M. Due to high cost, further dredging of John Redmond Reservoir is likely not an economically viable option.

12.5.4 Replacement water supply

The dredging project's environmental study (USACE 2014) reported on project alternatives to provide an alternative water supply as a replacement to the conservation pool in John Redmond Reservoir. Based on the analysis of four alternative sites, the option of constructing a new water supply dam and reservoir was estimated to cost a minimum of $250M, plus mitigation costs which would be even greater than the dam construction cost. The analysis also estimated the cost of transferring from the Kansas River via a 60 mi, 36 in. diameter pipeline. Projected capital

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[10] Greg Estep, USACE Tulsa District, personal communication, 30 September 2014.

[11] USACE. 2009. Draft report. *Dredging Assessment John Redmond Dam and Reservoir, Kansas*.

costs for this pipeline exceed $288M and may require annual operation and maintenance investments greater than $3M. Transferring water from the Kansas River could also impact water supply availability for municipalities and industries in that basin.

12.5.5 Wolf Creek cooling water reservoir, Kansas

At John Redmond, a relatively small conservation pool of 63,000 acre-ft is being operated to supply makeup water to the 113,000 acre-ft Wolf Creek Reservoir, which serves as a heat sink for the 1200 MW Wolf Creek nuclear power plant. Make-up water is required because Wolf Creek's small watershed cannot by itself compensate for evaporative losses from the heated lake. A 120 ft^3/s pump station located downstream from John Redmond lifts water from the Neosho River to Wolf Creek Reservoir.

Ideally, it would be possible to divert excess flows from John Redmond into Wolf Creek because it would essentially increase the conservation storage in the overall system. However, two factors constrain this option. First, the original Wolf Creek design specifies a stable water level, meaning there is no live storage capacity. Second, because the pump station on the Neosho River has a limited capacity, there is essentially no ability to capture and divert flood spills from John Redmond into Wolf Creek.

Simulations by the KWO[12] showed that while pump station capacity may limit Wolf Creek operations during short-term droughts, simulations based on the 1950s drought of record showed that the limiting factor for continued operation of the power plant is the conservation pool at John Redmond under the criteria that Wolf Creek Reservoir water level not be allowed to drop. Thus, operational flexibility at John Redmond could only be achieved if some variability in pool levels were allowed at Wolf Creek. This alternative has not been examined.

12.5.6 Sediment pass-through for existing condition

The operating rule for John Redmond, like most reservoirs, is based on water management only. Sediment management represents neither an operational goal nor a constraint. However, if sediment pass-through were added as an operational goal, and the entire operational strategy were

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[12] Chris Shultz, Kansas Water Office, personal communication, 2 January 2020.

re-examined in this light, it is likely that an adjustment to the operating rule to enhance downstream sediment discharge could be found.

Sediment inflows into John Redmond Reservoir consist primarily of silts and clays having low settling velocities. Sediment pass-through can represent a viable strategy for reducing the rate of sediment accumulation at John Redmond. Pass-through strategies should focus on minimizing the detention time in the reservoir for inflows having high sediment concentrations. Two strategies can be used to minimize detention time of sediment-laden inflows: (1) optimize the reservoir operating rules and (2) modify reservoir geometry. Because the reservoir is shallow, stratification and turbidity currents are not anticipated during inflow events.

Sediment pass-through may be achieved by passing floods through the reservoir at the lowest possible pool level. In the analysis of continuous turbidity inflow and outflow data (converted to suspended sediment concentration), Lee and Foster (2011) documented the relationship between reservoir trap efficiency and pool elevation during monitored inflow/discharge events. This relationship (Figure 51) shows that a significant reduction in trap efficiency is in fact achieved as the reservoir is operated at progressively lower levels during floods.

The impact of minimizing reservoir levels during flood events, while continuing to meet downstream flood-control endpoints (maximum discharges at specified locations) identified in the reservoir operational manual are shown in Table 19. The analysis was performed for 48 measured flood inflow/release events of sediment during the study period from February 2007 to September 2010, a period of above-normal inflow, with each studied event transporting at least 40,000 ton of suspended sediment. The impact of an altered management was analyzed based on the trap efficiency relationship in Figure 51 and also by simulation with the CE-QUAL-W2 model. By minimizing the reservoir level, it was possible to decrease average pool elevations for these events from 1,047.8 to 1,045.4 ft, and residence times from 19.9 to 13.1 days, while meeting flood control endpoints. This strategy achieves a long-term reduction in sediment trapping equivalent to approximately 50,000 ton/yr, equal to approximately 51 acre-ft/year at 45 lb/ft^3 bulk density, a volume equivalent to approximately 7% of the annual capacity loss in the conservation pool.

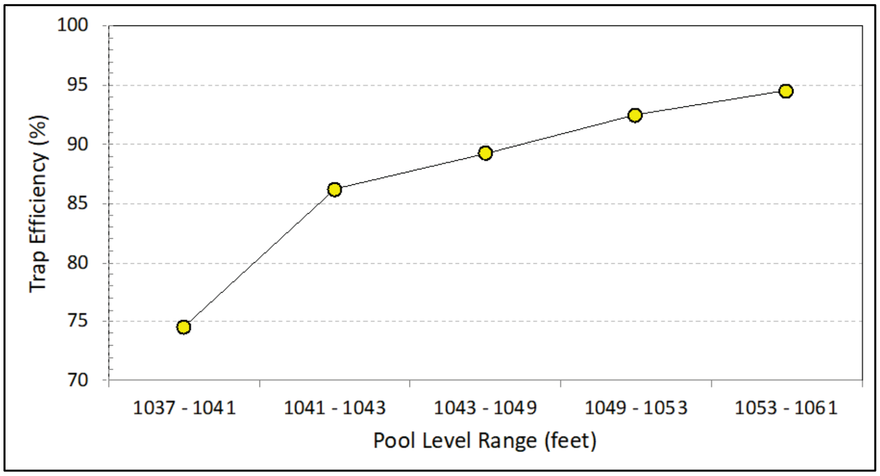
Table 19. Flood control endpoints below John Redmond Reservoir.

Flood-Control Endpoint	Approximate Travel Time from Spillway (hr)	Maximum Discharge (ft^3/s)
Neosho River at Burlington, Kansas	2	14,000
Neosho River at Iola, Kansas	24	18,000
Neosho River at Chanute, Kansas	36	18,000
Neosho River at Parsons, Kansas	60	17,000
Neosho River at Commerce, Oklahoma	84	22,000

Costs to implement sediment pass-through were not estimated in the study, it is assumed that an initial cost of $250,000 for simulations and modification of hydrologic-hydraulic modeling software needed to optimize reservoir management for pass-through. Given the current availability and utilization of real-time hydrologic data in the watershed, no additional data collection costs are assigned. If the initial cost is evenly pro-rated over a 20 yr period ($12,500/yr), this is equivalent to approximately $245/acre-ft or $0.15/$yd^3$ for a 51 acre-ft/year reduction in sedimentation.

Pass-through is more than an order-of-magnitude less costly than any other alternative (Table 18). Even though pass-through will not by itself control sedimentation, it is the least cost of all options and should be incorporated into the long-term sediment management strategy as a high priority, as it will reduce the amount of sediment that must be treated by other methods. For example, compared to dredging it represents an avoided cost exceeding $0.5M/year.

Figure 51. Variation in sediment trap efficiency as a function of the reservoir pool elevation during the inflow event (drawn from data in Lee and Foster 2011).



12.5.7 Storage loss and change in future flood endpoints

As sediment encroaches onto the flood control storage, it will eventually reduce capacity to the point that the current benefit levels cannot be sustained. It will be possible to continue to control the smaller and more frequent flood events, while the ability to control the largest events diminishes.

Sediment pass-through can be expected to help reduce sedimentation in the flood control pool as well as the conservation pool. The analysis of sediment pass-through may be extended to include scenarios with larger flood control endpoints (maximum discharges at locations specified in the water control manual) and smaller flood control capacities, to determine the extent to which sediment pass-through efficiency is increased by incrementing flows above the current endpoints. This information, combined with a revision of the spectrum of flood damage impacts for events of all magnitudes, can help determine whether it makes any sense to consider a modification of the flood control endpoints at this time, or whether it should be postponed until some decades in the future.

In this post-design life phase, it is necessary to rethink reservoir operations and develop a new long-term management plan. This should involve reanalysis of the reservoir’s flood control capability as a function of progressively diminished pool capacities based on anticipated sedimentation. Consider performing this analysis at 50 yr intervals and extending up to 300 yr into the future. Although it is not possible to accurately predict sedimentation rates far into the future, it is certain that sedimentation will occur, and the main uncertainty will be the timing of volume loss, not whether or not it will occur.

Diminished storage capacities will produce correspondingly higher flood levels downstream, but with higher downstream endpoints it should also be possible increase the efficiency of sediment release during floods. This exercise will provide a long-term overview of the sedimentation process, its future impacts and the potential to reduce sedimentation by enhancing sediment pass-through.

With respect to revising the endpoints, several considerations are particularly relevant.

- Revise flood control endpoints using a long planning horizon. The original flood control endpoints were determined based on flood capacities that could be sustained over the project design life, which was achieved by assigning a sacrificial sediment storage pool. When looking forward, it is appropriate to use a similarly long planning horizon, defining new endpoints that can be sustained for the next 100 yr. Simultaneously develop a new operating rule that will optimize sediment release, minimizing the rate of storage loss and extending the duration of the new endpoints. Reduced flood control benefits (higher endpoints) are an inevitable consequence of storage loss. Implement sediment management to delay the next endpoint revision for as long into the future as possible.
- Decrease sedimentation rate. Raising flood control endpoints can increase the ability to pass sediment through the reservoir. Thus, when increasing flood control endpoints in the future, it can make sense to set these endpoints at a level that will contribute to a significant reduction in the rate of reservoir sedimentation, thereby extending the reduced level of flood protection further into the future.
- Downstream preparedness for higher flood levels. If future increments in flood control endpoints are identified now, along with the probable timetable, the to-be-affected properties can be proactively protected with land-use controls to prevent high-value development in future areas of elevated risk or by implementing other protective measures. As a minimum, property owners should be advised of the zones where flood hazards are anticipated to increase in the future as a result of reduced flood control capacity. This might take the form of an additional boundary or as a note on Federal Emergency Management Agency flood maps, for example.

Depending on the results of the analysis, plus additional information on the sedimentation rate by a resurvey of the flood control pool, it may be determined that these actions need not be taken until 50 yr hence. Nevertheless, it will provide a long-term roadmap of the consequences of inaction and the types of sediment management strategies that may be appropriate in the long run.

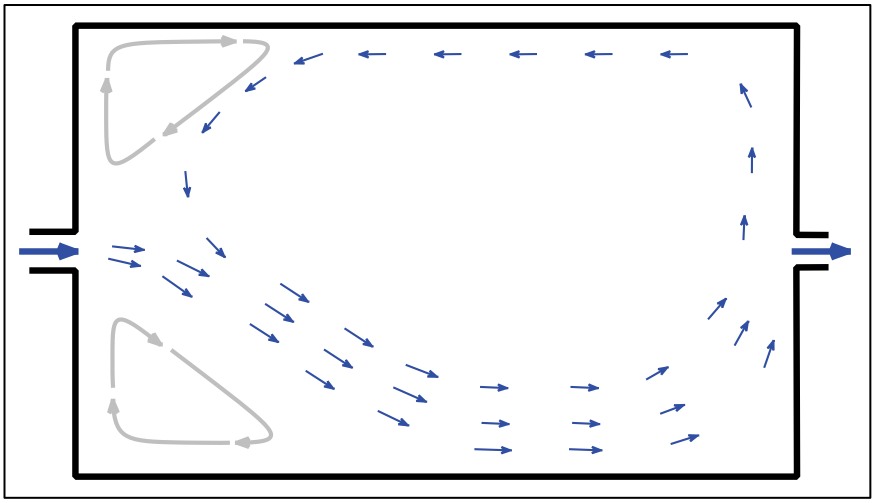
12.5.8 Modify reservoir and outlet geometry

The John Redmond Reservoir geometry is wide (nearly circular) and shallow. These factors tend to not favor sediment pass-through. Although the reservoir is not expected to have turbidity currents due to its limited depth, sedimentation has nevertheless been concentrated along the original river channel (Figure 47), a pattern that may reflect a combination of turbidity flows during smaller inflows plus sediment redistribution into deeper areas by wave action in shallower water.

The inflowing sediment load consists largely of fine sediment, and being a shallow reservoir, there is the possibility of modifying the flow path to promote hydraulic short circuiting to rapidly deliver inflowing sediment to the vicinity of the discharge point, as previously described in Section 9.3 and illustrated in Figure 35.

Flows through reservoirs do not necessarily take a straight line path from entrance to exit, and even under idealized laboratory conditions, flow has been found to typically set up a circular gyre (Figure 52). Furthermore, under laboratory conditions, it has been observed that the circulation pattern could be significantly modified by both sediment concentration and changes in the bottom configuration due to sedimentation. Not all multidimensional numerical models accurately simulate the setup of these circulation patterns, which are revealed by physical modeling (Kantoush and Sumi 2010b).

Figure 52. Circulation pattern observed with clear water in a rectangular tank (redrawn from Kantoush and Sumi 2010b).

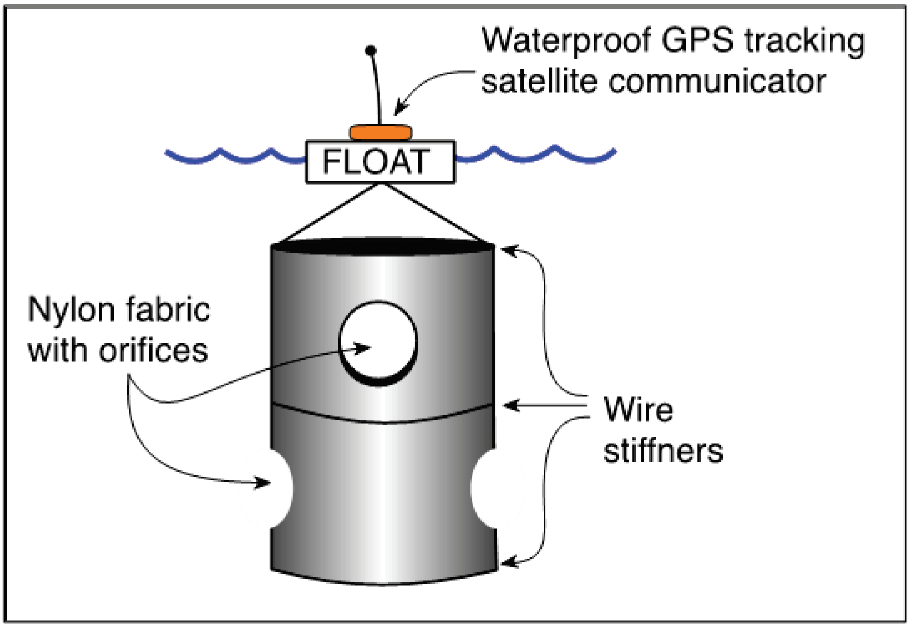


Flow patterns are currently unknown at John Redmond Reservoir. These can be documented during significant inflow events. Flow patterns can be tracked by deploying multiple current drogues or *drifters* consisting of a submerged *holey-sock* type drogue attached to a float fitted with a position transmitter. An economical, off-the-shelf option may be a tracking satellite communicator attached to a drogue and set to broadcast its position at 10 min intervals. Small waterproof units are currently available for under $350. This overall arrangement is conceptually shown in Figure 53, and variations on the holey-sock drogue are given by Barter et al. (2012). A variety of historical drogue designs are illustrated by Monahan and Monahan (1973). Drogues can be simply and inexpensively constructed, and the selected design should maximize the underwater cross section to minimize the impact of wind on drogue movement.

Multiple events should be monitored as current patterns may vary over the duration of an event or between events based on changes in water level or other factors. It would also be prudent to, at least initially, use different drogue depths to determine if the current at, for example, 10 ft depth differs from near-surface currents. This can provide data needed to verify the calibration of 2D numerical models, which can be used to analyze alternatives to direct inflow toward the dam by creating a hydraulic short-circuit, as illustrated previously in Figure 35.

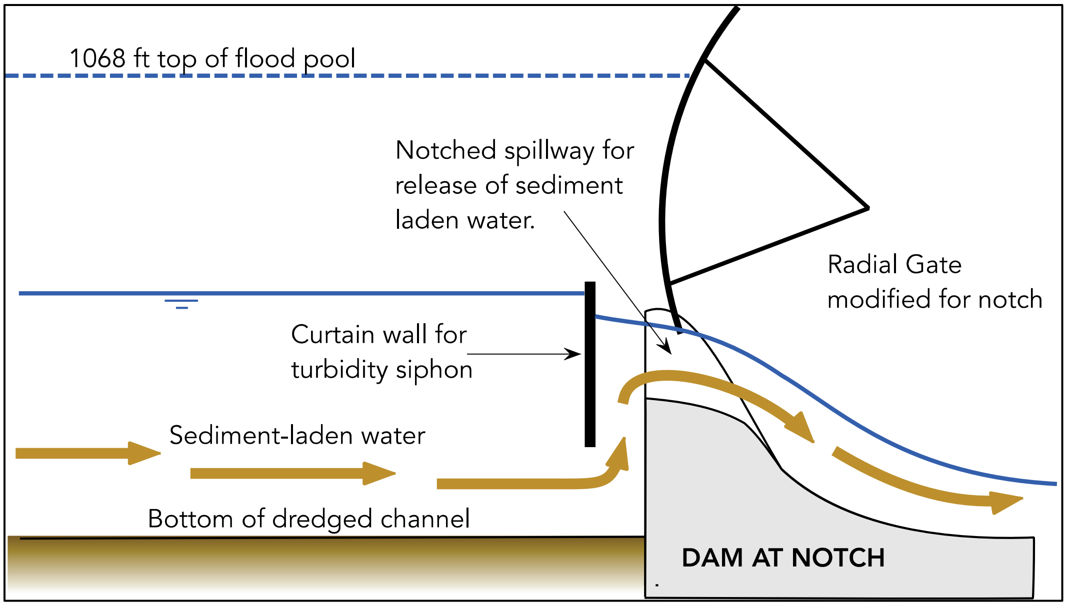
Two-dimensional modeling, verified against drogue data, can be used to estimate the sediment release efficiency that can be achieved by different geometries. For example, what would be the benefit of dredging the original river channel instead of simply dredging a square as accomplished in 2016?

Figure 53. Shallow, holey-sock type drogue with GPS tracking satellite communicator to document circulation in the reservoir during flood.



In addition to modifying the reservoir geometry, the outlet works can also be modified to enhance sediment release. Consider, for example, using a turbidity siphon extending below the level of the spillway crest to preferentially aspirate sediment-laden water from the previously described dredged channel designed to conduct sediment-laden water as efficiently as possible to the reservoir outlet. A conceptual schematic is presented in Figure 54 based on notching the spillway and modifying the radial gates to make all releases preferentially through the turbidity siphon.

Figure 54. Conceptual schematic showing use of a notched spillway with curtain wall turbidity siphon to aspirate sediment-laden water over the spillway.



12.6 Recommended sustainability strategies to consider

John Redmond Reservoir has lost a larger percentage of its conservation storage than most other federal reservoirs in Kansas. As such, it makes sense to use it as a demonstration site to develop and pilot strategies that may be useful at other reservoirs with similar conditions. To minimize sedimentation will require the utilization of traditional techniques, such as erosion control, combined with new techniques focusing on hydraulic management of the reservoir. It will require monitoring data and analysis procedures beyond periodic bathymetric measurements and updating of elevation-area-capacity curves. Some of the specific approaches that may be useful at this site were outlined in this section and are summarized below.

12.6.1 Optimize operating rule to include sediment pass-through

Implement the sediment pass-through procedure based on minimizing detention time during major inflow events, as analyzed by Lee and Foster (2011) and outlined in Section 9.2. Designation of a multiuse pool above elevation 1,041 ft, under the concept outlined in Section 11.3 should also be analyzed within the context of the same modeling. The strategy could include partial drawdown of the conservation pool (below 1,041 ft) at the start of the wet season to further enhance sediment release as compared to management of the flood pool alone.

Following up on the work performed by Lee and Foster (2011), perform long-term simulation modeling of reservoir operations to determine the extent to which detention time can be minimized as a function of increasing discharge at downstream flood control points and incorporating the multiuse pool. The two main objectives of an optimized operating rule would be to reduce detention during sediment inflow events to minimize sediment deposition, and to increase the effective capacity available for conservation storage by incorporating a seasonal, multiple-use pool within a portion of the existing flood pool, based on the data that can be made available from real-time hydrologic forecasting.

12.6.2 Better document sedimentation patterns and rates

Although the rate and pattern of sedimentation in the conservation pool is well documented, the information available for the flood-control pool cannot be considered reliable. Undertake a new lidar survey to confirm the prior survey results and determine sedimentation patterns over the 19 yr since the prior lidar. Consider installation of sedimentation plates or other reference markers in different areas of the flood control pool to ground truth deposition depth against lidar data and determine unit weights of deposited material.

12.6.3 Sediment compaction

Four sediment cores taken along the deepest areas of the reservoir show the continuously submerged sediment to have a relatively low density but to also be subject to significant compaction (Figure 49). A fifth core located in shallower water had little sediment. Additional cores should be taken in dispersed areas of the reservoir with the objective of better documenting the true bulk density of the average deposit reservoir wide and to also better determine the potential for sediment compaction in areas of shallower water. Sediment compaction will have a significant impact on the long-term rate of capacity loss at John Redmond and the comparative economics of different management strategies.

12.6.4 Evaluate options to modify reservoir geometry

Use current drogues or other tracer methods to document reservoir circulation during floods and use these data to calibrate a 2D circulation model. Exercise the calibrated model to determine what types of geometric modifications can increase the hydraulic short-circuiting between reservoir inflow and outflow points during flood events, to direct inflowing sediment-laden flood water to the spillway with the minimum detention time. Geometric modifications may include dredging the original river channel (or other configuration), side-casting dredged material to create a long linear spoil island to help guide sediment toward the outlet, etc.

12.6.5 Improve documentation of river bank erosion

There is uncertainty concerning the importance of riverbank erosion as a source of sediment supply to the reservoir, since eroded bank sediments can be redeposited farther downstream and there is not a clear pattern of widening or incision of the river channel that would occur if it were a large net exporter of sediment.

Inasmuch as bank erosion responds to river hydraulics, rather than rainfall impact, it may be possible to test the net rate of bank erosion by monitoring the impacts of controlled releases from upstream reservoirs during periods absent of rainfall and sediment inputs from land surface processes. Upstream-downstream suspended sediment gage pairs should be used to document the increased net sediment loading that results from hydraulic forces against streambanks. The monitoring of upstream and downstream suspended sediment gages for a period of at least 1 yr may also provide significant additional information on the dynamics of sediment delivery. Given the highly variable nature of suspended sediment, and the potential for error inherent in point sampling of suspended sediment, use the longest practical distance between the upstream and downstream station. Both the Neosho and the Cottonwood Rivers should be monitored.

13 Example: Prado Reservoir, Los Angeles

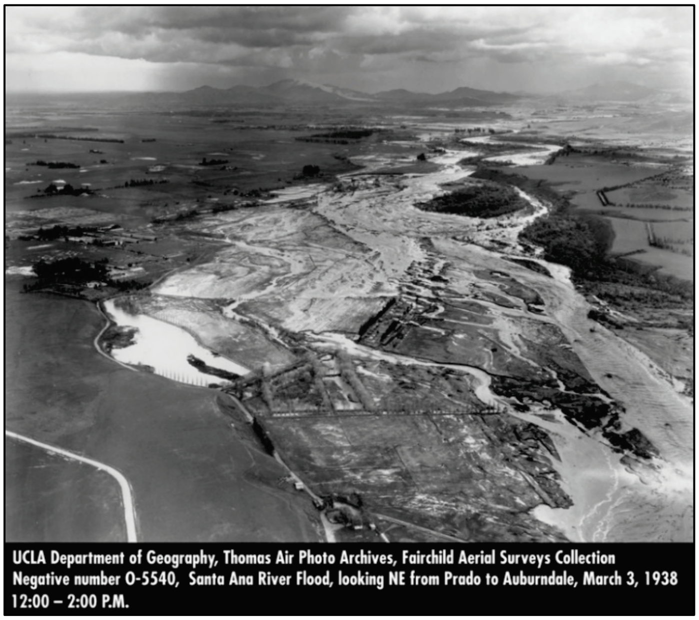
13.1 Key points

Prado Dam and Reservoir illustrate the importance of coarse sediment passage along the river and the challenges involved in reestablishing sediment continuity along the channel below the dam. It also provides an example of conjunctive use, with the flood control reservoir adjusting releases to maximize managed aquifer recharge along the downstream river channel.

13.2 Setting

The Southern California natural hydrologic environment is characterized by ephemeral rivers carrying heavy sediment loads (Figure 55). Watershed soils are highly erodible, specific sediment yields are high, and as rivers discharge from the mountains onto the flat coastal plain, transport capacity rapidly diminishes and sediments are deposited resulting in braided channels and floodwaters, which spread over wide areas (Figure 55). Starting in the 1930s, a large system of flood control channels, debris basins, and reservoirs, including Prado reservoir, were constructed to control flooding.

Figure 55. View looking upstream along Santa Ana River, flood of March 3, 1938, showing the braided pattern typical of southern California rivers crossing the coastal floodplain (With permission, University of California at Los Angeles Dept. of Geography).



UCLA Department of Geography, Thomas Air Photo Archives, Fairchild Aerial Surveys Collection
Negative number 0-5540, Santa Ana River Flood, looking NE from Prado to Auburndale, March 3, 1938
12:00 – 2:00 P.M.

Prado Dam, an earthfill structure, was constructed on the Santa Ana River in 1941 to control runoff and flooding from its 2,255 mi^2 tributary watershed, but it also provides a limited amount of temporary storage for water conservation. In response to increased flood peaks resulting from upstream development and the desire to increase the level of protection, the reservoir capacity is being enlarged (Table 20). Total cost of improvements, which are not yet completed, will be approximately $500M. Some features of the dam and reservoir are summarized in Table 20. The reservoir maintains a portion of the pool as multipurpose storage to sustain water supply releases downstream to the recharge areas operated by Orange County Water District (OCWD). The priority concern at Prado Dam is not storage loss but downstream impacts from the interruption of coarse sediment transport by trapping in the reservoir. The reservoir is relatively shallow, with an almost circular geometry, and is estimated to have 97% trap efficiency (Warrick and Rubin 2007).

Table 20. Key features of Prado Dam and Reservoir at top of flood pool.

Parameter	Original Structure	With Improvements	Change
Top of Dam elevation, ft	566	594.4	+28.4
Spillway Crest elevation, ft	543	563	+20
Reservoir Area, acres	6,695	10,256	–
Reservoir Maximum Capacity, acre-ft	217,000	362,000	–
Discharge Capacity, ft^3/s	10,000	30,000	20,000
Storage Loss Rate, acre-ft/yr	715	715	–
Storage Loss Rate, %/yr	0.33%	0.20%	–
Reservoir Half-Life, yr	152	254	102
Average Depth, ft	32	32	0

The Prado Dam and Reservoir project is normally dry, with just a base streamflow that passes through the outlet works. The Prado Reservoir contains critical habitat for several species listed by either the federal or state government: Santa Ana Sucker (*Catostomus santaanae*), an endemic fish species, Least Bell's vireo (*Vireo bellii pusillus*), Southwestern willow flycatcher (*Empidonax traillii extimus*), Yellow-billed cuckoo (*Coccyzus americanus*), Long-eared owl (*Asio otus*), Yellow warbler (*Setophaga petechial*), and Yellow-breasted chat (*Icteria virens*). The Prado Reservoir is also considered a wildlife corridor that links a number of open, native habitats. Habitat types within the basin are considered capable of supporting a range of wildlife species, including those identified as rare and/or sensitive. In California, less than 10% of the pre-settlement wetlands remain, the rest having been converted primarily to farming or urban uses (T. A. Dahl 2011). This makes the riparian habitat within the normally dry flood pool particularly valuable. Environmental concerns are a major factor impacting management alternatives at this site, even though the Prado Dam normal operation does not include regulating the impoundment for environmental support or recreation.

The critical role that Prado Dam plays in water supply is described by Hutchinson and Woodside (2019), who discussed the cooperation between the USACE and OCWD. The flood management reservoir is used for the temporary capture of stormwater with subsequent water release for groundwater recharge, without impacting the dam's primary flood risk management purpose. As an additional complication, water pooled at the dam submerges lands with habitat for endangered species. Use of the dam for recharge required overcoming three obstacles: (1) capturing stormwater without impacting the dam's flood risk management purpose, (2) solving endangered species habitat and nesting conflicts in the reservoir area where water is pooled, and (3) developing facilities downstream of Prado Dam to recharge stormwater.

Capturing stormwater at Prado Dam without impacting flood risk management requires the USACE to rapidly release stormwater captured under the program if holding the water would reduce flood management in a pending rainfall event. The USACE and OCWD coordinate closely to release stormwater captured at the dam so that release rates are maximized but do not exceed the OCWD recharge capacity. The USACE can temporarily store approximately 19,500 acre-ft at Prado Dam for downstream groundwater recharge. The OCWD recharge facilities are located approximately 12 mi downstream of Prado Dam, where two inflatable rubber dams divert Santa Ana River water released from Prado Dam into 22 surface recharge facilities. The recharge facilities sustainably recharge river water at peak rates of 350 to 700 ft^3/s , allowing full release of the temporary storage volume in Prado Reservoir to recharge during approximately 25 to 40 days.

13.3 Sedimentation impacts and issues

The historical sediment balance along Southern California rivers has been severely modified by flood management activities. Large-scale flood control works were initiated in the 1930s with the construction of large trapezoidal flood channels, many of them concrete lined, plus upstream dams to control peak discharge and upstream debris basins to capture coarse sediment that would otherwise deposit in and obstruct flood control channels. Sediment excavated from debris basins is deposited into containment areas.

The water control plan for the Prado Reservoir requires a minimum water surface elevation during the flood season to serve as a debris pool. The purpose of the debris pool is to allow excess sediment and floating debris to settle within the reservoir rather than having it pass through the outlet works. This limits potential abrasion and debris damage to the outlet works and tunnel, but the trapping of coarse sediments by Prado Dam contributes to downstream problems including incision of the riverbed, which impacts infrastructure such as bridges and pipeline crossings; accelerated stream bank erosion; and coarsening of the river bed, which allows fines to penetrate and clog the riverbed at greater depths with a consequent reduction in recharge to the aquifer on which Orange County relies for water supply. It also reduces sand supply to coastal beaches.

Water supply is a major concern in the area. Starting in 1936, the OCWD began purchasing portions of the Santa Ana River channel for ground water recharge, and it now owns a 6 mi section of the river and operates over two dozen separate facilities covering over 1,000 acres, including recharge basins that range in depth from 5 to 150 ft, plus two low-head inflatable rubber dams in the river for diverting water into recharge basins. Recharge water includes downstream releases from Prado Dam and highly purified municipal wastewater (OCWD 2018). The Santa Ana riverbed typically recharges approximately 100 ft^3/s , and additional flows released by the dam are diverted into offstream recharge basins. However, when river flow starts to exceed approximately 400 ft^3/s , the temporary water spreading berms in some areas of the riverbed can be washed out. The recharge rate through the riverbed has been declining at approximately 1% per year. It is thought that the decline in recharge is due to armoring of the bed with resultant clogging of the sub-armor sediment with fines (Woodside 2012).

Incision and coarsening of bed material in river channels below dams are a well-known response to the interruption of the coarse sediment supply by dams (Kondolf 1997). High flows released from the dam transport sediment farther downstream along the river, and without upstream replenishment the bed incises. Because smaller sediments are transported more rapidly than larger grains, this winnowing of the smaller material results in a coarsening of the bed. This can cause bed armoring, which progressively immobilizes the smaller sediment (e.g., sands), which are trapped beneath the armor layer. Fine sediments, silts, and clays, which are carried in suspension by the river, enter and accumulate in the void spaces between the coarse sediment grains in the river bed. If the bed is not intermittently mobilized by floods to wash out this accumulation of fines the permeability of the riverbed will diminish, and the bed may also become cemented. Replenishment of the riverbed with appropriately sized bed material, and in appropriate quantities, can help offset this condition by preventing armoring, and creating a sandy surface layer that can be readily mobilized to flush out fines.

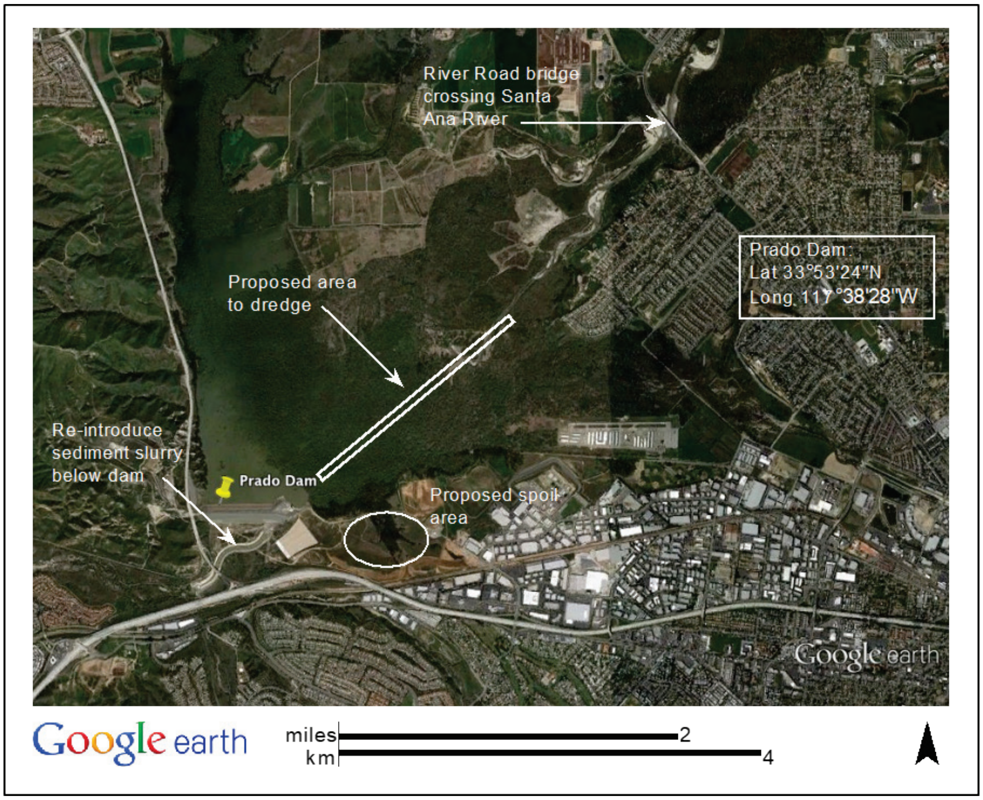
A survey of riverbed conditions by Engineering and Hydrosystems (E & H 2009), which included the sampling of 17 riverbed locations below Prado Dam and comparison against historical size gradations reported between 1975 and 2003, concluded that the grain size is coarsening as compared to the historical conditions. There were also obvious signs of continuing river incision, such as the grade control structures originally constructed by the USACE below bed level but which are now exposed. Areas of bed cementation (caliche) were also documented.

The downstream channel can be conceptualized as consisting of three segments. Immediately below the dam there is a narrow *canyon reach* with steeper slopes; below that the *recharge reach,* where most of the ground water recharge facilities are located; and the last segment, which extends to the ocean or the *outlet reach*. Prado Dam interrupts the supply of coarse sediment to the channel downstream of the dam, but significant amounts of sediment are contributed to the channel downstream of the dam. WEST Consultants (2011) used the Sediment Impact Analysis Method model (USACE 2010; Little and Jonas 2010) to analyze the sediment balance along the river below the dam, finding that the canyon reach was characterized by degradation, the recharge reach was approximately balanced with respect to sediment transport while the outlet reach was characterized as a depositional environment.

There have also been sedimentation impacts upstream of the reservoir. Coarse sediment (sand and gravel) deposition in the Santa Ana River has led to aggradation of the stream upstream of the reservoir. The River Road Bridge, originally constructed in 1927, crosses Santa Ana River at the upstream end of the reservoir (location shown in Figure 56). Coarse sediment deposition in this area has raised the riverbed level, and a combination of raised bed level, which reduced bridge clearance, plus the repeated trapping of woody debris, caused the River Road Bridge to be replaced. This work was completed in 2011 at a cost of $48M following damage by flood and debris.

The desirability of restoring a coarse sediment balance along the Santa Ana River below Prado Dam gave rise to an engineering study to examine options for coarse sediment replenishment (HDR-RBF-Golder 2011). Benefits envisioned above the dam include (1) recovery of capacity for flood control and water conservation; (2) reduced sedimentation rate in the reservoir; and (3) reduced upstream growth of delta deposits, which may impact infrastructure and habitat such as wetlands. Anticipated benefits below the dam include (1) offset streambed incision and associated accelerated channel bank erosion, which threatens both infrastructure and wildlife habitat; (2) halt or reverse streambed armoring, which decreases the hydraulic capacity of groundwater recharge facilities; and (3) replenish sand to coastal beaches. The general concept is to extract sediment from the zone where the river enters the impoundment, the area where most coarse sediment is deposited, and to place it in the river below the dam (Figure 56). The OCWD attempted to establish a demonstration project, removing 125 acre-ft of sand from upstream areas of the reservoir and reintroducing it into the river below the dam to restore coarse sediment supply to the below-dam channel while also helping to preserve reservoir capacity (Olsen 2015). However, the options for sediment removal could not get approved with respect to environmental impacts, and this sediment management alternative was dropped.

Figure 56. Aerial view of Prado Dam and Reservoir, illustrating the proposed dredging area for the sediment management demonstration project.



13.4 Sedimentation

13.4.1 Rate of reservoir sedimentation

The current sedimentation rate in Prado Reservoir is approximately 711 acre-ft/yr, computed as the average from Table 21, eliminating the maximum and minimum values. Of this, approximately 370 acre-ft/yr deposits in the temporary conservation storage, the loss of which would impair water supply for recharge (Olsen 2015).

Table 21. Sedimentation rates estimated for Prado Reservoir (adapted from Table A1 of HDR-RBF-Golder 2011).

Source	Period	Sedimentation Rate (acre-ft/yr)	Specific Sediment Yield (acre-ft/mi^2/yr)
USACE (2003)	1960–1988	751	0.33
USACE (2005)	1956–2005	580	0.26
Warrick and Rubin (2007)	1968–2001	810	0.36

Table 21 (cont.). Sedimentation rates estimated for Prado Reservoir (adapted from Table A1 of HDR-RBF-Golder 2011).

Source	Period	Sedimentation Rate (acre-ft/yr)	Specific Sediment Yield (acre-ft/mi^2/yr)
HDR-RDBF-Golder (2011)*	1988–2008	715	0.32
USACE (1967)	1941–1960	311	0.14
Subcommittee on Sedimentation (1992)	1941–1979	700	0.31
Dept. of Boating and Waterways and State Coastal Conservancy	1979–	855	0.38

* Appendix A in HDR-RBF-Golder (2011).

The half-life of Prado Reservoir, following enlargement, is summarized below based on a continuation of current operating and hydrologic conditions:

	Acre-ft	Percentage of Total
Total reservoir capacity	362,000	100%
Annual storage Loss	711	0.20%
Reservoir Half Life	255 yr	

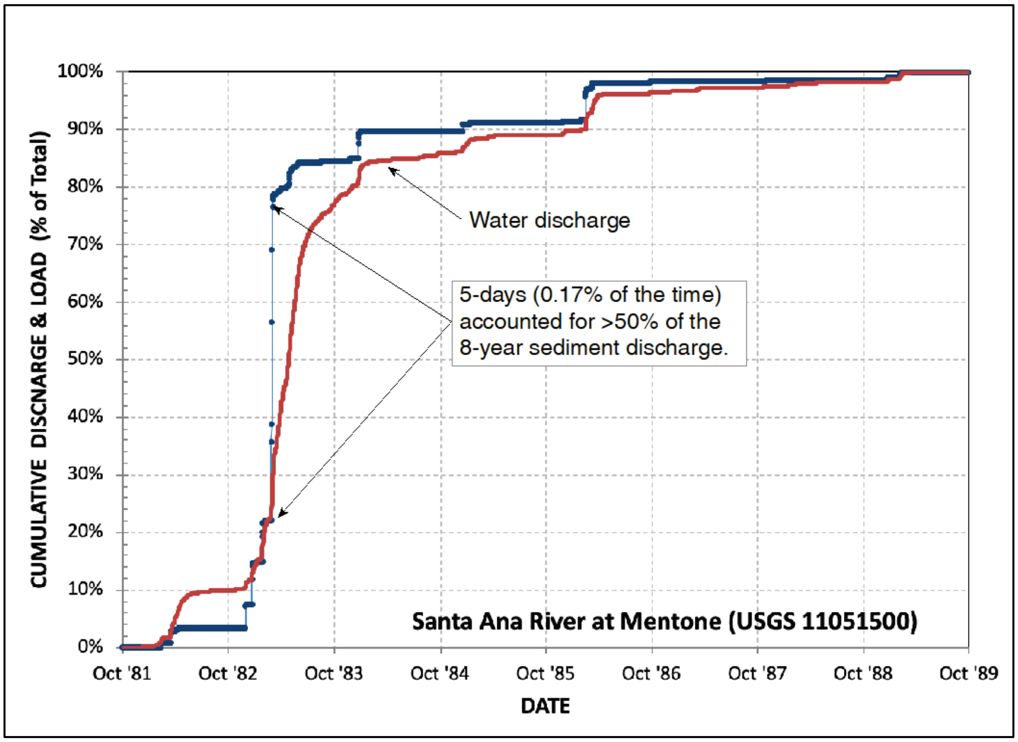
13.4.2 Sediment flux in Santa Ana River

The Santa Ana watershed experiences a Mediterranean-type climate, and streams are ephemeral. Sediment production is episodic and driven by seasonal winter rainfall with almost all precipitation occurring between November and April. Most sediment discharge from Southern California rivers occurs as suspended load and is transported during one or a few extreme rainfall and flood events each year (Tramblay et al. 2010). The upper 1504 mi^2 Santa Ana River watershed, tributary to Prado Dam, accounts for 87.6% of the river basin while an additional 197 mi^2 drains to the river below the dam. The lower basin drainage area includes the Santa Ana Mountains (maximum elevation 5,670 ft). By 2000, approximately 40% of both the upper and lower basin had been urbanized.

Daily suspended sediment data are available above Prado Reservoir for the 8 yr period from October 1981 to September 1989 at the USGS gage for

Santa Ana River at Mentone (gage 11051500) with a drainage area of 210 mi^2, equivalent to 9.3% of the watershed tributary to Prado Dam. Suspended sediment and discharge data are plotted in Figure 57 as cumulative percentage of the total period-of-record delivery. Sediment discharge is highly concentrated in time: 55% of the 8 yr sediment load was transported during a 5-day flooding starting February 27, 1983.

Figure 57. Cumulative discharge of suspended sediment and discharge over time, as percentage of the 8 yr total, Santa Ana River at Mentone, CA.



Below Prado Dam, analysis by Kroll (1975) found that, during the 40 yr period ending in 1971, half of the suspended sediment load in the Santa Ana River watershed was transported during only 10 days. By analysis of long-term suspended sediment data for the lower reach for the period 1968–2001, Warrick and Milliman (2003) reported that 90% of the sediment discharge occurs on an average of 3 days per year while 70% of the time the river discharge to the ocean is zero. During the 34 yr period, over half the load was discharged during 1969 following the 1967 Paseo Grande wildfire. It was concluded that the sediment concentrations were declining over time due to dilution by increased flood flows by urbanization, coupled with the lack of sediment contribution from the concrete-lined flood channel but that the sediment load was probably not trending over the measurement period.

13.5 Demonstration project sediment management strategy

The OCWD sponsored a preliminary engineering study to identify the preferred option for a demonstration project to assess the feasibility of long-term sediment management, removing sediment from Prado Basin and reentraining that sediment in a controlled manner into the Santa Ana River immediately below the dam. The demonstration project focuses on the replenishment of coarse sediment supply to the river below the dam.

The demonstration project would assess the impacts of this sediment management procedure on (1) patterns of sediment aggradation and erosion, (2) river bed infiltration, (3) riparian and wetland habitat, (4) municipal water diversions, and (5) sedimentation rate within Prado Reservoir. An important constraint for the demonstration project was to not interfere with existing operations related to the dam: "The overall goal of the sediment extraction and entrainment operations is to conduct them so that changes in dam operation are not necessary" (HDR-RBF-Golder 2011, 2.9).

Four options were examined; two of these entailed dry excavation and two entailed dredging. The preferred option consists of dredging between 155 and 310 acre-ft of sediment with re-entrainment into the river below the dam. Sediment would be dredged along the river channel, which runs across the floor of the normally dry flood control basin, pumped into a containment area next to the spillway, and sediment would be delivered into the river by slurry pump during periods of high flow.

The three listed species and additional habitat concerns related to the forest and wetlands within the reservoir basin constrain management options. The dredging area was selected to minimize environmental impact, avoid upstream infrastructure (such as River Road Bridge), which could be affected by upstream headcutting of the dredging pit, and work closer to the dam so pumping distance is reduced. The downstream limit of the proposed dredging area, schematically shown in Figure 56, comes within approximately 600 ft of the dam and does not extend upstream into the area where the river width is limited and the coarsest sediments are located. As illustrated in Figure 56, the dredging template consists of a long straight channel (6,000 ft × 200 ft). Preliminary modeling suggested that this dredged area is not anticipated to refill with sediment quickly (HDR-RBF-Golder 2011).

Ideally the sediment released downstream of the dam would consist entirely of coarse sediment (sand and gravel), but a review of the five geotechnical borings in the proposed dredging area suggest that approximately 40% of the sediment consists of silts, with small amounts of clay. The desire to minimize deposition of fine sediment onto the riverbed used for recharge led to the following re-entrainment strategy. First, reentrainment is limited to periods of adequate flow, keeping the sediment concentration at 1% once diluted by river flow. Dredged sediments would be discharged to the river when flows exceed 2000 ft^3/s because above this discharge, the instream rubber dams at the recharge areas are deflated, which would allow fine sediment to pass these barriers without deposition. Second, sediment re-entrainment would be performed by creating and pumping slurry from the temporary containment area because this allows the greatest control over both the timing and concentration of the sediment re-introduced into the river. Bulk placement into the river channel (recall Figure 42) is less desirable because it creates the possibility of sediment scour and release during periods when it could interfere with water diversion and infiltration operations by OCWD.

The total cost of an operation to dredge and reintroduce 500,000 yd^3 of sediment by this method is estimated at \$8.7M, equivalent to \$17.40/yd^3 (\$28,000/acre-ft). With an annual rate of storage loss of 715 acre-ft/yr, to achieve a sediment balance across Prado Reservoir by this method would cost on the order of \$20M/yr, assuming the downstream channel could accept this volume of sediment. Downstream discharge would be further complicated by a large-scale project to dredge and discharge below the dam because the remaining area of the reservoir will have finer material. If the dredging is expanded to other areas in the reservoir, increasing the amount of fine sediment delivered to the downstream river, it would increase clogging and impair operation of the groundwater recharge basins on which Orange County depends for municipal water supply.

Another aspect that was analyzed was the potential to capture sediment within the dredged area, essentially creating a sediment trap that could be repeatedly (or continuously) dredged for sediment management. Several different dredging footprints were analyzed, as summarized in Table 22, which shows the total dredging volume under each alternative dredging footprint analyzed, plus the annual rate of sediment capture in each footprint, as compared to the total amount of sediment trapped in the reservoir. Even by optimizing the configuration of the dredging area along the Santa Ana River, it will be possible to capture only 3.1% of the annual inflowing load within the area of the dredging footprint.

Table 22. Sediment loading and extraction for alternative dredging configurations (Table A-2 of HDR-RBF-Golder 2011).

Dredging Alignment	Total Sediment Volume			Average Sedimentation Rate		
	yd^3	acre-ft	Percentage	yd^3/yr	acre-ft/yr	Percentage/yr
Prado Basin (1988–2008 only)	24,240,370	15,025	100.0%	1,154,303	715	100.0%
V–Shaped	400,656	248	1.7%	19,079	12	1.7%
Santa Ana River Only	559,563	347	2.3%	26,646	17	2.3%
Chino Creek	300,181	186	1.2%	14,294	9	1.2%
Optimized Santa Ana Alignment	754,730	468	3.1%	35,940	22	3.1%

The demonstration project represented a good starting point in the analysis of strategies to address downstream problems related to reduction of coarse sediment inputs to Santa Ana River below the dam. However, unless substantially enlarged, it would not significantly alter the rate of storage loss within the reservoir. The OCWD recently put the Demonstration Project on hold[13], and it is uncertain if they will try to resume this project in the future.

13.6 Considerations for long-term sustainability

Prado Reservoir is a flood control structure, and most of the long-term sediment load is delivered during the large floods that the reservoir is designed to retain (recall Figure 57). Even smaller floods are captured and released slowly to match the infiltration rate in the downstream recharge basins. This means there is essentially no potential to enhance sediment pass-through by either sluicing or flood bypass unless the capacity of the downstream channel is increased.

Approximately 40% of the watershed above the dam is urbanized. Undeveloped portions of the watershed are semiarid, sparsely vegetated, and mountainous. Sediment yield does not appear to be unusually high. It

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[13] Kim Gilbert, USACE Los Angeles District, personal communication, 4 September 2019.

is not clear that a significant reduction in sediment yield could be achieved in a cost-effective manner, especially given the impact of extreme flood events on sediment yield.

Given the limitations at this site, in the long term it is likely that dredging or dry excavation will be the preferred management option for achieving a sediment balance at Prado. At 711 acre-ft/year (1.15 Myd^3), the volume of material involved is not extraordinarily large, and the area protected from flooding and provided water supply by the dam has the economic resources to pay for excavation. Nevertheless, it seems unlikely that sediment accumulation will reach the point that this action will become urgent in the foreseeable future, especially given the current enlargement in storage capacity.

13.6.1 Data collection

The dynamics of sediment delivery into Prado Dam is not well documented; the only suspended sediment gage station upstream of the dam covers just 9% of the tributary watershed and was discontinued in 1989 after 8 yr of operation. This limits the potential to evaluate strategies for sediment routing. Continuous sediment monitoring is recommended upstream and downstream of the dam to document event-specific trap efficiency as a function of detention time. This monitoring should include collection of data on grain size distribution.

Better information on the distribution of sediment within Prado Reservoir may be collected by establishing sedimentation monuments as a check against data obtained by successive lidar surveys and to better document variations in bulk density and grain size of deposits.

13.6.2 Dredging of coarse sediment

A strategy to pass coarse sediment below the dam by dredging was analyzed in the demonstration project. If it were possible to reduce the fine sediment fraction in the material released below the dam, there would be less concern about bulk sediment placement into the river below the dam so that river flows can erode and wash it downstream (recall Figure 42). This strategy could be less costly than the procedure outlined in the demonstration project that involves the additional material handling cost of resuspending stockpiled sediment for discharge to the river as slurry. Several alternative strategies may be useful for capturing predominantly coarse sediment and discharging it below the dam.

14 Example: Lewis and Clark Lake at Gavins Point Dam, Upper Missouri River

14.1 Key points

This case study gives a short overview of alternative sediment management options, and the potential evolution of reservoir geometry in the transition from conventional operation with continual sediment tapping, to a sustainable operation with the objective of eventually achieving a sediment balance.

14.2 Problem statement

Gavins Point Dam near Yankton, SD, impounds the Missouri River in Lewis and Clark Lake approximately 70 mi below Ft. Randall Dam, along a reach of the river that defines the boundary between South Dakota (left bank) and Nebraska (right bank). It is the smallest and most downstream of the six mainstem reservoirs on the Missouri River cascade. Upstream dams act as efficient sediment traps, and little sediment enters Lewis and Clark Reservoir from Ft. Randall Dam. Over half the sediment enters the reservoir from lateral tributaries: the Niobrara River, Ponca Creek, and several smaller streams.

The trapping of sand by Gavins Point Dam eliminates the natural inputs of bed material to the downstream river, resulting in adverse consequences including channel incision with accelerated bank erosion and loss of instream habitat related to river sandbars. To offset these impacts, Element IV.B of the 2000 Biological Opinion requires the USACE to initiate sediment bypass studies in an attempt to provide sandbar material to the more productive riverine reaches below the dam. Gavins Point Dam/Lewis and Clark Lake was selected as the first study site due to the reservoir's characteristics and the relative magnitude of other sedimentation issues. In addition to these downstream issues, the dam is losing storage capacity at an annual rate of 0.47% and had lost 30% of its storage capacity by 2020.

14.3 Setting

Gavins Point Dam was closed in 1955 to create Lewis and Clark Lake. The authorized uses are navigation, hydropower, flood control, recreation, water supply, fish and wildlife (including endangered species), water quality, and irrigation. Lewis and Clark Lake attracts more than a million visitors each year to its shores. Recreation opportunities around the lake include camping, fishing, hunting, hiking, boating, sailing, swimming, birdwatching, and photography. Loss of the lake and associated recreational use would have substantial adverse economic impact on nearby Yankton, SD.

The peak discharge of record occurred in July 2011 when releases reached 160,000 ft^3/s , causing considerable flooding and damage to property and crops both above and below the dam. The historical pre-impoundment flood at Yankton occurred in the spring of 1952 and approached 500,000 ft^3/s . The hydropower plant can pass 34,000 ft^3/s and generate 132 MW at full load. The impact of dam construction on below-dam streamflow is illustrated in Figure 58. The maximum discharges are typically in the range of 30,000 to 40,000 ft^3/s.

Lewis and Clark Lake has an elongated geometry, as seen in Figure 59. It was originally approximately 25 mi long, but growth of the delta has reduced the length of the reservoir to approximately 15 mi, and the width varies from approximately 1.5 to 2 mi. Water levels in the reservoir are normally stable, typically ranging from 1,205 to 1,208 ft (NGVD 1929). The river passes through the delta as a braided stream, and most of the delta surface is vegetated by cattail (*Typha*) and invasive *Phragmites*. The extreme flood of 2011 washed away the surface vegetation, but in most cases did not remove the roots. Views of the delta approximately 6 months following the extreme flood flows are presented in Figure 60.

Figure 58. Daily discharge, Missouri River at Yankton below Gavins Point Dam. Gage discontinued in 1995 (Information available from the USGS at https://waterdata.usgs.gov/nwis/dv/?referred_module=sw&site_no=06467500.).

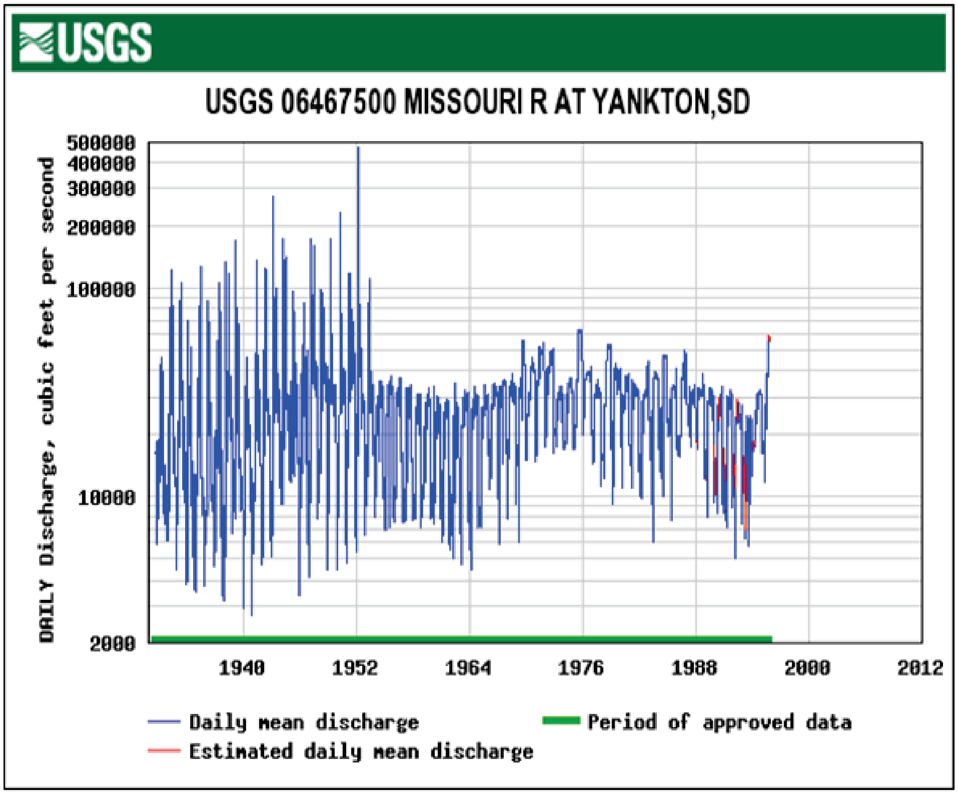
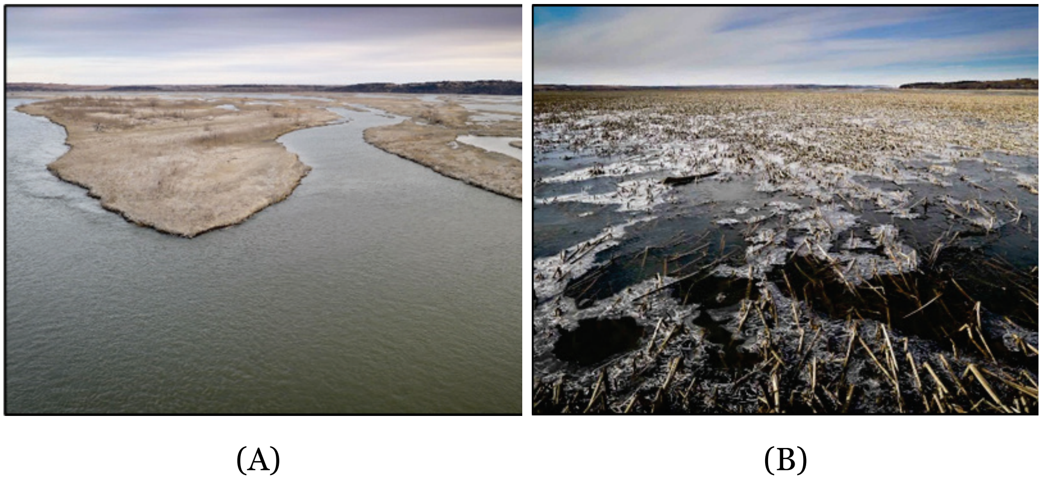


Figure 59. Aerial view of Lewis and Clark Lake and Gavins Point Dam (Image source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community).

Figure 60. Views of the delta at Lewis and Clark Lake. (A) View looking downstream along Missouri River from Chief Standing Bear Bridge. (B) View looking upstream at Bazile Creek boat launch showing that the extreme flood during the summer of 2011 washed out the cattails and *Phragmites,* but their roots remained.



(A) (B)

14.4 Reservoir sedimentation

Sedimentation conditions in the dams along the Missouri are summarized in Table 7. Lewis and Clark Lake is the smallest of the impoundments on the Missouri River and, despite the upstream dams which trap sediment, it is also losing capacity faster than any of the other dams (Table 7). Based on the 2011 reservoir survey, Lewis and Clark Lake is losing its capacity at the rate of 2,600 acre-ft/yr, with a total sediment volume of 148,000 acre-ft. Over half of the sediment load to Lewis and Clark Lake is delivered by the Niobrara River which enters the Missouri River approximately 10 mi above the original Lewis and Clark Lake (approximately 30 mi above the dam). Sediment sources entering the reservoir are summarized in Table 23.

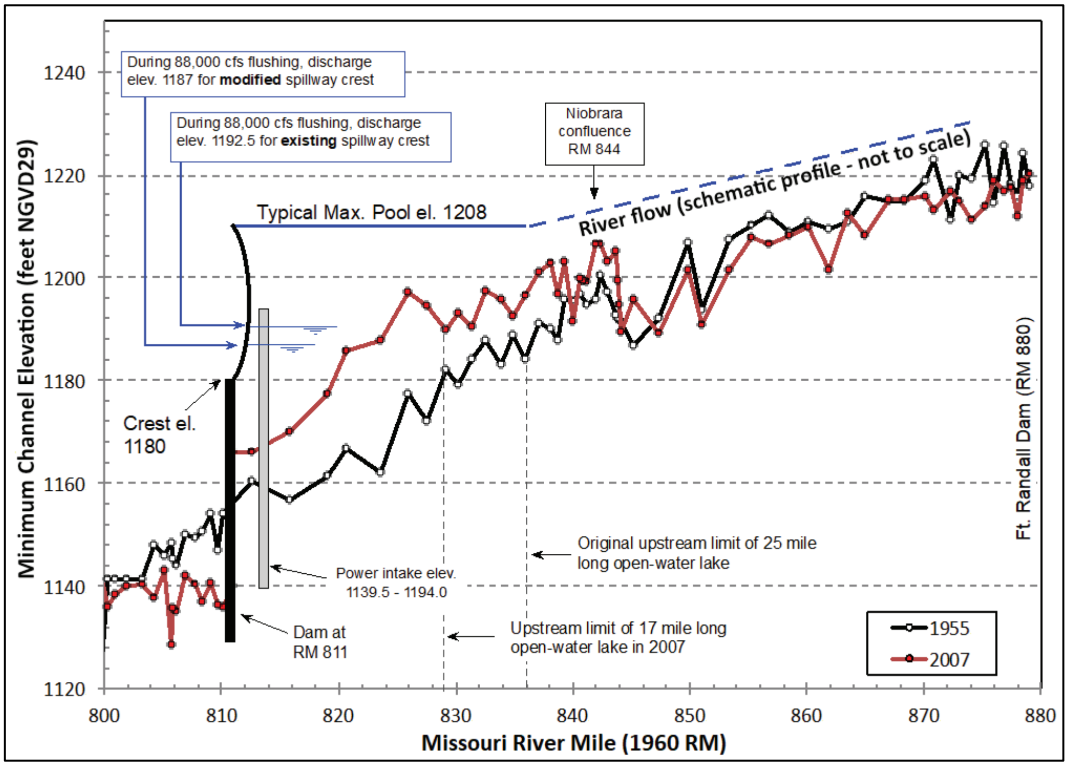
Table 23. Sources contributing sediment to Lewis and Clark Lake.

Sediment Source	Percentage of Total
Niobrara River	45%
Missouri River	45%
Other drainages	10%

Source: Sweeney et al. (2016).

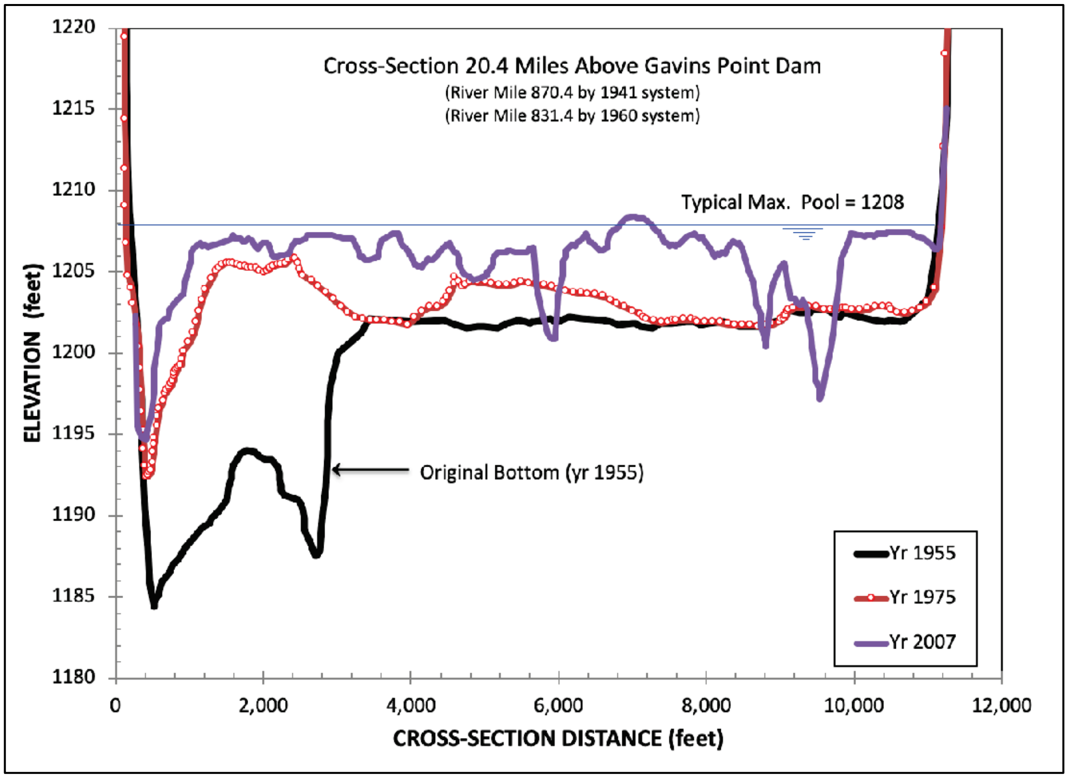
The most visible sediments in the reservoir are accumulating in the form of a delta. Figure 61 shows the change in the river channel profile along the Missouri River, including Lewis and Clark Lake. This profile shows delta growth along the reservoir, the extension of the delta above the original upstream pool limit, and channel degradation below the dam due to reduced coarse sediment supply. It also shows a zone of finer sediment deposition between the delta and the dam. The elevation of the top of the delta, not plotted, normally extends above the reservoir level. Due to the elevation of the spillway crest gates at Gavin's Point Dam and the high water levels, the reservoir acts as an extremely efficient trap for coarse sediment, even during the historic 2011 flood event.

Figure 61. Longitudinal profile of Lewis and Clark Lake showing progression of the river thalweg profile between pre-impoundment (1955) conditions and the 2007 bathymetric survey (thalweg profile from USACE Omaha District).



Successive cross sections from a point approximately 20.4 mi above the dam are plotted in Figure 62 showing the rapid infilling of the original river channel and subsequent stabilization of the top of the delta. The pool is normally maintained between elevation 1,205 and 1,208 ft, exceeding this level only during flood risk management operations.

Figure 62. Successive cross-section profiles showing the advancement of the delta to infill original river channel and stabilization of the top of delta elevation.



The size gradation of surface sediments was documented in sampling performed in 1975 and reproduced in Figure 63 up to the Niobrara confluence. Surface sampling was again performed in 2007 by the USGS, and a comparison of grain sizes reported in the area of the delta within 25 mi of the dam is summarized in Table 24 for the two study dates. Because coarse sediments transported along the top of the delta will prograde over finer sediments as the delta advances downstream, the surface sediments are not representative of the average composition of the sediment deposits. It is not known how much fine sediment may be trapped in the delta, but to the extent that fines do exist, they are effectively buried by the coarser deposits. However, if flushing occurs that causes the river to incise into the delta, finer sediments buried beneath the surface of the delta may be mobilized.

USACE analysis of cross sections taken in different years showed that the 2011 flood scoured channels within the delta mostly downstream of the confluence with the Niobrara River and moved this material downstream to contribute to some of the delta advancement into the reservoir

(Sweeney et al. 2016). This is a common mechanism for delta advancement within reservoirs.

Figure 63. Variation in grain size along delta in Lewis and Clark Lake based on sampling in 1975. The area with no grain size data corresponds to the portion of the lake downstream from the delta (constructed from data reported in Yang and Ahn 2010).

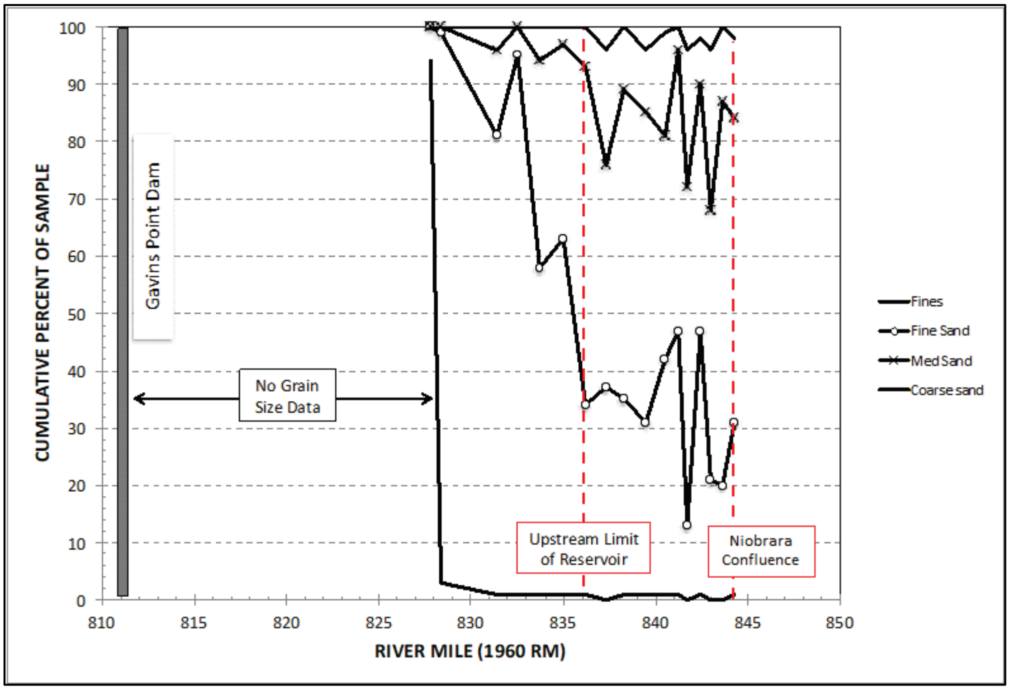


Table 24. Average grain size of surface sediment on Delta of Lewis and Clark Lake.

Data Year	Silt and Clay <0.062 mm	Very Fine and Fine Sand 0.062 to 0.25 mm	Medium Sand 0.25 to 0.5 mm	Coarse and Very Coarse Sand 0.5 to 2.0 mm	Gravel >2.0 mm
1975	1.3	70.3	25.0	3.3	0
2007	4.3	65.4	18.1	9.4	2.7

Source: Computed from data in Yang and Ahn (2010).

14.5 Sediment management approaches and options

14.5.1 Options previously analyzed and discarded

Sediment management options for Lewis and Clark Lake were reviewed by Engineering and Hydrosystems (E & H 2002), indicating that three options had been considered potentially feasible by the USACE. With over half the sediment derived from Niobrara River, one of the options was to reroute sediment from that river to discharge its sand load downstream of

Gavins Point Dam. This corresponds to a pipeline distance of approximately 33 mi or an overland haul distance of approximately 39 mi. While technically feasible, these are both very costly options and would capture approximately only 55% of the inflowing sediment.

A second option reviewed by the USACE was dredging. However, given an annual sedimentation rate averaging approximately 2,600 acre-ft/year, and assuming sediment discharge below the dam and a dredging cost on the order of at least $10/yd^3 ($16,000/acre-ft), annual dredging costs would run approximately $42M/year. A major cost factor affecting dredging is the long pumping distance, approximately 15 mi between the dam and the delta face where dredging would occur. Dredging is not considered an economically feasible option.

Sediment pass-through, which focuses on passing inflowing sediment through the reservoir during natural inflow events, was discussed in the E & H (2002) report but was discarded due to the nature of the sediment and transport processes along the Missouri. Unlike fine sediment, which is eroded and delivered to the watershed in large pulses by severe rainfall events, the transport of sand-sized bed material is directly related to stream hydraulics, and sand is continuously in motion. The natural pre-impoundment flow regime along the Missouri river included approximately 6 months of high flows, with the continuous transport of sand during this period. Inasmuch as this sand transport is not highly focused in time, it was not considered feasible to pass a large fraction of the annual load through the dam in only a few days as a pass-through procedure.

14.5.2 Preliminary analysis of sediment flushing

Reservoir flushing was analyzed and favorably recommended in the E & H (2002) report, which reached the following conclusions:

> The physical conditions at Gavins Point Dam and Lewis and Clark Lake are amiable for flushing because the spillway consists of a low sill and very large gates. In addition, the presence of Fort Randall Dam upstream of Gavins Point Dam provides the opportunity to artificially create flushing flows of the desired magnitude and duration. Hydrographs released from Fort Randall Dam can be tailored to optimize flushing and minimize downstream environmental impacts.

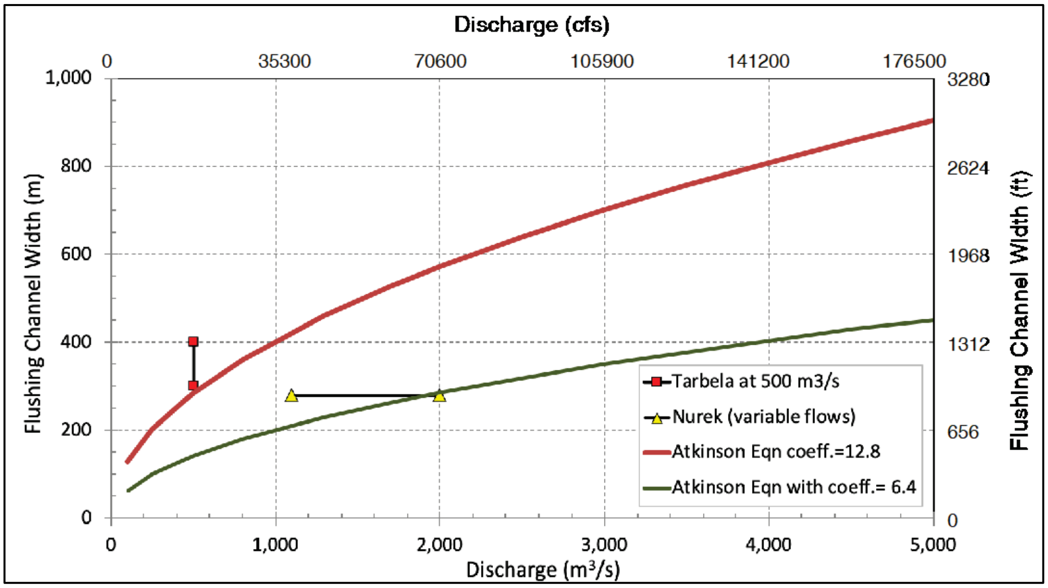
> The preliminary conclusions indicate that flushing could potentially be undertaken without significant structural modifications and that the flushing duration will most probably be limited to a few days per year, which makes this approach potentially attractive. (E & H 2002, Executive Summary)

Three critical elements in the E & H study are as follows. First, it was assumed that flushing would last only a few days per year. Second, it was desired to maintain the largest possible reservoir capacity in the long run, achieved by using a large flushing flow to maximize the width of the flushing channel. Flushing channel width was estimated by the regime-type equation given by Atkinson (1996):

$$W = 12.8\, Q_f^{0.5},$$

where W = channel bottom width (m) and Q_f = flushing discharge (m^3/s). This relationship is given in Figure 64, which also shows channel widths observed (Morris 2020) at other large reservoirs with sand-silt sediments during drawdown periods.

Figure 64. Computed flushing channel width compared to observed channel widths during drawdown from two other large reservoirs with heavy sand-silt sediment loads, Tarbela on the Indus River (Pakistan) and Nurek Reservoir on the Vakhsh River (Tajikistan).



Third, it was desired to achieve a long-term sediment balance, removing annually at least as much sediment as enters, which required a large discharge as computed by the Tsinghua University equation (Morris and Fan 1998):

$$Q_S = \psi \frac{Q_f^{1.6} \, S^{1.2}}{W^{0.6}},$$

where Q_s = sediment discharge (t/s), S = longitudinal energy gradient, and ψ = coefficient related to the type of sediment. As a result, it was concluded that to remove a year of sediment input during the period of several days, and to maximize the width of the scour channel, very large discharges would be required. The computed discharges meeting these requirements were 88,287 ft^3/s for 10 days, or 176,573 ft^3/s for 4 days. These discharges, in turn, were analyzed by the numerical modeling performed by Yang and Ahn (2010). These are very large discharges that produce flood damage downstream, and the latter discharge exceeds the highest discharge to date released from the dam.

14.5.3 Numerical modeling of reservoir flushing

The modeling of flushing operations was performed by Yang and Ahn (2010) with GSTARS4, a 1D unsteady-flow numerical model (Table 25). The point of hydraulic control is the dam, and two stage-discharge relationships were developed, one for the existing spillway configuration and another for a 10 ft deep notch extending along half the spillway length to further lower water levels.

Table 25. Summary of amount of water and sediment discharged through the Gavins Point Spillway during potential flushing scenarios (Yang and Ahn 2010; Ahn et al. 2013).

Scenario Number	Total Operation Days	Cumulative Water Past Gavins Point Dam	Cumulative Sediment Transport Past Gavins Point Dam		Ratio of Discharged Sediment/Water
		10^5 acre-ft	10^6 ton	10^3 acre-ft	
1	25	52.6	99.7	95.4	0.0180
2	25	26.6	72.0	68.8	0.0260
3 and 5	8	6.2	3.9	3.8	0.0062
4	25	52.8	178.4	170.6	0.0320

Simulations showed that the first flushing event(s) would not discharge sand beyond the dam; they would first need to infill the deep area immediately upstream of the dam. Also, large flushing flows are ineffective in discharging sediment due to limited spillway capacity. In a flushing operation, it is critical that high flow velocities be achieved all the way to the dam, otherwise any sediment scoured from upstream will not be carried beyond the dam. This condition is not achieved at high discharges that create significant backwater upstream of the spillway, which results in reduced flow velocities and greatly reduced capacity to transport sediment. The spillway at Gavins Point Dam is approximately only 650 ft wide, yet the reservoir width varies from approximately 8,000 to 9,000 ft wide in the area immediately upstream of the dam and at high discharge this area becomes a low-velocity backwater zone that will not transport sand until the geometry of this area has become modified by sedimentation.

As a precursor to more extensive simulations at Gavins Point, E & H (2002) recommended modeling of sediment flushing at Spencer Dam on the Niobrara River, which is the principal source of sand delivered upstream of the Gavins Point Dam. The small Spencer Dam was flushed twice a year[14]. As reported by Gibson and Boyd (2016), HEC-RAS was used to simulate a flushing event at Spencer Dam. This modeling predicted the measured sediment deposition within the reservoir to within 5% and also provided a reasonable simulation of the timing and concentration of downstream sediment release but underpredicted erosion in the lower part of the reservoir by 43%, missing the lateral channel erosion phenomena.

Subsequent modeling by the USACE using HEC-RAS indicates that in-channel flushing flows, coupled with annual flushing events, dam gate modifications, and channelization of flushing flows, significantly increase the efficiency of sand fraction and total sediment discharge over time. This is the subject of ongoing study.[15]

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[14] The Spencer Dam failed on 14 March 2019 during a major flood and ice run. The flood, exacerbated by ice jams that increased peak flows, also destroyed several bridges across the Niobrara River. Sediment stored behind Spencer Dam was not determined to be a significant contributor to the dam failure (ASDSO 2020).

[15] Paul Boyd, USACE Omaha District, personal communication. 1 October 2019.

14.5.4 Strategy to flush sand beyond Gavins Point Dam

To successfully flush sand beyond the dam it will be necessary to use a discharge rate, which will minimize backwater, thereby creating the high-velocity conditions required for sand transport. It will also be necessary for sand deposits to reach the sill of the spillway gates, a condition that will not be achieved during the first flushing event.

A review of historical data indicates that in most years, a discharge of between 30,000 and 40,000 ft^3/s is sustained for significant periods. In 40 yr of post-impoundment daily streamflow at Yankton, discharge from Gavins Point Dam exceeded 30,000 ft^3/s 37% of the time. Referring to the stage-discharge curves for the dam, a flushing discharge of 30,000 ft^3/s will produce the following stages at the spillway:

• Existing spillway	1186 ft
• Notched spillway	1180 ft

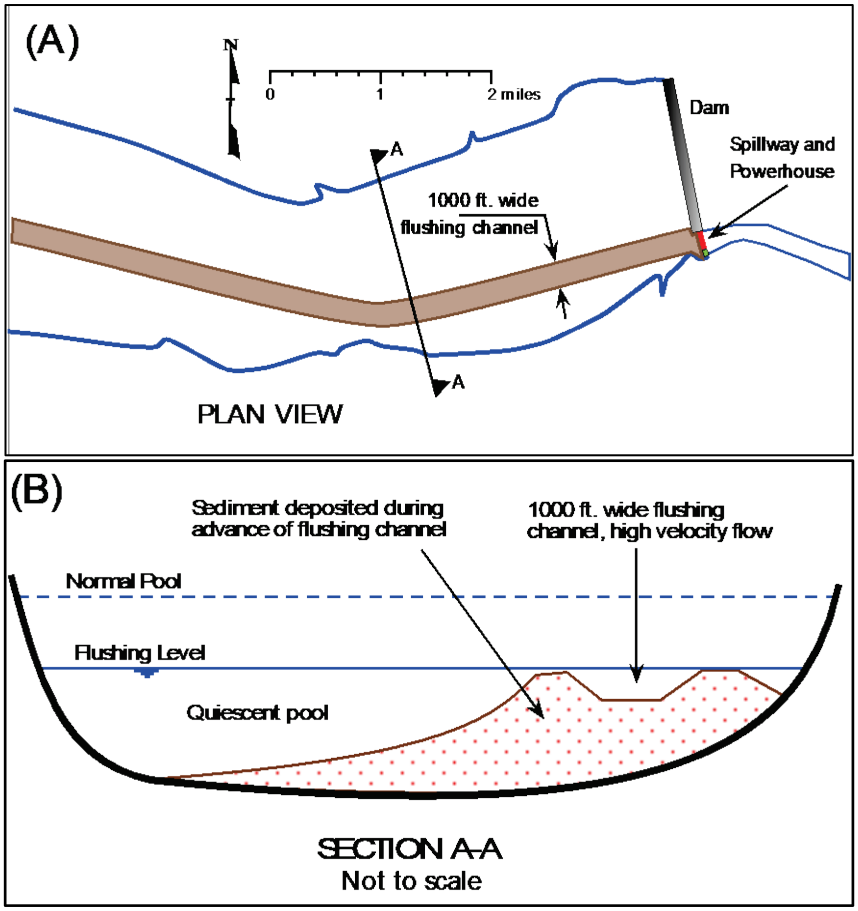
The flushing width relationship from Figure 64 indicates a discharge of approximately 35,000 ft^3/s would produce a flushing channel width in the range of 650 to 1,300 ft.

The Lewis and Clark delta has historically progressed downstream by a process that infills the entire width of the reservoir. However, it is not clear that this pattern will continue to the dam under flushing conditions. The deltas in a number of other reservoirs progress in the form of a river channel that advances into the reservoir, with coarser sediment depositing along the banks of the advancing channel while finer sediments deposit in off-channel areas, as previously illustrated in Figure 5 and Table 2.

If a similar pattern is produced in Lewis and Clark Lake during drawdown for flushing, coarse material may advance to the area of the spillway, allowing export of sand downstream in a much shorter period than would be calculated under the assumption that the delta will advance by filling the entire reservoir width. Also, if the flushing channel does not fill the entire reservoir width, this means that a significant pool will remain available as a refuge for aquatic species during the flushing drawdown period, as conceptually illustrated in Figure 65.

Once the flushing channel has been created, the inflowing sediment will tend to be focused into the flushing channel. This will facilitate its removal during subsequent flushing events and will retard (but not prevent) sedimentation in off-channel areas.

Figure 65. (A) Plan view of zone near the dam conceptually illustrating the advance of the flushing channel toward the spillway. The flushing channel will probably develop meanders, not shown in the simplified illustration. (B) Conceptual section view showing that the flushing channel does not fill the full reservoir width.



14.6 Sediment management considerations Gavins Point Dam

Sediment flushing is considered to be feasible at Gavins Point Dam under the appropriate conditions, and these conditions are being investigated by numerical modeling. The following approach is recommended to better analyze flushing options and identify a feasible management strategy.

1. Pass-through. Sediment pass-through during large floods is not anticipated to be technically feasible for several reasons, including the backwater created by the existing spillway limitations. Nevertheless, this alternative can be easily simulated by numerical modeling to confirm this conclusion.

2. Dredging. Dredging is technically feasible but is too expensive to be considered economically viable, especially given the long pumping or haul distances.
3. Flushing. Drawdown flushing is considered feasible. To identify the preferred option will require numerical simulation of a variety of operating rules to examine different criteria for initiation of flushing, duration, and movement of sediment along the channel below the dam. Long-term (e.g., 50+ yr) simulations may be anticipated to be used. Modeling should be approached with the objective of defining optimal management strategies and discharges, and many simulations should be anticipated to understand how the system works and define the preferred alternative.
4. River below the dam. Downstream impacts were previously analyzed with the HEC-6T model but only with input of fine sediment as predicted to be discharged by the modeling performed above the dam. The analysis of downstream impacts should be revisited using larger grain sizes as new modeling results from flushing data become available. The time series of water and sediment discharge at the dam that is developed by the flushing model may be used as input for the downstream river model, which should also be run for long-term (e.g., 50 yr) simulations.
5. Evolution of flushing geometry. During flushing events, an elongated delta may advance toward the dam at the flushing level. During drawdown for flushing, areas of open water can be expected to remain on either side of the flushing channel (Figure 65).

   When flushing is initiated, it will scour a channel into the existing delta, and this may scour finer sediments buried deeper in the delta. However, after several flushing events the channel geometry should become relatively stable, scouring only the sediments deposited since the previous flushing event.

6. Gradual improvement of sediment balance. The initial objective is not to immediately achieve a sediment balance across the reservoir, and this will not be possible in any event because some years will be required to establish the new within-reservoir geometry. Also, it will be preferred to increase downstream releases incrementally to allow for monitoring and any needed adjustments. As flushing work progresses and experience is gained at the site it will be possible to refine management strategies to gradually improve the reservoir's sediment balance and maximize sustainable reservoir capacity.

7. Timing of flushing. At reservoirs where flushing is performed, it is often necessary to discharge a significant amount of water after flushing is completed to move the flushed sediment downstream along the river channel (Morris and Fan 1998). For this reason, it will probably be most desirable to perform flushing at the beginning of the flood season so that the full season of flood flow is available to move sediment downstream.

   Timing of flushing may also be influenced by biological factors such as spawning dates for aquatic species or other considerations. River ice may also represent a factor that influences flushing dates. These potential constraints should be understood and incorporated into the modeling as early as possible.

8. Hydropower intake. Flushing will affect sediment deposits in the vicinity of the power intake. Structural modifications to the intake will be required to raise it above the equilibrium profile established by flushing. This modification should reconfigure the intake to draw water from a zone that is maintained free of sediment by scour during flushing, similar to configurations used for run-of-river hydropower intakes. There will be no power production during flushing.

15 Example: Jennings Randolph Reservoir, Baltimore District

15.1 Key points

This case study examines the uncertainties in sedimentation conditions that result from limited and conflicting survey data and illustrates alternative strategies to analyze sedimentation conditions.

15.2 Problem statement

Jennings Randolph Reservoir represents the largest emergency water supply for the Washington, DC, metropolitan area and also has important water quality and flood control functions. Sedimentation studies performed prior to impoundment predicted a long-term average sedimentation rate of 20 acre-ft/yr (Burns and MacArthur 1996). However, the April 1997 bathymetric survey indicated the loss of 8,231 acre-ft (equivalent to 484 acre-ft/yr), indicating a rate of storage loss over 20 times the original estimate. This case study highlights the difficulties and uncertainties that can be associated with attempting to accurately determine the sedimentation rate when challenged with limited and conflicting data.

15.3 Setting

Jennings Randolph is a 296 ft tall rock-fill, rolled-earth, multipurpose dam constructed over the period 1971–1981 at a cost of $175M. Impounding began in May 1981. The dam impounds runoff from the upper 263 mi^2 of the North Branch of the Potomac River along a reach where the Potomac defines the border between Maryland and West Virginia.

The reservoir is used for flood control, water supply, water quality enhancement, and recreation. The water supply pool is managed by the Interstate Commission on the Potomac River Basin (ICPRB). A 10 MW private hydropower intake and power plant is currently under consideration for licensing. This hydropower facility would entail the construction of a second (redundant) intake at the left abutment, near the spillway, but no changes in reservoir operations are proposed. The approximate pool allocation capacities are given in Table 26.

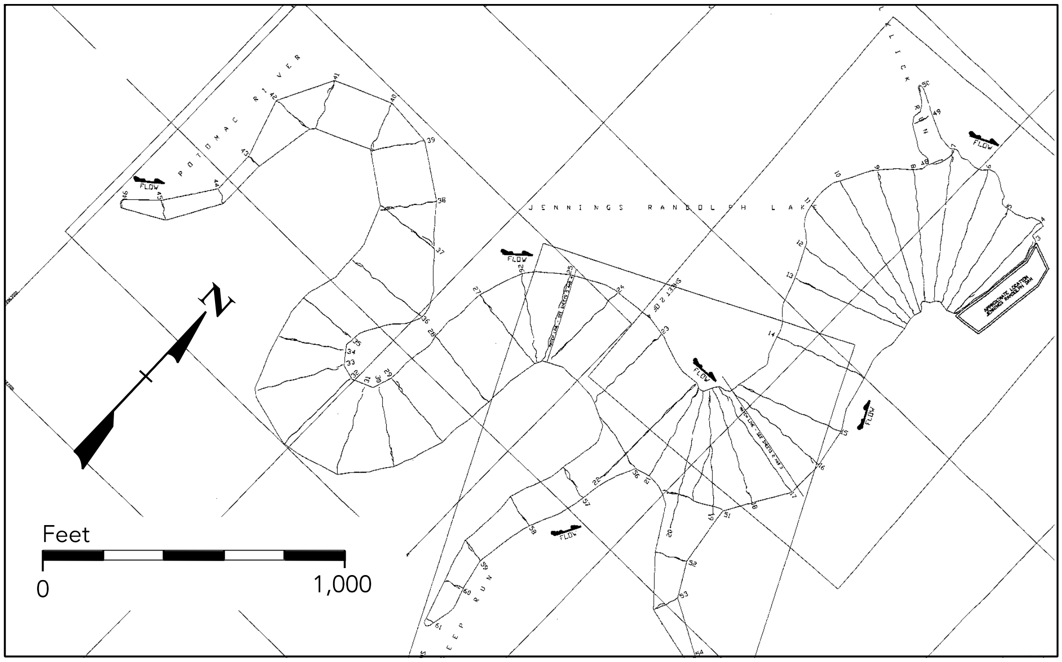
Table 26. Approximate pool volumes, Jennings Randolph Reservoir.

Pool	Capacity, acre-ft	Percentage of Total Volume
Flood Control	30,000	25%
Water Quality	50,000	41%
Water Supply	40,000	33%
Inactive (sediment storage)	2,065	<2%
Total	122,065	

A general view of the reservoir is shown in the photograph in Figure 66, and a plan view showing the reservoir's elongated configuration is shown in Figure 67. The tainter gates, opened only for flood emergencies, are located at the left side of the dam.

Figure 66. Photograph of Jennings Randolph Reservoir, showing the intake tower and the gated spillway on the opposite side of the reservoir to the left of the intake (photo G. Morris).

Figure 67. Aerial view of Jennings Randolph Reservoir, with the dam on the right side (39°26′ N lat., 79°07′ W long.).



The typical variation in reservoir level is shown in Figure 68. The reservoir has a multiple-level selective withdrawal intake, and water is withdrawn from different depths within the lake to optimize downstream water quality. Water quality releases are made from deeper water in the reservoir to provide cold water (<55°F) for downstream fisheries. The reservoir also makes high-volume releases on two or three weekends during the spring to create downstream whitewater recreational opportunities. The previous dam operator indicated that withdrawals are selected and blended from different depths to meet downstream targets for water quality, particularly temperature. Temperature profiles are shown in Figure 69.

Figure 68. Typical variation in water level at Jennings Randolph Reservoir.

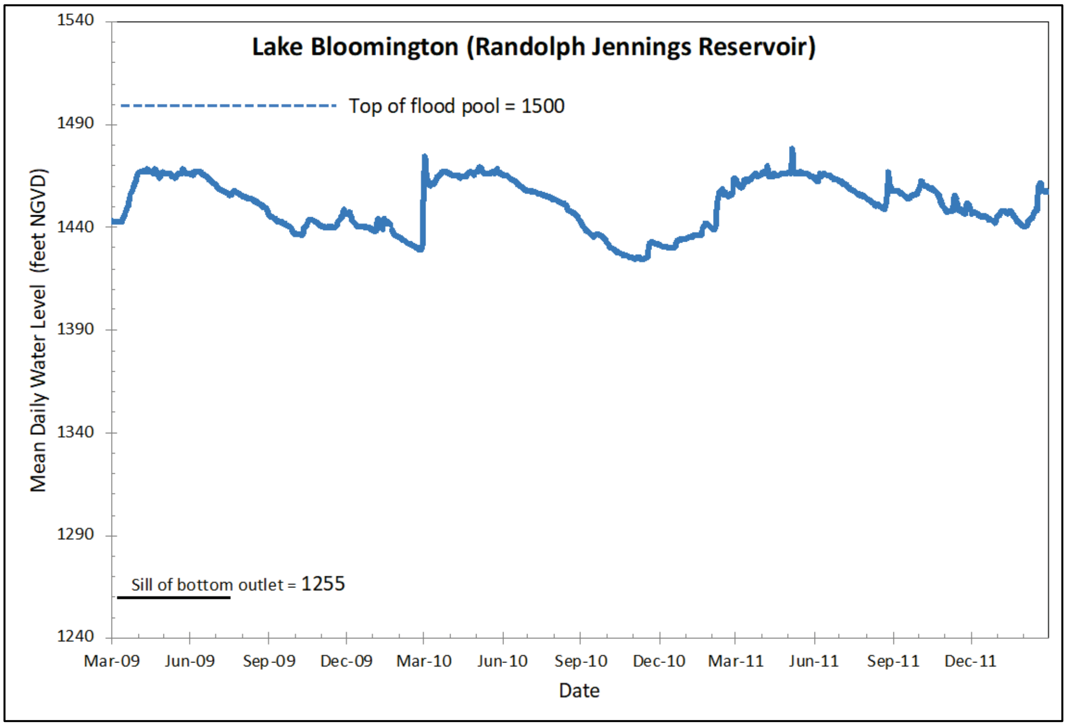
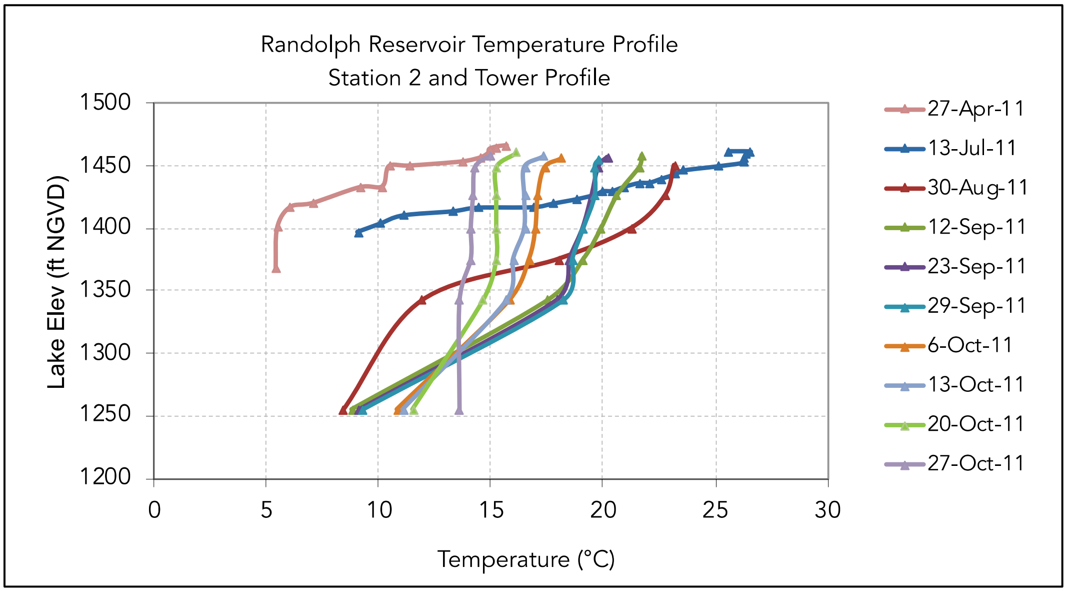


Figure 69. Dam tender's tower profiles showing temperature profiles for Jennings Randolph Reservoir during 2011. The data show that stratification was broken (overturned) at the end of October.



The 263 mi² tributary watershed is primarily forested with limited logging activity, but there are numerous abandoned coal mines. Acid drainage has been an important environmental problem throughout the watershed, and prior to reclamation, the streams were so acidified that they were toxic to fish and other aquatic organisms. This problem has been addressed using active treatment systems (lime dosing), passive systems (such as treatment wetlands and limestone beds), plus selective withdrawal from Jennings Randolph Lake. Sedimentation within the reservoir removes precipitated acid mine drainage metals such as iron, and selective withdrawal of cold bottom water supports a downstream trout fishery. The resulting improvements in environmental quality plus management of the reservoir for recreational releases has resulted in a dramatic growth in recreational activity on the North Branch Potomac, and expenditures by visitors, plus at least 13 private outfitters, is estimated to inject $3M/yr into the rural economy (Hansen et al. 2010).

15.4 Reservoir sedimentation

The 1997 bathymetric data presented a disturbing picture of very high sedimentation rates. Without performing a new survey, several sources of data could be used to better assess the sedimentation issue.

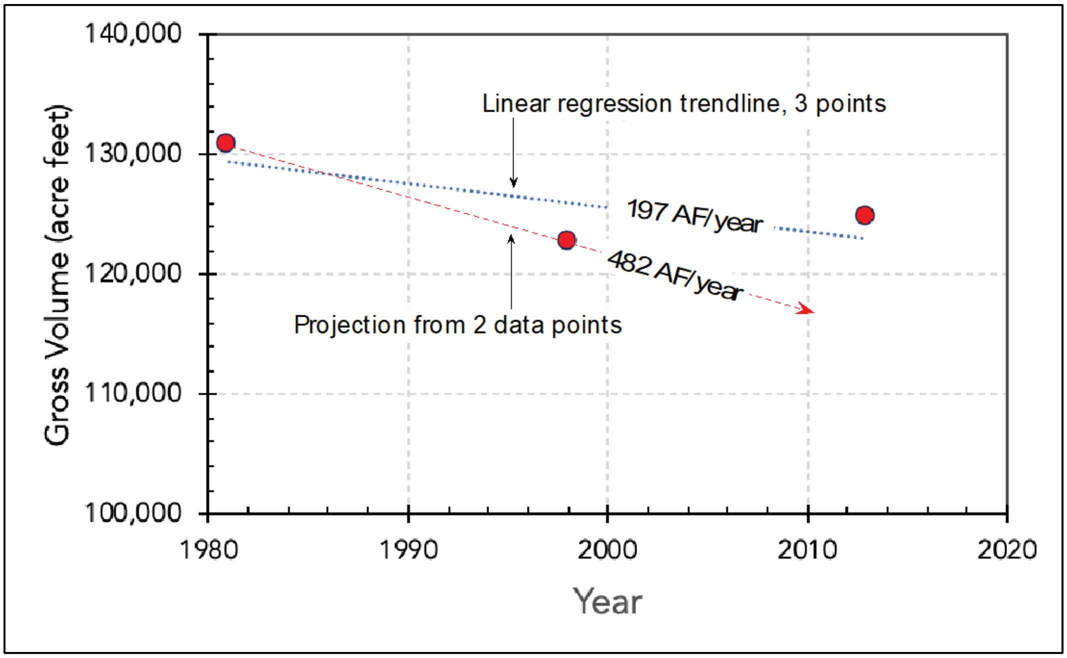
Data from two bathymetric surveys are now available, but when this study was initiated, the 2013 bathymetric survey had not yet been performed. The currently available bathymetric data are summarized in Table 27. The pre-impoundment capacity is based on survey data from 1964. Figure 70 plots the capacity estimates over time and illustrates the uncertainty in future sedimentation rates, even with the new bathymetric data.

Table 27. Reported values of gross capacity for Jennings Randolph Reservoir.

Parameter	Original (1981)	1997	2013
Gross Capacity at elevation 1,500 (acre-ft)	130,928	122,725	124,801
Total Storage Loss (acre-ft)		8,203	6,127
Annual Storage Loss (acre-ft)		482.5	191.5
Specific Storage Loss (acre-ft/mi^2/yr)*		1.83	0.73
Total Percentage Storage Loss		6.3%	4.7%
Annual Percentage Storage Loss		0.37%	0.15%
Reservoir Half-Life (yr)		136	342

* Based on 263 mi^2 watershed area.

Figure 70. Reported values of gross storage for Jennings Randolph Reservoir, and the associated uncertainty in future sedimentation rates.



15.5 Observations by the operator

Reservoir operators can offer useful information on sedimentation conditions, even absent specific measurements. For example, at Jennings Randolph, the reservoir is strongly stratified in the summer, and the operator reported that in the spring and summer the inflowing warm turbid water will often remain on top of the thermocline. Clear cold water will be discharged from the low-level outlet while the surface water is turbid.

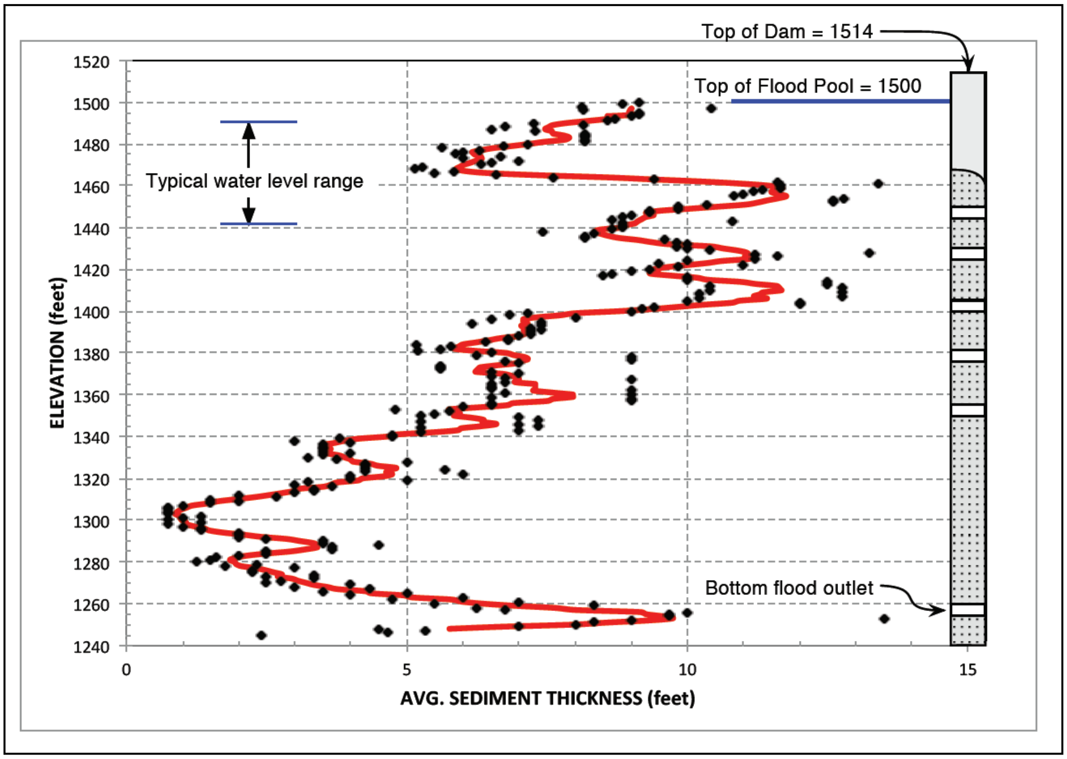
Using a 5°C temperature below the thermocline, and 20°C inflow (Figure 69), a suspended sediment concentration of 3,000 mg/L would add sufficient mass to form turbidity currents. The operator's observation that turbid water stayed on top of the reservoir suggests that the inflowing suspended sediment load is not particularly high.

A review of the available bathymetric data showed that the reservoir bottom slopes uniformly upstream from the dam, with no evidence of flat turbid density current deposits extending upstream from the dam. This coincides with the operator's observation that the bottom outlet normally discharged clear water and is also consistent with the pattern of sedimentation by depth increment shown in Figure 71.

15.6 Deposition patterns

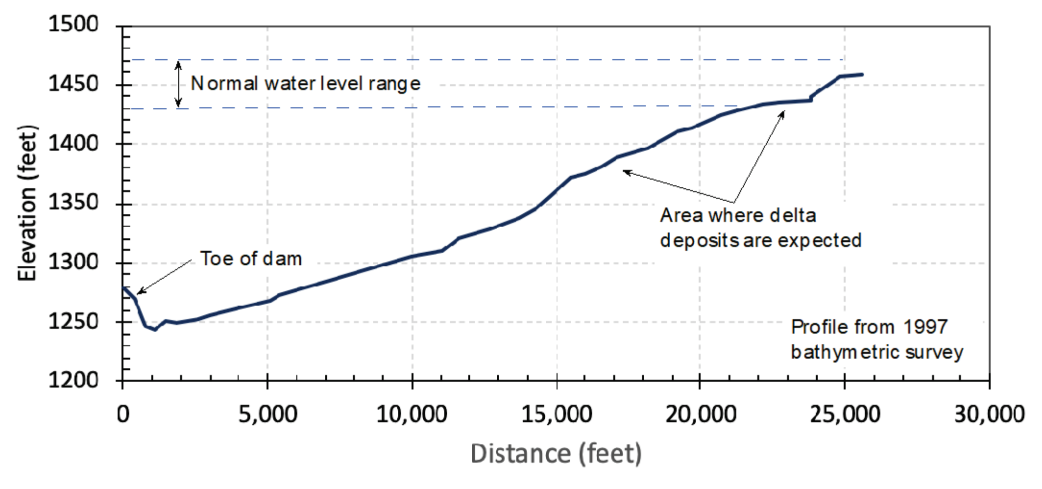
To get a better picture of where the sediment has been deposited in the reservoir, two procedures were used. Data from the original and 1997 elevation-area-capacity curves were processed to compute the average sediment deposition thickness at each 1 ft depth interval (Figure 71). This comparison indicated that there has been relatively little sedimentation at the bottom of the reservoir and that most sediment appears to be depositing at shallower depths. This indicates there should be several thousand acre-ft of delta deposits.

Figure 71. Storage loss by depth increment, Jennings Randolph Reservoir.



Data were also extracted from the 1997 bathymetric survey sheets to plot a longitudinal profile, shown in Figure 72. That plot shows that turbidity currents are not depositing significant amounts of sediments against the dam and there is very little evidence of a delta deposit containing thousands of acre-ft of sediment.

Figure 72. Profile of reservoir thalweg from 1997 survey, showing absence of turbidity current deposits and very limited delta deposition.



The operator’s description and photographs of sediment along the Potomac suggested that most of the sediment consists of fine-grained material, and the lack of extensive sandy deposits in delta areas in aerial photography during drawdown all indicate that the inputs of coarse sediment (sands) are limited. At the Kitzmiller bridge, approximately 3 mi upstream of the reservoir, the Potomac River has a cobble and gravel bed, again suggesting limited sand transport. In an elongated, narrow reservoir such as Jennings Randolph, if a significant amount of coarse material is being deposited, it should be readily visible as a large and visually impressive delta, yet neither the longitudinal profile nor the operator’s observations indicated large volumes of coarse sediment (delta), and there is also little evidence of fine sediment deposition near the dam.

15.7 Sediment rating reported by US Geological Survey (USGS)

On the North Branch Potomac River at Kitzmiller, MD, approximately 3 mi upstream of the reservoir, the USGS operated a stream gage during 1949–1983 and 2003–present. Suspended sediment data are reported for that gage for 229 consecutive days during calendar year 1980. Those data were previously presented in Figure 18 in the format of a concentration vs. discharge rating relationship.

Mean daily concentration was computed by dividing the daily load by the mean daily discharge. The trendline equation computed by Excel accounted for only 35% of the total load in the dataset. The Solver equation was developed using the trendline values as seed and setting as the objective that the sum of the daily loads computed by the equation should match the sum of the loads reported in the field data. The trendline and Excel Solver relationships are both superimposed over the data in Figure 18.

It is desirable to have several years of data, including several large inflow events. In contrast, the available data at this gage cover less than a full year. It is not necessary to collect data continuously to improve this dataset but to focus on the high-discharge events that transport most sediment (e.g., days over 1,000 ft^3/s).

The Solver rating relationship was applied to all the available streamflow data since 1949 to develop an estimate of the mean annual load at the gage station, and this was multiplied by the ratio of watershed areas between the dam and the gage (263 mi^2/225 mi^2 = 1.17) to estimate the average annual inflow into the reservoir as 75,760 ton/yr. An important weakness of this methodology is that the sediment rating relationship developed over 229 days has been applied to a streamflow dataset spanning 70 yr, a period that has seen extreme events and land use change.

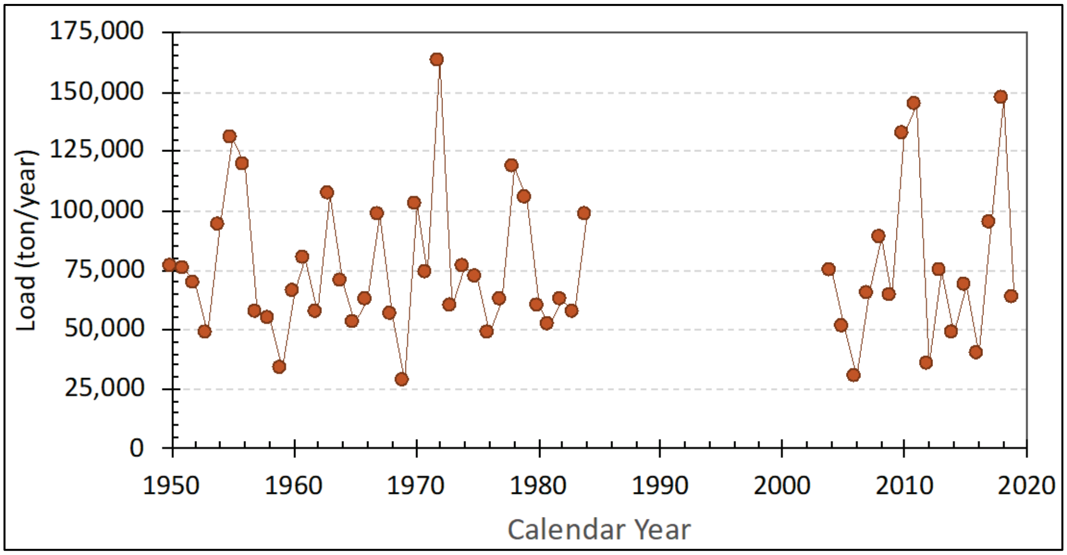
Not all inflowing sediment is trapped in the reservoir. Based on the Brune (1953) relationship (Figure 25), the average annual sediment trap efficiency and capacity loss is estimated as the following:

Mean annual inflow, ft^3/s	461
Mean annual inflow volume, acre-ft	334,046
Original reservoir gross capacity, acre-ft	130,928
Capacity:inflow ratio	0.39
Trap efficiency (%) from Brune median curve	96%
Total sediment load entering reservoir, ton/yr	75,762
Sediment trapped in reservoir, ton/yr	72,732
Bulk density of sediment deposits, lb/ft^3	55
Average annual capacity loss, acre-ft/yr	60.7
Specific capacity loss, acre-ft/mi^2/yr	0.23

Absent data on the bulk density of the sediment at Jennings Randolph, or even information on the grain size of the deposits, the bulk density of 55 lb/ft^3 has been assumed.

The resulting calculation of average annual capacity loss is significantly less than the values indicated based on bathymetric survey. This *average* value also obscures the large year-to-year variations, seen in Figure 73.

Figure 73. Variation in annual sediment inflow into Jennings Randolph Reservoir based on the developed rating equation and daily flows for Potomac River at Kitzmiller.



15.8 Estimate based on erosion and sediment delivery

Land use and sediment yield from the upper 285 mi^2 of the North Branch Potomac River watershed have been studied by the Maryland Dept. of Environment (2006). Jennings Randolph Dam impounds 263 mi^2 of this watershed. Sediment loads for the study watershed were computed by the Chesapeake Bay Program Phase V (CBP P5) watershed model, which computes edge-of-field land use sediment loading rates. This was combined with the computed sediment delivery ratio, to determine the resulting edge-of-stream (EOS) sediment yield. Delivery ratio or *delivery factor* was computed by the NRCS National Engineering Handbook (USDA NRCS 2007) procedure as the following:

$$DF = 0.417762 * A^{-0.134958} - 0.1270097,$$

where DF = *delivery factor* or sediment delivery ratio, and A = drainage area (mi^2).

The EOS load is the amount of sediment that actually enters the mainstem of the river and includes land surface erosion as well as the intervening processes of deposition on hillsides and sediment transport through smaller rivers and streams. The resulting sediment loads are presented in Table 28, indicating that the single largest contributor of sediment is pasture, which constitutes approximately 13% of the land area and is estimated to contribute approximately 51% of the total sediment load to the river.

Table 28. Land use and sediment yield upper Potomac Basin (Maryland Dept. of Environment 2006).

Land Use		Land Area		Sediment Load		Specific Sediment Yield
		Acres	% of Area	ton/yr	% of Load	ton/acre/yr
Crops	Animal feeding operations	24	0.01%	56	0.29%	2.36
	Hay	7,851	4.31%	760	3.95%	0.10
	High till	1,399	0.77%	851	4.42%	0.61
	Low till	404	0.22%	115	0.60%	0.29
	Nursery	165	0.09%	365	1.90%	2.21
Extractive	All types	1,449	0.80%	1,141	5.93%	0.79
Forest	Forest	138,597	76.07%	3,048	15.83%	0.02
	Harvested forest	1,400	0.77%	710	3.69%	0.51
Pasture	Natural grass	726	0.40%	206	1.07%	0.28
	Pasture	22,245	12.21%	9,895	51.41%	0.44
	Trampled pasture	116	0.06%	492	2.56%	4.23
Urban	Barren	58	0.03%	127	0.66%	2.19
	Impervious	419	0.23%	476	2.47%	1.13
	Pervious	7,352	4.04%	1,007	5.23%	0.14
TOTALS		182,205	100.00%	19,249	100.00%	

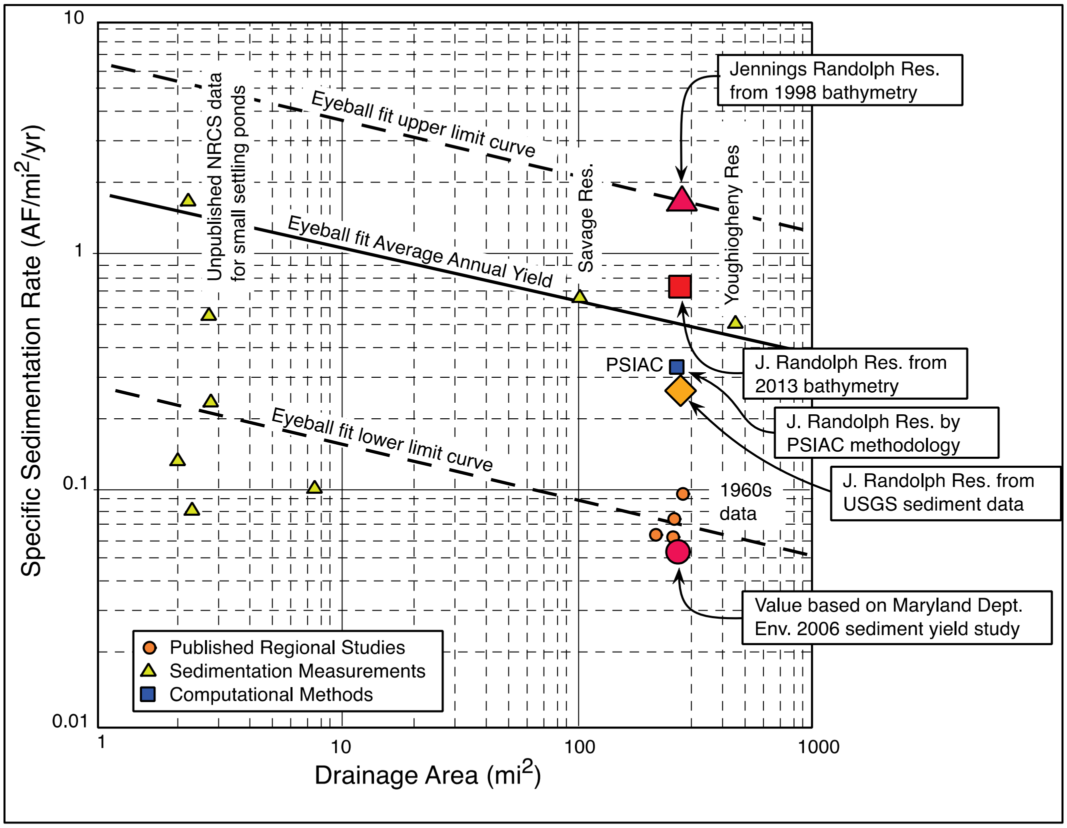
These computed sediment yield values were used to estimate the rate of capacity loss in the reservoir as follows:

Ton/yr of sediment from study watershed (285 mi^2)	19,249
Ton/yr of sediment from reservoir watershed (263 mi^2)	17,763
Bulk density of deposited sediment, silt, or silt-clay, lb/ft^3	55
Annual volume of sediment deposited, acre-ft	14.8
Specific sedimentation rate, acre/ft/mi^2/year	0.056

15.9 Comparison of sedimentation estimates

Burns and MacArthur (1996) reported that a sediment survey performed in January 1986, after tropical storm Juan in 1985, indicated that 900 acre-ft of sediment had been deposited in the reservoir. The Baltimore District office indicated that these older surveys were apparently range-line type surveys focusing on the upper branches of the reservoir and that detailed data from these surveys were not available, having been lost in an office move. The two different values of specific sedimentation rate are superimposed on the values previously reported by Burns and MacArthur (1996) in Figure 74.

Figure 74. Specific sedimentation rate vs. drainage area, showing the sedimentation rate based on the 1998 and 2013 bathymetric surveys, and other methods described, superimposed on the graph of values developed by Burns and MacArthur (1996).



15.10 Considerations for long-term sustainability

Sedimentation rates and processes are poorly understood at Jennings Randolph Reservoir. At this point, the true sedimentation rate is unknown.

- The original 1964 topographic survey may not be accurate.
- The 1998 survey is, apparently, inaccurate because the more recent 2013 survey reports a larger reservoir capacity than the 1998 survey. Thus, sedimentation rate cannot be determined by comparing the two surveys.
- Comparison of the 2013 survey data against the capacity from the 1964 topographic survey will also give an incorrect value if the 1964 data are incorrect (and older survey data are often not accurate).
- The results of both the 1998 and 2013 bathymetric surveys show sedimentation rates much higher than the sedimentation rate estimated by any other method.

In summary, at this point the true sedimentation rate at Jennings Randolph Reservoir is unknown. Two methods are recommended to address this uncertainty: (1) reinstall a sediment monitoring station at the USGS Kitzmiller gage, a short distance above the reservoir and (2) perform a repeat bathymetric survey in 2023, at the 10 yr anniversary of the 2013 survey, replicating the 2013 survey methodology in every aspect possible, including the data reduction and contouring methodology to minimize insofar as possible any differences introduced by changed methodology at any point in the measurement process. Repeat surveys at 10 yr intervals.

The reservoir survey data should be reported in formats consistent with those recommended in this report, to help understand sediment deposition patterns.

After the deposition patterns have been identified by comparison of the 2013 and 2023 surveys, undertake sediment coring using vibracore equipment to characterize the grain size and bulk density of the identified deposits.

By implementing these measures, by year 2024 a much clearer picture of sedimentation rates, patterns, and processes will be available for Jennings Randolph Reservoir. This will provide the necessary basis for identifying appropriate management strategies.

At this point, with only a limited understanding of sedimentation process in the reservoir, it would be premature to suggest strategies other than to address the data uncertainties previously noted.

Given the importance of this reservoir to the local economy and also as an emergency water supply for metropolitan Washington, DC, to skimp on data collection appears to be a false economy. Reinstallation of a continuous sediment gage at Kitzmiller, together with regular surveys (10 yr intervals instead of 20 yr), can provide invaluable information on sediment inflow and from this the potential strategies for better managing sediments to preserve this infrastructure. Once the sedimentation rate is better documented, a 20 yr survey interval may be appropriate, but at this point, more frequent surveys are needed to understand the true magnitude of the sedimentation problem at Jennings Randolph Reservoir.

16 Conclusions and Recommendations

16.1 Conclusions

This study examined typical sediment problems and potential management options at USACE reservoirs.

- Designated sediment storage pools at many USACE reservoirs are becoming filled with sediment, meaning that all future sedimentation will be focused into beneficial use pools.
- Sediment is already starting to impact a variety of beneficial uses in USACE reservoirs, including flood control, navigation, water supply, hydropower, water quality, and ecosystems.
- Outlet works and beneficial pool capacities will start to be impacted when only a small fraction of the total capacity has been lost. Impacts may be considered *severe* when approximately half the original capacity has been lost.
- When considering the challenge of maintaining reservoir functions in the future, against continuing sedimentation, the current type and amount of monitoring data are frequently insufficient to accurately predict future sedimentation rates and identify appropriate mitigation measures.
- Much of the available data are not analyzed in a format beyond updating the elevation-capacity curve, which gives very little information on the sedimentation processes involved, and there is no standardized format for organizing and reporting the data. A first essential step in solving this particular problem is to transfer and maintain reservoir sediment data in a system like the RSI.

  A comprehensive information database, supported by recent bathymetric survey data at all sites, is critical to understanding the full extent of this developing problem and identifying the most critical sites for immediate action.

- Sustainable reservoir management requires achieving a balance between sediment inflow and outflow while maintaining usable capacity. Multiple strategies are available and can be used in combination to achieve a sediment balance. These include (1) reducing sediment yield entering the reservoir, (2) bypassing the sediment around or through reservoirs, and (3) removing previously deposited sediment by dredging or flushing.

- A fourth group of strategies consists of measures that help offset the impacts of sedimentation, without addressing the sediment balance. These may include storage reallocations, more efficient operational rules, provision of additional storage (e.g., raising the dam), conjunctive use with groundwater systems, etc. In some cases, it may involve project decommissioning if the cost of sediment management cannot be justified.
- It will not generally be possible to recover large volumes of lost reservoir capacity. For this reason, it is urgent to start addressing sedimentation problems now since lost capacity will be very difficult to recover due to problems including high cost and lack of disposal sites.
- Dams interrupt the natural flow of sediment along rivers, and the cumulative sediment volumes are huge. The continual removal of this volume of fluvial sediments from rivers, with placement onto upland containment areas, is not a practical long-term solution. The overall objective will be to re-establish the transport of sediment downstream along rivers while maintaining reservoir storage.
- Long-term sediment management strategies and action plans are needed at all reservoirs to understand the anticipated timing of critical impacts and the types of management strategies that may be used. Identification of potential long-term management strategies will help ensure that near-term actions are consistent with identified long-term objectives.

16.2 Recommendations

All reservoirs need to be surveyed regularly. Surveys should be at shorter intervals in reservoirs having more rapid sedimentation, but in general an interval of approximately 10 yr is recommended. After several such surveys, a decision may be made to prolong the survey interval in reservoirs with low annual rates of capacity loss.

Data management and presentation are just as important as data collection. To this end the, USACE needs to establish a standard *minimum* format for bathymetric survey reports and data display, and all existing and future information should be stored into the RSI database. Critical graphic data that should be presented for every reservoir survey report include the following:

- Location map with relevant features and latitude/longitude of the dam site.
- Time-wise graph of gross and conservation pool capacities, also indicating dredging dates and volumes, when flushing was initiated, etc. These plots, together with data from multiple surveys, are essential to discern changes in sedimentation rates.
- Time-wise history of water surface elevation plotted together with a schematic showing the locations of different outlet works, to help interpret depositional (or scour) patterns.
- Longitudinal thalweg profile along the reservoir, plotting data from each survey successively to visually show the longitudinal sedimentation pattern.
- Elevation-capacity-area curves, showing original and updated curves, also presenting the information in tabular format.
- Map of the reservoir showing the tracks made during the survey. When multiple methods are used (e.g., bathymetric plus lidar), indicate the zones surveyed by the different methods, as well as the dates and water levels corresponding to different survey activities.
- Establish a GIS geodatabase for every reservoir. This database should be populated with all elevation data for the particular reservoir (bathymetry, lidar, etc.) to facilitate the analysis and mapping of x-y-z data as it changes over time. Mapping products should include the following:
  - Contour or shaded relief map showing depth.
  - Shaded relief map showing sediment thickness since the prior survey. Note that as sedimentation progresses, the zone of active sedimentation can move, especially in the case of a delta face that is advancing downstream. For this reason, to understand sedimentation processes it will typically be most useful to develop a deposit thickness map based on the most recent surveys, rather than comparing the current survey against the original reservoir geometry, although this can also be a useful map to develop if the original data are in a compatible format.
  - Plots of selected (representative) cross sections showing original bottom and successive survey data.
  - Track lines for representative cross sections should be archived to facilitate identification and resurvey of these same cross-section locations in the future.
- Research and development efforts are needed to improve existing reservoir sediment management techniques and develop new methods

and technologies. This includes improvements to numerical and physical modeling techniques that support decision-making. These efforts should be accompanied by outreach to the water management, operations and maintenance, and regulatory communities both within and outside of the USACE.

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Abbreviations

AdH	Adaptive Hydraulics
CPR	Climate Preparedness and Resilience
DHP	Delta Headwaters Project
DTM	Digital terrain map
Engineer Manual	EM
EOS	Edge-of-stream
GIS	Graphic information system
KBS	Kansas Biological Survey
KWO	Kansas Water Office
OCWD	Orange County Water District
RESSED	Reservoir sedimentation
RSI	Reservoir Sedimentation Inventory
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamation
USGS	US Geological Survey

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14. ABSTRACT

The US Army Corps of Engineers (USACE) maintains and operates 419 reservoirs nationwide for diverse purposes. This infrastructure is essential to the nation's continued economic progress and provides numerous benefits. Sedimentation in reservoirs causes the loss of storage capacity, leading to interference with operations, reduction of project benefits, and can eventually render project operation technically infeasible or uneconomical. All reservoirs trap sediment, and sustainable long-term operation can be achieved only if sedimentation is managed. With many of the USACE reservoirs now reaching 50 years of age, sedimentation is starting to encroach on the beneficial pools. Under the paradigm of sustainable use, it is important to identify and implement strategies to sustain reservoir operation in the long term, beyond the period contemplated in the original project design life.

This report outlines the major types of sediment management strategies available for reservoirs. Because the rate of new reservoir construction by USACE is very low, this report focuses on remedial strategies at existing reservoirs and presents a general methodology for the preliminary analysis of such sites. This report examines four example USACE reservoirs with known sedimentation issues to highlight the types of problems encountered and the development of strategies that can lead to sustainable use.

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