Frequently Asked Questions about Reservoir Sedimentation and Sustainability

Contribution and review by the Subcommittee on Sedimentation

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1. **What is a dam and reservoir system, and what are the benefits provided by dams and reservoirs?**

A dam is any structure built to store water for later release or raise the water surface elevation for diversion or navigation. The stored body of water is called a reservoir. Reservoir water storage can be used for many beneficial purposes including municipal and industrial water supply, irrigation, flood damage reduction, hydropower, recreation, and for providing downstream minimum flows for water quality and navigation. The reserving of space in the reservoir to store flood waters will reduce the downstream flood risk.

2. **How do dams and reservoirs function?**

Dams function by restricting the passage of water traveling down a watercourse, and storing this water in a reservoir. Dams and reservoirs can be divided into two categories: those in which the dam has human-controllable features, such as outlet works and gated spillways, and those without human-controllable features, such as detention ponds with no gates on the spillway. All dams and their associated reservoirs are operated to maximize the benefits provided while minimizing risk associated with varying hydrology. For Federal projects, operations are focused around the authorized project purposes. These can include flood risk reduction, water supply, water quality, fish and wildlife, navigation, hydropower, irrigation, recreation, and others. In many cases, the operation can be a compromise that results in some benefits to all purposes. However, in the case of flooding, management for flood risk reduction is paramount.

The operational constraints of a reservoir are identified in the water management plan, which prescribes the management actions to be taken during varying inflow, outflow, and storage conditions. The water management plan serves as a guidebook for dam and reservoir management. Water management plans are updated periodically through a process that may include local, regional, and national input. At Federal projects, these are generally called a Standing Operating Procedure (SOP) or a Water Control Plan.
How many dams are there?

As of 2016, the United States National Inventory of Dams (NID) contains the records of 90,580 dams meeting at least one of the following two criteria: 1) the dam has a height equal to or greater than 7.62 m (25 ft) and the storage volume exceeds 18,500 m³ (15 acre-feet); 2) The storage volume exceeds 61,674 m³ (50 acre-feet) and the dam height exceeds 1.82 m (6 ft). There are hundreds of thousands of smaller dams (perhaps millions) or other water impounding structures that do not meet these criteria and thus are not included in the NID. The exact number of these smaller dams is not known.

What is the process of reservoir sedimentation?

All rivers naturally transport sediment. However, when the flow velocity and energy of the water is reduced as the river enters a reservoir, most of this sediment settles along the bottom of the reservoir where it becomes trapped, rather than continuing downstream. Over a period of years and without sustainable management, the sediment deposits will gradually displace the volume that was previously used for water storage, until eventually the reservoir becomes completely filled with sediment. As water storage volume is lost, the beneficial uses that depend on storage – such as water supply and flood control – also decline and will eventually be lost.
5. **What are the problems associated with reservoir sedimentation?**

Continued sedimentation threatens the project benefits of the nation’s reservoirs and impacts the downstream river channel and coastal areas. Eventually, reservoir sedimentation will bury dam outlets, other water intakes, and boat ramps, while making water depths too shallow for operation of marinas. Turbines in hydroelectric power plants can be ruined by the abrasive properties of sand and gravel. For example, reservoir sedimentation has caused plugging of the outlet at Paonia Dam in Colorado (Figure 1) and sand has abraded the turbine at Jhimruk hydropower plant, Nepal (Figure 2). Over time, sedimentation reduces the storage capacity of the reservoir, along with the natural sediment supply to the downstream river channel and coastal areas.

*Figure 1. About 60 feet of sedimentation in Paonia Reservoir has plugged the outlet of Paonia Dam near Hotchkiss, CO.*

*Figure 2. Sediment abrasion of the turbine runner at the Jhimruk hydropower plant, Nepal*
One of the most obvious impacts from reservoir sedimentation is the loss of water-storage capacity, which will eventually lead to the reduced reliability of water and power supply. Reduced reliability will have the largest impact in regions exposed to multiple-year droughts, which may be exacerbated by the effects of climate change. Other impacts often occur long before the reservoir completely fills with sediment:

- Burial of dam outlets and water intakes
- Reduced water depths, interfering with or preventing operation of boat marinas, and burial of boat ramps, as well as changes in aquatic habitat that may impact species use and survival.
- Reduction in surface area for recreation.
- Increased dam safety risks from sediment loads against the dam, abrasion of outlets and spillways, and loss of functioning outlets.
- Aggradation of upstream channels, which can lead to reduced conveyance capacity, increased flooding, and increased ground water table elevations (which can cause waterlogging and soil salinization).

Trapping sediment behind dams, meanwhile, also impacts the downstream channel areas:

- Degradation of the downstream channel bed and stream-bank erosion.
- Alteration of downstream channel and riparian habitat.

a. **When and where do these problems occur?**

Reservoir sedimentation tends to occur most rapidly during floods and especially during floods following wildfires or other disturbances in the watershed. The effects of reservoir sedimentation often go unnoticed until a dam outlet or reservoir water intake are plugged, a boat ramp or marina become too shallow for use, or there is an increased frequency of flooding upstream. Sedimentation naturally occurs, at various rates, in all reservoirs on natural waterways.

b. **How is safety of the dam affected?**

Reservoir sedimentation can increase or decrease the safety of a dam. Sedimentation decreases the storage available for flood-risk reduction. Accumulation of sediment against an arch dam can increase the stress on the dam, whereas, sediment accumulation against a gravity dam can help buttress the dam. Sediment plugging of a dam outlet works can reduce or eliminate the ability to lower or drain the reservoir
should a problem be detected with the dam. The various effects of reservoir sedimentation on dam safety are described in more detail below:

- **Water storage volume reduction.** The hazard that a dam poses to downstream lands and communities depends on the volume of water that would be released during a dam failure. As the reservoir loses water storage capacity to sedimentation, the volume of water to be released downstream during a failure will be reduced by a corresponding amount. However, the reservoir sediment also would be released downstream during a dam failure.

- **Sediment release.** Dam failure in a reservoir containing a significant volume of sediment could allow a large volume of sediment to be scoured and released downstream as the reservoir sediments are eroded by water draining from the reservoir and reservoir inflows. Downstream sedimentation (burial) would add to the effects of dam failure, increasing downstream damages.

- **Spillway capacity and increased flood flow.** In reservoirs which use their storage to reduce downstream flood risk, the spillway is typically designed to pass flood inflows (without overtopping the dam) that exceed the outlet works capacity after the reservoir has filled. As the flood storage pool fills with sediment, the ability to reduce the downstream flood risk is less. If the reservoir has completely filled with sediment, coarse sediment (sand and gravel) inflow will pass over the spillway and cause abrasion of concrete linings. Concrete abrasion will lead to additional maintenance costs or potentially a dam safety problem during flood releases.

- **Earthquake hazard.** Sediment can accumulate against the structure of the dam. In the case of earthquake shaking, the forces exerted against the dam will be different than if the upstream face of the dam is filled with water only. Also, for certain types of sediment, and if delta deposits approach the area of the dam, earthquake shaking may cause the coarse sediments to liquefy and slump toward the dam, blocking low-level outlets. This may represent a hazard if it interferes with the ability to release flood flows from the reservoir.
6. What are the effects of sedimentation and why should we care?

Reservoir sedimentation decreases project benefits, and causes negative impacts upstream and downstream of the dam. The decreased project benefits, such as the reduction of reliable water supply, or limited storage capacity for floods, negatively impacts those who rely upon these benefits. Over time, sedimentation reduces the storage capacity of the reservoir and will eventually impair the dam outlets and other facilities associated with the reservoir. In addition, sand and gravel deposition forms a delta at the upstream end of the reservoir. The delta often extends upstream of the reservoir pool and increases groundwater levels and the flood stage along the upstream river channel. Downstream from the dam, the release of clear water, or “hungry water”, can result in the accelerated erosion of the channel bed and banks. This erosion tends to disconnect the channel from the floodplain and impair habitat for fish and wildlife.

a. What happens to the river channel downstream of dams?

Prior to dam construction, natural stream flows and sediment loads maintained the characteristics of the downstream river channel, including the channel width, depth, meander bend amplitude, and the presence of sand and gravel bars. These channel characteristics form the substrate for the aquatic and terrestrial environment for which fish, wildlife, and riparian vegetation depend upon.

Trapping sediment behind a dam not only causes sediment to accumulate in the reservoir, but simultaneously results in a decreased sediment supply to the downstream river channel and a hungry water condition, which often results in downstream erosion of the stream bed and banks, and a coarser bed. At some reservoirs, the water is diverted for other purposes and is not normally released to the downstream channel. In these cases, sediment supplied from downstream tributaries can actually aggrade the channel. Where water is routinely released from a reservoir into the downstream channel, a decrease in the natural sediment supply can degrade the channel along with the habitat for fish and wildlife. The channel can become narrower and deeper with less frequent inundation of the floodplain. Habitats associated with sand and small gravel may be absent. In streams where native fish evolved under turbid or muddy conditions, the clear water released from dams can deprive them of the turbidity cover needed to hide from predators. Erosion of the downstream river channel can create problems for infrastructure, such as roads, bridges, water intakes, and loss of property.
b. **How does reservoir sedimentation affect the different water storage uses of the reservoir pool?**

Sediments deposit along the entire length of the reservoir bottom. The coarse sediment particles (cobble, gravel, and sand) deposit first at the upstream end of the reservoir forming a delta. Finer particles (silt and clay) deposit farther downstream. These longitudinal patterns of reservoir sedimentation are illustrated in Figure 3. Reservoir sedimentation decreases storage capacity for all elevations and allocations (e.g., flood control, water supply, etc.), which can affect all different water storage uses of the reservoir pool.

![Figure 3. Example reservoir sediment profile (Randle and Bountry, 2017).](image-url)
7. **Is sedimentation a problem in all regions of the USA?**

Yes, reservoirs on natural stream channels in all regions of the USA (and worldwide) will eventually experience sedimentation problems. While the rates of sedimentation can vary greatly from region to region, all reservoirs will fill with sediment over time in the absence of sustainable management. The most immediate sedimentation problems are evident in small reservoirs in areas of high sediment yield, such as the Coast and Transverse Ranges of California, where a number of dams have filled already, creating the need for expensive sediment stabilization and/or dam removal (Minear and Kondolf, 2009).

8. **Is the nation’s capacity to store water decreasing over time?**

Yes. White (2001) and Garcia (2008) estimate the average annual reservoir storage capacity loss rate to be 0.2 percent for North America due to reservoir sedimentation. From the reservoir sedimentation database (RESSED) (Gray et al., 2010), the average loss rate of the Bureau of Reclamation reservoirs is 0.19 percent of volume capacity per year. Meanwhile, according to National Inventory of Dams, the rate of dam construction has decreased rapidly over time since the 1960's. With few federal dams being constructed, and therefore little gain in new reservoir capacity, the nation's ability to store water is decreasing over time as a result of reservoir sedimentation. This process of reservoir storage loss over time is occurring because new reservoir capacity (through dam construction) is now being added at a much slower rate today than before the 1960’s and because of insignificant efforts to sustainably manage reservoir sediment.

Globally, Annandale (2013) reports that reservoir storage capacity peaked at 4,300 billion m$^3$ in the late 1990’s, and is predicted to gradually decrease in future years as sediment continues to accumulate behind existing dams. However, with population increase, the per capita storage peaked to 760 m$^3$/per person in the early 1980’s (Figure 4). It has been decreasing since that time due to loss of capacity from sediment accumulation, such that the per capita reservoir storage in 2010 decreased to the same level as existed in the 1960’s - and is expected to continue decreasing in the future.
9. **What was the original plan to manage reservoir sedimentation behind dams?**

The original plan to manage sediment in large dams was to account for the volume of sediment anticipated to be trapped and stored in the reservoir for some defined period of time. The period of time is known as the sediment design life, which was typically 50 or 100 years, and many dams are nearing, or even exceeding, their design life. The original reservoir designs did not include design features or operational plans for removal of the sediment. No provision was made for managing the impacts from sedimentation or maintaining the reservoir benefits over the long-term.
10. Is reservoir sedimentation managed in the USA?

With only a few exceptions, the answer is “no.” Reservoir sediment is managed where acute problems exist (such as clogged dam outlets or water intakes, turbine abrasion, or sediment burial at marinas or boat ramps), but often at tremendous expense. As of 2016, reservoir sedimentation is only managed at a small number of dams in the USA. Where sediment is not managed, the inflowing sediment is assumed to either pass downstream because it is so fine, or deposit along the reservoir bottom in the so-called “dead storage” zone. There are only a few known exceptions to this practice. One is at Guernsey Dam on the North Platte River in Wyoming, where the reservoir water is emptied annually through low-level outlets and passed downstream. A portion of the sediments erode as the reservoir is drained and these are transported to the downstream channel. The sediment-rich water is diverted into irrigation ditches, where farmers believe that the settling silt particles help to seal the canals and ditches and slow down the rate at which irrigation water seeps into the ground. This, they believe, extends the irrigation time for their crops. The other example is Spencer Dam on the Niobrara River in Nebraska, where the dam gates are temporarily opened each year to allow sand to pass over the spillway to the downstream receiving waters. This is a long-established practice and required because the reservoir fills so quickly with sand.

11. Who is responsible for managing reservoirs?

Ultimately, the responsibility for managing the reservoir sediment lies with owners and operators of a dam. Regulatory agencies can directly influence dam and reservoir operations, and sediment management in some cases. Stakeholders and water users can influence dam operations and sediment management actions through their local water associations and districts. However, dam owner’s objectives may not always coincide with those of stakeholders and water users.

The lack of past reservoir sediment management actions has allowed the question of responsibility to be ignored. There may be good opportunities to discuss and plan for future reservoir sediment management when new operation and maintenance plans are being developed, when a project is being relicensed, or when a project is turned over to another agency or company?
12. How can reservoir sedimentation be measured and monitored?

The first obvious signs of a reservoir sediment problem may be the plugging of a dam outlet or reservoir water intake with wood and sediment. This is analogous to human heart disease where the first obvious symptoms may be a stroke or heart attack. Topographic (above water) or bathymetric (below water) reservoir surveys are periodically needed to monitor the reservoir sediment accumulation over time and to estimate when the various reservoir facilities may be impaired by sediment. Without periodic monitoring, crisis management will eventually be necessary to continue dam and reservoir operations (Randle et al., 2017).

Fortunately, the cost of monitoring (topographic and bathymetric surveys) has been decreasing over time while the quantity and quality of data has increased. Older surveys were more labor intensive and only measured data along widely spaced cross-sections of the reservoir identified by permanent monuments. Modern methods employ LiDAR from aircraft for topographic surveys or just a few people on a survey boat utilizing GPS survey-grade instruments for positioning and “multi-beam” depth sounders that can measure the reservoir bottom bathymetry over a wide area as the boat and survey equipment move across the reservoir.

Comprehensive reservoir surveys are typically accomplished by combining topographic information collected for the portion of the reservoir area above the reservoir pool level with a bathymetric survey for the portion below water. Reservoir sediment volumes are determined by comparison with past reservoir surveys or by analysis of reservoir sediment thickness measurements made with drills, probes, or acoustic waves.

Another sedimentation monitoring technique involves the use of continuous monitoring of streamflow and suspended sediment concentration or turbidity of the reservoir inflow and outflow.
13. **Where does the sediment come from?**

Sediment is derived from weathered rock and surface soils and can be categorized by size as cobble, gravel, sand, silt, and clay. Reservoir sediment comes from upland and in-channel sources. Upland sources may include fields, gullies, and vegetated and forested areas, or disturbed areas where vegetation may have been cleared in preparation for a land use change. Channel sources include stream bank and stream bed erosion.

a. **How does watershed sediment yield change over time?**

Changes in sediment yield over time will depend on watershed management, land use, sediment control measures, hydraulic structures, hydrology, and other factors, such as changes in hydrologic variability. Wildfires, landslides, volcanic eruptions and other phenomena will affect sediment yield. Glacial retreat and melting of permafrost create new sediment sources, which may increase sediment loads.

Dam and reservoir operations, construction of new dams or other sediment retention structures, or removal of dams will affect watershed sediment yield to areas downstream of the dams. In particular, as we start managing more reservoirs for sustainable development, we may induce changes in downstream sediment yield.

b. **How does land use change affect sediment yield?**

Land use management affects the amount of soil loss by erosion. Different land uses result in different erosion rates. Best management practices can be implemented to reduce the erosion rate. Urbanization increases the total runoff, including the peak discharge. This results in increased channel erosion, and increased sediment transport. In addition, construction projects have the potential to produce high sediment yields without active implementation of sediment control measures. Deforestation (for agricultural activities or urbanization) increases the amount of eroded soil that ends up in the stream. So how the watershed is managed, affects the amount of sediment from the upland areas, and may also affect the instream erosion.

c. **How does wildfire affect reservoir sedimentation?**

Wildfires can dramatically change the hydrologic response of a watershed, leading to greatly increased peak flows and increased erosion rates for a given storm. The heat from wildfires can cause the soil to become temporarily hydrophobic, where water
collects on the soil surface rather than infiltrating into the ground. With the tendency of the soil surface to become hydrophobic and “sealed” with fine sediment or ash particles from the fire, water runs off the post-fire surface more readily, rather than infiltrating into the soil, thus contributing to increased runoff peak flows. These higher peak flows possess higher energy, and can, therefore, carry greater amounts of sediment. Meanwhile, wildfires also reduce the stabilizing effect of vegetation cover, which can dramatically increase erosion and sediment yields after high-severity fires.

Post-fire flooding, erosion, and sediment transport are major concerns for water suppliers and society because of their potential adverse effects on water quality, aquatic habitat, and reservoir sedimentation. Every year tens of millions of dollars are spent on post-fire rehabilitation treatments in order to reduce flooding, erosion, and downstream sedimentation and water quality degradation.

Wildfires not only dramatically increase the amount of sediment entering a reservoir, but also dramatically change the pattern of deposition within the reservoir. The high concentrations of sediment coming into a reservoir often result in deposition, not at the upstream end, but downstream near the dam and outlet works. Sediment is carried in sub-aqueous debris flows and turbidity currents. These deposits may interfere with the ability to operate the outlet works and potentially affect dam safety because the ability to drain the reservoir may be impaired.

14. **How do droughts and floods affect reservoir sedimentation and water supply?**

Greater variability in hydrologic events, with more frequent floods and droughts, will reduce the reliability of a reservoir water supply. Reservoir water levels reduce during droughts and refill during floods. However, the rates of sediment entering a reservoir increase significantly during floods. With lower initial reservoir levels, sediments can be carried farther into the reservoir, closer to outlet works. We intuitively expect droughts to deliver lower-than-average sediment loads to reservoirs, but recent research has shown that this is not true. In Texas, researchers found that drought increased upland sediment yield dramatically. The reduction of vegetative cover during the drought left the rangeland so vulnerable to erosion that this factor outweighed the reduction in rainfall frequency, intensity and erosivity. The net effect was a 70-fold increase in the sediment yield, compared to relatively drought-free conditions that prevailed after 1970 (Dunbar, et al, 2010).
During drought, there is not sufficient inflow to sustain normal operation levels, which will affect the quantity and quality of water supply. During floods, the inflow may be highly turbid (impacting water supply and quality) and the amount of incoming water may be more than the reservoir can store. In addition, the extreme events reduce the reliability (the firm yield) of the reservoir.
15. How will climate variability affect sediment yield?

Climate variability may mean an increased frequency of very heavy precipitation storms (e.g., convective storms and hurricanes). Increases in heavy precipitation will result in increased sediment loads, since high flows have a much greater erosive capacity than lower flows. This will result in increased sediment yields even if annual precipitation volume remains the same. Sediment yields will also increase if more precipitation falls as rain instead of snow because stream flows will be higher and flashier with greater sediment transport capacity, and soils more erodible.

The increased frequency of floods and greater sediment yields will change stream channel morphology, which includes the dimensions of a stream channel (width, depth, and meander wavelength and gradient). The changes in stream morphology may include both channel incision and widening throughout entire watersheds. This has two major impacts on sediment yield:

- A larger channel has more surface area (bed and bank) to supply sediment during periods of high stream flow. An incised channel has higher banks, meaning that normal channel migration results in increased sediment delivery to the channel. For instance, if the river is 6 feet deep instead of 4 foot deep (due to incision), a one-foot lateral movement of the channel results in 50% more sediment load delivered to the channel from bank erosion.

- A larger channel contains a higher percentage of flow in the channel, rather than spreading out into the broader floodplains, thus resulting in less attenuation of a flood wave as it passes downstream. For any given event, this will result in increased peak flows, higher sediment transport capacity, and increased sediment yield.

Hotter, drier weather, and earlier snowmelt, result in a greater number of wildfires and an increased number of acres burned. Sediment yields from burned areas are significantly higher than for unburned areas. Post-fire annual sediment yields increased by two orders of magnitude in small watersheds in the San Gabriel Mountains of California (Wohlgemuth, 2006). The ratio of post-fire annual sediment yield to pre-fire annual sediment yield (the “erosion ratio”) varied from 7 to 2,900 for the first post-fire year in various geologic terrains (Moody and Martin, 2004). Sediment yields normally fall off sharply in following years, as the burned watershed recovers.

Decreased snow cover and earlier snowmelt may both cause increased sediment yields by leaving more area open to erosion by rainfall.
The retreat of glaciers is anticipated to increase sediment yield in at least two ways. First, the retreat of the glacier increases the sediment contributing area of the watershed. This new area is unvegetated and frequently rich in unconsolidated, highly erodible material. Second, there are often landslides associated with glacial retreat that contribute large volumes of sediment.

Increased thawing of permafrost along streams and rivers can cause increased flooding and erosion.
16. How does reservoir sedimentation affect downstream environments?

Reservoirs behind dams trap sediment and release unnaturally clear water which deprives the downstream river of sediments essential to maintaining channel form and to supporting the riparian ecosystem. Coastal areas that rely on riverine sediment supply are especially vulnerable to impacts of reduced sediment supply, such as sand-starved beaches that have narrowed or disappeared, accelerating erosion of coastal cliffs and deltas. For example, the Mississippi River Delta has lost over 4,800 km², due largely to reduced sediment supply from trapping in upstream reservoirs. Of the world’s 33 major coastal deltas, 24 are sinking, largely from human causes including reduced sediment supply; in combination with an assumed 0.46-m rise in sea level by 2100, this would lead to a 50% increase in coastal flooding, with profound consequences for coastal populations.

Downstream from dams, reduced supply of sand and gravel has resulted in channel incision and consequent impacts to bridges and other infrastructure. Downstream erosion also leads to the degradation of aquatic habitat quality, including loss of gravels needed by many fish species for spawning and rearing. Gravels are transported downstream, but not replaced by gravels supplied from upstream.

Loss of a river’s natural fine-grained sediment load can have a range of negative impacts, because the native species in a river are, by definition, adapted to the natural conditions. Reduced turbidity below Glen Canyon Dam created conditions benefiting exotic fish and extirpating or reducing the populations of native fish species. Because out-migrating juvenile salmon can avoid predators in turbid water better than in clear waters, artificially clear releases below reservoirs have likely contributed to high predation rates on juvenile fish in some rivers.

Conversely, disruptions in sediment balances can cause downstream reaches to erode rapidly, creating increased localized fine sediment loads that can, subsequently, deposit further downstream and ‘choke’ spawning beds and other habitat features.
17. **What will happen if nothing is done to manage reservoir sediment?**

Eventually all reservoirs on stream channels will fill with sediment and future incoming sediment loads will pass over the dam to the downstream stream or river. This will eliminate all project benefits, but will begin a process of restoring the downstream river channel to pre-dam conditions.

Severe reservoir sedimentation may also affect dam safety. There is always some probability of a dam failure, but this probability is normally very small and balanced by all the project benefits. With severe reservoir sedimentation, the dam outlet may become inoperable, the spillway may be subject to abrasion from sand or gravel, and there is little or no capacity to store flood waters, which results in more frequent use of the spillway. Therefore, the effects of severe reservoir sedimentation can increase the probability of dam failure and there may be no project benefits left to pay for a robust dam safety program. Therefore, a decision to remove the dam may be necessary to provide safe conditions. The management of reservoir sediment during dam removal is often the largest project cost, and the mass movement of reservoir sediment produces the greatest environmental impact.

18. **What is reservoir sustainability?**

Reservoir sustainability is the concept that a reservoir should be able to continue to fulfill its authorized purposes (e.g., flood risk management, hydropower, navigation, water supply, etc.) in perpetuity. This involves passing incoming sediments downstream (completely or partially) without disrupting the ecological functions of the downstream channel.
19. **What are the beneficial uses of reservoir sediment?**

Sediments accumulated in reservoirs can have multiple beneficial uses: environmental enhancement of the downstream channel and coastal areas, construction, commercial, and agricultural applications.

If delivered to downstream reaches, gravels can improve spawning substrate for salmonids, sands can replenish downstream beaches in both the riverine and ocean environments, and finer suspended sediments can restore turbidity to natural levels upon which native species depend for cover. If mechanically extracted from the reservoir, sands and gravels can be used as construction aggregate (for example, concrete road base, and subbase, sands can be used for sandblasting and fracking, clays (if of sufficient quality) can be used for brick manufacturing and ceramics, silts can be used to enhance agricultural lands, and poorly-sorted mixtures can be used as construction fill. Given that using reservoir sediments for these beneficial applications yields the added benefit of restoring some part of the reservoir’s original capacity, we could expect that reservoir sediments would be more commonly used for these beneficial purposes.

The principal constraints include difficulties accessing suitable deposits without drawing down the reservoirs, the transport costs of moving the sediment from reservoirs (often reservoir deltas) to sites where they would be commercially used, and short-term turbidity increases due to disturbance of the deposits. For example, as long as other aggregate sources are available at a cheaper price (due to shorter transport distances and perhaps better sorting of source deposits), mining reservoir deltas for construction aggregate will remain uncommon. This argues for development of economic incentives to mine reservoir sediments rather than mining channel or floodplain sediment from the river, which has greater environmental consequences.
20. **Is sediment a pollutant?**

Because sediment is the product of natural erosion of earth materials, it is NOT inherently a pollutant. It forms an essential part of healthy aquatic ecosystems. Many aquatic species, particularly in historically-muddy rivers, are suffering from a lack of sediment.

Most state and federal laws do consider sediment to be a pollutant, however, because when too much fine sediment is suspended in the water in certain biological environments, it has the potential to impair habitats and harm aquatic life. Fine suspended sediment (clay and silt) reduces light availability which can limit the growth of aquatic macrophytes and phytoplankton. Suspended sediment also can clog fish gills and, for fish that are visual predators, it can limit feeding efficiency by decreasing the ability to see and react to prey. On stream and lake beds, excessive sediment accumulation can smother invertebrate habitat and fish spawning sites and otherwise alter habitats to the extent that they become unusable for sensitive species.

Fine sediment can also serve as a carrier for various chemical contaminants in the aquatic environment. Contaminants are more likely to attach to clay and silt particles than to sand and gravel. Well-known examples of sediment-associated contaminants include phosphorus, metals, PCBs, and certain pesticides, which can be present in agricultural, urban, or industrialized land areas within the contributing watershed, and carried into streams and rivers by natural water flow and erosion.

21. **What are the problems associated with contaminated sediments?**

Contaminated sediment can be problematic for wildlife and humans, depending on the type, distribution, and concentrations of chemical contaminants that are present. Contaminated sediment, suspended in the water, degrades water quality. Contaminants previously attached to deposited sediment can be released into the water and adversely affect water quality. Sediment-associated phosphorus can potentially cause excessive algal growth in lakes which can be detrimental to aquatic life, limit recreational use, and possibly result in the production of algal toxins and cause taste-and-odor problems. Sediment containing various contaminants (e.g., metals, PCBs, pesticides), when ingested, introduces the contaminants into the food chain where organisms may be adversely affected by bioaccumulation and bio-magnification. For similar reasons, chemically contaminated sediment may not be suitable for beneficial reuse, even if its physical properties are considered desirable (as discussed in Question 19, above).
22. What are the potential sediment management strategies, and when are they most applicable?

Several strategies can be used to manage reservoir sedimentation to achieve long-term sustainability. These strategies can be broadly classed as methods to: (1) reduce sediment delivery from the watershed, (2) minimize sediment deposition by passing sediment through or around the reservoir, (3) removal of deposited sediment, and (4) adaptive management strategies. These four broad categories, and the sub-techniques within each strategy, are illustrated in Figure 5.

![Classification of methods to manage reservoir sedimentation](Morris, 2015)

The principal strategies are described below:

a. **Reduce sediment delivery.** The best known practice to retard the rate of sedimentation is to implement erosion control in the upstream watershed, reducing the amount of sediment delivered into the reservoir. This strategy has been practiced, with varying degrees of success, most actively since the 1930s. This is the most universally applicable strategy. However, it has its limitations because erosion control can be very costly on land that has been severely degraded (by over-grazing, for example), because decades
May be required for a significant reduction in sediment yield to be realized, and also because there will always be a natural or “background” rate of erosion and sediment delivery which is unavoidable.

b. **Pass sediment through or around a reservoir.** Sediment is eroded and transported primarily by floods, and another group of management strategies focuses on keeping the flood water moving to minimize sediment trapping in the reservoir.

One strategy is to pass floods around the reservoir by constructing the dam off-stream or off-channel, in the form of a storage basin outside of the main river channel. This allows relatively clean water to be diverted into the reservoir, while the extreme floods, with their high sediment loads, are bypassed around the storage reservoir. Under favorable conditions this may reduce the rate of sediment delivery into a reservoir by as much as 90%.

![Figure 6. Comparison of on-stream and off-stream storage.](image)

Another strategy is to pass sediment through the reservoir by temporarily lowering the reservoir water level during passage of the flood. This increases the flow velocity, and decreases the flood detention time, helping to pass sediment through the reservoir because it has less time to settle out onto the bottom. Similarly, a reservoir which is used seasonally, such as an irrigation reservoir, may remain empty during the first part of the wet season. This is the period when the sediment concentration is normally higher, and flow through the empty reservoir can also scour out some of the deposits from the prior year. The reservoir is then filled with inflow from the latter part of wet
season. As a limitation, this strategy can only be used in hydrologically small reservoirs, which capture a small percentage of annual runoff volume.

In the case of some hydrologically large reservoirs, it is possible to release turbid density currents. These occur when sediment-laden flood water, which is denser than clear water, flows along the length of the reservoir bottom and reaches the dam. If this turbid water is released, it will reduce the rate of sediment accumulation (Figure 7).

![Figure 7. Reservoir inflows with high sediment concentrations can form density currents that sink and travel along the reservoir bottom and can be vented through low-level outlets in the dam (Morris and Fan, 1998).](image)

c. **Sediment removal.** The third class of management measures involves the removal of sediment after it has been deposited. Sediment may be removed by dredging, which removes sediment from underwater while the reservoir remains full. This is the most common type of sediment removal used in the USA, but it is employed infrequently due to its high cost. Broadly speaking, dredging can be accomplished by mechanical methods, using a digging bucket or drag-line, or by hydraulic methods, where material is pumped out of the reservoir in the form of a flowable water-rich slurry.

Another related strategy is to remove sediment using conventional earth-moving equipment when the reservoir pool is low or empty. This strategy is suitable for normally-dry flood control reservoirs and in debris basins designed to trap sediment.
The applicability of sediment removal strategies is limited by a combination of high cost plus the scarcity of sites suitable for the disposal of large volumes of excavated sediment. In some cases the sands and gravels removed from the reservoir may be used for construction fill or similar purposes, but most of the sediment in reservoirs consists of large volumes of fine sediment (silt and clay), which has limited beneficial use.

Another sediment removal strategy, termed reservoir flushing, involves complete emptying of the reservoir to allow the river to flow across and erode the sediment deposits. This eroded sediment passes through a low-level outlet in the dam and is discharged into the downstream river. This technique is practiced on a regular basis in some areas outside of the USA, but is virtually unknown in the USA due to concerns with sediment release and downstream water quality. Downstream impacts can vary greatly, depending on the way the flushing is performed. A properly conducted flushing operation may help restore the natural flow of sediment along rivers which have become “sediment-staved” by upstream dam construction.

Finally, it must be recognized that at many reservoirs it will not be considered feasible to stop the sedimentation process or recover capacity by dredging, due to a combination of high cost plus technical and environmental considerations. Therefore, it is important to consider a variety of other techniques which can be used to increase the benefit of the available reservoir storage, despite the encroachment of sediment. These adaptive methods focus on optimizing the benefits from a more limited storage volume. Several examples are given below:

i. **Optimize operating rule.** The operational rules for many reservoirs, and especially those for flood control, were developed as much as 50 years ago, prior to the advent of real-time data collection and hydrologic modeling. Implementation of modern hydrologic techniques (improved runoff forecasts and predictive models) may enable reservoir benefits to be maintained, despite a decrease in reservoir volume, without any structural changes. This will often be the least-cost strategy for partially offsetting or delaying the impacts of sedimentation.

ii. **Increase water use efficiency.** When water availability is reduced by reservoir sedimentation, users may increase their water use efficiency by implementing conservation measures or by moving away from water-intensive or low-economic value activities.
iii. **Conjunctive use.** In some systems surface and ground water resources can be managed as a system, maximizing withdrawals from reservoirs during wet periods, while during dry periods reservoir withdrawals are reduced and ground water increased. This may be an attractive alternative for municipal suppliers having both surface and ground water sources, for example.

iv. **New water sources.** In some cases it will be feasible to build a new dam, to raise an existing dam to increase storage volume to combat sedimentation, or to develop a more-distant (and costly) water supply source.

v. **Project decommissioning.** At some sites the most feasible way to deal with a sedimentation problem will be to decommission the project. This may be particularly applicable to older and smaller dams. Not only will these typically be the first to lose their capacity, but as water use has grown over the decades and new larger projects have been constructed, their importance with respect to the total water supply may by substantially diminished. Decommissioning costs can be quite high, especially if it involves dam removal with large sediment volumes.

In summary, there are a wide variety of methods which may be used to manage sedimentation and its impacts, and the particular strategy or combination of strategies will be highly site-specific. Nevertheless, at many sites – and perhaps most of them eventually – it will not be economically possible to sustain current reservoir volumes. For this reason it is important that long-term sustainable-use strategies be identified, analyzed and implemented as early as possible to reduce the rate of reservoir storage loss, and eventually stabilize storage capacity.
23. **What are the elements of an effective reservoir sediment management plan?**

An effective reservoir sediment management plan consists of data collection, data analysis, development of long-term strategies, engineering analysis, project selection, implementation, and monitoring.

a. **Data collection to assess present reservoir and river condition.** Information is needed on the extent of sedimentation (bathymetric mapping), the sediment grain size distribution along the reservoir (sediment cores), and the potential for sediment contaminants (upstream industries, mines, agricultural activities, etc.). Many reservoirs in the USA, including many federal reservoirs, have not been recently surveyed to determine the present status of sedimentation, and many reservoirs have never been surveyed since their original construction. Other important data includes daily measurements of streamflow and suspended sediment concentration entering the reservoir, reservoir operational data (water surface elevation and downstream discharge), and site-specific limitations or sensitive issues including regulatory, financial, public perception, environmental, and political considerations.

A basic understanding of the overall fluvial system is also required, including information on the sources of sediment, erosion conditions and past erosional history in the upstream watershed, plus the presence of other dams or users (such as water supply intakes) which may influence, or be influenced by, any sediment management activity at the reservoir under study. In the case of multiple reservoirs along a single river, they would, ideally, be analyzed and managed as a system.

b. **Data analysis and development of long-term strategies.** Assess reservoir sediment management options within the context of the reservoir and river system. The listing of alternative strategies provided in Figure 5 can be used as a starting point in the evaluation of alternatives to help insure that a reasonable range of strategies have been considered. The overall objective of the data analysis step is to identify those alternatives which may be feasible, and which warrant additional analysis, while eliminating those alternatives which are infeasible. This step in the process may also involve preliminary numerical modeling of hydrologic, hydraulic, and sediment transport processes to better understand the extent how project benefits, such as water supply or flood control, will be affected as sedimentation proceeds (no action alternative) and to provide a preliminary assessment of sediment management alternatives. If dredging is
considered, a suitable disposal area should be identified (possibly the downstream channel).

It is important to point out that sediment management is usually not a one-step process. Rather, management measures are more typically implemented sequentially. Some measures, such as erosion control and the release of turbid density currents, may start in the first year of operation (in a new reservoir), while other techniques may only become feasible after a substantial storage volume has been lost. Therefore, the identification of strategies should not be limited to current sedimentation conditions. Rather, identify the sequence of strategies which may be useful to retard the rate of storage capacity loss until sediment inflow and outflow come into balance, or failing this, the project is decommissioned. The purpose of taking this long-term viewpoint is to insure that any future operational or structural modifications support the attainment of long-term sustainable use.

**Preliminary engineering analysis.** A preliminary engineering analysis will be undertaken on the short-list of alternatives considered to be potentially feasible. This evaluation would normally include the development of conceptual designs to size the principal components so that a conceptual-level (i.e., parametric) cost analysis can be prepared, plus a preliminary evaluation of constructability, environmental impacts, regulatory requirements, and similar issues which may have a significant bearing on the cost and feasibility of project implementation. If hydrologic and sediment transport modeling was not undertaken previously, it would normally be performed at this stage to help identify the point at which different management strategies would need to be implemented. Numerical modeling will also aid in the sizing of any structural modifications which may be warranted.

**Project Selection, Implementation and Monitoring.** Based on the preliminary engineering analysis, one or more strategies would be selected for implementation. This may involve additional monitoring, watershed activities, operational changes, or the design and construction of civil works. Some of the identified measures may not be scheduled for implementation until decades into the future, in which case it would be appropriate to re-assess the original recommendations in the future, taking benefit of additional operational experience and monitoring data, plus any changes in technology and costs. Monitoring is a critical aspect of implementation; it is the only way to obtain feedback on the effectiveness of the measures implemented, and to provide information that can increase their efficiency.
24. **What are the costs of not managing reservoir sedimentation?**

Dams and reservoirs were typically designed to trap sediment over the sediment-design life. The costs of sedimentation over this period were normally accounted for in the economic study for the particular project. However, the costs of continued sedimentation (beyond the sediment-design life) were not typically accounted for. These additional costs will be related to the mitigation of sediment burial of dam and reservoir facilities (such as outlets, turbines, spillways, water intakes, boat marinas, and boat ramps), loss of water storage capacity and associated project benefits, dam decommissioning, and the replacement of lost dam and reservoir benefits.

The costs for mitigation of sediment burial of dam and reservoir facilities will depend on the methods employed. Dredging would commonly be employed to remove sediment on an emergency basis from a buried outlet or water intake. Woody debris contained within sediments will make sediment removal more difficult and expensive than the dredging of sediment alone. Design and construction of a new low-level outlet or sluiceway may be necessary to pass sediments to the downstream channel. The costs of constructing a new outlet in an existing dam will be greater than if the outlet had been constructed with the original dam.

The costs associated with the continued loss of reservoir storage capacity will depend on the value of the project benefits and the allocation of the storage loss to the various benefits. The costs of storage loss could also be considered equal to the cost of replacing the lost benefits at some other location or in some other way. For example, lost hydropower benefits could be replaced by another type of power generation. Lake recreation benefits perhaps could be replaced by another type of recreation. Flood control benefits could be partially replaced with the construction of new or improved levees.

Eventually, continued reservoir sedimentation will eliminate the remaining project benefits and decommissioning will be necessary to leave the project in a safe condition. This will often lead to dam removal. The costs of project decommissioning will include the planning, public involvement, permitting, initial implementation, and any operation and maintenance costs. The costs associated with reservoir sediment management can be a significant portion of the total decommissioning costs. For large reservoirs that become filled with sediment the dam removal costs could be tens of millions to hundreds of millions of dollars.
25. How would we pay for reservoir sediment management?

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

The assumed interest rate (or discount rate) for the economic analysis is very important because the higher the interest rate, the lower the value of future benefits. For example, a benefit worth $100, 50 years into the future, would be worth $60.67 now at a 1 percent interest rate, but only worth $8.25 now at a 5 percent interest rate. Future generations could be faced with difficult and expensive reservoir sedimentation problems if decisions are made today that primarily benefit the present generation (Annandale, 2013).

<table>
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<tr>
<th>Future Value</th>
<th>Interest Rate</th>
<th>Present Value</th>
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For dams already constructed, an operating fee of some kind often will be required to fund reservoir sediment management. This practice is common in other natural resources extraction industries where, to prevent the catastrophic over-harvesting of trees, grass, or fish, for example, operators are either limited in their harvesting activities or are required to replace the resource following extraction. A fee imposed on the beneficial users of reservoir water storage could be established to pay for sediment management projects.
Dam and reservoirs, as part of larger water projects, take about a generation of people (20 years) to conceive, plan, design, permit, and construct. The next generation begins receiving the project benefits and starts paying back the initial capital investment and the operation and maintenance costs. A couple of generations later (30 to 50 years), the original capital costs are repaid and the beneficiaries only pay the operation and maintenance costs. This would be a good opportunity for beneficiaries to start paying for sustainable sediment management.

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

References


