# STATE OF THE PRACTICE OF SEDIMENT MANAGEMENT IN RESERVOIRS: MINIMIZING SEDIMENTATION AND REMOVING DEPOSITS

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**Abstract:** Sedimentation in reservoirs is becoming more problematic as water storage and supply become increasingly endangered with the aging American infrastructure. Three general strategies for addressing reservoir sedimentation are currently utilized: reduction of incoming sediment yield, minimization of sediment deposition, and removal of sediment from reservoirs. This paper addresses the latter two strategies and their associated management methods. The main management methods associated with minimizing sediment deposition are construction of sediment bypass structures, sediment pass-through (or sluicing), and venting of a sediment-laden density current. The main overall advantage of sediment bypass structures is that they do not interfere with regular reservoir operation; however, the method is difficult to apply, requires careful planning, and cannot be utilized in arid climates where the need for water is high. Sluicing is one of the more often used sediment-management techniques, but depends upon the existing structure of the dam and can cause adverse impacts to the downstream environment if not carefully monitored. Density current venting is seldom-used due to its reliance on the existence and surveying of a density current; however, it has been shown to be effective under certain circumstances. The main management methods associated with removing sediment from reservoirs nearing critical storage loss are flushing and dredging. Drawdown flushing has been studied extensively and has been found to work optimally on narrow, gorge-shaped reservoirs where the water can be fully drawn down. Pressurized flushing is not implemented as often as drawdown flushing as its main purpose is in clearing the area immediately surrounding the bottom outlets of the dam. Flushing generally has more noticeable effects on the downstream ecosystem than sluicing. Dredging, the most often used sedimentation management technique, is also a highly expensive and time-consuming practice, although efficacious when complimented by other methods, particularly for settling basins at the inlet of the reservoir.

## INTRODUCTION

America is aging, and its reservoirs are no exception. A report published in 1968 determined that the average annual storage loss of U.S. reservoirs was slightly more than 0.2 percent of the total initial capacity (Dendy, 1968). Though this statistic was not alarming in 1968, after nearly 50 years, about ten percent of the total initial capacity will have been lost due to sedimentation. In fact, the life expectancy of most reservoirs is only 100 to 200 years, and at least 200 of the largest United States reservoirs were more than 40 years old as of 2008 (Baker, et. al, 2008). Figure 1 is a photograph of a dam for floodwater storage in northwest Iowa that was completely silted in from years of soil erosion from land in its watershed.

Figure 1. Dam in northwest Iowa completely silted in and no longer functioning to store floodwaters (Photo by Tim McCabe; Photo courtesy of USDA Natural Resources Conservation Service; Photo by USDA NRCS).

Sediment management is now more than ever a challenge for the current generation (Morris and Fan, 1998). The predicament is further complicated with environmental concerns related to sediment capture and release. Already the effect of dams on American rivers has been so great from an ecologic or hydrologic standpoint that even the predictions of future global climate change impacts are in no way comparable (Graf, 1999). Perhaps the largest problem, however, is the lack of data for the majority of U.S. reservoirs. A report on Kansas reservoirs stated that most of the nearly 6,000 regulated reservoirs do not have bathymetric data, which is essential information for any sediment-management project (Baker, et. al, 2008). This review of the state of the practice of sediment management aims to inventory the feasibility, efficiency, and environmental impacts of various techniques currently in use.

Three main strategies exist for dealing with reservoir sedimentation: reducing incoming sediment yield, minimizing siltation, and removing deposited sediment from reservoirs. Within each of these strategies various techniques present themselves for certain situations. This review will focus on techniques from the latter two of the three aforementioned strategies. Sediment bypass structures, sluicing, and density current venting aim to minimize siltation in reservoirs; and flushing and dredging remove sediment that has settled on the bottom of reservoirs. These techniques battle the issue of sedimentation in reservoirs so that situations such as the one shown in Figure 2 of Lake Red Rock in central Iowa can be prevented or resolved.

Figure 2. Sediment filling Lake Red Rock in central Iowa at rates much faster than anticipated. (Photo by unknown photographer; Photo courtesy of USDA Natural Resources Conservation Service; Photo by USDA NRCS).

## MINIMIZING SILTATION

Many effective means of preventing storage loss in United States reservoirs focus on the upstream environment and the transport of sediment entering the low-velocity area where particles settle out; however, minimizing settling inside reservoirs also serves an important purpose in regions where flood events carry the majority of sediment, and reservoirs serve only as water supply. The main management methods associated with this particular strategy are construction of sediment bypass structures, sediment pass-through (or sluicing), and venting of the density current.

**Sediment Bypass** Sediment bypass structures route high-sediment flows, generally resulting from floods, around the reservoir using canals, pressurized pipelines, or tunnels. Construction of canals is an expensive practice with its viability depending upon local topography, reservoir size and shape, and hydraulics of the river system. Pressurized pipelines for bypassing sediment are also rarely used and not often mentioned in literature due to the specific conditions necessary for its successful implementation and the high cost of construction (Batuca and Jordaan, 2000). Bypass tunnels are more common than canals or pressurized pipelines, but also suffer from high investment and management costs. A majority of these structures are operated in Switzerland and Japan where slopes are high (1% - 4%) due to mountainous topography and reservoirs are small (Sumi et al., 2004). The effectiveness of this management method is seen in the Nunobiki Dam in Japan whose tunnel has allowed the reservoir to maintain a constant storage volume since 1908 (Annandale, 2013).

Abrasion at the inlet due to high sediment concentrations is the main challenge with bypass tunnels. A design suggestion to combat the degradation of the inlet involves utilizing high strength concrete (30 N/mm$^2$ or more) and allowing for deep abrasion protection (10 – 35 mm); however, more research is necessary on the topic (Sumi et al., 2004).

From an ecological standpoint, sediment bypassing boasts a lesser impact on the downstream environment when compared to sluicing, flushing, or no management strategy at all. During flood events, sediment from the upper reaches of the river, which would naturally flow downstream without the existence of a reservoir, remains in suspension at approximately the same concentration (Auel and Boes, 2011). The suspended sediment concentration is neither higher from scouring of the reservoir bottom nor lower from releasing the clear water at the top of the reservoir.

The main overall advantage of sediment bypass structures, however, is that they do not interfere with regular reservoir operation, as no drawdown of the water level is needed. However, the method is difficult to apply, requires careful planning, and cannot be utilized in arid climates where the need for water is high (Tigrek and Aras, 2011). In addition, regions with flood control concerns will find that sediment bypassing undermines the original intent of the reservoir (Annandale, 2013).

**Sluicing** Sediment pass-through, also known as sluicing, is another way of abating sediment deposition in reservoirs. For this method, the reservoir level is drawn down during the flood season and allowed to flow through the sluice gates to maintain the incoming sediment in suspension (Tigrek and Aras, 2011). When particles enter the low-velocity area of a reservoir, they settle and form a delta consisting first of the heavier coarse sediments, then further on a more shallow layer of fine sediment. This phenomenon can be seen in the illustration in Figure 3. A depiction of the sluicing technique to reduce the development of this delta is shown in Figure 4. A 1996 study of the North Fork Feather River in Northern California determined that using sluicing as a sediment-management technique viably maintained the equilibrium of sediment between the reservoir and downstream environment over an extended operating period (Chang et al., 1996). The study also showed that sluicing would not result in adverse impacts on the fish habitat downstream as long as it followed the suggested operating rules.

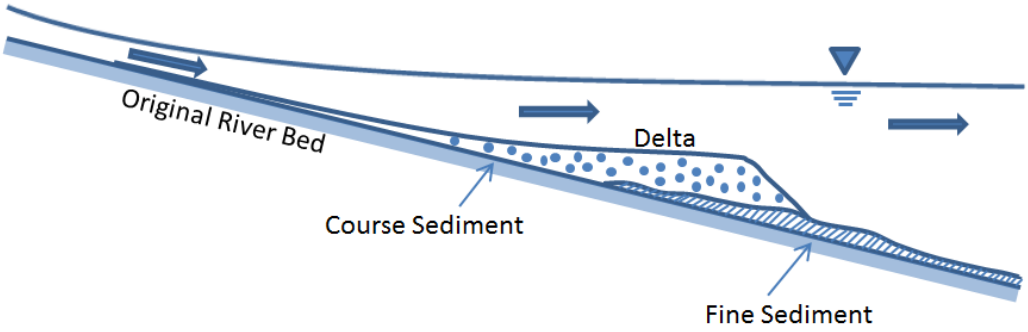

Figure 3. Longitudinal reservoir profile with delta formation.

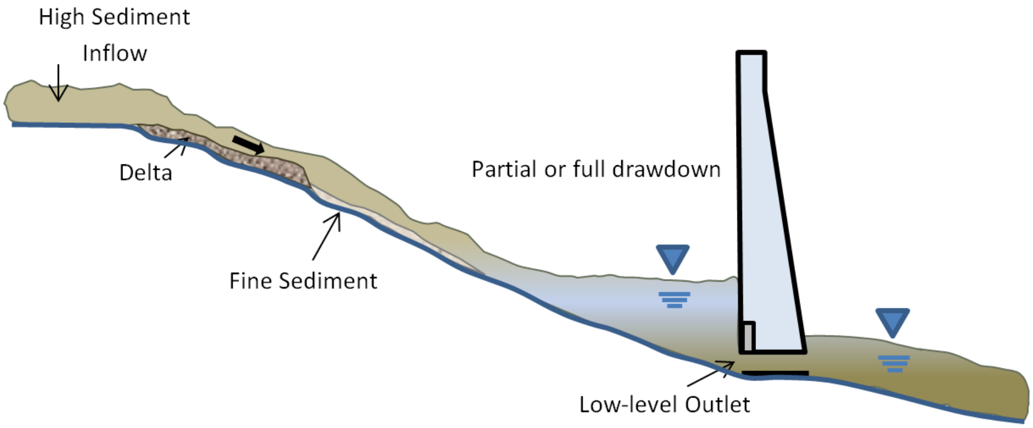

Figure 4. Longitudinal reservoir profile with sediment sluicing.

One restriction of sluicing is its dependence upon the existing structure of the dam, as sluice gates must be positioned appropriately along the bottom for the sediment to flow through efficiently. A 1988 assessment of several countries' sluicing techniques recommended that the sluice gates be at a height of 1.5 to 2.5 meters with an area determined from design curves presented in their paper (Paul and Dhillon, 1988). They also advised that only the width of the gate should be changed to increase effectiveness. In addition, Bogardi (1974) suggested that the sluicing technique is most effective when: 1) water depths are low and discharge is high; 2) sluice gates are wide and located near the bottom of the dam; 3) the original stream bed is steep and the reservoir has a short, straight bottom; 4) and the reservoir is in an advanced stage of siltation and the deposits consist of fine grained, recently settled material. With these specifications met, sluicing has been found effective in many instances, especially in China, where it is practiced routinely due to high sediment loads (Hotchkiss, 1990).

**Density Current Venting** Density current venting, a seldom-used technique, involves the discharge of turbid sediment-laden water from a low-level outlet (like a sluice gate) while the surface waters remain clear or unchanged. Turbidity currents develop when water with a high sediment load enters a reservoir and immediately plunges to the bottom, travelling through the original channel until settling near the dam in what is called a "muddy pool" (Morris and Fan, 1998). Management of these currents can drastically reduce sediment build-up at the base of a dam. However, density currents form only under certain conditions and can be difficult to detect. Under optimal conditions, approximately 50% of the total sediment can be vented, though the average is closer to 20% since early detection methods are lacking (Utah Division of Water Resources, 2010). One innovative way of managing density currents was developed in Japan at the Katagiri Dam where a curtain wall permitted only the sediment laden density current at the bottom of the reservoir to spill over the top of the dam (Annandale, 2013). A depiction of the standard density current venting method is shown in Figure 5.

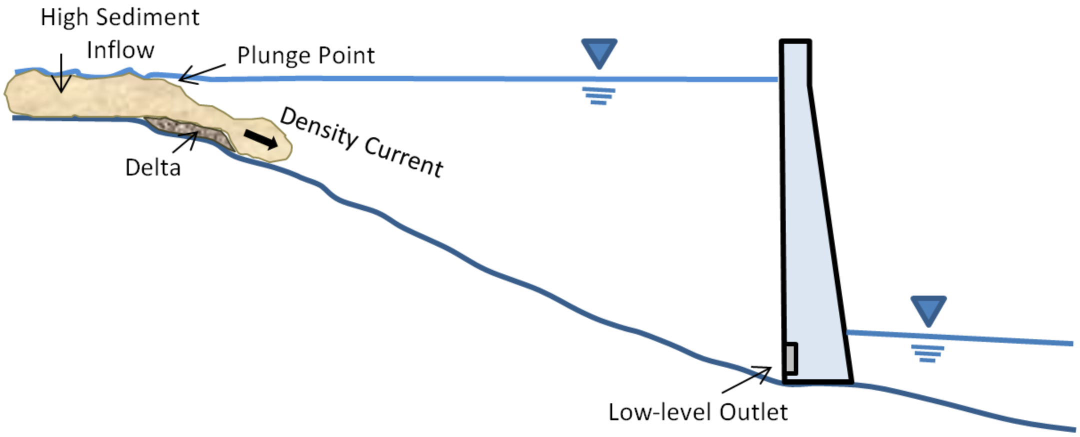

Figure 5. Density current along longitudinal reservoir profile.

A recent study of this method conducted on the Tsengwen Reservoir in Taiwan using 3D numerical models as well as measured and simulated typhoon flood events proposed the following formula for estimating the outflow concentration and venting efficiency of an outlet (Lee et al., 2014):

$$C_O = KC_L\left[\frac{(s-1)gh_L{}^5}{Q_O}\right]^{1/5} \qquad \text{Eq. 1}$$

where $C_o$ is the outflow concentration [$ML^{-3}$]; $K$ is the venting coefficient calibrated based on the outlet structure [$ML^{-3}$]; $C_L$ is the layer averaged concentration of the density current [$ML^{-3}$], $s$ is the specific weight of the suspended solid [$ML^{-2}T^{-2}$], $g$ is gravitational acceleration, $h_L$ is the distance between the outlet center and the interface of clear water and dense layer [L], and $Q_o$ is the outflow discharge [$L^3T^{-1}$].

## REMOVING DEPOSITS

Removing sediment is quickly becoming an issue of great concern as reservoirs which were constructed decades ago without any consideration of sediment management have slowly built up enormous deposits of silt and sand and now are reaching levels which impede recreation and impact water supply. The main management methods associated with removing sediment from submerged reservoirs are flushing and dredging. Flushing can be further characterized as either drawdown or pressurized.

**Drawdown Flushing** Drawdown flushing is highly similar to sluicing; however, it is not executed during flood season. Rather, it is done when the river is at low-flow conditions so that drawing down the water level takes less effort and does not affect the water supply (Annandale, 2013). The operationally-favorable conditions for drawdown flushing generally occur before the flood season or at the end of the dry season (Batuca and Jordaan, 2000). A depiction of drawdown flushing is shown in Figure 6.

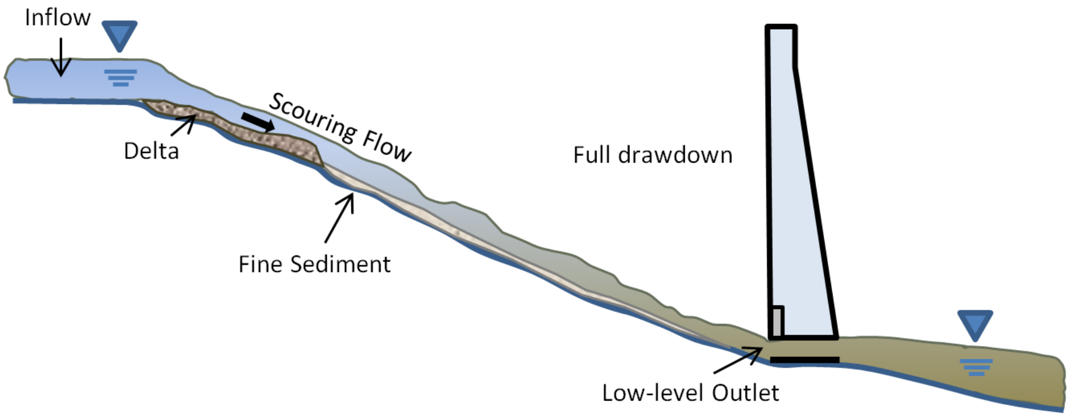

Figure 6. Longitudinal reservoir profile with sediment flushing.

A study of the Tapu reservoir in Taiwan used optimization of operational-rule curves to increase flushing efficiency, with a final recommendation that the particular reservoir be flushed every two to four years in the months of May or June (Chang et al., 2003). A more recent study on the Kali Gandaki hydropower reservoir used a three-dimensional numerical modelling program called Sediment Simulation in Intakes with Multiblock Option (SSIIM) to prove that this could be a practical alternative to the difficult task of planning and optimizing the flushing process for complex reservoir geometries (Haun and Olsen, 2012). The study also identified limitations of physical modeling of reservoir flushing, stating that the magnitude of bed forms is challenging to properly scale in a physical model.

Drawdown flushing is generally most effective in narrow, gorge-shaped reservoirs like the Gebidem reservoir in Switzerland, and water must be allowed to be fully drawn down, making it near impossible to implement in hydropower dams (Tigrek and Aras, 2011). This technique is also impossible to implement in reservoirs without low-level outlets, such as sluice gates.

**Pressurized Flushing** Pressurized flushing removes only a fraction of the amount of sediment when compared to drawdown flushing. This method is rarely used and its main purpose is to clear the area immediately surrounding the bottom outlets (Annandale, 2013). As the sediment is flushed out, the area around the outlet forms a funnel-shaped crater, known as a "flushing cone" (Emamgholizadeh et al., 2006). Meshkati et al. (2009) addressed the development of the flushing cone and identified a set of non-dimensional relationships which could be used to estimate the development of the cone and, therefore, increase efficiency and sediment output. Despite this progress, keeping the bottom outlets clear of sediment will likely continue to be the only valuable use of pressurized flushing.

The impact on the ecosystem downstream of the reservoir is an important consideration with either drawdown or pressurized flushing as a sediment-management method. A study of the Valgrosina reservoir in northern Italy where free-flow flushing was utilized to maintain reservoir capacity found that fish densities decreased up to 73 percent while biomass decreased up to 66 percent after a flushing event (Crosa et al., 2010). To avoid spikes in suspended solid concentration and to manage scouring effects, they recommended that a yearly flushing occur in that particular reservoir. An earlier study of regulated rivers in California suggested that flushing could help clean fine sediment deposits from downstream gravel to encourage fish spawning

(Kondolf and Matthews, 1991). However, it also observed that flushing could be counterproductive as potential high flow velocities might end up carrying some of this ecologically important bed load away with the fine sediment.

In addition to the effect on the downstream ecosystem, the associated high sediment concentrations also affect downstream infrastructure. Sediment can clog irrigation canals and heat exchangers for industrial cooling systems, wear down hydropower turbines, and cause issues at water purification plants with low capacities for suspended solids (Morris and Fan, 1998).

**Dredging** An expensive but effective solution to extreme storage loss in reservoirs, dredging is perhaps the most often used sediment-management technique. Dredging removes deposited sediment from the bottom of reservoirs using pumps, hydraulic suction, or clamshell buckets (Utah Division of Water Resources, 2010). A photograph of sediment-laden water being pumped as part of a dredging operation at Lake Panorama in central Iowa is shown in Figure 7. In 2010, the average cost of dredging reservoirs was estimated to be $\$8.70/m^3$, a serious investment for any small city operating on a budget (Smith et al., 2013). According to a 2008 study of Kansas reservoirs, dredging one of the larger reservoirs in the state could cost more than 100 times the original amount invested in constructing the reservoir (Baker, et. al, 2008).

Figure 7. Sediment-laden water pumped as part of a dredging operation at Lake Panorama in central Iowa (Photo by Lynn Betts; Photo courtesy of USDA Natural Resources Conservation Service; Photo by USDA NRCS).

One main issue with dredging is the environmental impact of disturbing several years of settled sediment. Closed buckets are recommended for areas with contaminated silts since they minimize the seepage of polluted water into the environment (Utah Division of Water Resources, 2010). However, it has also been proven that dredging can reduce eutrophication in shallow lakes and reservoirs. The 2009 report on the dredging of Lake Yuehu in central Wuhan, China, showed that internal nutrient loads were reduced and the zooplankton community had progressed toward a less eutrophic balance post-dredging (Zhang et al., 2009).

Dredging is often chosen over employing conventional best management practices (BMPs) concerning croplands. This can be attributed to the limited effect of these BMPs in comparison to the cost of implementation. It was determined in a 2013 economic study that BMP enactment should be carefully planned to optimize cost-effectiveness, and even the most effective practices may not preclude the need for future dredging (Smith et al., 2013).

## SUMMARY

Sediment management in reservoirs is a complex and expensive undertaking no matter which technique is used. A perfectly sustainable solution for every situation does not exist, but efforts can be optimized for the particulars of each reservoir. Methods concerned with preventing the deposition of sediment such as sediment bypass structures, sluicing, and density current venting can be most effective in regions where high sediment loads occur often and in a predictable manner. Methods concerned with removing sediment deposits such as flushing or dredging are often used as a result of non-sustainable reservoir design in an effort to reclaim lost storage. With the aging of America's infrastructure, more attention must be focused on the upkeep of the nation's reservoirs before sedimentation renders them useless.

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