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Sustaining United States reservoir storage capacity: Need for a new paradigm

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ABSTRACT

Although the hydrologic cycle is a continuously renewable resource, the natural rate of water delivery is highly variable. Water is made available to our society on a consistent and reliable basis largely due to flow regulation by storage reservoirs. However, under current management, the reservoir storage capacity needed for flow regulation is a non-renewable resource because this capacity is steadily being lost to sedimentation. Today's reservoirs occupy unique sites and may be considered largely irreplaceable, making the nation dependent on a non-sustainable resource.

Sedimentation is steadily depleting storage capacity and progressively degrading the ability of reservoirs to fulfill their designated purposes. Sedimentation is also causing environmental impacts upstream and downstream of reservoirs. In the United States, the combined impacts of sedimentation and population growth have resulted in an estimated 35% decline in storage capacity per capita since this value peaked around 1970. In absolute terms, the estimated total reservoir storage capacity in the U.S. has dropped from a peak of 850 Gm^3 in the late 1980s to 810 Gm^3 today. Yet, sustaining the nation's long-term reservoir storage capacity has not been a priority for many public or private dam owners, especially when they lack a reservoir sedimentation monitoring policy.

In many regions, future reservoir storage will have to serve an important role in the mitigation of climate change to help ensure water, food, and energy, and the reduction of flood risk. There is an imperative need to preserve existing reservoir storage capacity due to rising demands associated with population growth, and increasing hydrologic variability associated with climate change, and the challenges and costs associated with either expanding existing capacity or decommissioning and developing new storage capacity. The trapping of sediment behind dams has also contributed to the decline of freshwater and coastal environments downstream of dams.

Reversing these dangerous trends in storage capacity and environmental integrity will require increased monitoring of reservoirs, application of both established and emerging sediment management technologies, and a new paradigm for sustainable reservoir design and management. It requires moving from the traditional design life (reservoir life expectancy) approach to the adoption of sustainable use as the appropriate criteria for reservoir design and operation, achieving a sediment balance across reservoirs to permit the indefinite operation of this critical infrastructure.

1. Introduction: What's at stake

The 90,000 + registered large dams in the USA (taller than 7.6 m or greater than 18,000 m^3 of capacity) (National Inventory of Dams, 2017) constitute a critical component of the country's infrastructure. These dams and their reservoirs provide water supplies for municipal, agricultural, and industrial uses, hydropower production, flood risk reduction, navigation, water quality regulation, and recreation. Delivery of these services largely depends on sustaining adequate storage capacity. The ability of reservoirs to store and regulate river discharge is an issue that affects the very existence of many communities, determining which continue to exist in relative safety, where crops can be grown, and what economic activities can be pursued.

However, these reservoirs are steadily losing storage capacity due to sedimentation, and, at some sites, sediment deposits already interfere with the operation of dam outlets, water supply intakes, and boat ramps. Sediment trapping in reservoirs has also disrupted fluvial sediment continuity, reducing sediment supply to downstream reaches, leading to erosion of downstream channels and coastlines, with impacts to both infrastructure and habitat. As conceptually illustrated in Fig. 1, the current paradigm of accepting the continued trapping of sediment is not a sustainable long-term strategy. As outlined by Morris and Fan (1998), the objective of sediment management is to achieve a sediment balance across reservoirs while maximizing usable storage capacity or other benefits once this balance is reached. They also argued that sustainable use should be incorporated as an engineering criterion for dams and reservoirs, similar to the way that dam safety is accepted as a design and operational requirement. This paper discusses this sustainability issue and outlines the path towards a sustainable use paradigm for reservoirs.

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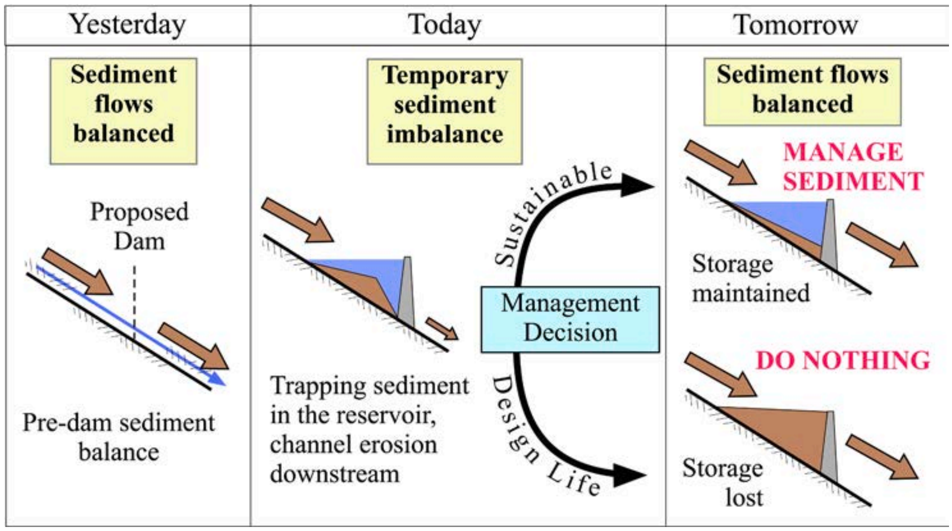

Fig. 1. Trapping sediment in a reservoir and releasing clear water downstream is neither a natural nor a sustainable option over the long term. Preservation of long-term reservoir storage capacity is a management decision and requires the downstream release of sediment to match natural inflows (Morris, 2020).

2. Loss of storage capacity

Since about 1990, the USA (and the world) has lost reservoir storage capacity to sedimentation at a faster pace than new storage has been created by new dam construction (Fig. 2) (Annandale et al., 2016; Randle et al., 2019). The trend of declining storage capacity means that future water supplies will also decline in reliability. When reservoir storage capacity is computed on a per capita basis, the per capita storage is declining much more rapidly due to the combined effects of sedimentation and increasing population. Per capita storage has been declining since about 1970 (Fig. 3). As a result, by 2020, per capita reservoir capacity in the USA had declined to the mid-1900s level, but with one very important difference. In the mid-1900s storage volume was trending upward due to the continued construction of new dams and reservoirs, but today reservoir storage capacity is trending downward.

Even limited amounts of sediment accumulation can interfere with water delivery outlets and other critical components. For example, starting in 2010, and with less than 25% loss in gross reservoir capacity, Paonia Reservoir in Colorado experienced outlet blockages that prevented water delivery and required emergency actions (Huang et al., 2019). Many parts of the world are losing reservoir storage faster than the USA. In Taiwan, naturally high erosion rates have resulted in rapid reservoir sedimentation, forcing engineers to aggressively confront loss of storage capacity and function, providing a 'preview of coming attractions' for the USA (Wang et al., 2018).

Against the backdrop of gradually declining capacity, the requirement for reservoir storage is increasing over time as climate change makes streamflows increasingly variable (Hoegh-Guldberg et al., 2018). Increased hydrologic variability, which manifests as more extreme episodes of drought and flood, requires larger storage volumes to sustain a given level of water supply or flood protection. Even though large increases in water use efficiency have been experienced in all sectors, producing a gradual decline in water use within the USA, this is not a sign of water abundance. Rather, it is a response to drought. For

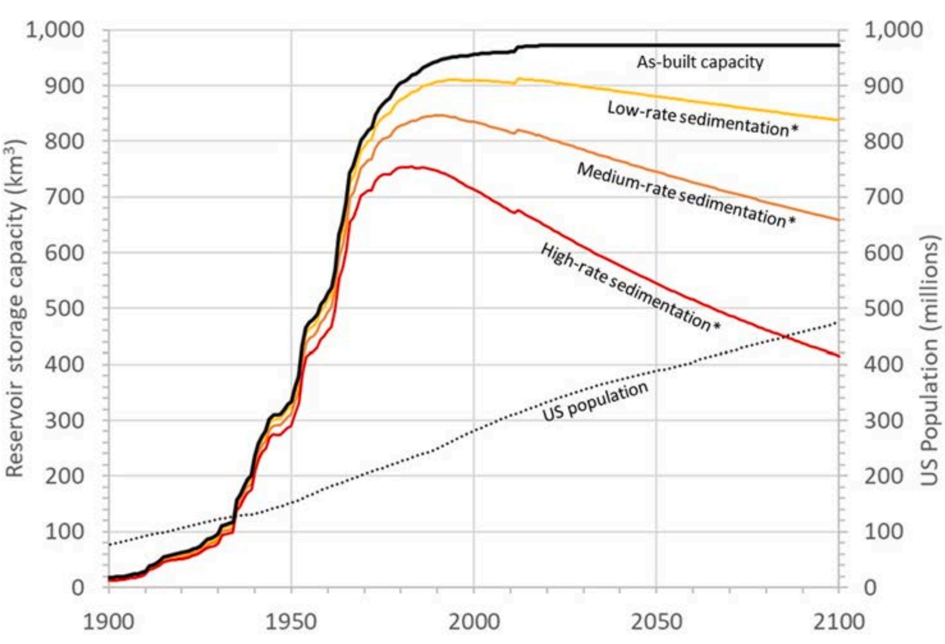

Fig. 2. Changes to United States reservoir storage capacity over time due to dam construction and reservoir sedimentation, for different rates of capacity loss. The curves presented in this plot are based on data from the National Inventory of Dams (constructed reservoir storage capacity, shown on vertical axis) and assumed rates of storage capacity loss due to sedimentation. Constructed reservoir storage capacity data are based on 68,000 dams in the national inventory that were constructed since 1900. Assumed annual storage capacity loss due to sedimentation was 0.4, 1.0, and 2.0 percent per year (Graf et al., 2010) for small reservoirs (constructed storage capacity less than 100,000 acre-feet) and 0.1, 0.2, and 0.5 percent per year for large reservoirs (greater than 100,000 acre-feet) based on experience at larger Federal reservoirs. The three curves show a range in storage capacity loss over time and represent the range of uncertainty. A systematic reservoir sedimentation monitoring program for the nation's reservoirs would be needed to reduce this uncertainty. The U.S. population data from the U.S. Census Bureau (2018a, b).

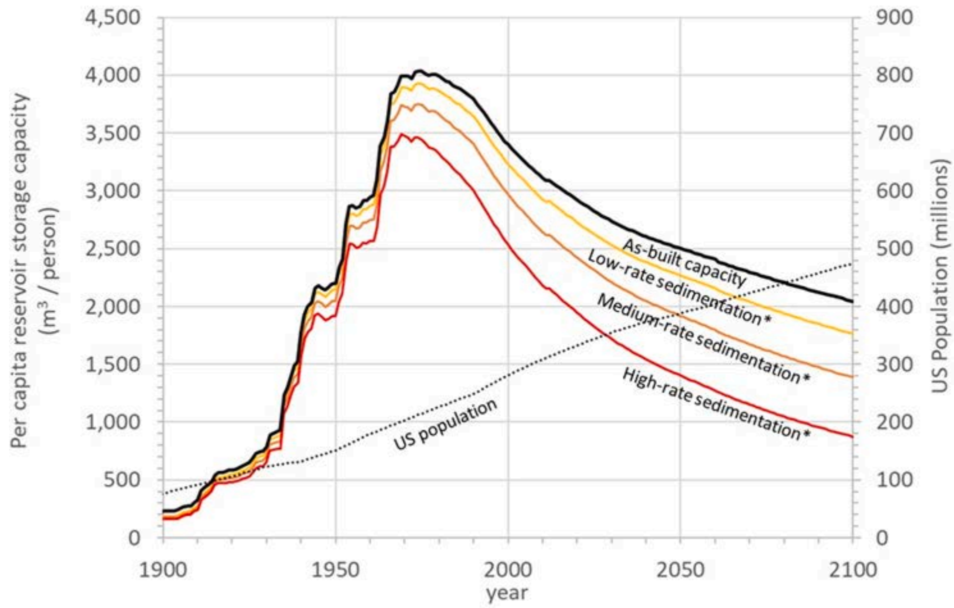

Fig. 3. Per capita changes to United States reservoir storage capacity over time due to dam construction, reservoir sedimentation, and population increase. The per capita reservoir storage in 2020 is about the same as in was in the mid-1900s. See Fig. 2 for a description of the data.

example, both California and Texas saw substantial declines in water use during the 2015 drought (Dieter et al., 2018). Water supplies are already constrained in the American west. Continuing population and economic growth will require that existing supplies be sustained or increased. Yet sedimentation unceasingly reduces usable reservoir capacity and water supply reliability, at the same time more capacity is needed to help mitigate the effects of climate change (Tullos et al., 2020). Some services provided by dams, such as electricity from hydropower, can be generated from alternative sources, but there is no practical substitute for water in uses ranging from municipal supply to crop irrigation. In many regions, future reservoir storage will have to serve an important role in the mitigation of climate change to help ensure water, food, and energy and reduce flood risks. Thus, sediment management must be considered to sustain reservoir storage capacity (Schleiss, et al., 2016).

River water, and the nation's existing networks of reservoirs, remain the resource with the greatest potential for sustainable supply of fresh water (Annandale, 2013). In most locations, a water supply deficit from reservoirs cannot be overcome using natural groundwater, which itself is often overutilized and continues to be depleted (Famiglietti, 2014; Konikow, 2011). Alternative water supply solutions, such as seawater desalination, have historically been energy intensive and expensive. Furthermore, declining reservoir storage capacity cannot be solved by simply building new dams. Today's reservoirs already occupy the best sites, and alternate locations are generally inferior or impractical due to the high cost of dam construction and reservoir land acquisition due to existing development, environmental constraints, or simply because no suitable alternative dam site exists given topographic and geologic limitations (Morris and Fan, 1998).

3. Design life vs. sustainability

Sustaining the critical functions of reservoirs for future generations requires adoption of a new paradigm of sustainable use, as opposed to the traditional design life concept which ignores consequences beyond a project's formal planning horizon (Palmieri et al., 2003). The design life approach has critically hindered management of our aging infrastructure, much of which is past or near the end of its design life (ASCE, 2017), and for which funds for repair and maintenance have steadily declined (McGinnis, 2014). The key element of sustainable use is sediment management seeking initially to mitigate storage loss, and ultimately to achieve a balance between sediment inflow and outflow while maximizing usable storage capacity (Annandale et al., 2016; Morris and Fan, 1998; Randle et al., 2019). Many of today's reservoirs could be converted into sustainable assets that will continue to supply benefits long into the future, but this will require adopting a new management approach (Fig. 1).

Unfortunately, there is currently no consistent national policy to manage reservoirs for long-term sustainable use, nor is there an articulated "exit strategy" for eventual decommissioning of dams and their associated reservoirs. Those instances in which decommissioning has occurred or is anticipated, such as in the case of San Clemente Dam (Harrison et al., 2018), Matilija Dam (AECOM and Stillwater Sciences, 2016), or Elwha Dam and Glines Canyon Dam (Bountry et al., 2018; Ritchie et al., 2018), have largely been undertaken in response to near complete loss of storage capacity or in the face of pressing environmental concerns. The vast majority of dams decommissioned to date are small diversion or hydropower dams (Foley et al., 2017). Avoidance of the huge challenges and costs that would accompany the decommissioning of dams with large sedimentation volumes is another factor favoring the sustainable use paradigm.

The current path of continued reservoir sedimentation leads to intergenerational inequity in which future generations will be asked to pay for sediment management to sustain limited remaining reservoir benefits compared to those enjoyed by previous generations or pay for dam decommissioning which may generate no benefits other than damage avoidance. Intergenerational inequity consequences associated with the design life paradigm are outlined below for a typical reservoir:

- 1st generation conceives, plans, designs, and constructs a dam and reservoir.
- 2nd generation receives full benefits, repays capital costs, pays O&M costs, but does not pay for sediment management or sedimentation impacts.
- 3rd generation receives close to full benefits, finalizes repayment of capital costs, continues to pay O&M costs, but does not pay for sediment management or sedimentation impacts.
- 4th generation receives declining benefits, continues to pay O&M costs, begins to pay for some sediment management.

- Last generation is burdened with the costs of either full sediment management or dam decommissioning while foregoing reservoir storage benefits and may also need to pay for a new water supply.

The sustainable use paradigm achieves intergenerational equity by not pushing all the costs onto the last generation. Transition to a sustainable use paradigm makes engineering, environmental, economic, and ethical sense. Too much is at stake to continue down the path of a design life paradigm, the impacts of which, described below, will be lasting.

4. Reservoir sedimentation: Processes and impacts

All rivers naturally transport sediment eroded from upstream watersheds, including stream beds and banks. Natural erosion rates can be greatly increased by human activities that disturb vegetation, soils (Wilkinson and McElroy, 2007), or harm wildlife (such as beavers), or that alter stream channel processes (Belmont et al., 2011), such as increased erosion by floods amplified by urban development. Rates of erosion and sediment yield are also accelerated by wildfires, which are affecting increasing areas of land in the American West (Congressional Research Service, 2018). Best management practices for land and streams throughout the watershed (Duriancik et al., 2008; Mausbach and Dedrick, 2004) can reduce erosion to rates that are closer to natural background levels, but erosion and sediment yield will never reach zero, even in an undisturbed watershed. Continued availability of sediment is necessary to preserve the fluvial geomorphic character of rivers and streams that is essential to sustaining freshwater and coastal ecosystems.

Most sediment accumulation occurs underwater and is unseen. Sand and coarser particles tend to settle first and form a delta while finer particles tend to deposit along the reservoir bottom beyond the delta. When high concentrations of suspended sediment enter a reservoir, turbidity currents can flow along the bottom of narrow reservoirs and reach the dam (Morris and Fan, 1998). Sedimentation will occur in the vicinity of dam outlets if turbidity currents reaching the dam are not vented through the dam. The long-term process of sediment accumulation is illustrated in Fig. 4.

Reservoirs in the USA have generally been sized to store sediment during the design life (typically 50 or 100 years) before encroaching on the lowest dam outlet. However, this approach ignored the consequences of continuing sedimentation beyond the original design life. Virtually no US dams have structural features, operating measures, or a management strategy to deal with the reality of sedimentation and its effects. As described below, important sediment-related problems can occur well before even half of the reservoir capacity has been lost. As sedimentation progresses, depending on local conditions, some or all the following impacts can be anticipated.

4.1. *Diminishing reliability of water supplies*

As the storage capacity available to capture stream flows diminishes, the ability to regulate releases and deliver reliable water supplies during drought also diminishes. This problem will be exacerbated by increased hydrologic variability associated with climate change (IPCC, 2014; Arnell and Gosling, 2013). The shrinking ability to reliably supply water to urban population centers and to irrigated agriculture is a critical issue.

4.2. *Interference with dam outlets and water intakes*

Sediment and submerged woody debris can clog outlets and water intakes, rendering them inoperable (Fig. 5a). Because floods transport large volumes of both sediment and woody debris, clogging can occur suddenly, even if it was preceded by years of steady sedimentation that went unattended and, if not monitored, perhaps even unnoticed. Sediment can also be drawn into pump stations, hydropower turbines, irrigation canals, or other infrastructure, greatly increasing maintenance and repair requirements for equipment and spillways due to abrasion damage (Fig. 5b). These impacts can occur long before the reservoir fills with sediment, because these sediments can first be carried into the dam outlet works when the reservoir is partially emptied during seasonal drawdown.

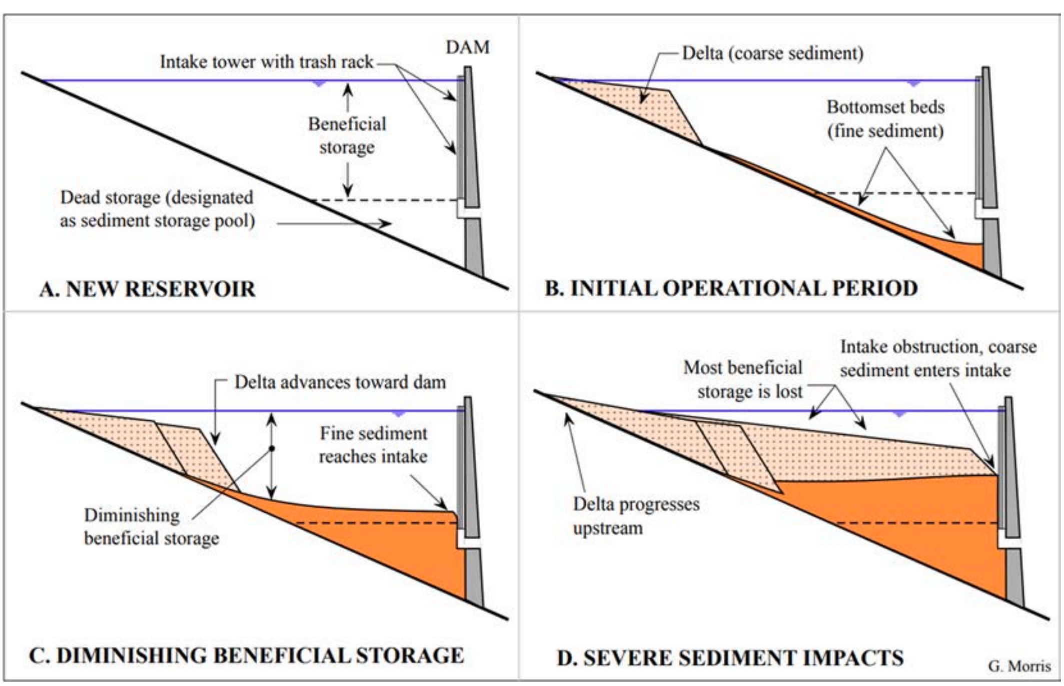

Fig. 4. Process of reservoir sedimentation. A) new reservoir showing zone of beneficial storage and the designated sediment storage pool; B) initial operational period with minimal sediment impacts, showing the deposition pattern for both coarse and fine sediments; C) significant sediment encroachment into the beneficial pool with substantial growth of the delta; and D) severe sediment impacts including loss of beneficial storage, intake obstruction and upstream progression of the delta.

Fig. 5. Example impacts of reservoir sedimentation. a) reservoir sedimentation has reached the level of the outlet at Sumner Dam near Fort Sumner, NM. (source: Bureau of Reclamation); b) sand has abraded the spillway at the Milburn Diversion Dam near Sargent, NE. (source: Bureau of Reclamation); c) sedimentation had substantially filled the reservoir behind Spencer Dam, near Spencer, NE, and large portions of the reservoir can be waded (source: U.S. Army Corps of Engineers; d) degradation of the Missouri River channel downstream from Gavins Point Dam, NE has exceeded 3 m (source: U.S. Army Corps of Engineers); and the loss of reservoir storage capacity between e) 1994 and f) 2013 due to sedimentation (source: Google Earth).

4.3. Increased flood hazard

Reservoirs reduce downstream flood risks by temporarily capturing flood peaks and releasing the captured water downstream at a reduced rate over a longer time period. Sedimentation progressively diminishes the reservoir's ability to capture water to mitigate flooding. However, sedimentation can also create upstream flooding when the sediment delta at the upstream end of a reservoir extends up river above the full reservoir pool. This increases the riverbed level resulting in higher upstream flood levels, and can also increase the local groundwater levels, waterlogging soils and affecting upstream properties. A well-known example is on the Missouri River, where delta deposits at the head of Lewis and Clark Lake Reservoir caused backwater flooding, which resulted in the relocation of Niobrara, Nebraska.

4.4. Increased dam safety risks

Sedimentation may pose a dam safety hazard by increasing both the frequency and magnitude of spillway discharge due to the loss of flood storage capacity. Spillways typically have a shorter service life than dam outlets, being designed to be used only when the discharge capacity of dam outlet is exceeded. Dams are normally designed to withstand earthquake shaking when filled with water, and the accumulation of sediment against concrete dams can increase the seismic load.

4.5. Impairment of ancillary infrastructure

Navigation channels, boat ramps, marinas, and the area and depth of open water available for recreation are reduced by sedimentation (Fig. 5c).

4.6. Downstream channel degradation

Dam construction interrupts the natural flow of sediment along a river, trapping sediments in the reservoir and releasing sediment-starved water to downstream channels (Kondolf, 1997). Downstream alluvial channels, starved of coarse sediments (sand and gravel), experience downcutting and increased bank erosion, undermining streamside infrastructure such as roads, bridges, pipeline crossings, and levees, and impairing stream and floodplain habitat for fish and wildlife (Fig. 5d). Sediment trapping behind dams also reduces sand delivery to coastal areas and deltas, contributing to shoreline erosion (Meade and Moody, 2010; Willis and Griggs, 2003). Trapping of silts and clays can reduce nutrients that support the food chain in downstream reaches, which has led to drastic and risky attempts at restoring food webs by techniques such as fertilizing rivers (Chowanski et al., 2020).

4.7. Decommissioning

A reservoir that has lost its benefits due to sedimentation would typically be decommissioned, especially a high hazard dam where failure "will probably cause loss of human life" (ASDSO, 2021). Dam decommissioning would include all necessary activities associated with the full or partial removal of a dam and restoration of the river (USSD, 2015). Although a dam could potentially be left in place after the reservoir has filled with sediment, the cost of continued maintenance, environmental impact, and the liability from potential failure would be too much for most dam owners, especially when the reservoir benefits have ended. Once a reservoir has filled with sediment, abrasive coarse sediments would pass over or through the dam and significantly increase maintenance costs. San Clemente Reservoir on the Carmel River, California (Fig. 5e), was built to supply water to the Monterey Peninsula in 1921, but by the end of the century it had lost 95% of its capacity to sedimentation (Fig. 5f) and was considered structurally unsafe. In 2015, the dam was removed, and the river restored at a cost of $83 million (Aragon, 2016).

5. Sediment management strategies

The methods available to manage reservoir sedimentation and its impacts can be classified into four broad categories (Annandale et al., 2016; Kondolf et al., 2014; Morris, 2020; Morris and Fan, 1998; Randle et al., 2019). Three categories focus on balancing sediment outflows and inflows to stabilize reservoir capacity:

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

The fourth category encompasses measures that adapt to capacity loss:

4. Adaptive strategies that reduce the impact of sedimentation, without focusing on improving the sediment balance across the reservoir, include increasing storage capacity (raising the dam), modifying intakes to avoid sedimentation impacts over the short term, complementing declining reservoir storage with groundwater storage using managed aquifer recharge, water conservation activities that help users adapt to reduced water supplies, or dam decommissioning.

Fig. 6 provides some examples of each of these approaches. Fig. 7 provides a more complete summary of the type of activities that fall under each of these broad categories. A site-specific combination of

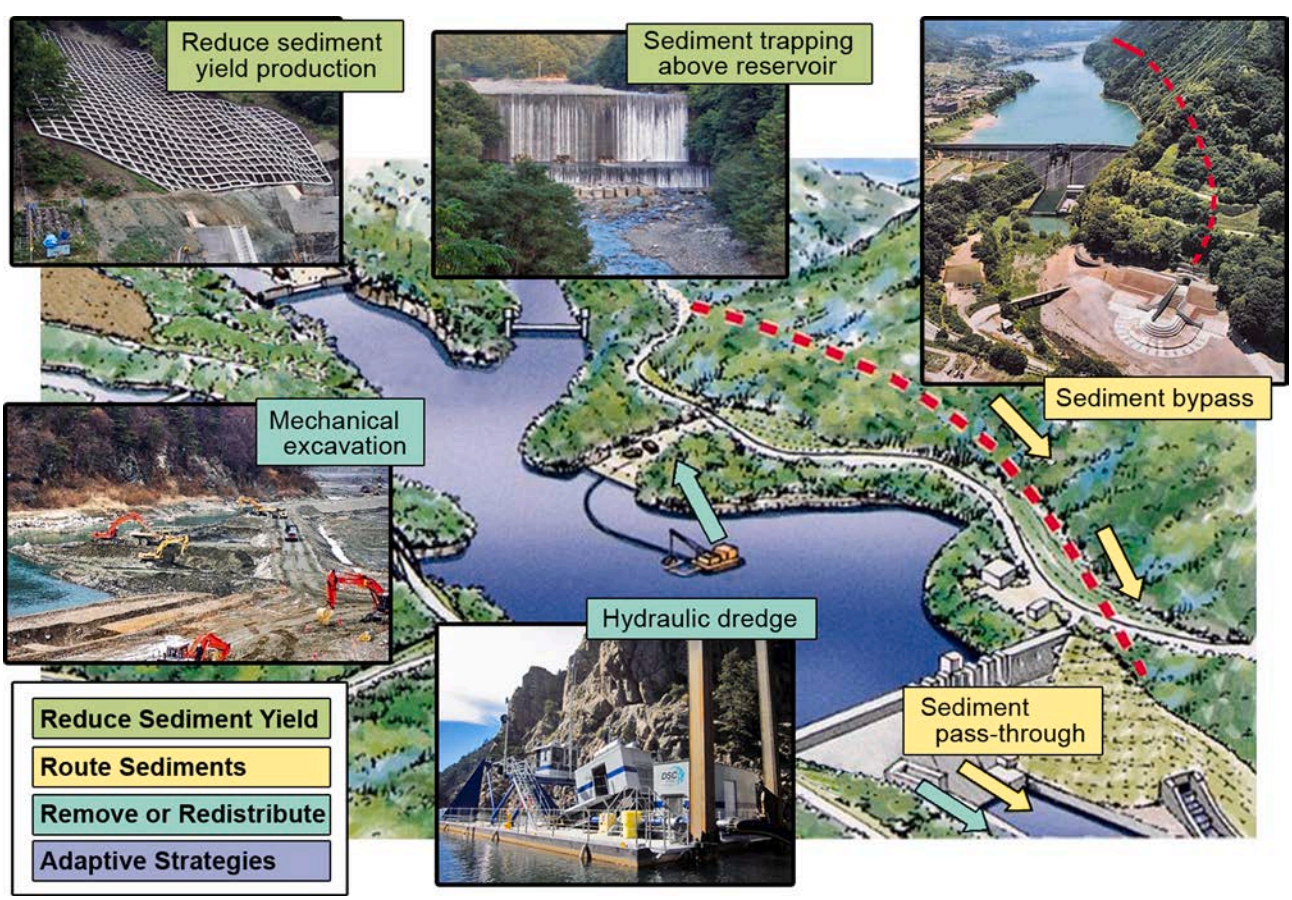

Fig. 6. Illustration of sediment management strategies (modified from Sumi et al., 2017).

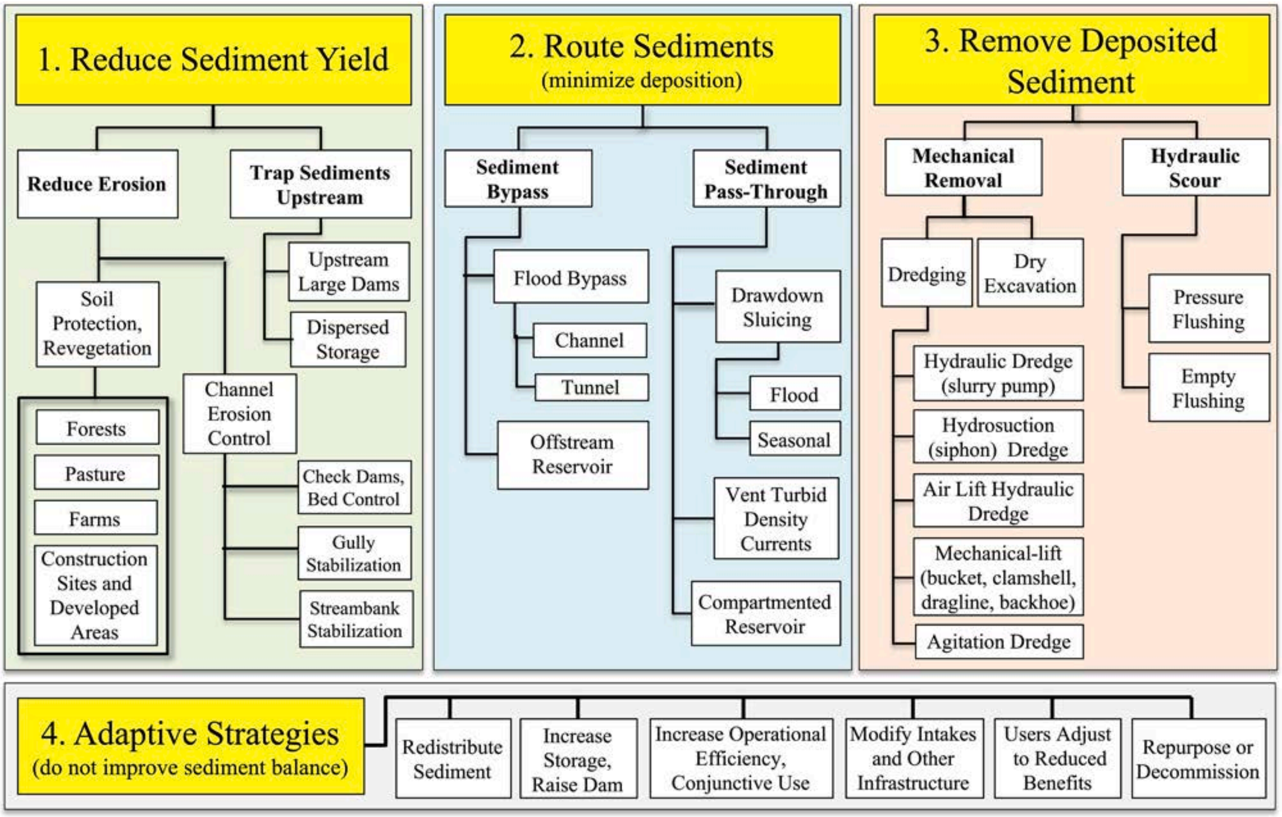

Fig. 7. Classification of methods to manage reservoir sedimentation (Morris, 2020).

strategies across the spectrum of methods will typically be employed, either concurrently or sequentially. For example, the release of turbid density currents through a low-level dam outlet, together with watershed protection, may be the most relevant strategy early in the reservoir life. However, as storage capacity is lost to sedimentation, strategies such as drawdown for sediment sluicing may become necessary. More detailed discussions of specific methods may be found in Annandale et al. (2016), Basson and Rooseboom (1999), Morris (2020), Morris and Fan (1998), and Schleiss, et al. (2016). Turbidity currents can be a significant process in some reservoirs and venting them through dam outlets reduces sedimentation. Considerable research has focused on methods (e.g., water jets) to keep sediments from turbidity currents suspended near the dam for entrainment through the outlet works (Chamoun et al., 2016, 2018; De Cesare, et al., 2018; Jenzer Althaus et al., 2015).

6. Elements of sustainable reservoir management

Sediment management has typically been implemented to address reservoir sedimentation issues in response to crisis situations. Examples include sediment accumulation impacting operational control of a dam (Paonia Dam, CO), a sudden and major loss of storage capacity (e.g. post wildfire, Devil's Gate Dam, CA), water quality impacts (Strontia Springs Reservoir, CO), or failure to deliver water during a drought (Loíza Reservoir, PR). Once the crisis level is reached, the available options are often reduced to expensive remedial measures to extend the useful life for an appreciable amount of time, or even costly new project construction.

In contrast to the existing reactive approach, typically associated with the design life paradigm, a sustainable use paradigm will proactively address sedimentation to avoid crisis management. Given that most reservoirs in the USA were constructed, and continue to operate under the design life model, crisis management of water supplies will be increasingly common without a new management paradigm.

New dams and reservoirs should be planned and operated using the sustainable use paradigm. The large inventory of existing dams should be converted from their "design life" paradigm to the sustainable management paradigm (Fig. 8).

Initial efforts in this direction are underway. The Subcommittee on Sedimentation, which included most Federal agencies concerned with water and sedimentation, prepared a resolution to encourage Federal agencies to adopt sustainability policies. This resolution was adopted by the parent Federal Advisory Committee on Water Information (2014). A similar resolution was adopted by the U.S. Society on Dams (USSD, 2017).

The implementation of such a reservoir sustainable design and operational plan approach involves three stages: (1) **monitoring and screening** to identify the most critical reservoirs, (2) **problem diagnosis and alternative formulation** at the critical sites, and (3) **implementation**. Regardless of whether it is a federal agency with responsibility for hundreds of dams, or a local government or private company responsible for only one dam, the concepts outlined below are equally relevant.

7. Monitoring and screening

Systematically measuring reservoir capacity over time is necessary to quantify rates and patterns of storage loss and allows for calibration of numerical models used to predict future sedimentation impacts. Periodic reservoir surveys are the most important monitoring procedure to determine sedimentation levels and changing rates over time, to understand which beneficial uses will be affected, and to predict when impacts will occur. Repeated volumetric survey monitoring is a recognized best management practice for all reservoirs and is a critical proactive step to avoid unanticipated service failure and crisis management (Randle and Larsen, 2021). Even though many reservoirs have not been

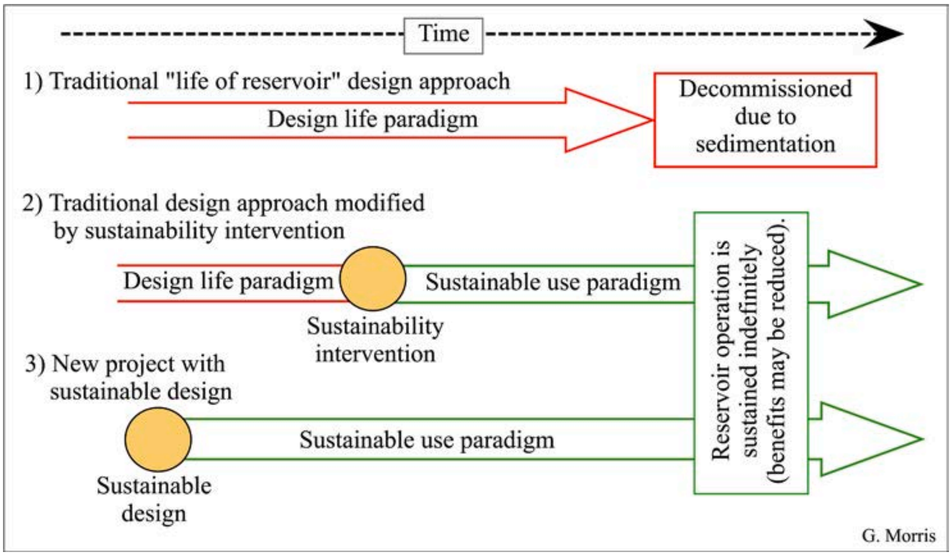

Fig. 8. Converting reservoirs from design life paradigm to sustainable use paradigm (Annandale et al., 2016).

surveyed since their initial filling, a recent survey (within the past decade) is needed to begin sustainable sediment management planning. Reservoir surveys could be prioritized by considering the following factors: any known reservoir sedimentation issues, recommended reservoir survey frequency and years since the last survey, and the economic value of the reservoir storage capacity.

Although sustainability interventions are desirable at all reservoirs, it is recognized that this work will start with a small group of high priority sites. Initial screening should be performed to identify the highest priority reservoirs for action. The highest priority reservoirs could be selected based on the remaining time left in the sediment design life and importance of storage benefits. Screening may identify some reservoirs as having more potential for a successful intervention than others due to technical, environmental, funding, or other considerations. Sites having more potential for successful (and more rapid) implementation may also be prioritized.

Implementation of sediment management actions may require real-time monitoring of sediment concentrations flowing into and out of the reservoir and frequent monitoring of sedimentation levels near the dam outlets.

8. Sediment management plan formulation

Planning begins with a diagnosis of the reservoir sedimentation problem and continues with the formulation and evaluation of alternative management solutions.

Diagnosis. Field data collection, analysis, and modeling are needed to diagnose the sedimentation problem and identify management alternatives (Randle et al., 2019). The diagnosis begins with the compilation and review of available data and design documents. Field data collection includes repeat bathymetric surveys (using the same methods) to measure the volume and spatial distribution of sediments (Ferrari and Collins, 2006) and sampling to measure sediment grain size, bulk density, and chemical composition (Randle and Bountry, 2017). Sedimentation measurements are not simple and specific monitoring plans need to be developed for each reservoir. Installation of upstream gaging stations to measure streamflow and sediment transport may be needed (Diplas et al., 2008; Gray and Simões, 2008; Turnipseed and Sauer, 2010). A downstream gaging station is recommended if there is significant sediment transport through the reservoir.

Analysis of sedimentation monitoring data will help reveal how historic sedimentation rates may be changing due to variable hydrology or changes in land use or climate. Numerical models can be utilized to simulate historic reservoir sedimentation and, if successful, can be used to simulate future reservoir sedimentation (Morris and Fan, 1998) to help assess impacts on water storage capacity and dam and reservoir facilities over time.

Alternative Formulation. Alternatives should be formulated to represent a reasonable range of sediment management strategies that meet the project objectives. Any alternative without sediment management should include reduced storage capacity and loss of benefits over time, possible upstream and downstream sediment impacts, eventual decommissioning of dam and reservoir (USSD, 2015; Randle and Bountry, 2017), and lost storage benefits.

Multiple sediment management methods may be used together or in sequence. For example, the release of turbid density currents through a low-level outlet at the dam may be used in a new reservoir, while sediment sluicing may become increasingly viable as sedimentation progresses. Venting of turbidity currents could be combined with coarse sediment augmentation to the downstream channel with periodic high-flow releases to help restore floodplain ecology (Stähly et al., 2019). Annual dredging may be a stand-alone alternative or combined with other less-costly methods. Unlike drawdown sluicing or flushing, dredging does not interfere with normal reservoir operations or require the discharge of a relatively large volume of stored water. However, permitting to deliver dredged sediment to the downstream channel and cost could be important limitations. Some alternatives may incorporate structural modifications such as reconstruction of the spillway to install larger and deeper gates (Sumi and Kantoush, 2018) or construction of a sediment bypass tunnel (Auel et al., 2011). Each alternative should identify the likely sequence of sediment management methods leading to long-term sustainable use, describing the anticipated evolution of management strategies over time to help ensure that actions implemented today support other methods planned for the future.

Adaptive measures can be considered to reduce sedimentation impacts, independent of measures to directly control sedimentation. For example, when sedimentation has reduced flood storage capacity, a real-time hydrologic flood-forecast system could be utilized to release stored water at safe rates in advance of floods and the subsequent partial storage of flood inflows. Water supply could be maintained by operating reservoir storage in conjunctive use with groundwater storage (including using reservoir water for aquifer recharge), or by raising the dam height to increase the storage capacity. The demand for water could be reduced by implementing water conservation measures to use a shrinking water supply more efficiently.

Many rivers in the USA have multiple reservoirs in series. Sediment released from an upstream reservoir can be trapped in the next impoundment downstream, and successive management of reservoirs in series will be necessary over the long term. When reservoirs in series are close together, there may be opportunities to bypass sediment discharged from an upstream reservoir through or around the downstream reservoir by coordinated sluicing or using a long sediment bypass tunnel. Operational hydraulic flushing experiments conducted on a series of reservoirs on the San Gabriel River in California suggest that significant volumes of sediment can be removed at a fraction of the cost of conventional methods and with lower environmental impacts (Weirich, 2014).

Engage with regulators early in the alternative planning process, as sustainable sediment management is a new management paradigm that may challenge the regulatory process (Tullos, et al., 2021). Remind regulators that it will be impossible to forever hold back the natural downstream transport of sediments. A sediment balance will eventually be achieved at all sites, the result of either management or natural phenomena. Decommissioning due to sedimentation has multiple adverse ramifications in terms of both high cost and the environment, including the impacts of replacement project construction.

Alternative Evaluation. A feasibility assessment of each alternative is needed, following the process prescribed by the National Environmental Policy Act (NEPA). The Reservoir Conservation Model (RESCON 2 Beta) (Efthymiou et al., 2017) may be used to assess the technical and economic viability of sediment management alternatives. The RESCON 2 Beta model has methods to consider intergenerational equity and the effects of climate change. Hydrologic and sediment transport modeling may be needed to evaluate sediment routing alternatives both within the reservoir and downstream. Each alternative will need an economic analysis of costs and benefits.

Consider the environmental implications of different alternatives. Environmental assessments and impact analysis are prepared in conjunction with alternative formulation. Some reservoir sediment management alternatives, such as flushing or sluicing, will help restore the sediment balance along the downstream river, but may cause problems for downstream water users and can negatively impact downstream habitats if sediment releases are not designed to match the timing of natural sediment loads.

8.1. Implementation

Following selection of a sediment management alternative, the project moves to design, final environmental review and permitting, and implementation. As mentioned previously, the selected alternative may consist of multiple methods or strategies and may be undertaken gradually and incrementally. Short- and long-term monitoring plans should be developed as an integral aspect of the sustainable management plan. The diagnosis, alternative formulation, impact analysis, permitting, and funding could take a decade or more to complete. Therefore, reservoir sedimentation monitoring and advance planning are needed to avoid crisis management arising from unanticipated impacts on critical reservoir facilities.

Implementation strategies will vary considerably reflecting site specific factors including hydrology, sediment yield, environment, regulations, downstream users, operational constraints, dam design, value of storage, project costs and client's financial capacity. For example, rapid reservoir emptying for flushing would be precluded at an earthen dam, due to dam safety limits on reservoir drawdown and refill rates but may be feasible at a concrete dam. At existing dams, sediment release options may be limited by the capacity of dam outlets. Bypass tunnel construction may be limited by geologic factors. Sluicing may be highly efficient in an environment where cyclonic storms deliver extreme episodic sediment loads but may be ineffective at a reservoir having a similar configuration but different hydrology and sediment loads. Sediment-sensitive downstream infrastructure and ecosystems can impose critical limitations. In the case of dredging, limitations may be high cost and either permits to deliver sediment downstream or the availability of sites for settling sediment and long-term disposal of dredged material.

In all cases, an equitable plan is needed to fund modifications at dams and reservoirs. An operating fee of some kind may be required to fund either sustainable reservoir sediment management or future dam decommissioning. This practice is common in other natural resources extraction industries where, to prevent the catastrophic over-harvesting of trees, grass, or fish, for example, operators are either limited in their harvesting activities or are required to replace the resource following extraction. For example, a fee requirement could be established for the beneficial users of reservoir storage capacity to pay for sustainable sediment management practices. Some reservoir storage capacity benefits (e.g., flood risk reduction, recreation, fish and wildlife) may be assigned to the general public and taxes could be used to pay for a portion of the sediment management or decommissioning costs.

8.2. Alternatives evaluation and economic valuation

Within the new paradigm, economic evaluations need to (1) include the comprehensive analysis of all costs related to sedimentation (e.g., declining storage benefits, upstream and downstream impacts, dam decommissioning), regardless of when they occur; and (2) avoid the discounting of future costs at a rate so steeply that they do not adequately influence the benefit-cost analysis.

Project economic analyses have not historically considered the costs of sedimentation and its impacts. Generally, any costs beyond the economic planning horizon (50 or 100 years) were simply ignored, and costs occurring in later decades were heavily discounted.

For existing reservoirs, the "no action" alternative does not exist over the long term. The project has already been built and, eventually, an action will be required: either sustainable sediment management or dam decommissioning. Even with slow sedimentation rates, the dam outlet, reservoir water intakes, and boat ramps typically will become vulnerable to impairment long before the reservoir has half filled with sediment. Thus, for an existing reservoir, the relevant question is to identify the economic costs and benefits (or lost benefits) of the alternative paths forward to help select the preferred action. Although desirable for benefits to exceed costs, this is not a requirement when some action will eventually have to be taken. The least cost alternative that is environmentally and socially acceptable should be implemented.

In contrast, for new or enlarged dams and reservoirs, benefit-cost criteria become relevant since the no-build option does exist. Here the selection of both the type and rate of economic discounting model to be employed becomes critical to the analysis. The economics of a design-life sediment management approach is conceptually compared to the sustainable sediment management approach in Fig. 9. Both economic scenarios include the initial costs of planning, design, and construction of a dam and reservoir. Under the typical design-life management approach (Fig. 9a), there are no sediment management costs, but the project benefits gradually decrease over time with reductions in reservoir storage capacity. Eventually, costs would be incurred for emergency sediment management, subsequent dam decommissioning, and the lost storage benefits of the reservoir. If a site for a replacement dam and reservoir can be obtained, then storage benefits can be recovered but additional costs would be incurred for planning, land acquisition, design, and construction. For a future replacement reservoir, a new economic analysis would be needed that would demonstrate benefits exceed costs, and the costs associated with sedimentation would have to be considered. Under sustainable management (Fig. 9b), sediment management costs are incurred on a regular basis, though project benefits may decline until a stable level is reached. There is no need to repeat the planning, design, and construction of a replacement facility.

Economic analyses will discount future costs and benefits to present dollars. For the commonly used exponential discounting method, the discount rate will have a large impact on present value. High discount

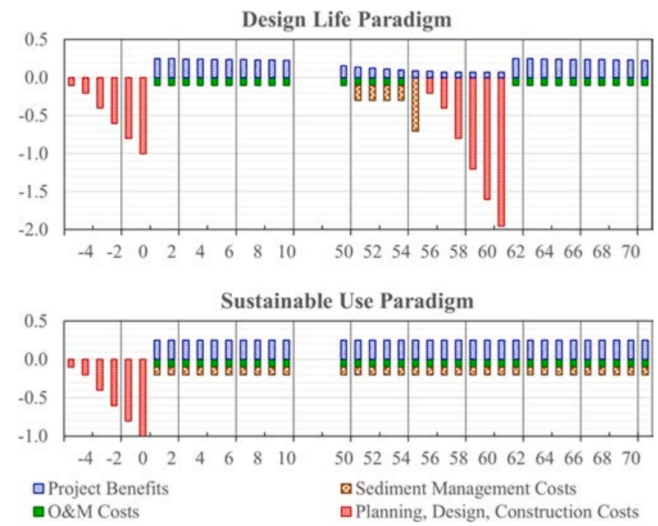

Fig. 9. Economic comparison of sediment design life paradigm (a) and sustainable use paradigm (b) (Randle et al., 2019).

rates heavily favor today's generations over future generations. If a sustainable design entails greater initial cost (not always the case), traditional economic analysis will tend to favor the design-life approach. This is true even if dam decommissioning is included because a high discount rate will decrease a decommissioning cost 50 + years in the future to a negligible present value. In contrast, low discount rates give more weight to future generations, and thus favor sustaining long-term benefits. Several discounting methods (e.g., intergenerational, hyperbolic, green book) specifically give relatively more weight to future generations compared with the traditional exponential discounting method (Harpman and Piper, 2014).

Economic analysis should consider all costs associated with sedimentation, including either sustainable management costs or the impacts that occur absent sediment management (e.g., upstream and downstream impacts, reduced storage capacity over time, dam decommissioning, lost storage benefits). The period of economic analysis should be long enough to consider intergenerational equity and include the time to either achieve a sustainable balance between sediment inflow and outflow, or to incorporate end-of-life decommissioning costs. In the end, the selection of a discounting method and the discount rate used for computation is simply a value judgement imposed on the analysis (Arrow et al., 2013). The decision essentially becomes one of how much value we give to our grandchildren's welfare and the consideration of how the benefits derived from reservoir storage capacity can be maintained over the long term.

Given the absolutely critical role of reservoir storage capacity to sustain socio-economic well-being in countries across the globe, Morris and Fan (1998) recommended adapting an engineering criterion-based approach for defining and implementing sustainable reservoir management at both existing and new dams. This is similar to the approach used for dam safety, which is treated as engineering design criteria. The engineering community always seeks to design safe dams and should also incorporate sustainability measures as a standard component of the design process.

9. Environmental permitting

Environmental regulations currently consider sediment to be a pollutant and thus the process for authorizing sediment management at reservoirs is typically extensive, costly, and discourages managers from passing sediment to downstream reaches to re-establish sediment continuity along the fluvial system. Environmental permits are important for protecting downstream ecosystems, as sediment flushing has been shown to produce devastating impacts of ecosystems when not carefully designed (Espa et al., 2016). However, management activities that pass inflowing sediments through or around the reservoir can have less impact on the downstream channel than trapping the sediments in the reservoir, providing that sediments are passed downstream at rates, timing, and grain sizes similar to the natural supply rates from upstream, and provided that the sediments are free from chemical contamination above natural background levels. A number of changes are needed in both the engineering and permitting of sediment management to support a more efficient regulatory process, including: (a) greater coordination among regulators, resources agencies, and permittees; (b) establishment of a community-of-practice to share tools and experiences with sediment management at reservoirs; (c) reinterpretation of the de minimis standard for when permits are required by the U.S. Army Corps of Engineers; and (d) establishing regional permits that account for geographical variation in ecosystem and infrastructure needs (Tullos et al., 2021). Policy needs to be adjusted to facilitate the downstream movement of sediment, at rates, grain sizes, and seasonal patterns consistent with natural sediment flows insofar as possible.

10. Conclusions

The USA's 90,000 + large dams and their reservoirs represent critical infrastructure required to support economic activity and social well-being. They provide reliable water supplies for municipal, agricultural, and industrial use as well as hydropower, flood risk reduction, navigation, and recreational benefits. However, their capacity is steadily being diminished by sedimentation. Sediment trapping also deprives downstream river channels and coastlines of their natural sediment loads, with resultant environmental impacts.

The current practice of allowing reservoirs to continually fill with sediment is not sustainable. Reservoirs do not have the capacity to trap sediment indefinitely and, without management, sedimentation will eventually displace all usable storage capacity. The current design-life management paradigm does not lead to sustainable water supplies, and impairment is already being experienced at an increasing number of reservoirs. Storage capacity loss by sedimentation also exacerbates vulnerability to climate change. Options exist to achieve long-term sustainable management and adapting a sustainable use approach will lead to long-term benefits. However, the sustainable use paradigm has not yet been widely embraced by the water management community. When compared to the long-term consequences of inaction, a sustainable management approach will often represent the least-cost approach to maintaining essential reservoir infrastructure that supports the national economy and social welfare.

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

First, a national scale survey program of all water storage reservoirs is needed to screen and identify priority reservoirs for targeting sediment management. The periodic monitoring of storage capacity loss needs to be implemented at every reservoir to document the rate and pattern of sedimentation and provide baseline data for developing a long-term management strategy. Repeated reservoir surveys are essential to track changes in sediment yield over time and to estimate when sedimentation will impact reservoir operations. Monitoring is an essential proactive step to avoid crisis management. Survey frequency should correspond to the rate of capacity loss but should typically not be longer than 20 years. In addition, real-time monitoring of sediment concentrations may be needed to implement sediment management.

Second, develop long-term sediment management plans at critical sites. This will require data from the reservoir surveys, monitoring of water and sediment inflows to construct sediment-discharge rating relationships, and sampling of reservoir sediments. These data are needed to calibrate models to predict future sedimentation patterns and test alternative management strategies. The plan should identify current and future sedimentation process and problems, followed by an alternatives analysis to identify the most viable solutions. The plan needs to identify the choice of either sustainable sediment management with a target long-term storage capacity, or eventual project decommissioning. Sustainable management practices will enable continued reservoir function through a combination of methods that bring coarse and fine sediment inflow and outflow into balance, releasing sediments through mechanisms that are functionally, environmentally, and economically feasible. For existing reservoirs, the no action alternative generally does not exist, and the least cost alternative that is environmentally and socially acceptable will need to be implemented, even if benefits do not exceed costs.

The costs for implementing either sustainable sediment management practices or dam decommissioning plans are likely to be substantial, and equitable methods to pay for these activities need to be identified, considering the inter-generational aspect of both costs and benefits.

Environmental permitting processes will require modernization. From a permitting perspective, restoration of fluvial sediment continuity along rivers (for both fine and coarse sediment) should be considered an environmental benefit. Management should focus on restoring sediment flows below dams at grain sizes and concentrations not markedly different from that which would occur naturally without the dam, or that naturally occur in the reservoir inflow.

The ultimate objective is to adapt sustainable use as an engineering design and operational criteria for storage reservoirs, and to gradually convert the nation's inventory of critical reservoirs into sustainably managed infrastructure. This process will require many decades, but by starting to address the problem sooner rather than later, the total cost can be reduced and spread out over a longer period, and a larger ultimate capacity can be preserved.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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