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Reservoir sedimentation management: A sustainable development challenge

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RESERVOIR SEDIMENTATION MANAGEMENT: A SUSTAINABLE DEVELOPMENT CHALLENGE

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Suitable dam and reservoir sites are scarce resources that should be sustainably developed and managed to satisfy the needs of current and future generations. Historic and current dam development approaches do not address the issue of sustainable development (*i.e.* that reservoir water storage is needed for both current and future generations). Figure 1 shows that estimated global net reservoir storage, after allowing for storage loss due to sedimentation, is either stagnating or declining despite continued dam construction worldwide. Average global storage loss due to reservoir sedimentation is estimated to be on the order of 0.8% or 1% per year[1]. Globally, the per capita reservoir storage has been in decline since about 1980, with current per capita storage on the same order as it last was in the late 1950's.

In the United States (US), the nation's 90,000 dams and reservoirs constitute a critical component of the country's infrastructure. These dams and reservoirs serve both to provide fundamental societal needs such as ensuring the stability of water and energy supplies and flood risk reduction. Figure 1 indicates that the trend in net water storage, after allowing for storage loss due to reservoir sedimentation, is negative and that more reservoir storage space is lost each year to reservoir sedimentation in the US than what is being added by construction of new dams. Once a reservoir has completely filled with sediment (Figure 2), the project benefits are lost and it is often cost prohibited to remove the sediment to restore the reservoir storage.

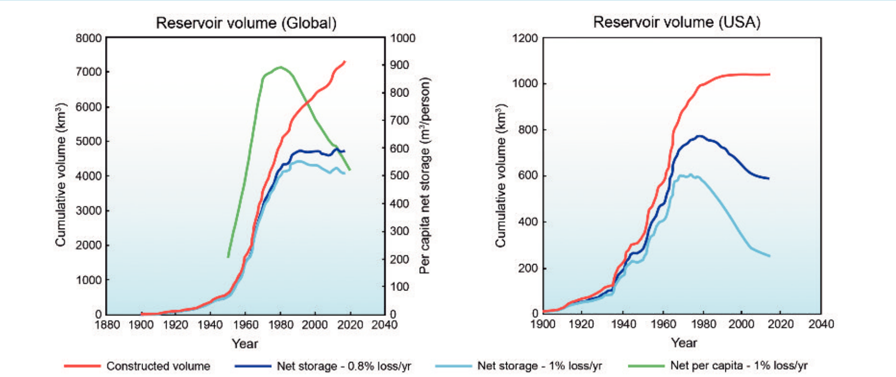


Figure 1. Total and estimated net storage globally and for the USA. Plots are based on the current global database of International Commission on Large Dams (ICOLD)

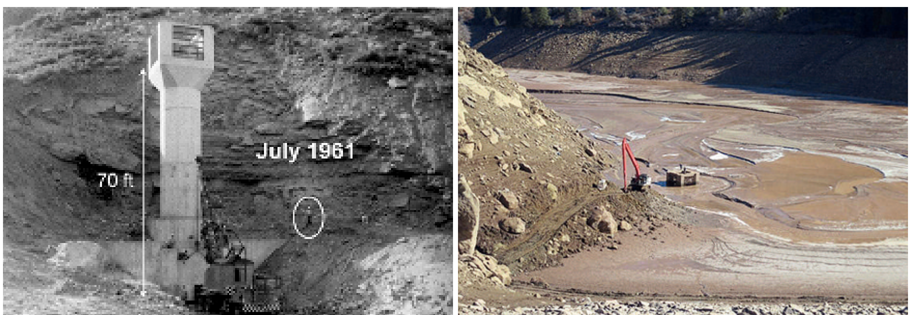


Figure 2. Paonia Reservoir near Hotchkiss, Colorado reached the end of its sediment design life after 50 years when the outlet became clogged with sediment and woody debris. The outlet was constructed in 1961, 21 m above the reservoir bottom (left). By 2014, the sediment level at the dam was 1 m higher than the outlet works (right). Photographs courtesy of Bureau of Reclamation

Concerns about inadequate reservoir sedimentation management activities in the US resulted in the Federal Advisory Committee on Water Information (ACWI), Subcommittee on Sedimentation (SOS) to pass a resolution encouraging Federal agencies to develop long-term reservoir sediment-management plans for the reservoirs that they own or manage. In addition, SOS has formed the National Reservoir Sedimentation and Sustainability Team (NRSST) to provide helpful information on these important topics. This Team, composed of volunteer specialists from Federal agencies, universities, and consultants, is developing an approach towards reservoir sustainability based on the below principles.

Sustainable Development

The principal focus of sustainable development is creation of intergenerational equity, as clearly indicated in one of the most quoted lines in the Brundtland Report[2]: "Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future." Facilitating sustainable development requires reconsideration of development strategies, including approaches to engineering design and operation and economic evaluation of projects. How we view the future determines whether we will be successful in enabling sustainable development. Changing development approaches from a design life to a life cycle management approach can accomplish this goal[3, 4].

Renewable and exhaustible resources

Renewable resources can be sustainably developed, while exhaustible resources cannot. The question then arises whether reservoirs should be designed and operated to be renewable or exhaustible resources. Undoubtedly, in the past and currently, it is assumed that reservoir storage space is an exhaustible resource. General design and development philosophy assumes that reservoirs are exhaustible resources that will be filled with sediment over time, eventually losing all reservoir storage space. Experience on some reservoirs has shown that they can be sustainable and that reservoir storage space can either be completely maintained or its rate of loss significantly reduced[5].

Dual Nature of Reservoir Storage

Dam construction creates water storage space in upstream valleys. The storage space is an enhanced natural resource that can either be an exhaustible or a renewable resource depending on decisions made during investment decision making, design, and operation. If the investor, designer, and operator decide to allow the reservoir to fill with sediment, it is classified as an exhaustible resource. However, if the decision was to implement reservoir sedimentation management approaches to preserve storage space or minimize storage loss due to sedimentation, the reservoir storage may be classified as a renewable resource[4].

Historically, reservoir storage space has mostly been planned, designed, and operated to be exhaustible. To change this, modifications are required to economic evaluation, design philosophy, and operating strategy for dams and reservoirs.

Managing Reservoir Sedimentation

The techniques that are available to manage sediment in reservoirs can be classified in four categories, as shown in Figure 3. The initial selection of appropriate reservoir sedimentation management approaches can be accomplished by making use of prior experience[3]. Figure 4 relates reservoir life (reservoir capacity volume (CAP)/mean annual sediment volume (MAS)) and retention time of water flowing through a reservoir (reservoir capacity volume/mean annual river flow (MAF)) for various projects where different techniques have been implemented, either successfully or not. Generally, implementation of reservoir sedimentation management techniques has been successful for projects located above the black curve, and not successful for projects below the curve; giving rise to the classification of "potentially sustainable" and "non-sustainable". Eight techniques with known performance are labeled and categorized on the graph. The sediment management categories corresponding to these techniques are (1) reduce sediment yield (check dams), (2) route sediments (sluicing and bypassing), (3) remove or redistribute sediment deposits (pressure flushing, drawdown flushing, dredging, and dry excavation), and adaptive strategies (storage operations). Figure 4 only provides an indication of techniques that may be implemented, which should then be further tested at pre-feasibility level with techniques such as the RESCON 2[6] software tool. Once potential solutions have been identified using RESCON 2 more detailed analysis is required through computer model simulation and physical hydraulic model studies.

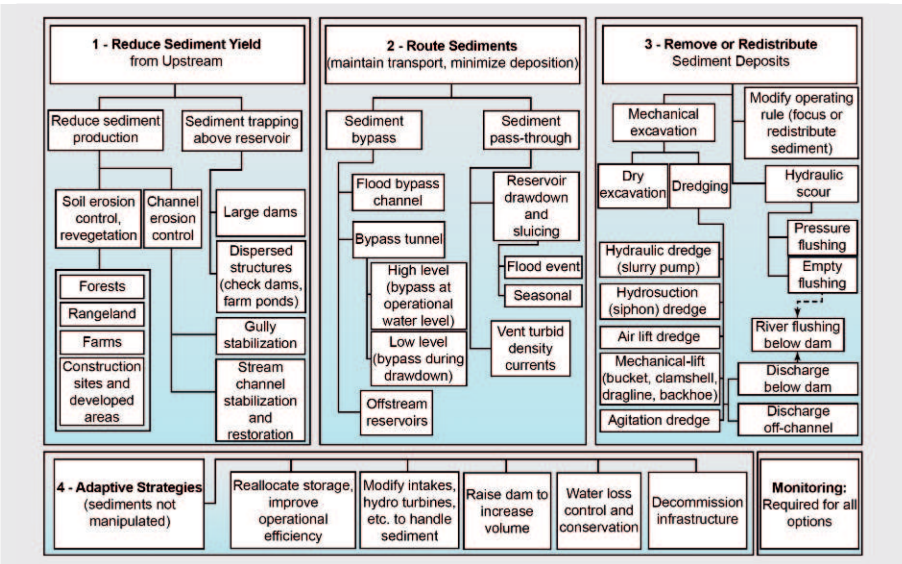
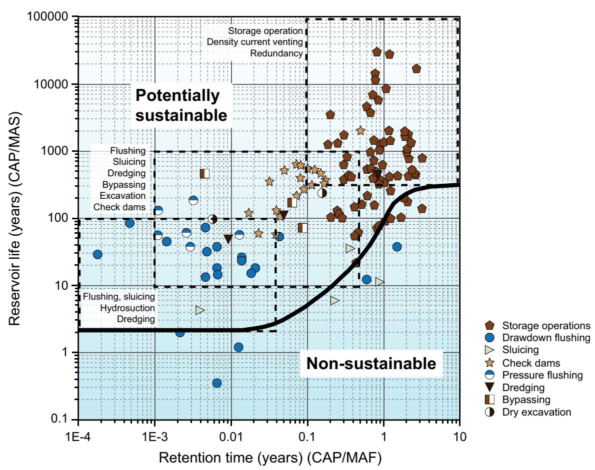


Figure 3. Classification of reservoir sedimentation management techniques[4]

Figure 4. Practical experience with implementing various reservoir sedimentation management approaches[3]



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Design and Operating Philosophy

The question that arises is why reservoir sedimentation management approaches are not more commonly considered in project selection, design, and operations; given that reservoir sedimentation management technology is available and has been successfully implemented on selected projects. The answer to this question is found in currently accepted practice as it relates to the economic evaluation of projects, engineering design philosophy and operations.

When considering sustainable development concepts, it is important to distinguish between the needs and objectives of national policy and operational demands. National policy should focus on the long-term welfare of the nation and emphasize the importance of sustainable development. Design and operational aspects of projects usually focus on short-term demands that more often do not consider the needs of sustainable development. Engineering design philosophy is largely influenced by operational needs and does not honor the criteria set by sustainable development policy and goals.

This results in engineering design philosophy adopting a "design life" approach, where a dam and reservoir are designed for a certain "life" of 50 or 100 years with no regard for conditions after this period (Figure 5). The design life is reached when sedimentation has filled to the level of critical dam or reservoir facilities such as the dam outlet, water intake, or boat marina. This sediment design life is reached long before the reservoir completely fills with sediment. The design life approach encourages viewing reservoirs as exhaustible resources that cannot be developed in a sustainable manner. The Team has great concern about this approach as it clearly leads to non-sustainable development of the nation's water resources, as shown in Figure 1.

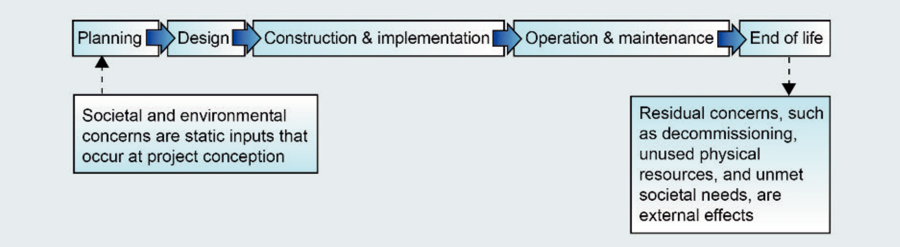
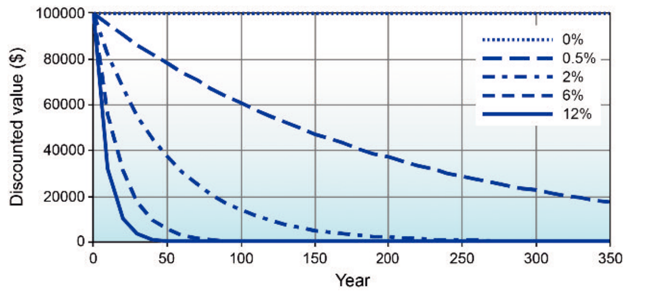


Figure 5. "Design life" approach to dam design[4]

Figure 6. Present value of $100,000 at different points in time using various constant discount rates.



Discount Rate	Approach without sediment management for 30 years	Approach without sedimentation management including decommissioning for 30 years	Approach with sediment management including decommissioning after 100 years of operation	Approach with sediment management including decommissioning after 200 years of operation
Constant Discount Rate 12%	$268 million	$239 million	$239 million	$239 million
Constant Discount Rate 6%	$478 million	$473 million	$482 million	$482 million
Declining Discount Rate	$492 million	$482 million	$509 million	$520 million

Table 1. The effect of alternative discount rates on the net present value of the PB Soedirman Project[6]

Economics

For achieving sustainable development goals it is important to acknowledge that the future is all that remains of time, and the present is the vantage point from which we view it[7]. How we shape our view of the future determines whether we will reach sustainable development goals. Current economic analysis philosophy views the future as less importance than the present and uses discounting techniques to evaluate projects. This approach is obviously in conflict with sustainable development goals that aim at creating intergenerational equity. The reasoning often given for discounting the future is that technological advances will resolve problems ignored in economic analysis. This approach may not be able to solve water storage, water supply, and irrigation problems.

Normally, a constant discount rate is used to conduct economic analysis and determine the net present value, *i.e.* the sum of benefits and costs expressed in terms of present value. Figure 6 shows the present value of $100,000 for constant discount rates of 12%, 6%, 2%, 0.5% and 0%. The graph shows that the present value of $100,000 is virtually zero after 50 years when using a discount rate of 12% (the previous default rate of the World Bank). When using the current discount rate of 6% used by the World Bank, its value becomes zero after about 80 years. This means that the costs and benefits to future generations are completely ignored after 50 to 80 years. For example, high decommissioning costs that occur 100 or 150 years from now would not be reflected in the present value. However, these decommissioning costs will be borne by a future generation who has not benefitted from such a project. The issue of intergenerational equity is not acknowledged in conventional economic analysis. If the same calculation is performed using smaller discount rates of 2% and 0.5%, greater credence is given to future costs and benefits. One may also ask why it would be expected of a future generation to place less value on $100,000 than a current generation. Using a 0% discount rate could resolve such an issue (Figure 6).

A different approach is required to incorporate the long-term costs and benefits of reservoir sedimentation management in economic analysis[7,8,9,10]. The literature recognizes two types of objectives, two types of discount rates, and the potential benefit of and justification for using a declining discount rate. The two types of objectives are those intended to augment social welfare and those aimed at achieving a net financial benefit for all. The discount rate associated with maximizing financial return is generally known as the investment-based (or finance-based) discount rate, while that associated with augmenting social welfare is known as the consumption-based discount rate. The consumption-based discount rate is the rate at which society is willing to trade consumption in the future for consumption today. Obviously, selection of a particular discount rate reflects society's commitment to intergenerational equity.

The impact on the Net Present Value (NPV) of a case study on the PB Soedirman Dam in Indonesia when using these different discounting techniques is shown in Table 1[6]. NPV is shown in columns two to five for discount rates of 12% and 6%, and a declining discount rate. Each column represents a different project scenario. Column two represents the NPV in the case where no sediment management is implemented, and the project life is limited to 30 years. Column three represents the same scenario, but adding the cost of decommissioning at the end of 30 years. Columns four and five represent NPV in cases where reservoir sedimentation management approaches are implemented for periods of 100 and 200 years, respectively, with decommissioning at the end of each of those periods. From the values in the table, it is evident that the declining discount rate approach more readily displays the intergenerational equity created by implementing reservoir sedimentation management strategies to extend the life of the reservoir. Neither of the constant discount rate calculations clearly illustrate the value of sediment management to future generations, while the declining discount rate approach does.

The long-lived character of dams and their reservoirs justifies use of a declining discount rate approach to economic analysis. Selecting this approach provides a means of quantifying the value to future generations of reservoir sedimentation management. Because the benefits or reservoir sedimentation management accrue over the long term, it is important to account for the benefits over the long term as well, thereby the need to use a declining discount rate.

Recommended Approach to Reservoir Management

An alternative approach to the economic evaluation, design and operation of dams and storage reservoirs is to follow a life cycle management approach. The life cycle management approach[3,4] relies on understanding that reservoirs can either be renewable or exhaustible depending on decisions made by the developer, design engineer and choices of the operator. When designing and operating a dam with an objective to maintain water storage through reservoir sedimentation management, the reservoir may be classified as a renewable resource.

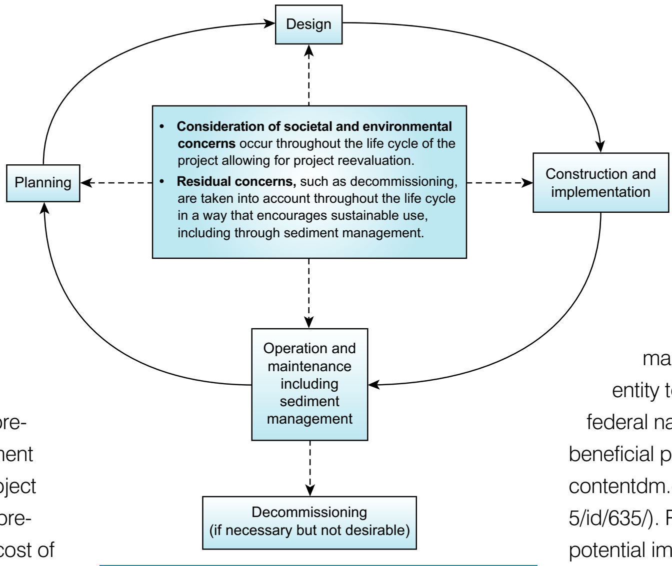


Figure 7. Lifecycle Management Approach[3,4]

Adopting a life cycle management approach (Figure 7) means designing and constructing a dam that is operated in a manner that regularly passes sediment through or around its reservoir; removes deposited sediment; and is refurbished on a regular basis with the intent of using the facility in perpetuity, and not assigning it a finite life. If a dam is designed and operated with the intent to maintain storage volume in perpetuity, both current and future generations benefit, thereby creating intergenerational equity and facilitating sustainable development. This approach will obviously require modification of conventional economic evaluation of reservoir projects, using low or declining discount rates or even considering the use of a zero discount rate[7] to reflect the value of developed resources to future generations.

Activities in the United States

Like other countries, the United States has not yet adopted a Lifecycle Management Approach (Figure 7) to the operation of its existing reservoirs. Doing so may require congressional action to modify existing policies governing Cost/Benefit analysis and how damages due to sedimentation and scour are addressed. However, both the U.S. Army Corps of Engineers (USACE) and the U.S. Bureau of Reclamation (Reclamation) are increasing their attention and activity in this area. USACE and Reclamation are compiling a national reservoir sedimentation database that allows federal employees to query and analyze sedimentation trends and conditions (www.usace.army.mil/Portals/2/docs/civilworks/climate/docs/ReservoirSedimentInformationplain06-11-2015.pdf?ver=2017-11-30-104449-697). They are also engaged to find ways to streamline the complex regulatory procedures that would simplify obtaining a permit to manage sediment at all U.S. dams. They have also sponsored two training seminars on sediment management at dams; one for managers and regulators and one for engineers.

The USACE is offering two pilot programs focused on sediment management. One allows a non-federal entity to profit by removing sediment from federal navigation projects and using it for beneficial purposes (https://usace.contentdm.oclc.org/digital/collection/p16021coll5/id/635/). Proposals are being reviewed for potential implementation. The other pilot program, not yet funded, offers the same opportunity to those dredging sediment from federal reservoirs (https://usace.contentdm.oclc.org/digital/collection/p16021coll5/id/635/. Additionally, there is a call for a feasibility study to manage the sediments on the Missouri River as a consequence of constructing six dams along its watercourse (http://cdm16021.contentdm.oclc.org/utils/getfile/collection/p16021coll5/id/1174).

The U.S. Bureau of Reclamation recently sponsored an international workshop on the topic with field trips to two reservoirs in Colorado where sediment is a special challenge. The SOS, along with its parent organization, the ACWI, passed a resolution in 2014 strongly encouraging federal agencies to prepare sediment management plans for each dam in their portfolio by the year 2030 (https://acwi.gov/sos/). To date, the NRSST has published Answers to Frequently Asked Questions (https://acwi.gov/sos/faqs_2017-05-30.pdf) and has recently aired six webinars on reservoir sedimentation including presentations on management, permitting, economics, and measurement techniques (https://cires.colorado.edu/news/announcing-reservoir-sedimentation-management-webinar-series). ■

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