Reservoir Sustainability and Sediment Management

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Abstract: Despite mounting demand for a more sustainable worldwide water supply system, available reservoir capacity is relentlessly diminishing due to sedimentation. Neither sustainable reservoir life spans nor intergenerational equity is achieved through conventional cost-benefit analyses (CBAs), which render all benefits and costs projected to occur more than several decades into a project as negligible. Consequently, future costs, including dam decommissioning or retrofitting with sediment management facilities, would be regarded as nonfactors in an analysis. CBAs have also historically failed to account for infrastructure and environmental impacts of sedimentation over time. Alternatives to the traditional application of the CBA do exist, however, such as dam owners instituting retirement funds or insurance policies, beneficiaries paying for rehabilitation or maintenance, and economists incorporating infrastructure damages and potentially logistic discount rates into their analyses. A brief case study of Gavins Point Dam shows that available information on damages due to a lack of sediment management account for 70% of the actual construction cost and would likely exceed construction costs if all damage information were available. By integrating these alternatives, economic analyses for reservoirs will be more accurate, reservoir life spans will be more sustainable, profits will be extended indefinitely, and the economic burdens placed on future generations will be lessened. **DOI: 10.1061/(ASCE)WR.1943-5452.0000720.**

Introduction

With an ever-increasing global population, mounting demand exists for a more sustainable water supply system. Despite this demand, worldwide water storage capacity is relentlessly diminishing due to reservoir sedimentation (Annandale 2013; Juracek 2014). Neither sustainable reservoir life spans nor intergenerational equity is achieved by use of traditional economic analyses of reservoirs because of the application of conventional cost-benefit analyses (CBAs). The CBA renders benefits more than a few decades into the future as negligible, causing future costs, including costly dam decommissioning or retrofitting with sediment management facilities, to be seen as nonfactors in the design stage—despite the large costs which will be incurred in the future generation. Furthermore, the CBA has traditionally overlooked infrastructure and environmental damages caused by reservoir sedimentation. By considering alternatives and modifications to the CBA, economic analyses for reservoirs will be more accurate, reservoir life spans will be more sustainable, profit horizons will be extended, and the economic burdens placed on future generations will be lessened. The purpose of this paper is to demonstrate that current operational practices at dams in the United States are not sustainable and that sustainability will require a modified application of the CBA.

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What Does Sustainability Mean for Reservoirs?

Dam construction creates a valuable resource of stored water but disturbs the natural sediment equilibrium present in typical streams and rivers. The reservoir upstream from the dam traps sediment transported as bed load, as well as a portion of the suspended sediment due to the decreased flow-through velocity. Over time, the deposition of sediment extends upstream of the dam and results in a loss of storage space within the reservoir (Hotchkiss and Bollman 1996). Fig. 1 depicts a typical reservoir's sediment profile. Severe problems related to sedimentation can appear after only a small percentage of lost storage capacity (Morris and Fan 1998). Stream reaches downstream from dams often incise into the existing channel or produce coarser grain-size distributions due to a lack of sediment passing the dam. Damages associated with within-reservoir and upstream sedimentation and downstream scour will be identified and examined in more detail subsequently.

In light of the continual process of sediment transport in streams and rivers, it would seem logical to design dams as often as possible to pass sediment downstream indefinitely. Such has not been the case, however, because dams have typically been designed to create a storage volume sufficiently large to contain estimated sediment deposits for 50 years. This 50-year period, known as the economic life of the project, is a result of the conventional application of the cost-benefit analysis (Morris and Fan 1998). The benefits of dams, ranging from irrigation water and hydropower generation to flood control and recreation, are each linked to the reservoir's economic life span (Palmieri et al. 1998).

A sustainable approach must include a sediment management plan to either directly address the mitigation of sediment or provide a fund with sufficient money to do so later. Otherwise, a filled reservoir with minimal project benefits becomes an economic burden for the following generation. This burden entails the weighty decision to either abandon the dam, or decommission or retrofit it for sediment management. The former, do nothing approach involves safety and legal concerns, while the latter approaches will incur large costs (Thimmes et al. 2005; Engberg 2002; Palmieri et al. 2003). It is recognized that there are other potential means of promoting sustainability for reservoirs through modified operational

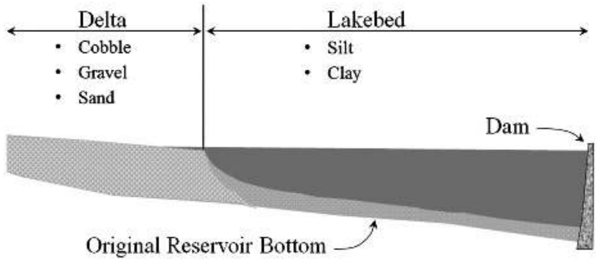

Fig. 1. Typical reservoir's sediment profile (adapted from Randle and Ferrari 2010)

policies (Yin et al. 2014). However, because each reservoir is highly unique based on its bathymetry, geology, hydrology, watershed characteristics, and hydraulic infrastructure, the focus of this paper will be restricted to the economics of sedimentation in general rather than investigating which particular approach to implement. A sustainable reservoir would theoretically have an indefinite design life. As is, most dams do not have the necessary facilities for such a task. In order to promote long-term economic viability, dam owners (e.g., hydropower companies) and legislative bodies are encouraged to reconsider the traditional, short-sighted reservoir design approach (Pattanapanchai et al. 2002).

Is There a Sedimentation Problem?

Because all rivers transport sediment, dams disrupt the sediment load equilibrium in natural waterways. Evaluating the extent of this disruption is essential for predicting sedimentation rates and aids in sediment management planning.

Bathymetric Surveys

Determining the current capacity of a reservoir requires performing a bathymetric survey. Consistently performing these surveys allows for comparisons between the results, which reveal the change of available storage capacity in the reservoir. The change in capacity over time can be used to predict regional sedimentation rates. Such rates are valuable for future operation and maintenance considerations. Unfortunately, a recent analysis of bathymetric surveys of reservoirs in the United States revealed that a reservoir's most recent survey is, on average, more than two decades old (Podolak and Doyle 2015). Nevertheless, certain reservoirs have been surveyed more consistently. Data from these reservoirs in conjunction with sedimentation rate predictions allow for generalized estimations regarding sedimentation at worldwide and nationwide scales.

Worldwide Storage

The International Commission on Large Dams has estimated that there are more than 42,000 large (more than 15 m tall) dams on the planet and several times as many smaller structures (ICOLD 1988). The resulting worldwide storage capacity and rate of storage loss are approximately 7,000 km^3 and between 0.5 and 1% annually, respectively. This rate of loss corresponds to adding approximately 50 km^3 of storage per year worldwide, with a replacement cost of approximately US\$13 billion each year in 2003 dollars (Palmieri et al. 2003). A continuously increasing global population exacerbates this situation further. As population rises, demand for water (and thus water storage) also rises, despite the dwindling worldwide storage capacity (Annandale 2013; Juracek 2014). A decrease in dam construction coupled with reservoir sedimentation caused the global net reservoir storage capacity to begin declining in 1995 (Kondolf et al. 2014). If society continues allowing reservoirs to shrink, the demand for water will eventually overcome the supply, creating a worldwide water crisis (Annandale 2013).

Certain reservoirs are more susceptible to sedimentation than others. For example, the Welbedacht Reservoir in South Africa lost 86% of its original storage volume between 1973 and 2005. The first 3 years of the reservoir's life resulted in a loss of one-third of the storage capacity (Huffaker and Hotchkiss 2006). In addition, the Tarbela Reservoir in Pakistan traps a significant amount of sediment from the Indus River. Its original volume was reduced by 20% in the first 20 years of operation (Palmieri et al. 2001). An extreme case occurred in Venezuela, where the Camaré Reservoir lost all available storage space to sedimentation in less than 15 years (Morris and Fan 1998). It is obvious that the economic benefits of such projects were compromised as a result of the sedimentation.

Storage in U.S. Reservoirs

This phenomenon occurs within the United States as well. Nordin (1991) discusses the Zuni Dam in New Mexico, which lost 80% of its capacity in a period of approximately 25 years. The reservoir formed by the Gavins Point Dam in Nebraska lost 18.3% of its original storage volume between 1955 and 1995 (Remus et al. 2007). It has undoubtedly lost even more storage since 1995. The majority of the United States west of the Mississippi River experiences sedimentation rates greater than 1.2% per year; many of these states suffer from an average storage loss rate even greater than 2% (Graf et al. 2010). This is particularly concerning because the western states are highly dependent on reservoirs for their water supply.

The U.S. Army Corps of Engineers' (Corps) National Inventory of Dams estimates that there are more than 87,000 dams over 7.5 m tall in the United States (U.S. Army Corps of Engineers 2014). These dams, which were primarily constructed between 1950 and 1980, have a resulting average age of 55 years. A specific concern with old dams, besides safety, is that sediment will eventually fill the anticipated dead storage zone and begin to interfere with the lowest outlets on the structure. Most dams were designed with an intended lifespan of 50–100 years. Sedimentation rates typically vary from the estimates used during the design stage, causing some dams' lowest outlets to plug earlier than expected (Podolak and Doyle 2015). Tim Randle, group manager of the U.S. Bureau of Reclamation's (Reclamation) Sedimentation and River Hydraulics Group, has provided a spreadsheet documenting Reclamation reservoirs' age and other pertinent facts. A simple spreadsheet analysis showed that the average age of Reclamation dams is 67 years and that within 25 years one-third of Reclamation dams are predicted to be experiencing issues related to sediment reaching the lowest outlets (T. Randle, personal communication, 2015). Decisions must be made in the near future regarding how to manage sediment trapped within these reservoirs.

Physical and Environmental Impacts

In addition to the aforementioned concerns regarding lost storage space, sedimentation also damages infrastructure and the environment. The Aswan Dam has reduced sediment flow down the Nile River by 98% (Schwartz 2005). This has caused the Nile Delta to shorten at rates as high as 125–175 m/year. The Mississippi River Delta also suffers significant erosion due in part to the many dams and locks along the river (Schwartz 2005). Of the 33 major worldwide deltas, 24 are currently shrinking because of reservoir sedimentation. These coastal regions will be particularly vulnerable to disastrous flooding as the coastlines continue to erode and if the sea level rises an expected 0.46 m by 2100 due to climate change

(Kondolf et al. 2014). There are also significant infrastructure and environmental concerns upstream of the coast due to reduced riverine sediment loads.

Even after only a small percentage of storage capacity is lost, severe problems related to sedimentation can appear (Morris and Fan 1998). Hotchkiss and Bollman (1996) identified such impacts of sedimentation, which include main stem and tributary aggradation upstream and degradation downstream. Secondary and tertiary impacts include increased flood frequency, a rise in groundwater levels and concomitant crop failures upstream, and stream channel instability, loss of access to diversion works, undermining bridge piers and abutments, and altered geomorphology downstream. Restoration of these nonstorage-related damages can be extremely costly and their effects are not included in economic analyses that justify initial construction.

It is understood that the total elimination of sedimentation is neither viable nor possible. As such, sediment must be managed and preventative measures must be taken in order to alleviate the aforementioned catastrophic loss of reservoir storage space. Nevertheless, many reservoirs have neglected implementing sediment management practices to counteract the aforementioned consequences (Kondolf et al. 2014). A warning in the *Reservoir Sedimentation Handbook* states that the "sudden loss of the world's reservoir capacity would be a catastrophe of unprecedented magnitude, yet their gradual loss due to sedimentation receive little attention or corrective action" (Morris and Fan 1998). This is clearly a significant environmental problem.

Cost-Benefit Analysis

History of the CBA

The CBA is a measure that determines the cost-effectiveness of available options in order to see whether the net benefits outweigh the costs. It is employed to balance society's interests, rather than just those of an individual (Turner et al. 1993). CBAs have undergone significant changes in the United States from their beginnings involving the Corps' Federal Navigation Act of 1936. This act specified that if projected benefits outweighed the costs, then the project could be pursued (Crabb and Leroy 2008). By 1960, many techniques were used among federal agencies regarding benefit and cost categorization and evaluation, including the Federal Interagency River Basin Committee's Green Book (Subcommittee on Benefits and Costs 1950), the Bureau of the Budget Circular A-47 (1962), and the various organizations' internal standards and procedures (Hanley and Spash 1993; Hufschmidt 2000). Budget Circular A-47 was particularly conservative through its focus on national economic efficiency and the use of discount rates to emphasize a 50-year horizon for projects (Hufschmidt 2000).

Mounting academic concern led to the scrutiny of these processes, resulting in the Bureau of the Budget organizing a panel of consults to improve federal economic analyses (Hufschmidt 2000). The result was Senate Document No. 97, which was adopted in 1962 and ultimately retained several conservative aspects of the former techniques, including discount rates, but expanded its scope from national economic development to include the "preservation of aesthetic and cultural values" (Hufschmidt 1961). This expansion in scope was further developed in subsequent revisions to economic policy and is currently referred to as environmental quality in analyses (Hanley and Spash 1993). Prior to the 1970s, CBAs largely ignored the environmental impacts of projects (Hanley and Spash 1993).

The current policy guiding CBAs is "Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies," approved in U.S. Water Resources Council (1983) (Hufschmidt 2000). Modifications and additional standards have been established since 1983, with the most applicable being the recent memorandum on "Incorporating Ecosystem Services into Federal Decision Making" (Donovan et al. 2015). This memorandum directs agencies to "incorporate the value of natural, or "green," infrastructure and ecosystem services into federal planning and decision making (Donovan et al. 2015).

Common Criticisms

The use of the CBA to evaluate long-term environmental projects has long been scrutinized (Lind 1995). Ackerman (2008) explains that the arbitrary assignment of monetary values for the priceless (e.g., human lives, environmental protection) does not represent reality, and that biased groups can sway the results of an analysis. He concludes that the CBA, despite meticulously identifying costs, fails to capture the complex relationships between society, the economy, and the environment (Ackerman 2008).

The other prevailing criticism of the CBA, and a focus of this paper, is directly related to the use of constant discount rates. Discount rates account for the time value of money, meaning that a certain amount of money in the present is considered to be worth more than the same amount in the future because it could have been invested and earned interest. As part of the CBA, present values are calculated for all future values using a standard discount rate. Nearly all future benefits and costs beyond 30 years are inconsequential. Consequently, the present-oriented focus of these analyses is referred to as "the tyranny of discounting," or intergeneration inequity (Pearce et al. 2003; Turner et al. 1993). This tyranny has three results: (1) damages to infrastructure and the environment occurring in the future have present values considerably smaller than the actual damage done; (2) projects with benefits that are beyond 50 years in the future are difficult to justify; and (3) exhaustible resources are more easily abused in the present (Turner et al. 1993). As such, discounting seems to be counterintuitive with regards to achieving sustainable development (Pearce et al. 2003).

Some critics have purported that discounting should not be used at all. This, however, is essentially discounting with a 0% rate, and implies that the present generation's needs are meaningless compared with those of people living hundreds or thousands of years in the future (Pearce et al. 2003). If this was true, and assuming a positive interest rate in the general economy, then society would save its resources and invest on behalf of the next generation. The following generation would act likewise for the ensuing generation, and so on and so forth (Pearce et al. 2003). Not discounting is not a solution to the tyranny of discounting.

Sustainable Development

A common description of sustainable development comes from the Brundtland Commission (1987): "Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs."

Resolving sustainability with discounting is difficult because the underlying rationale for discounting is to more highly value the present, without anticipating being fair to future generations (Turner et al. 1993). While sustainable development is not the principal purpose of discounting in the CBA, alternatives do exist to the traditional CBA approach that can lead to the sustainable development of resources. These alternatives will be detailed subsequently.

As is, many issues with detrimental long-term effects that require action in the present are largely ignored because of the economic results based on a certain discount rate (Guth 2009; Pearce et al. 2003). For example, both nuclear waste storage and climate change mitigation are long-term problems that will severely affect ensuing generations unless action is taken in the present. These concerns are all issues of intergenerational equity (Lind 1995). Reservoir sedimentation is also an intergenerational issue affected by economic analyses and legislation.

What Contributes to Short-Sighted Designs?

The standard 50- to 100-year reservoir design life is a result of using the traditional CBA to determine present values in an economic study. As discussed previously, the policy guiding Congress during the 1950s and 1960s emphasized a short-term horizon for projects through the use of constant discount rates and was criticized by many water project proponents as severely limiting (Hufschmidt 2000). This time period was when the vast majority of dams in the United States were either built or designed (Fig. 2), meaning that they were approved based on a relatively short design life (U.S. Army Corps of Engineers 2014; Hufschmidt 2000). This type of economic analysis heavily favors projects that avoid large initial costs and promise large short-term benefits, effectively eliminating long-term reservoir projects that require the installation of sediment management facilities as part of the capital cost (Hotchkiss and Bollman 1996).

Alternatives to Traditional Cost-Benefit Analysis

There are several financial alternatives available to supplement or modify the traditional application of the CBA that will either foster more sustainable reservoirs or mitigate the economic burden passed to future generations.

Retirement Fund and Insurance Policy

If sediment is not managed at a site, then once the economic benefits from the dam are diminished or exhausted (i.e., the reservoir has become silted in), a decision must be made regarding the structure. The available options are (1) abandoning the dam; (2) decommissioning the dam, defined as removing a dam either completely or partially (Committee on Dam Decommissioning 2015); or (3) implementing a sediment management plan, which may require retrofitting the dam (Engberg 2002). The latter two options are very costly, while the first option entails a higher degree of risk.

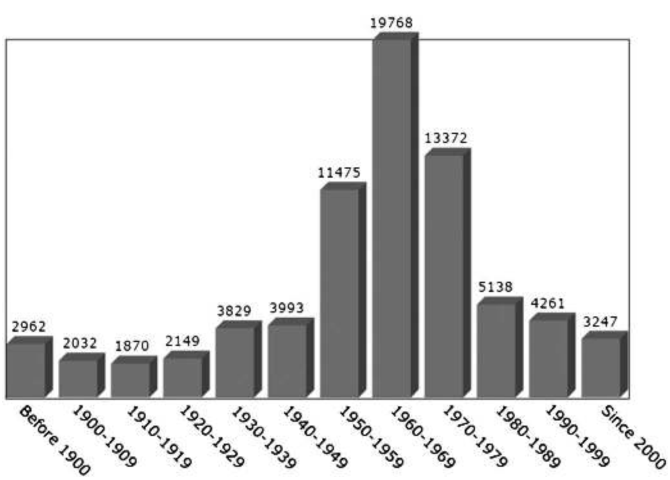

Fig. 2. History of dam construction in the United States

Decommissioning dams has become more common in recent years, despite the many challenges unique to each dam site (Graf 2002). Unfortunately, most dams have been built without a plan to either manage the sediment or retire the facility (Engberg 2002).

Palmieri et al. (2001) suggested that a retirement fund be established throughout a dam's life span to eventually pay for decommissioning. They argue that if the salvage value of a dam is expected to be negative (as most eventually will be if sediment management has not been considered), then a certain amount of the net monetary benefits generated should be set aside on a consistent basis to pay for retirement or retrofitting. As is, dam owners are typically not held liable for such costs. Retiring dams is not as sustainable as managing the sediment to promote an indefinite life span; nevertheless, a retirement fund would still relieve economic stress on future generations.

A related suggestion encourages dam owners to invest in an insurance policy. The policy would provide the owner protection against unexpectedly large costs associated with decommissioning (Palmieri et al. 2001).

User Fees

A recent report written by the Committee on U.S. Army Corps of Engineers Water Resources Science, Engineering, and Planning (2013) supports the beneficiary pays principle. That is, the users of the resources generated by a dam should be contributing to the necessary costs for operation, maintenance, and rehabilitation. Payment for physical and environmental damages is a sensitive topic, and is not always the solution for these issues. However, when natural resources are mismanaged and there are environmental impacts and damages to infrastructure that were unaccounted for in the preliminary economic analysis, there is increasing justification for user fees (Engel et al. 2008).

Implementing said user fees would require educating policymakers and citizens alike. By limiting government subsidies and passing costs to the users, the community will be able to help contribute to the sustainability of infrastructure, water supply, and energy production for their posterity.

Declining Discount Rates

In addition to strictly monetary alternatives, how the cost-benefit analysis itself is performed can affect the resulting policy decision. As previously mentioned, discount rates incorporate the time value of money into economic analyses. The traditional CBA uses a set discount rate, dependent on government regulations; discount rates can even vary significantly from country to country (Evans and Sezer 2002). The higher the discount rate, the more quickly future benefits and costs become negligible in an economic analysis. For example, discounting \$1.00 over 75 years at a typical 5% discount rate yields a present value of \$0.03, while using a 2% rate gives a present value equal to \$0.23, almost eight times larger than the 5% rate value. When these rates are applied to large-scale projects, the discount rate used becomes critical in determining whether to pursue the project or not.

To avoid the present-oriented approach caused by constant discount rates, declining discount rates can be used (Arrow et al. 2013; Annandale et al. 2016). In a CBA, a declining discount rate causes the discount rate to decrease throughout the project's life span, resulting in more prominent future values in the analysis (Oxera Consulting Ltd. 2002). This helps counter the present-oriented bias of standard discounting and promotes intergenerational equity (Annandale et al. 2016).

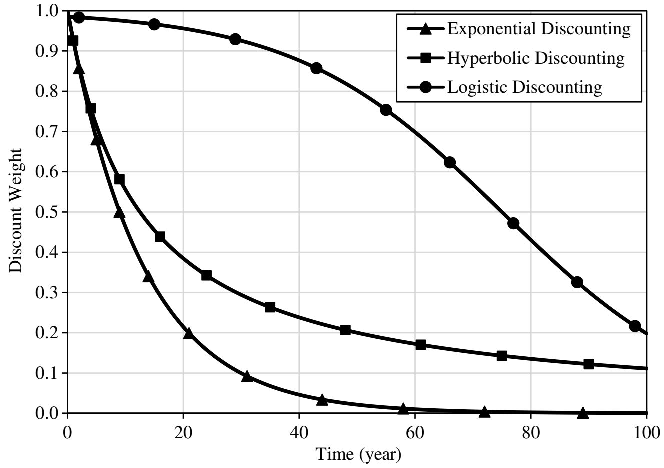

Fig. 3. Weight factor comparison for exponential, hyperbolic, and logistic discounting

A weight factor can be calculated for a discounted value in the future for any point in time of an economic analysis by dividing the future value by its original present value. This weight factor expresses how much the original value is discounted at a certain point in time. Fig. 3 shows the relative discount weight factors for hyperbolic discounting versus traditional exponential discounting over a 100-year time frame. As might be expected, however, the use of hyperbolic discounting will introduce new concerns, such as time inconsistency. Time inconsistency occurs when one group makes a decision, which is later altered by a different group at some point in the future (Pearce et al. 2003).

Logistic discounting, however, employs a declining discount rate while potentially maintaining time-consistent behavior compatible with standard economic theory (Harpman 2014). It has already been implemented in a variety of contexts including economics, statistics, population ecology, and medical research (Harpman 2014). Applying logistic discounting to long-term water resources projects' economic analyses may alter project objectives and lead to more sustainable designs. Fig. 3 also shows the relative discount weight factors for logistic discounting versus traditional exponential discounting over a 100-year time frame. As illustrated in the figure, logistic discounting assigns a higher discount weight to future values than hyperbolic discounting.

Fig. 3 shows that exponential discounting assigns a discount factor of 0.025 as early as 50 years into the future. This means that a $1,000,000 project benefit or cost incurred 50 years in the future has a discounted present value of $25,000 in the CBA analysis. Such a discounted value will largely be ignored, despite the ramifications 50 years later. Logistic discounting, however, assigns a weight factor of 0.8 after 50 years. That same $1,000,000 value will have an equivalent $800,000 present value in the CBA, which could affect design and constructions decisions related to that project.

Logistic discounting has the potential, if implemented properly, to limit the tyranny of exponential discounting and allow for more sustainable long-term water resources projects (Pearce et al. 2003; Harpman 2014). Additional research in this area is recommended to determine whether it would be beneficial to implement logistic discounting rates in future CBA analyses.

Complete Cost-Benefit Analyses

For new projects it is now possible to project potential damages due to upstream sedimentation and downstream scour. These costs should be included in the CBA to account for the lack of a sediment management plan. A better understanding of the cost to remediate actual damages unaccounted for at existing projects would help justify this claim. This will require gathering cost estimates for reservoir sedimentation–related damages; there is little published information regarding the economics of such processes (Palmieri et al. 2003). By collecting these data, research with more concrete results will be available for consideration for new projects. By including the projected damages due to not having a sediment management plan, the CBA may indeed show a favorable result when averting those damages by including capital costs for sediment management (large, low-level outlets, for example).

Through collaboration with the Corps, financial data were gathered for a project in an effort to calculate the amount of money spent remediating sedimentation impacts. The following section contains a case study for Gavins Point Dam that compares expenditures imposed by sedimentation impacts to the dam's original construction expenses.

Brief Case Study: Gavins Point Dam

Background

Gavins Point Dam was built from 1952 to 1957 on the Missouri River by the Corps near Yankton, South Dakota, to form Lewis and Clark Lake. The dam's construction was approved based on anticipated benefits from hydropower generation, flood control, recreation, irrigation, navigation support, and fish and wildlife enhancement. Construction costs were $50 million (U.S. Army Corps of Engineers Omaha District 2009). Sediment management techniques were not considered during the project's design phase, as was typical of most dams designed in the United States at that time (Vanoni 1975). Damages due to upstream sedimentation and downstream scour have been significant. Available damage costs are compared with the construction costs by converting both to present values to illustrate the importance of including averted damages into the CBA.

Upstream Damages

Sedimentation impacts within and upstream from Lewis and Clark Lake have clogged municipal water intake structures, increased flood frequency, and heightened groundwater levels (U.S. Army Corps of Engineers Northwestern Division 2006; Carter 1991; P. Boyd, personal communication, 2015). Clogged water intakes due to the upstream migration of the depositional delta occurred at Springfield, South Dakota (Fig. 4) and necessitated extensive redesign projects (U.S. Army Corps of Engineers Northwestern Division 2006). Channel aggradation has caused typical bankfull discharges to spill onto the floodplain (Hotchkiss and Bollman 1996), and Nebraska Highway 12 is currently undergoing a complete redesign due to frequent roadway maintenance from perennial flooding damages (HDR Engineering 2015). As the depositional delta migrated upstream from the lake, the town of Niobrara, Nebraska, suffered higher groundwater levels that eventually flooded most basements (Carter 1991). The entire town was relocated to a higher elevation in the 1970s, resulting in a $14.5 million expense that the Corps partially funded (Carter 1991). The Corps or other entities have also been required to continually dredge the channel to maintain clearance for watercraft (U.S. Army Corps of Engineers Northwestern Division 2006).

Fig. 4. Deltaic deposits in Lewis and Clark Lake near Springfield, South Dakota (reprinted from Missouri Sedimentation Action Coalition 2012, with permission)

Within-Lake Losses

Lewis and Clark Lake has lost more than 30% of its original storage capacity due to sedimentation. Because most project benefits are directly proportional to available storage capacity in the pool, as a reservoir's volume decreases due to sedimentation processes, many project benefits are adversely affected. Lewis and Clark Lake's capacity to retain typical flood events has been reduced, resulting in a loss of averted flood damage benefits, or an increase in actual flood damages (U.S. Army Corps of Engineers Northwestern Division 2006). Having less storage available in general can also reduce benefits associated with hydropower generation and irrigation supply due to the inherent value of storage space. Recreational benefits have been impacted by the reduced storage capacity through a decreasing water surface area and the burial of lake access points (Missouri Sedimentation Action Coalition 2013).

Downstream Damages

Several impacts are apparent downstream from the dam. Due to the sediment imbalance caused by a dam's obstruction of open-channel flow, clear water discharged downstream is deemed "hungry water." This type of water tends to scour the streambed and channel bars, leading to bank destabilization. Bank stabilization and sandbar construction have both been required downstream of Gavins Point Dam (U.S. Army Corps of Engineers Northwestern Division 2006). The sandbar construction is referred to as the Emergent Sandbar Habitat (ESH) Program and its purpose is to mechanically create quality sandbar habitat for two endangered species of birds (Missouri River Recovery Program 2016). The channel incision has also undercut stream banks and abandoned water intake structures (U.S. Army Corps of Engineers Omaha District 1991; Alexander et al. 2013). This incision has extended into tributaries and has disconnected the Missouri River from its floodplain, effectively preventing the natural rejuvenation of the floodplain forest and wetland habitat (Alexander et al. 2013). Infrastructure damages have followed the tributary incision. By incorporating sediment management into the project's initial design, these costs could have been significantly reduced.

Despite the numerous impacts that sedimentation processes have triggered at Gavins Point Dam, costs for only a few of the damages were available. The costs were gathered by working with the Corps' Omaha District Office (George 2016).

Table 1. Expenditures for Sedimentation Impacts at Gavins Point Dam

Expenditure	2015 value
City of Niobrara relocation	$20,328,000
Real estate acquisitions for relocation	$17,987,000
Highway 12 maintenance (2004–2014)	$1,659,000
Highway 12 redesign (minimum estimate)	$161,800,000
ESH construction and maintenance	$56,171,000
Sum	$257,945,000

Economic Analysis

To compare monetary values over a long time horizon, the values need to be converted to their equivalent worth in a specific year. For this study, the year 2015 was selected; all values were converted to their 2015 values by taking into account the time value of money through discounting. The results of an economic analysis can be altered significantly depending on the choice of discount rate (U.S. Environmental Protection Agency 2014). It is known that most water resources projects in the 1950s used a discount rate between 3.25 and 3.50% (Weisbrod et al. 1978). A discount rate of 3.50% was used in this analysis as a conservative estimate.

Once the discount rate is selected, converting an expenditure to its corresponding 2015 value is a simple process, as seen in Eq. (1). In the equation the 2015 value is treated as a future value because 2015 is in the future when compared with the year of the expenditure

$$\mathrm{FV} = \mathrm{PV} \times (1 + d)^n \tag{1}$$

where FV = future value (2015); PV = past value (between 1957 and 2014); d = discount rate; and n = number of years between FV and PV.

Discussion

Table 1 contains a summary of expenditures due to sedimentation impacts in 2015 dollars. This analysis follows the traditional economic approach by considering a discount rate and not incorporating an inflation rate.

The aforementioned $50 million construction cost for Gavins Point Dam is equivalent to $367.7 million in 2015 dollars. The ratio of the sum of costs in Table 1 compared with the construction cost is 0.70. This ratio would likely increase to be greater than 1.0 if the analysis considered all of the other damages resulting from sedimentation. Design and operations decisions for Gavins Point Dam could have been drastically different if these future expenditures from sedimentation impacts had been included in the initial economic analyses. While the understanding to incorporate such costs in 1950 was likely lacking, predictive technologies are available today that allow for potential damages due to sedimentation to be ameliorated by including sediment management in the construction costs.

Recommendations

In 1975, Bondurant warned of the inevitable filling of reservoirs and counseled that if society still relied on reservoirs in the future, then evaluating and managing the sediment would be necessary (Vanoni 1975). Bondurant's warning has largely been ignored; sediment management practices have not been adapted for the most part and society still heavily relies on reservoirs for water supply more than four decades later.

Achieving reservoir sustainability requires a sediment management plan for each dam to either directly address the mitigation of sediment or provide a fund with sufficient money to respond to the facility's condition appropriately. Otherwise, a filled reservoir with minimal project benefits becomes an economic burden for the following generation. A sustainable reservoir would theoretically have an indefinite design life. As is, most dams do not have the necessary facilities for such a task. In order to promote long-term economic viability, dam owners (e.g., hydropower companies) and legislative bodies are encouraged to reconsider the traditional, short-sighted reservoir design approach in favor of a life-cycle management plan that incorporates sediment management. The authors recommend:

- Increase the frequency of bathymetric surveys of state-owned and federally owned dams to better track the rate of reservoir storage loss;
- Discuss at multiagency levels changes to the traditional cost-benefit analysis for dams that would produce sustainable designs and include the costs of not managing reservoir sedimentation and the means of averting those costs (inclusion of sediment management alternatives);
- Investigate logistic discounting's potentially time-consistent nature and the feasibility of incorporating declining discount rates into long-lived water resources projects; and
- Consider the creation of funding to address sediment management issues at existing dams. Such funding could consist of user fees, a retirement fund, insurance, or similar financial instruments.

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