Technical Report No. ENV-2021-058

Reservoir Sedimentation Economics Model (RSEM) Description

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Cover Photo – Hydraulic dredge working in 2011 to remove coarse sediments from Strontia Springs Reservoir located on the South Platte River southwest from Denver, Colorado.

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Acronyms and Abbreviations

ASDSO	American Association of Dam Safety Officials
BCR	Benefit-cost ratio
BYA	base year for analysis
CCT	Construction Cost Trends
ENR CCI	Engineering News Record Construction Cost Index
F&W	fish and wildlife
FY	fiscal year
M&I	Municipal and industrial
MAF	mean annual flow
Mm	millimeter
MWh	megawatt hours
NFR	net farm returns
NPV	Net present value
OM&R	operation, maintenance, and replacement
POA	Period of analysis
RESM	reservoir sedimentation economics model
RPA	*revealed preference* approach
T&E	threatened and endangered
WTP	willingness to pay

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Executive Summary

The Reservoir Sedimentation and Economics Model (RSEM) has been developed to simulate and compare the economic benefits and costs of a reservoir, both without and with sediment management. The comparative simulations can be used to help determine where reservoir sediment management is economically preferred to a no action alternative without sediment management. RSEM can be applied to both new and existing reservoirs. RSEM is not meant to be a substitute for detailed hydraulic, sediment, and economic investigations but can provide useful results for understanding the economic outcomes of implementing sustainable sediment management versus ignoring the problem until forced to take action.

Dams and reservoirs provide substantial economic benefits to the nation, including water supply for irrigation, municipal, industrial, and firefighting use; flood risk reduction; boat or barge navigation; hydroelectric power; recreation opportunities; and fish and wildlife enhancement. However, the water storage capacity and wetted surface area that make these benefits possible are decreasing over time due to the continuing process of reservoir sedimentation (Strand and Pemberton 1982, Morris and Fan 1998, Randle et al. 2006, Morris et al. 2008, Annandale 2013, Annandale et al. 2016, Randle et al. 2019, Randle et al. 2021 and Anari et al. 2023). In addition, the trapping of sediment in a reservoir disrupts the sediment transport continuity of the river, often resulting in sediment aggradation along the upstream channel and degradation along the downstream channel. Upstream channel aggradation and downstream channel degradation can affect fish and wildlife habitat, infrastructure, and property along the river corridor.

Sediment management to sustain reservoir storage capacity and restore a river’s downstream sediment transport continuity may be more cost effective than ignoring sedimentation until the reservoir benefits are lost and the dam is decommissioned. Recovering storage capacity from past decades of sedimentation is difficult and expensive for large reservoirs because of the very large sedimentation volumes (millions to billions of cubic yards) and associated cost. However, sustaining the remaining storage capacity by managing inflowing sediment loads on an annual basis may be economically viable and potentially economically preferable to ignoring sedimentation into the future when costs are higher.

An economic analysis is needed to determine the most cost-effective sediment management alternative for a given dam and reservoir. The period of economic analysis needs to be long enough, and the spatial area of consideration large enough to include all significant benefits and costs. This approach is different than the historic economic analyses typically used to justify the construction of dams and reservoirs where the reduced benefits over time were not considered, nor were the costs considered related to upstream sedimentation, downstream degradation, and dam decommissioning (Anari et al. 2023).

RSEM annually simulates sedimentation within the reservoir and along the upstream river channel. Coarse sediments (sand and gravel) are assumed to deposit as a delta within the reservoir and along the upstream channel. Fine sediments (clay and silt) are assumed to deposit along the reservoir bottom between the dam and delta. Annual channel degradation is simulated along the downstream channel. RSEM annually simulates a comprehensive set of economic benefits and costs over future decades and centuries. Annual benefits are estimated under six beneficial use categories: irrigated agriculture, municipal and industrial water supply, fish and wildlife enhancement, flood risk reduction, hydropower generation, and reservoir-based recreation. Annual costs are estimated for the planning, design, and construction of the dam; land acquisition for the dam and reservoir; operation, maintenance & replacement; sediment management; upstream channel aggradation; downstream channel degradation; and dam decommissioning. RSEM uses inputs from the following categories:

- Reservoir age, size, and inflow characteristics
- Dam characteristics
- Reservoir sedimentation characteristics
- Reservoir benefits
- Dam & reservoir planning, design, and construction costs
- Design, construction, and contract contingencies cost additives
- Operations, maintenance, and replacement costs
- Dam decommissioning costs and benefits
- Upstream sedimentation costs
- Downstream channel degradation costs
- Without sediment management alternative parameters
- With sediment management alternative parameters

Benefits and costs are typically provided as unit values. Default values are provided for each parameter which can be easily overridden by the user. Most of the default values are dynamically linked to other values to help the user run the model.

The model uses exponential discounting as the standard approach. The user may also select other discounting approaches for research or comparison purposes (seven other economic discounting approaches are available). Model results for alternatives without and with sediment management include benefit-cost ratios and net present value over a range of analysis periods. Additional decision support metrics include breakeven and retirement fund analyses.

Organization

A summary of each chapter of the model report is presented below.

Sedimentation Management Overview. This chapter provides an introduction to the problems caused by reservoir sedimentation and alternative methods to manage sediment, mitigate impacts, and restore natural sediment loads to downstream channels.

RSEM Overview. This chapter describes the purpose and functions of the model at a high level and the model limitations.

Sedimentation Modeling. This chapter describes model inputs; how the model simulates reservoir sedimentation, upstream channel aggradation, and downstream channel aggradation; and model outputs (without and with sediment management).

Economic Modeling. This chapter describes model inputs, how the model simulates the economic benefits and costs of reservoir sedimentation (without and with sediment management).

Sediment Management Alternatives. This chapter describes how the model simulates a range of alternatives.

Example Case Study. This chapter presents how the model was used to simulate sedimentation and the resulting economic analysis for a hypothetical new and existing reservoir (Muddy Reservoir) under alternatives without and with sediment management.

Appendix A. RSEM User Guide. This appendix describes how to prepare input data to preform model simulation and explains the types of model output.

Appendix B. RSEM Organization. This appendix describes how the model worksheets are organized and the function of each worksheet.

1 Sedimentation Management Overview

1.1 Sedimentation Issues

Dams and reservoirs provide substantial economic benefits to the nation, including water supply for irrigation, municipal, industrial, and firefighting use; flood risk reduction; boat or barge navigation; hydroelectric power; recreation opportunities; and fish and wildlife enhancement.[1] However, the water storage capacity and wetted surface area that make these benefits possible are decreasing over time due to the continuing process of reservoir sedimentation (Morris and Fan 1998, Randle et al. 2006, Morris et al. 2008, Annandale 2013, Annandale et al. 2016, Randle et al. 2019, Randle et al. 2021, and Anari et al. 2023).

All rivers transport sediment particles (e.g., clay, silt, sand, gravel, and cobbles) that are naturally eroded from the upstream watershed, and reservoirs tend to trap this sediment (Strand and Pemberton 1982, Morris and Fan 1998, Randle et al. 2006, Morris et al. 2008, Annandale 2013, Annandale et al. 2016, Randle et al. 2019, Randle et al. 2021). Rates of sediment erosion can be accelerated due to certain land use activities in the upstream watershed and from increased severity of droughts and floods related to climate change (Annandale 2013 and Annandale et al. 2016). Sediment trapped in upstream reservoirs reduces the natural sediment supply to downstream rivers and coastal deltas.

As sediment is transported into a reservoir, the coarsest particles (sand, gravel, and cobble) tend to deposit first and form deltas at the upstream ends of the reservoir (Morris and Fan 1998 and Randle et al. 2006, Randle et al. 2019, Randle et al. 2021). Over time, a delta will often build and extend upstream of the reservoir pool. Finer particles (clay and silt) tend to be transported past the delta and deposit along the reservoir bottom, or past the dam in cases where travel time through the reservoir is short enough (Figure 1-1). If there is considerable drawdown of the reservoir pool, inflowing water will tend to erode the exposed delta and transport it farther downstream into the receded reservoir.

The intake structure of the dam outlet is designed to be above the sedimentation level over the sedimentation design life (Figure 1-1, A). Initially, sedimentation does not impair dam and reservoir operations (Figure 1-1, B). However, once the dead storge pool has filled with sediment (Figure 1-1, C), the dam outlet is vulnerable to burial and plugging by woody debris and sediment, even when sediments may have only filled one-quarter to one-half of the reservoir storage capacity. Dam decommissioning and removal will be the likely outcome for high hazard dams with severe sedimentation (Figure 1-1, D).

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[1] Benefits from dams are discussed in literature, for example United States Society of Dams (USSD) 2021 and American Association of Dam Safety Officials (ASDSO) 2021.

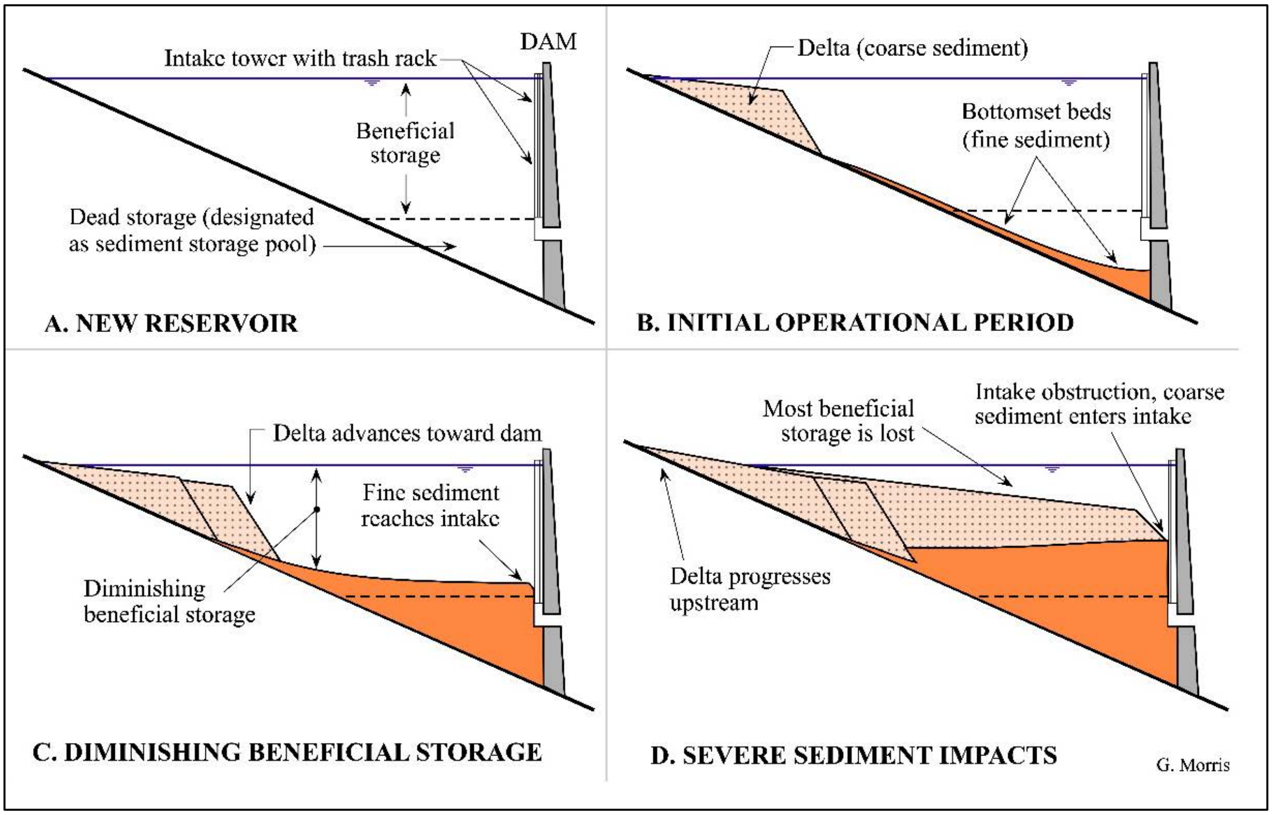


Figure 1 1.—Process of reservoir sedimentation (Randle, et al. 2019); A) New reservoir showing zone of beneficial storage and the designated sediment storage pool, B) Initial operational period with minimal sediment impacts, showing the deposition pattern for both coarse and fine sediments, C) Significant sediment encroachment into the beneficial pool with substantial growth of the delta, D) Severe sediment impacts including loss of beneficial storage, dam outlet obstruction and upstream progression of the delta (illustration created by G. Morris).

Sedimentation reduces the water storage capacity at nearly all reservoir elevations (Morris and Fan 1998, Randle et al. 2019, and Randle et al. 2021). Deltas deposit up to the normal reservoir water surface elevation (and higher elevations upstream) and reduce the wetted surface area for boats and recreation. Over time, downstream progression of the delta can bury boat ramps and marinas and can make reservoir areas over the delta too shallow for boat navigation. As the delta grows along the upstream river channel, reservoir storage capacity is reduced at the highest elevations, groundwater and flood stage elevations are increased, and upstream lands and infrastructure can be inundated. When coarse sediments are trapped within the reservoir, clear water released from the dam tends to degrade the downstream river channel, which leads to streambank erosion as the river seeks to establish a new floodplain within the incised channel.

Sedimentation can affect water quality, both within the reservoir and downstream. For example, high sediment concentrations entering a reservoir after a wildfire or during an intense rainstorm typically impair reservoir water quality and could temporarily affect recreation use and municipal water supply. When sediment is trapped within the reservoir, the lack of downstream turbidity may be detrimental to native fish but provide ideal water quality for non-native sport fish.

The economic benefits of water storage decrease over time as sedimentation continues to shrink the reservoir storage capacity (Randle et al. 2021 and Anari et al. 2023). These decreasing benefits include water supplies for such uses as irrigation, municipal, industrial, hydropeaking, and firefighting. Storage capacity is also reduced for flood risk reduction. The economic benefits from recreation decrease over time as continuing sedimentation shrinks the reservoir surface area.

In addition to the normal costs for dam operation and maintenance, sedimentation can lead to additional costs (Randle et al. 2021 and Anari et al. 2023), including:

- Emergency sediment removal around dam and reservoir facilities
- Upstream inundation of lands; relocation of buildings, roads, and railroads; and impairment of fish passage.
- Downstream channel degradation and lateral erosion impacts to habitat, lands, and streamside infrastructure and the construction of streambank protection to mitigate impacts
- Dam decommissioning when the costs of sedimentation impacts and the liabilities of the dam outweigh the remaining reservoir benefits.

1.2 Economic Analysis of Sedimentation Management Alternatives

Annandale (2013) and Anari et al. (2023) state that intergenerational equity ensures fairness between current and future generations, and that it is the core tenet of sustainable development. Brundtland (1987) defines sustainability as “the ability to meet the needs and aspirations of the present generation without compromising the ability of future generations to do so.”

For reservoir sediment management, Morris and Fan (2010) and Anari et al. (2023) define sustainability as “balancing sediment inflows and outflows across a dam while maximizing its long-term benefits.” Sustainable management can be achieved by any of several well-established alternatives for removing reservoir sediments and achieving sediment transport continuity.

Several reservoir sediment management alternatives exist to partially or fully sustain reservoir storage capacity and avoid, mitigate, or adapt to the impacts associated with reservoir sedimentation. These alternatives can be grouped into the following categories (Morris and Fan 1998, Annandale 2013, Kondolf et al. 2014, Annandale et al. 2016, Morris 2020, and Randle et al. 2021):

- Reduce unnaturally high sediment yield rates from the upstream watershed (e.g., soil erosion control, forestation, construction of check dams)

- Route inflowing sediments through or around the reservoir (e.g., sediment sluicing, venting of turbidity currents, sediment tunnel bypass)

- Remove sedimentation from the reservoir (e.g., flushing, dry excavation, or dredging)

- Use adaptive strategies to cope with sedimentation until dam decommissioning (e.g., improve operational efficiency, modify dam intakes, raise dam height, water conservation, relocation of boat ramps)

The first three categories of sediment management alternatives have the potential to sustain reservoir storage capacity, which may be more cost effective than ignoring reservoir sedimentation until the reservoir benefits are lost and the dam is decommissioned. The fourth category is adaptive strategies and these strategies are not sustainable. Specific alternatives under each of these four categories are presented in Figure 1-1.

For a new dam and reservoir, sediment management alternative should be incorporated into the design and operational plans. For an existing dam and reservoir, structural modifications may be needed, and the operating rules may need to be changed, to implement sediment management. Annandale et al. (2016) provides a good overview of sediment management alternatives for both new and existing reservoirs. Morris and Fan (1998) provides a more detailed description of alternatives along with case study examples.

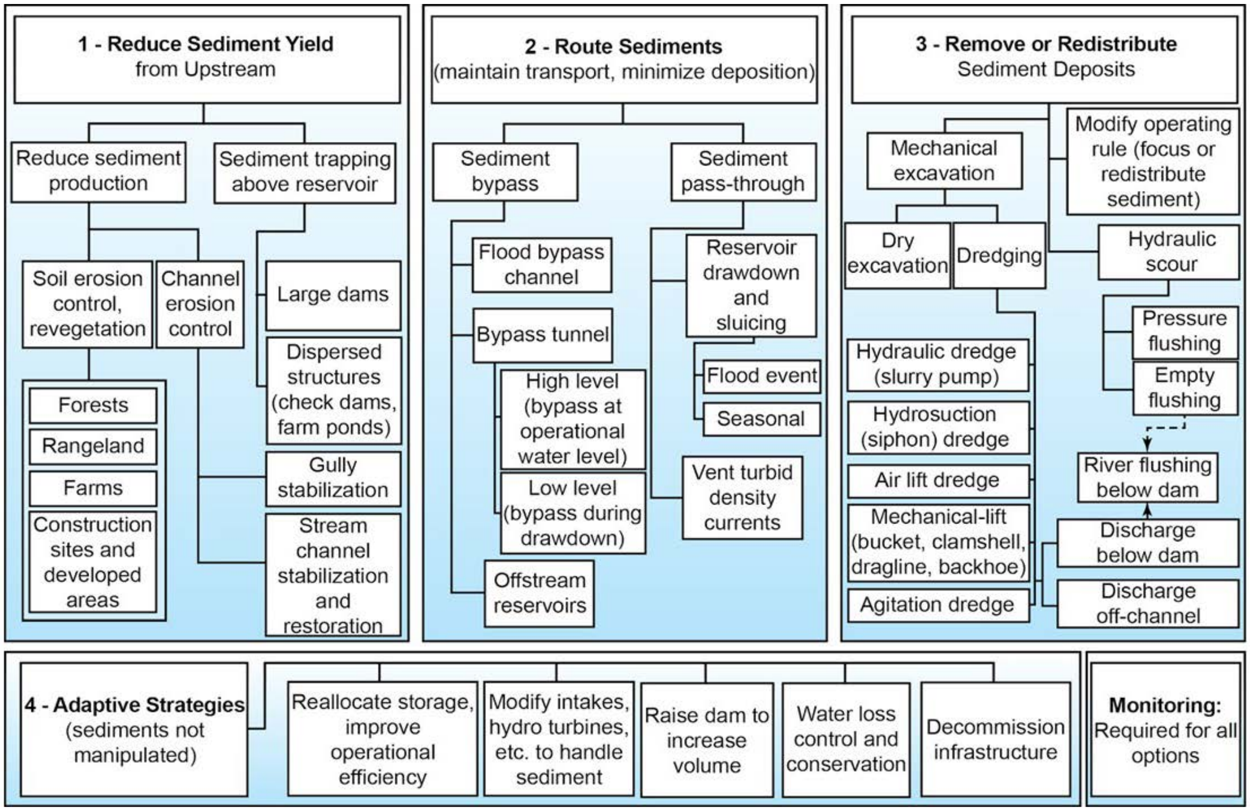


Figure 1-2.—Reservoir sediment Classification of methods to manage reservoir sedimentation (Morris, 2015).

An economic analysis is needed to determine which sediment management alternative has the greatest welfare to society. Economic metrics (e.g., benefit-cost ratio, net present value) can be compared among various sediment management alternatives and with the no action alternative without planned sediment management. The various alternatives require a wide range of initial capital costs and annual operation and maintenance costs. The possible range of sediment management alternatives is more fully described in Chapter 5, Sediment Management Alternatives.

The period of economic analysis needs to be long enough, and the spatial area of consideration large enough, to include all significant benefits and costs. This approach is different than the economic analyses used to justify the construction of many dams and reservoirs where the costs of upstream sedimentation, downstream degradation, and dam decommissioning were not considered (Anari et al. 2023).

The value of a particular cost or benefit varies depending on when it occurs. The comparison of benefits and costs that occur at different times over the period of analysis is made possible through a mathematical procedure known as discounting. Discounting is the process of adjusting future benefits and costs to a common point in time (e.g., the present) to allow for comparisons.

Anticipated future costs and benefits are *discounted* back to a “present value” to account for the “time value of money,” or the opportunity cost associated with tying up those dollars in the investment. The influence of discounting depends on when the benefits and costs occur, the discounting approach used, and the interest rate (opportunity cost) assumed.

Discounting approaches consider the value of money over time. These approaches are used to reduce the value of future benefits and cost so they may be compared from an equivalent time of reference (See 4.4.1 Discounting Benefits and Costs). The choice of the economic discounting approach (and interest rate) affects the rate that future benefits and costs are discounted, and in effect, how present and future generations are considered. Discounting approaches that more rapidly discount benefits and costs over time tend to favor the present generation over future generations and may lead to intergenerational inequity. For exponential discounting (the most commonly used approach), a lower interest rate gives more weight to future benefits and costs than a higher interest rate. Other discounting approaches reduce future benefits and costs more slowly, which gives more consideration to future generations (and intergenerational equity) than when using the exponential discounting approach.

Reclamation’s guidance recommends the commonly employed exponential discounting approach, which will generate results most readily comparable with other economic models. There is a lack of consensus surrounding the suitability of, and parameter definition for, most of the seven alternative discounting approaches available in RSEM. For these reasons, the user should always start with the exponential discounting approach, and in most cases should conduct all their modeling and report results using this approach, reserving alternative discounting approaches for research or comparison purposes.

For new dams and reservoirs, the choice can be to construct the dam and reservoir project with or without sediment management or not construct the project at all (no action alternative). For existing reservoirs, some sediment management action will eventually have to be taken—either sustainable sediment management in the near term or forced adaptive strategies later and until the eventual dam decommissioning. For existing reservoirs, the no action alternative would typically be continued dam and reservoir operations with no planned sediment management. However, some forced sediment management eventually may be required to keep dam and reservoir facilities functioning, and dam decommissioning may be needed after severe sedimentation. DOI Agency Specific Procedures (DOI, 2015) For Implementing the Council on Environmental Quality’s Principles, Requirements, and Guidelines for Water and Land Related Resources state the following:

> *The without-project condition is the most likely condition expected to exist in the future over the period of analysis in the absence of the project or program under consideration given current laws, policies, projects under construction or authorized, and any existing resources/conditions. It corresponds with the NEPA requirement to identify a “No Action” alternative in an EIS. It includes actions that may be expected by others.*

Benefit-cost (BC) ratio and net present value (NPV) are useful metrics for helping to select an alternative. The BC ratio describes the benefit per dollar of cost which is the preferred metric when multiple alternatives can be selected, as it will identify the combination of choices that maximizes the net benefit for society. In general, when selecting a single alternative, NPV is the preferred metric because it identifies the alternative with the greatest net benefit for society.

1.3 Available Models

Detailed models are available for estimating the economic benefits to agriculture, hydropower, flood risk reduction, and recreation, but these models typically do not directly consider a reduction in reservoir storage capacity or surface area over time due to sedimentation. There are only a few widely available numerical models that comprehensively link the economics to the impacts of sedimentation for new and existing reservoirs (Anari et al. 2023). These models simulate how different parameters affect reservoir operations and forecast the economic consequences of different reservoir sediment management alternatives. The most widely used model is REServoir CONServation (RESCON), which was designed for use in pre-feasibility studies (Efthymiou et al. 2017) to rank the economic performance of a selection of sediment management techniques for new and existing reservoirs. A new version of this model, RESCON 2, has been prepared to cover different discounting approaches and incorporate different types of benefits and costs (Efthymiou et al. 2021). The RESCON 2 model considers many aspects of reservoirs with an emphasis on hydropower, but the model does not yet simulate the economics of reservoir recreation or the upstream and downstream impacts of sedimentation.

A limited model was developed by Niu and Shah (2021) to determine the initial reservoir capacity of a dam to maximize lifetime net benefits with different sediment management efficiencies. We are not aware if this research model is yet available for general use.

2 RSEM Overview

2.1 About the Model

The Bureau of Reclamation’s (Reclamation) Reservoir Sedimentation Economics Model (RSEM) may be used by engineers and economists to evaluate and compare the economics of a new or existing reservoir under two competing alternatives: without and with planned reservoir sediment management. The model is not meant to be a substitute for detailed hydraulic, sediment, and economic investigations but can provide useful results for understanding the economic outcomes of implementing sustainable sediment management versus ignoring the problem until forced to take action.

RSEM is a planning tool for resource managers to better understand and compare the economic benefits and costs of reservoir sedimentation over time for alternatives without and with sustainable management. RSEM evaluates the economic benefits and costs to society, rather than the financial revenues or expenditures to particular organizations or stakeholders. The model was designed to help the user comprehensively consider how the economic benefits and costs of a reservoir may change over time with sedimentation. The model can help identify the relative importance of these benefits and costs and where additional investigations would be useful. RSEM has been developed to perform economic analysis considering a wide range of benefits and costs over a large spatial area and over long time periods. Successful application of the model requires knowledge of both civil engineering (sedimentation), economics, and cost estimating. RSEM could be applied by an experienced person with knowledge of both disciplines or a team of engineers and economists.

Sediment management options are simulated by specifying the portion of sediments removed each year, the amount of reservoir water used, and implementation costs (Figure 2-1). Model results compare the economic feasibility of alternatives without and with sustainable sediment management. RSEM can comprehensively account for all benefits and costs (upstream, downstream, and within the reservoir) assuming that data are available or can be estimated. RSEM applies the exponential discounting approach as the standard method to account for the time-value of money (see Section 4.4.1 Discounting Benefits and Costs). The user can also select an alternative discounting approach for research or comparison purposes. The model computes the benefit cost ratio and net present values for each alternative, based on the selected discounting approach.

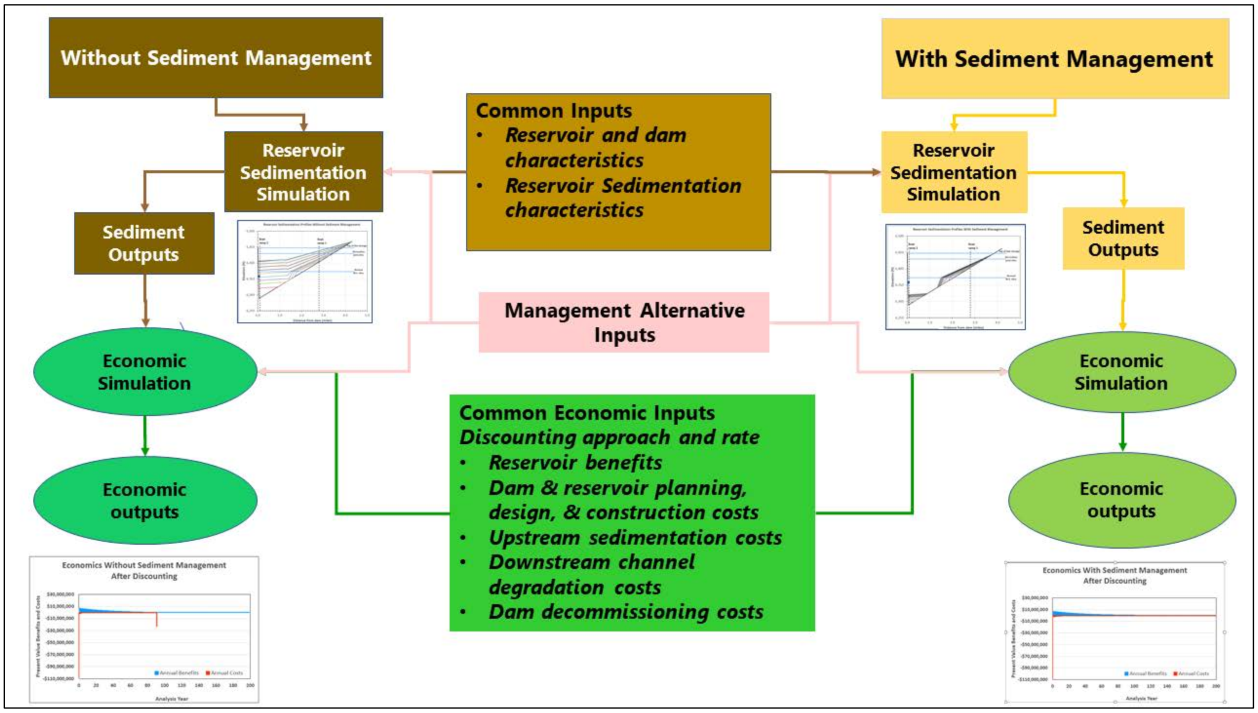


Figure 2-1.—Overview flowchart of RSEM.

RSEM simulates annual economic benefits and costs over a period of analysis up to five hundred years.

- **Benefits and costs before discounting.** Example economic results without and with sediment management are presented graphically for annual benefits and costs before discounting (Figure 2-3). The initial costs to build the dam are nearly the same for both alternatives ($120 million). Under the without sediment management alternative, sedimentation diminishes the benefits each year until the dam needs to be decommissioned at a cost of $220 million. Under the with sediment management alternative (reservoir sluicing), annual costs are about $120,00 per year. However, the reservoir benefits are maintained over the long term, and dam decommissioning is avoided under the with sediment management alternative.

- **Benefits and costs after discounting.** Example economic results without and with sediment management are presented graphically for annual benefits and costs after exponential discounting with a 2.5% discount rate (Figure 2-4). In this example of a new reservoir, sediment management is more economically justified (benefit-cost ratio of 1.71 after 100 years) than without sediment management (benefit-cost ratio of 1.48 after 100 years). A comparison of net present values is also recommended.

2.2 Muddy Reservoir Example

This manual uses a hypothetical example, the Muddy Reservoir in the mountainous portion of the western United States. Muddy Reservoir's primary purpose is for irrigation, municipal and industrial water supply, with secondary benefits for flood risk reduction, fish and wildlife habitat, and recreation. There is no hydroelectric powerplant associated with Muddy Creek Dam. The earthen dam that creates Muddy Reservoir has a hydraulic height of 160.5 feet (48.9 m). The reservoir has an initial total storage capacity of 20,950 acre-feet (25.84 Mm^3). Annual sedimentation rates of 101 acre-feet per year (0.125 Mm^3/yr) fill the reservoir dead storage within 50 years (See Chapter 6. Example Case Study).

Example model results for the hypothetical Muddy Reservoir are presented here to illustrate some of the available model output. RSEM simulates reservoir sedimentation profiles without and with sediment management. Example profiles are provided for the first century of reservoir life (Figure 2-2). For the example, without sediment management, the reservoir dead storage would fill with sediment after 50 years of reservoir operations. The entire storage capacity would be largely filled with sediment (including the upstream boat ramp) after a century of reservoir life. Annual reservoir sediment sluicing was assumed for the example sediment management alternative. The annual sediment sluicing substantially reduces the reservoir sedimentation rates and, as a result, the dam's outlet and boat ramps are still well above the sedimentation level after a century of operation, and the reservoir life is greatly extended.

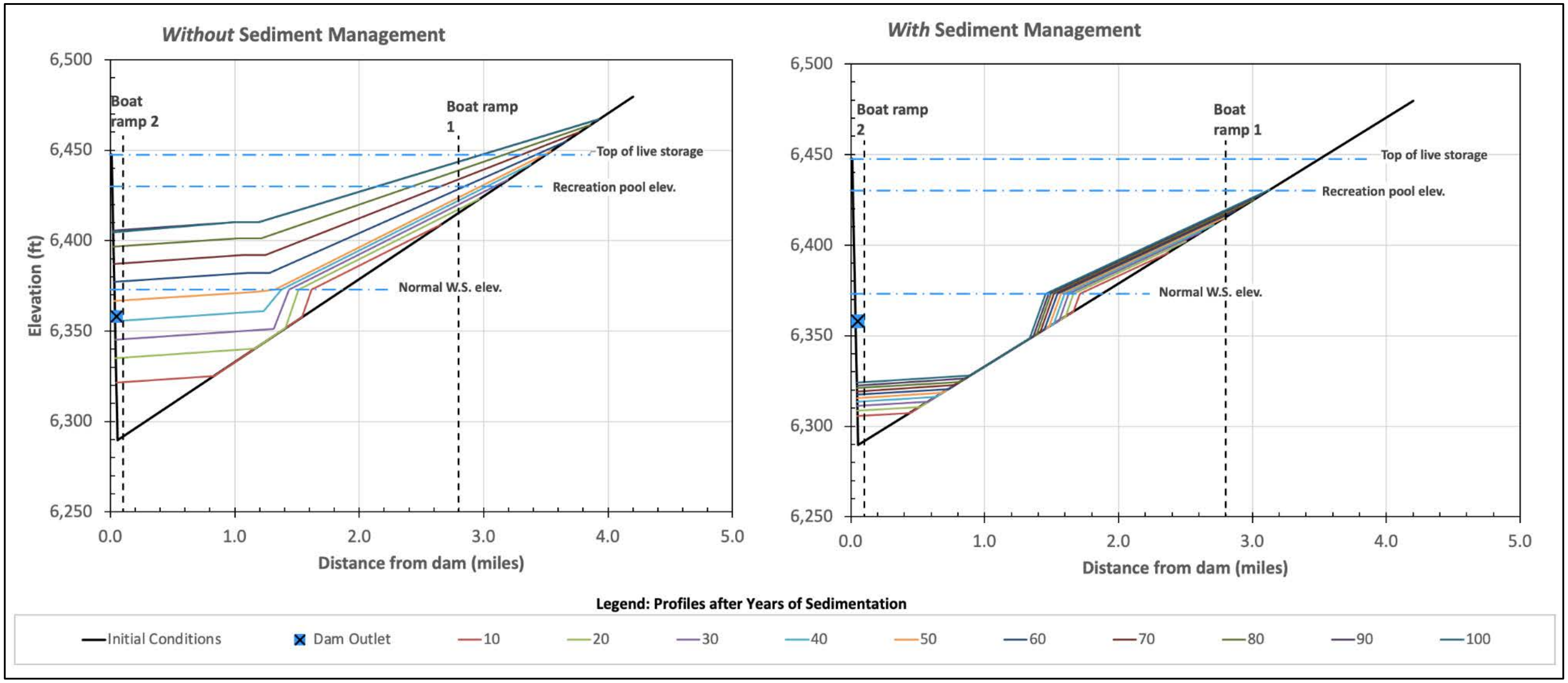


Figure 2-2.—Reservoir sedimentation profiles without (left) and with (right) sediment management over a century of reservoir life. Without sediment management, the upstream coarse sediments of the delta merges with the fine sediments of the reservoir bottom near the dam, filling the dead storage and burying the dam outlet. With sediment management, rates of sedimentation are substantially reduced, greatly extending the reservoir life. Note that these graphing results are based on the Case Study inputs described in Chapter 6 Example Case Study.

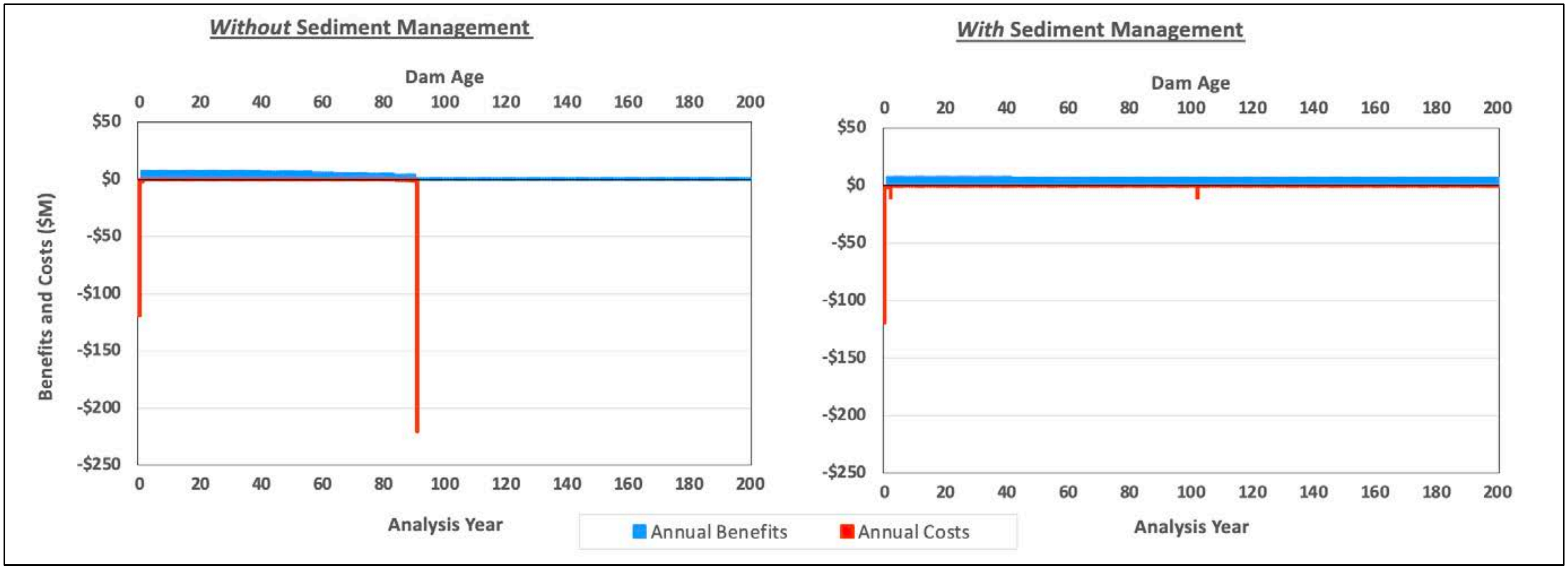


Figure 2-3.—Bar graphs of annual reservoir benefits (blue) and costs (red), before discounting, without and with sediment management over two centuries of reservoir operations. Without sediment management, benefits diminish over time until dam decommissioning in analysis year 91. With sediment management, both capital and annual costs are incurred, but the water storage benefits continue over the long term as the reservoir is sustained. Note that these graphing results are based on the Case Study inputs described in Chapter 6. Example Case Study.

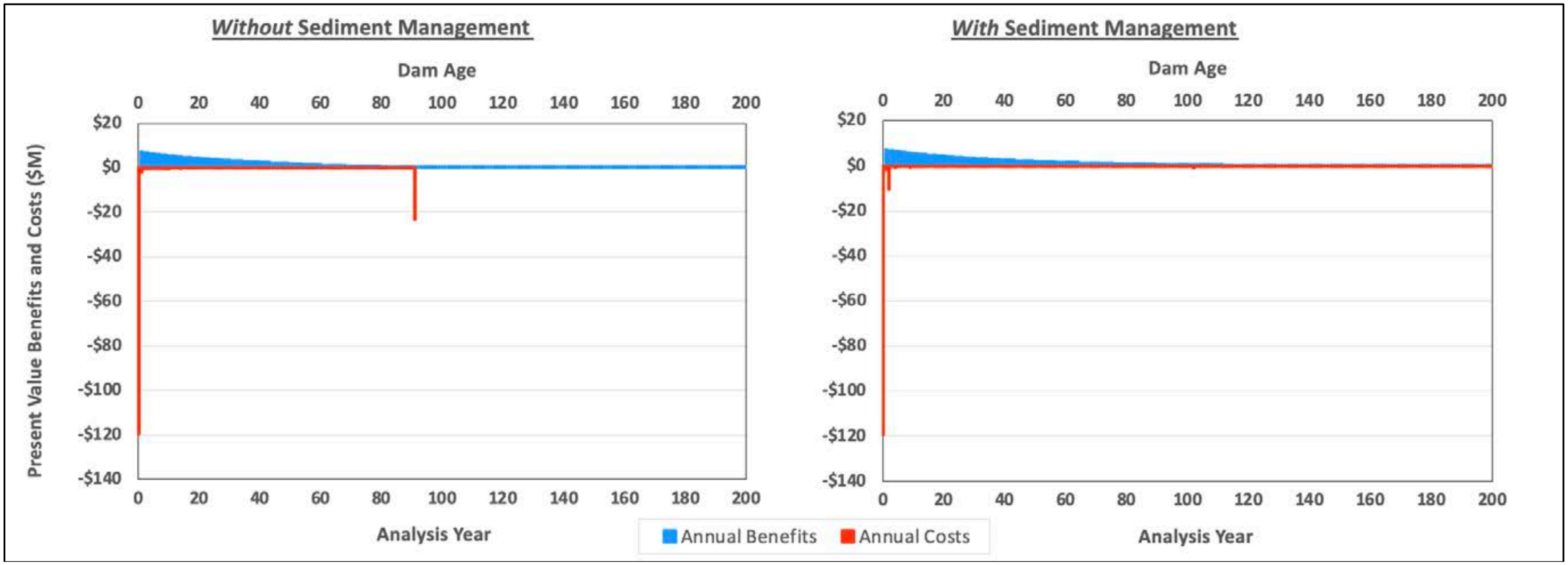


Figure 2-4.—Bar graphs of annual reservoir benefits and costs, after discounting, without and with sediment management over two centuries of reservoir operations. Benefits and costs diminish over time under exponential discounting, but they are not insignificant during the first century with an interest rate of 2.5%. Reservoir benefits end during the first century without sediment management but continue during the next century with sediment management. Note that even when discounted exponentially, the cost to decommission is still significant at analysis year 91. These graphing results are based on the Case Study inputs described in Chapter 6. Example Case Study.

2.3 RSEM Inputs

RSEM uses annual time steps to simulate reservoir sedimentation, upstream aggradation, downstream degradation, and the resulting benefits and costs. The following categories of input data are needed for RSEM simulations:

- Reservoir age, size, and inflow characteristics
- Dam characteristics
- Reservoir sedimentation characteristics
- Reservoir benefits
- Dam & reservoir planning, design, and construction costs
- Design, construction, and contract contingencies cost additives
- Operation, maintenance, and replacement costs
- Dam decommissioning costs and benefits
- Upstream sedimentation costs
- Downstream channel degradation costs
- Without sediment management alternative
- With sediment management alternative

RSEM requires 144 input parameters. A default value is provided for each of these parameters as an initial suggestion where site-specific data may not be readily available. Some default values are fixed, but most default values are dynamically linked to other input parameters specific to the simulation. The model user can easily override individual default values with site-specific data and is encouraged to do so.

Exponential discounting should be used to simulate the time-value of money (see Section 4.4.1 Discounting Benefits and Costs). For research or comparison purposes, the user may select from a choice of seven alternative different discounting approaches to account for the time-value of money. Some approaches (e.g., Ramsey, Green Book, exponential) discount benefits and costs much more rapidly than others (Gamma, Weibull, Intergenerational).

2.4 Sedimentation Model Approach

Accurate model results depend on accurate model inputs and the appropriateness of empirical methods used by RSEM to simulate reservoir sedimentation and channel degradation processes (see Chapter 2.7.). These empirical methods are adequate for most reservoirs. However, the detailed physical processes in complex reservoir geometries are more accurately simulated by one, two, or three-dimensional sediment transport models such as SRH-1D (Greimann and Huang 2018), HEC-RAS (Brunner 2021), SRH-2D (Lai 2020), and SRH-3D (Lai and Wu 2019).

RSEM uses basic information about the reservoir and predam channel geometry and the average annual inflows of water and sediment to simulate the deposition of coarse and fine sediment over time on an annual basis (Figure 1-1). Coarse sediments are assumed to form a delta across the upstream end of the reservoir. Over time, the delta grows longitudinally toward the dam and along the upstream river channel. Fine sediments are assumed to deposit along the reservoir bottom between the delta and the dam. Any sedimentation below the elevation of the dam outlet is assigned to the reservoir dead storage and any sedimentation above that elevation is assigned to the live storage.

Sedimentation in the dead storage pool (below the lowest dam outlet) does not affect the reservoir’s economic benefits, but sedimentation in the live storage pool does reduce the economic benefits over time. Therefore, RSEM keeps track of the annual sedimentation volumes in both the dead and live storage portions of the reservoir’s storage capacity. Downstream and upstream advancements of the reservoir delta over time reduces the surface area available for recreation benefits. The economic effects of downstream channel degradation are represented by the cost of streambank protection needed to preserve lands and stream-side infrastructure.

RSEM uses methods described by Strand and Pemberton (1982) to simulate the longitudinal reservoir sedimentation profiles (Section 3.1). The average-annual, reservoir-sediment inflow is computed as user-defined percentage of the original storage capacity. The top surface of the delta and lakebed sediments are assumed to deposit along user-specified slopes. Until sediments have filled the reservoir, all inflowing coarse sediments are assumed deposited within the reservoir delta. For fine sediments, the reservoir sediment trap efficiency is computed using a graph presented by Morris and Fan (1998) to determine the portion depositing along the reservoir bottom and the portion transporting past the dam to the downstream river channel. The sediment trap efficiency decreases over time as the reservoir fills with sediment.

RSEM uses the approach described by Pemberton and Lara (1984) to simulate downstream channel degradation over time. The depth of channel degradation is computed as a function of the coarse-sediment volume trapped within the upstream reservoir, the stable slope of the downstream channel, and the potential for channel armoring (Section 3.1).

The model was designed to compare the economic results of alternatives without and with sediment management. The various management alternatives (e.g., reducing the upstream sediment supply; reservoir sluicing, bypassing, dredging; turbidity current venting) are simulated by specifying the following information:

- Implementation year and capital cost
- Portion of sediments removed each year
- Amount of reservoir water used
- Annual implementation costs

2.5 Economic Model Approach

The economic benefits and costs under a given alternative are estimated as cumulative present value over the defined period of analysis (POA). These estimates are based on a set of economic assumptions and their interaction with the sediment conditions under that alternative.

RSEM accommodates benefits estimation for six beneficial uses of typical western reservoirs:

- Irrigation water supply (irrigation)
- Municipal and industrial water supply (M&I)
- Reservoir-dependent recreation (recreation)
- Hydropower production (hydropower)
- Fish and wildlife enhancement (F&W)
- Flood risk reduction (flood control)

RSEM provides default values in applicable units for each beneficial use (e.g., dollars per unit-reservoir-storage volume, dollars per visitor day). These default values represent typical benefits based on recent economic benefit studies conducted by Reclamation. However, these values can vary widely depending on many variables such as location, available substitutes, and economic factors. The RSEM user is advised to input site-specific values, as these inputs have a significant impact on model results.

Impacts to economic benefits due to sedimentation are realized through various mechanisms, namely reduction of benefits to uses that depend on:

- Water storage (e.g., irrigation)
- Reservoir surface area (e.g., recreation)
- Structures that could be buried by sediment deposits (e.g., boat ramps for recreation, dam outlets to deliver water and power)

In addition to estimating the reduction of economic benefits due to sedimentation, RSEM concurrently estimates the increased costs. In general, these include costs related to:

- Upstream sediment aggradation (e.g., lands, highways, railroads, bridges)
- Downstream channel degradation (e.g., streambank protection, habitat)
- Eventual dam decommissioning

RSEM recognizes that certain actions, such as dam decommissioning, can generate costs and benefits. In this example, the cost is the actual capital costs required to decommission the dam, while the benefits might be due to reestablishment of an ecosystem, fish passage, etc. Additionally, the authors acknowledge that there are likely costs and benefits not explicitly simulated by RSEM (e.g., unexpected costs to relocate boat ramps buried by sedimentation, rather than a loss of the associated recreation benefits for duration of the POA).

2.6 Suggested Application of RSEM

Data acquisition needed for application RSEM could be expensive and time-consuming for planning purposes. Therefore, application of RSEM, using an iterative approach, may provide useful efficiencies to reduce study time and costs.

Under an iterative approach, the user would begin model application with best available information. Some model input data may be well known with little uncertainty (e.g., dimensions of an existing dam). Some input data might be extrapolated from published studies of other, but similar dam and reservoir projects (projects) and have a moderate amount of uncertainty (e.g., economic benefits per unit storage volume or unit surface area or dimensions of a new dam). Other input data might be estimated based on professional judgement and have the greatest amount of uncertainty (e.g., channel degradation parameters, river restoration benefits of dam decommissioning). For each model input, we suggest estimating the lowest and highest values that are reasonably possible. The range of these values could be defined by cumulative probabilities (e.g., 5% and 95%).

Using best available information, preliminary model results can be inspected to determine which model inputs contribute most toward model outputs and the most sensitive model inputs. For example, determine which cost categories contribute most to total costs or which benefit categories contribute most to total benefits.

With knowledge of which model inputs contribute most toward model outputs and which inputs are most sensitive, additional studies can be undertaken to reduce uncertainty in the most important and sensitive model inputs. Some model inputs may have higher uncertainty but may not greatly contribute to model outputs. For these inputs, a relatively high uncertainty may be acceptable.

As more accurate input data become available, RSEM inputs can be updated, and the new outputs examined. This iterative approach will help focus supporting investigations on the most important model inputs and limit investigations on the least important model inputs.

2.7 RSEM Limitations

Reliable model results depend on model inputs that are accurate for the specific application. As stated in Section 2.6 (Suggested Application of RSEM), some model inputs are more important and are more sensitive than other inputs. Several supporting engineering and economic studies and investigations are needed to provide accurate model inputs and reliable results.

RSEM has the advantage that it links important time-dependent, reservoir sedimentation processes with economic analyses. However, RSEM, like all numerical models, makes simplifying assumptions which tend to reduce the accuracy of model results. While this simplification can be acceptable for planning-level studies, RSEM is not a substitute for more complex models of sedimentation processes nor site-specific economic analyses or models of project benefits. At this time, complex sedimentation and economic models are not linked.

RSEM limitations are listed below:

- RSEM evaluates economic benefits and costs to society but does not evaluate financial revenues and expenditures to specific organizations or stakeholders.
- RSEM uses annual timesteps and cannot simulate any seasonal variations in sedimentation or economics.
- RSEM assumes constant mean annual reservoir inflow and storage percent loss due to sedimentation, therefore, cannot simulate changes in reservoir inflow or sedimentation from year to year resulting from any abrupt changes.
- RSEM sedimentation and downstream channel degradation modeling are approximate and not a substitute for more complex numerical models.
- RSEM cannot simulate sedimentation profiles in tributary arms of the reservoir, only along the primary river channel.
- RSEM cost estimates of upstream sedimentation and downstream channel degradation are approximate. A unit cost is used for relocating road and railroads in aggregate. Also lost value per acre of inundated or lost land is a single unit value. In reality, land values within the project area could be quite variable.
- Benefit unit values are constant, when in fact the unit value is very dependent on the supply and demand condition. For example, a unit of water is considerably more valuable for agriculture during a drought than during a wet period.
- The parameters for alternative discounting approaches have a significant impact on results, but there is no consensus about how these should be defined or change over time.
- RSEM simulations are limited to two alternatives at a time (without and with reservoir sediment management). Additional sediment management alternatives must be simulated one at a time.
- RSEM has not yet been tested for the simulations of sediment management alternatives that attempt to recover reservoir storage capacity lost to past sedimentation. The complexities of locally reducing an existing sediment profile are more difficult to simulate than then continued growth of reservoir sedimentation at slow or fast rates. The model has been tested for simulations that attempt to maintain storage capacity.
- RSEM simulates the economic benefits from hydropower, but the algorithm is not as fully developed as the methods in RESCON 2.

3 Sedimentation Modeling

This chapter describes the methods used by RSEM to simulate reservoir sedimentation, upstream channel and floodplain aggradation, and downstream channel degradation. Reservoir sedimentation modeling also includes simulating the loss of live and dead storage and the reduction of wetted reservoir surface area over time. The simulation of these temporal changes is necessary for the modeling of economic benefits and costs (Chapter 4. Economic Modeling).

RSEM simulates the reservoir sedimentation and channel degradation each year using empirical mass-balance methods described by Strand and Pemberton (1982). The empirical mass balance methods are not as rigorous as established one-dimensional sediment transport models, such as SRH-1D (Greimann and Huang 2018) or HEC-RAS (Brunner 2021). These one-dimensional models can be used to simulate sedimentation along a series of reservoir and river cross sections, over time steps of hours or days, based on local fluid shear stress, or unit stream power, and the local sediment grain size. However, these models do not simulate economics. Using more simplified methods and annual time steps, RSEM simulates the important aspects of reservoir sedimentation and downstream channel degradation over centuries and provides an economic analysis by simulating how sedimentation processes effect benefits and costs over time.

The following sections describe the model methodology and user inputs. For details on how to specify user input data, please see Appendix A – Reservoir Sedimentation Economics Model (RSEM) User Guide.

3.1 Reservoir Modeling

RSEM simulates reservoir sedimentation using the average annual rates of water and sediment inflow from the upstream watershed and the average reservoir water surface elevation. Seasonal and year-to-year variations in reservoir inflow or water levels are not simulated. Although seasonal and year-to-year variations could be quite important for reservoir operations studies, they are not considered important for long-term economic analyses, especially when comparing the economics of alternative sediment management strategies.

Reservoir sedimentation is simulated using empirical rules to spatially distribute coarse and fine sediment deposits within the live and dead storage pools of the reservoir. Not all the inflowing sediments may deposit in the reservoir. The model estimates reservoir sediment trap efficiency each year to determine the portion of fine sediment that deposits along the reservoir bottom and the portion passing downstream. Inflowing coarse sediments are assumed to deposit within the reservoir delta until the reservoir has filled with sediment. The model will only allow the longitudinal sediment profile to fill the reservoir up to user-specified elevation at the dam. Once the sediment profile has reached the elevation limit at the dam, all subsequent inflowing sediments (coarse and fine) will be passed through the reservoir to the downstream channel. In addition, reservoir sediment management methods that pass specified sediment volumes to the downstream river channel are accounted for when quantifying downstream effects. At this time, RSEM cannot simulate one-time sediment removal strategies to recovery past decades of sedimentation. One-time sediment removal strategies may be feasible for small reservoirs, but not for large reservoirs where the sediment volumes may overwhelm the downstream channel and too large and expensive for off stream disposal.

3.1.1 Reservoir Age, Size, Inflow, and Dam Characteristics

Information about the reservoir and dam characteristics is necessary to simulate long-term sedimentation and the changing benefits and costs over time. The user specifies the base year, price level year, and the present dam and reservoir age (Table 3-1). The base year of analysis and price-level are used for economic analysis and are described in more detail in Section 4.1. All price information provided to the model must be first adjusted to the prices of the price level year. RSEM applies discounting to transform all future benefits and costs to the base year of analysis. The present age of the dam and reservoir is used to distinguish new reservoirs (age = 0) from existing reservoirs (age > 0). For existing reservoirs, previous sedimentation cannot be managed in those prior years.

Table 3-1.—User inputs of base year, price level, and reservoir age

Reservoir Year Inputs	Units	Notes
Base year for economic analysis	year	First calendar year of the period of analysis for which economic results will be presented (default is the present year)
Year that all dollar value inputs are indexed to (price level)	year	Price-level year that all benefits and costs are indexed to
Present Dam and Reservoir Age	years	An age of 0 indicates a new dam and reservoir

RSEM always simulates sedimentation from the first year the reservoir was placed in service, even for existing reservoirs where the economic analysis does not begin until the base year of analysis. The simulation of previous sedimentation in existing reservoirs provides an opportunity to calibrate sediment input parameters (sediment inflow rate and sedimentation slope) so that the simulated sedimentation profiles compare well with measured profiles.

The reservoir and dam size are defined by specifying various reservoir elevations (Table 3-2) and storage capacities (Table 3-3). Original storage capacities are specified, even for the simulation of an existing reservoir. The user specifies the original total and dead reservoir-storage capacities. RSEM then computes the live storage capacity as the difference between the total and dead storage capacities.

Table 3-2.—User inputs of original reservoir elevations

Reservoir Elevation Inputs	Units	Notes
Top of live storage	feet	Maximum (or full) reservoir pool elevation
Top limit of sedimentation	feet	Upper limit of reservoir sedimentation at the dam
Recreation pool elevation	feet	Median water surface elevation during recreation season
Normal water surface elevation	feet	Median reservoir water surface elevation over the reservoir history or the projected future
Incremental sedimentation height limit above dam outlet	feet	Sediment height above the dam outlet where impairment of operations can be expected
Sedimentation elevation limit for dam outlet function*	feet	Computed sedimentation elevation above the dam outlet where impairment of operations can be expected
Top of dead storage	feet	Invert elevation of dam outlet
Original streambed elevation	feet	Streambed elevation at dam prior to sedimentation

*Parameter computed by RSEM. This parameter can only be adjusted by changing the Incremental sedimentation height limit above dam outlet.

Table 3-3.—User inputs of original reservoir storage capacities (prior to any sedimentation)

Reservoir Storage Capacity Inputs	Units	Notes
Total storage volume at top of live storage	acre-feet	Original total storage capacity (live and dead storage)
Dead pool volume	acre-feet	Original dead storage capacity
Live pool volume*	acre-feet	Original live storage capacity

*Parameter computed by RSEM. This parameter may be overridden by the user, but the total of the dead and live storage capacities must equal the total storage volume at top of live storage.

The mean-annual reservoir inflow rate and standard deviation are specified by the model user (Table 3-4). RSEM computes the reservoir capacity to the annual-inflow ratio, annual coefficient of variation, and the 99% reliable yield.

Table 3-4.—User inputs of reservoir water inflow

Reservoir Inflow Characteristics	Units	Notes
Mean annual reservoir inflow	acre-feet/yr	Usually based on stream gage records
Standard deviation of mean annual inflow	acre-feet/yr	Usually based on stream gage statistics (RSEM computes the default value as 40% of the mean annual inflow)
Reservoir live storage capacity to inflow ratio*	dimensionless	Computed as the ratio of original live storage capacity to the mean annual inflow
Annual coefficient of variation*	dimensionless	Computed as the ratio of standard deviation to mean annual inflow
99% Reliable yield (% of mean annual flow)*	dimensionless	Computed from reservoir yield curves, mean annual inflow, and coefficient of variation
Annual water volume delivered at 99% Reliable yield*	acre-feet/yr	Computed as the product of the 99% Reliable yield and the mean annual inflow

*Parameters computed by RSEM. These parameters may be overridden by the user.

The reliable reservoir yield is used to determine the portion of live reservoir storage that can be applied to beneficial use. Interpolation of the reservoir yield curves presented by Annandale (2013) is performed to estimate the 99% reliable yield (% of mean annual flow) (Figure 3-1). The 99% reliable yield is based on the idea that a good water supply system would be able to supply water to consumers in 99 years out of 100 years on average. This acknowledges that water supply systems may not be able to fully satisfy the water demand during times of severe droughts. The reliable yield is estimated as a function of the ratio of live reservoir storage capacity to mean annual flow (MAF) and coefficient of variation. A value of 3 MAF means that the live reservoir storage is three times the mean annual flow. A value of 0.25 MAF means the storage capacity is one-quarter of the mean annual flow.

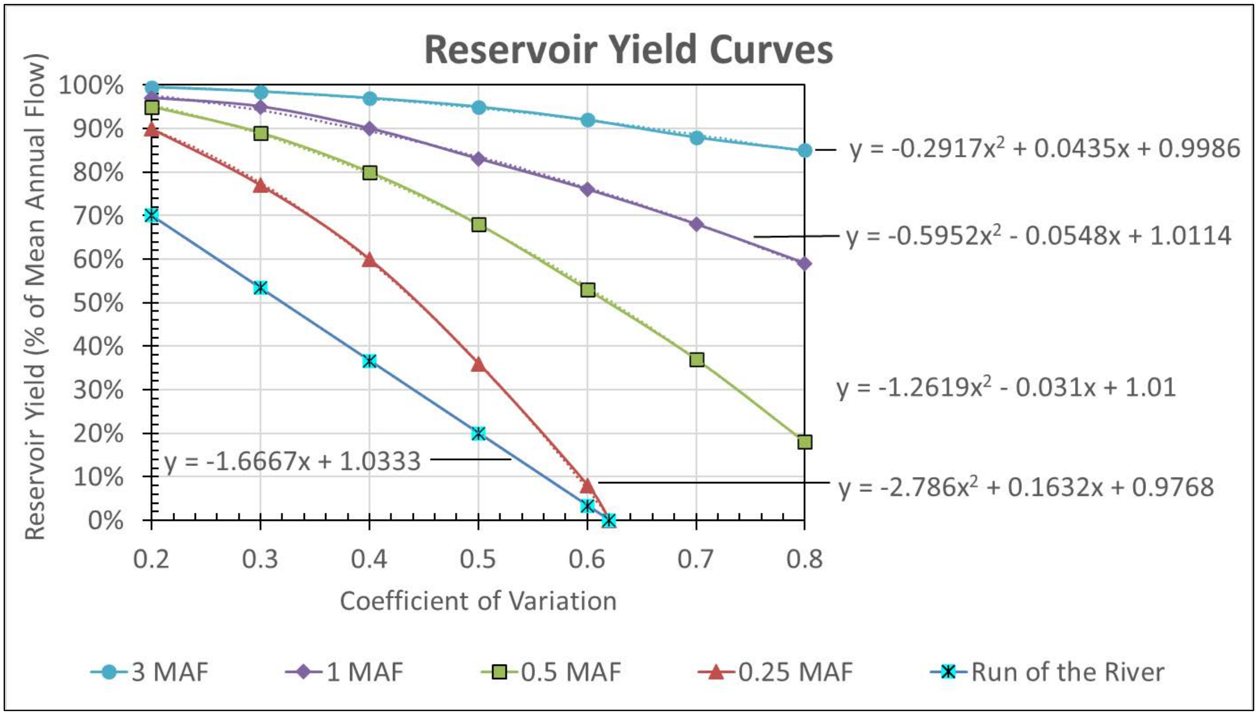


Figure 3-1.—Reservoir water yield curves at 99 percent reliability modified from Annandale (2013).

The user specifies the original reservoir valley length and wetted surface area at full pool (Table 3-5). The reservoir valley length can be measured from aerial photographs (e.g., Google Earth). The valley length is typically shorter than the original channel length, which may be meandering. RSEM computes the average surface width at the top surface of the full pool, average depth at full pool, average surface width at recreation pool, and surface area at the recreation pool. The number of boat ramps and their locations are also specified as distances upstream from the dam. The number and location of reservoir boat ramps or marinas are important for the simulation of recreation benefits, which are reduced if a boat ramp or marina becomes buried by sedimentation.

Table 3-5.—User inputs of original reservoir dimensions

Reservoir Dimensions at full pool	Units	Notes
Reservoir valley length at full pool	miles	Length of the full reservoir pool, along the valley alignment, prior to sedimentation (the original meandering channel length is not used here)
Reservoir surface area at full pool	acres	Water surface area corresponding to the full reservoir pool
Average surface width at the top surface of the full pool*	feet	Computed from the ratio of reservoir surface area over valley length
Average depth at full pool*	feet	Computed from the ratio of total reservoir storage capacity over surface area at full pool

Table 3-5.—User inputs of original reservoir dimensions

Reservoir Dimensions at full pool	Units	Notes
Average surface width at recreation pool*	feet	Interpolated from the reservoir pool elevations and computed average reservoir widths over the full range of reservoir depths
Surface area at recreation pool El.*	acres	Interpolated from the reservoir pool elevations, computed average-recreation-pool width, and predam river slope
Number of boat ramps or marinas		The number of boat ramps or marinas that may be simulated by RSEM is 0, 1, or 2 (If there are more than two boat ramps, specify the two ramps most likely to be impacted by sedimentation)
Boat ramp/marina #1 distance upstream from dam	miles	Distance to upstream most boat ramp (no value is provided if there is no boat ramp/marina)
Boat ramp/marina #2 distance upstream from dam	miles	Distance to downstream most boat ramp (no value is provided if there is no boat ramp/marina)

*Parameters computed by RSEM. These parameters may be overridden by the user.

The user specifies basic dam characteristics, such as the type (e.g., earth, rockfill, concrete gravity, concrete arch, concrete buttress), volume of material, hydraulic height, and crest length across the river (Table 3-6). The size of the dam is important for estimating the cost of dam decommissioning should the reservoir experience severe sedimentation.

Table 3-6.—User inputs of dam characteristics

Dam Characteristic Inputs	Units*	Notes
Dam type		Earth, rockfill, concrete gravity, concrete arch, concrete buttress (choose from a drop-down list)
Volume of dam material	yd^3	Volume of dam material that would have to be removed at dam decommissioning
Hydraulic height	feet	Elevation difference between the top of live storage (full reservoir water surface) and original streambed
Dam crest length across river	feet	Crest length of dam across the river

*yd^3 = cubic yards

In summary, the basic geometry of the dam and reservoir is defined using the inputs listed in Table 3-2 through Table 3-6, which is represented in the longitudinal profiles presented in Figure 2-2.

3.1.2 Upstream Sediment Supply Rate

The upstream sediment supply rate delivered to the reservoir, along with the sediment trap efficiency, are used to determine the sedimentation rate. The average annual sediment inflow rate is specified as a percentage of the reservoir storage capacity. Graf et al. (2010) found that average annual sedimentation rates ranged between 0.4 and 2 percent of the reservoir storage capacity for the small reservoirs they investigated. For larger reservoirs (greater than 100,000 acre-feet), Randle et al. (2019) estimated annual sedimentation rates of 0.1, 0.2, and 0.5 percent of the storage capacity, based on experience with federal reservoirs. The user can directly specify the annual sedimentation rate, especially if measured from past sedimentation surveys, or estimated from sediment yield maps, or sedimentation studies.

In addition to the average-annual sediment-inflow rate (percentage of storage capacity), the user specifies the portion that is fine sediment (clay and silt). Based on these inputs, RSEM computes the remaining portion of coarse sediment inflow, initial reservoir sediment trap efficiency, and the volumetric rates of total, fine, and coarse sediment inflows (Table 3-7).

Table 3-7.—User inputs of average annual sediment inflow rate

Sediment Inflow Rate Inputs	Units	Notes
Annual storage loss (as a percent of full pool volume) due to sedimentation	dimensionless	Typically, 0.4, 1, or 2 percent for small reservoirs (<100,000 acre-feet) or 0.1, 0.2, and 0.5 percent for large reservoirs (≥100,000 acre-feet)
Fine sediment percentage (clay and silt)	dimensionless	Typically, between 60 and 90 percent
Coarse sediment percentage (sand and gravel)*	dimensionless	Computed from fine sediment portion
Initial fine sediment trap efficiency*	dimensionless	Interpolated using method published by Morris and Fan (1998)
Annual total sedimentation rate*	acre-feet/yr	Computed using annual storage percent loss
Annual fine sedimentation rate*	acre-feet/yr	Computed using annual sedimentation rate and fine sediment portion
Annual coarse sedimentation rate*	acre-feet/yr	Computed using annual sedimentation rate and coarse sediment portion

*Parameters computed by RSEM. These parameters may be overridden by the user.

3.1.3 Reservoir Sedimentation Profile Slopes

Each year of the simulation, RSEM computes the reservoir sedimentation profile based on the original reservoir bottom slope, cumulative sedimentation volume, and the sediment deposition profile slopes that are specified by the user. RSEM makes the simplifying assumption that the delta is composed entirely of coarse sediment while the reservoir bottom is composed entirely of fine sediments. In reality, some fine sediments will deposit with coarse sediments in the delta (Morris and Fan 1998). Although reservoir bottomset is primarily composed of fine sediment, coarse sediments can deposit on the bottomset during times of delta erosion (during reservoir drawdown and floods) and from tributaries entering the downstream portion of the reservoir. RSEM is not able to simulate these complexities.

Coarse sediments entering the reservoir are assumed to deposit first and form a delta at the upstream end associated with the normal water surface elevation. The user specifies the topset and foreset slopes of the delta (Figure 3-2). Strand and Pemberton (1982) reported that the delta topset slope is typically 50 percent of the predam river channel slope. Alternatively, the topset slope could be computed using a sediment transport equation with the assumption that the slope is mild enough that bed-material is no longer being transported. For an existing reservoir, the measured topset slope should be specified, if known. Otherwise, use the measured topset slope from another reservoir in a similar setting or use the default ratio of topset slope to predam slope (0.5).

Strand and Pemberton (1982) reported that the average foreset slope in Reclamation’s reservoirs was 6.5 times greater than the topset slope, but that the foreset slope in some reservoirs can be much steeper. For example, the foreset slope in Lake Mead was reported to be 100 times steeper than the topset slope.

RSEM assumes that the location of the pivot point (intersection between the topset and foreset slope) is a function of reservoir’s normal water surface (NWS) elevation (Strand and Pemberton, 1982), which is less than the maximum water surface (MWS) elevation (Figure 3-2). Considerable reservoir drawdown will allow river inflows to incise a channel through the reservoir delta with redeposition within the drawn down reservoir pool. Seasonal, or year-to-year, reservoir drawdown will lower the normal reservoir water surface elevation and the elevation of the delta pivot point. The complexities associated with reservoir drawdown and incision are not simulated by RSEM. However, specification of the normal water surface elevation accounts for some of these processes.

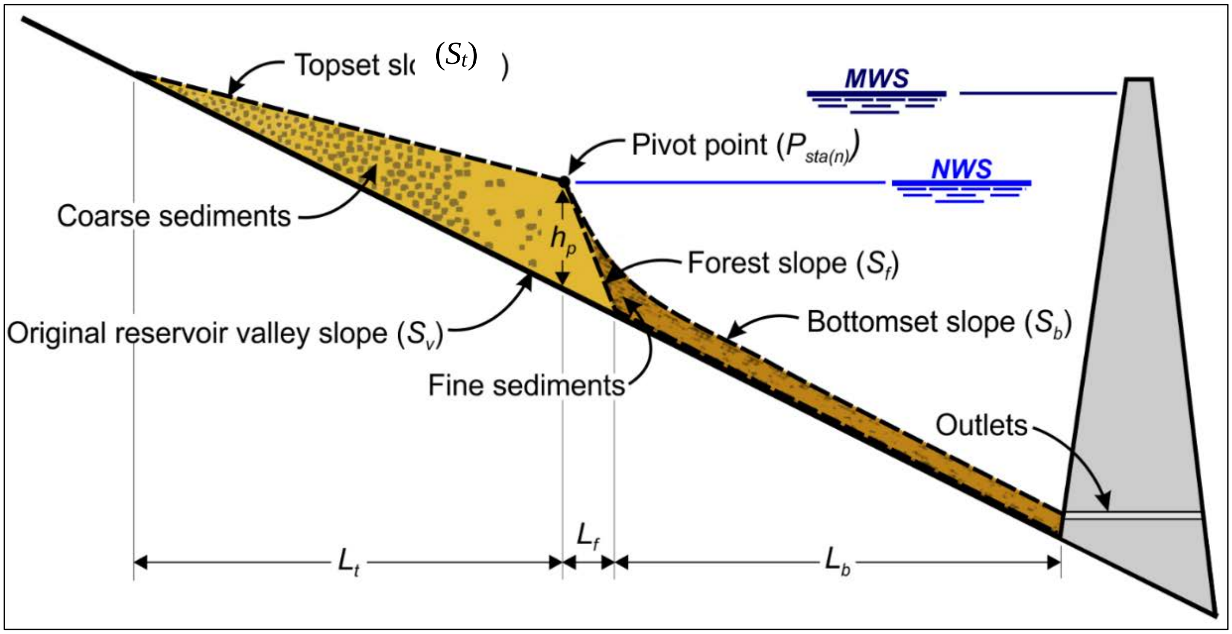


Figure 3-2.—Reservoir sedimentation profile of the delta and reservoir bottomset sediments (modified from Strand and Pemberton, 1982). The topset and foreset slopes define the delta profile and the pivot point between these two slopes. The elevation of the pivot point is typically equal to the normal water surface (NWS) elevation, which is lower than the maximum water surface elevation (MWS). The bottomset slope defines the geometry of the fine reservoir bottom sediments.

For many reservoirs, the bottomset slopes are parallel to the predam river slope. However, the bottomset slope may be flatter (e.g., the bottomset slope could be 10 percent of the predam channel slope) when turbid density currents are present or with considerable reservoir drawdown.

The user specifies the reservoir sedimentation slopes as a function of the predam river channel slope and delta topset slope (Table 3-8). User-specified longitudinal slopes of the delta topset and foreset are assumed to be constant throughout the simulation, with some adjustments to transition between delta and lakebed. If the deposition thickness of fine sediments along the reservoir bottom begins to exceed the delta thickness at the pivot point, then the pivot point elevation is adjusted upward to match the fine sediment thickness.

Table 3-8.—User inputs of reservoir sedimentation profile slope parameters

Sedimentation Profile Slope Parameters	Units	Notes
Delta topset slope factor	dimensionless	Multiplier of the predam river channel slope. A typical value is 0.5.
Delta foreset slope factor	dimensionless	Multiplier of the delta topset slope. A typical value is 6.5.
Bottomset slope factor, c_s	dimensionless	Multiplier of the predam river channel slope. Typical values range from 0.1 to 1.
Reservoir profile plotting interval for a total of 10 profile plots	Years between 10 profile plots	For example, a value of 1 would produce a profile plot every year for the first ten years, while a value of 10 would produce a profile plot every decade for the first 100 years.

3.1.4 Predam River Channel and Degradation Parameters

Information about the predam river channel is needed to simulate the potential for downstream degradation due to the trapping of coarse sediment within the reservoir and downstream release of clear water. For the predam channel, the user specifies the sinuosity (ratio of channel length to valley length) and average values of bankfull width, bank height, and roughness (Table 3-9). RSEM uses these values to compute the longitudinal channel slope, average bankfull flow velocity and discharge, and the ratio of bankfull discharge to the mean annual flow. The predam slope is computed from the hydraulic height of the dam, reservoir valley length, and channel sinuosity.

The user also specifies basic information about the potential for downstream channel bed armoring and degradation. This information includes the percentage of bed material that is armor size or coarser, the necessary armor layer thickness, and the reduction in longitudinal slope needed to achieve a stable channel. These parameters can be computed using a sediment transport equation (Pemberton and Lara, 1984) or estimated based on professional judgement.

Table 3-9.—User inputs of Predam River Channel and Degradation Parameters

Predam River Channel and Degradation Parameters	Units	Notes
Channel sinuosity	dimensionless	Ratio of channel length to valley length (typical values range between 1 and 3)
Longitudinal channel slope*	dimensionless	Predam average channel slope computed from the reservoir hydraulic height, reservoir valley length, and channel sinuosity
Average bankfull channel width	feet	Average wetted channel width during the bankfull discharge
Average flow depth at bankfull discharge	feet	Average flow depth during the bankfull discharge (the flow depth could be less than the bank height of previously degraded channels)

Table 3-9.—User inputs of Predam River Channel and Degradation Parameters

Predam River Channel and Degradation Parameters	Units	Notes
Average channel roughness (Manning's *n* coefficient)		Average Manning's *n* roughness coefficient is typically between 0.020 and 0.045
Average streamflow velocity*	ft/s	Average streamflow velocity at the bankfull discharge based on Manning's equation assuming normal depth
Bankfull discharge*	ft^3/s	Streamflow rate at the bankfull discharge
Percentage of bed material that is armor size or coarser	dimensionless	Percentage of bed material that is too large to be transported downstream
Armor layer thickness	feet	The necessary thickness of armor size material to protect the underlying material from being eroded and transported downstream
Percentage reduction in the original downstream channel slope needed to achieve stability	dimensionless	Channel degradation results in a stable channel after the original channel slope has been reduced by a certain percentage
Percentage of original downstream channel slope that would remain after stability has been achieved[a]	dimensionless	Channel degradation results in a stable channel after the longitudinal slope has been reduced to a certain percentage of the original slope

*Parameters computed by RSEM. These parameters may be overridden by the user.
[a]Parameter computed by RSEM. This parameter may not be changed.

3.1.5 Reduced Storage Over Time

If not managed, sedimentation will reduce the reservoir storage capacity over time. For each year of simulation, RSEM computes the volumes of inflowing coarse and fine sediment that will deposit within the reservoir and the volumes removed due to any sediment management (Figure 3-3). All the inflowing coarse sediment is assumed to deposit in the delta while the sediment trap efficiency is used to determine the portion of fine sediment that deposits along the reservoir bottomset (between the delta and dam). The computation of reservoir sediment trap efficiency is updated each year using the method described by Morris and Fan (1988) (see 3.1.7 Sediment Trap Efficiency).

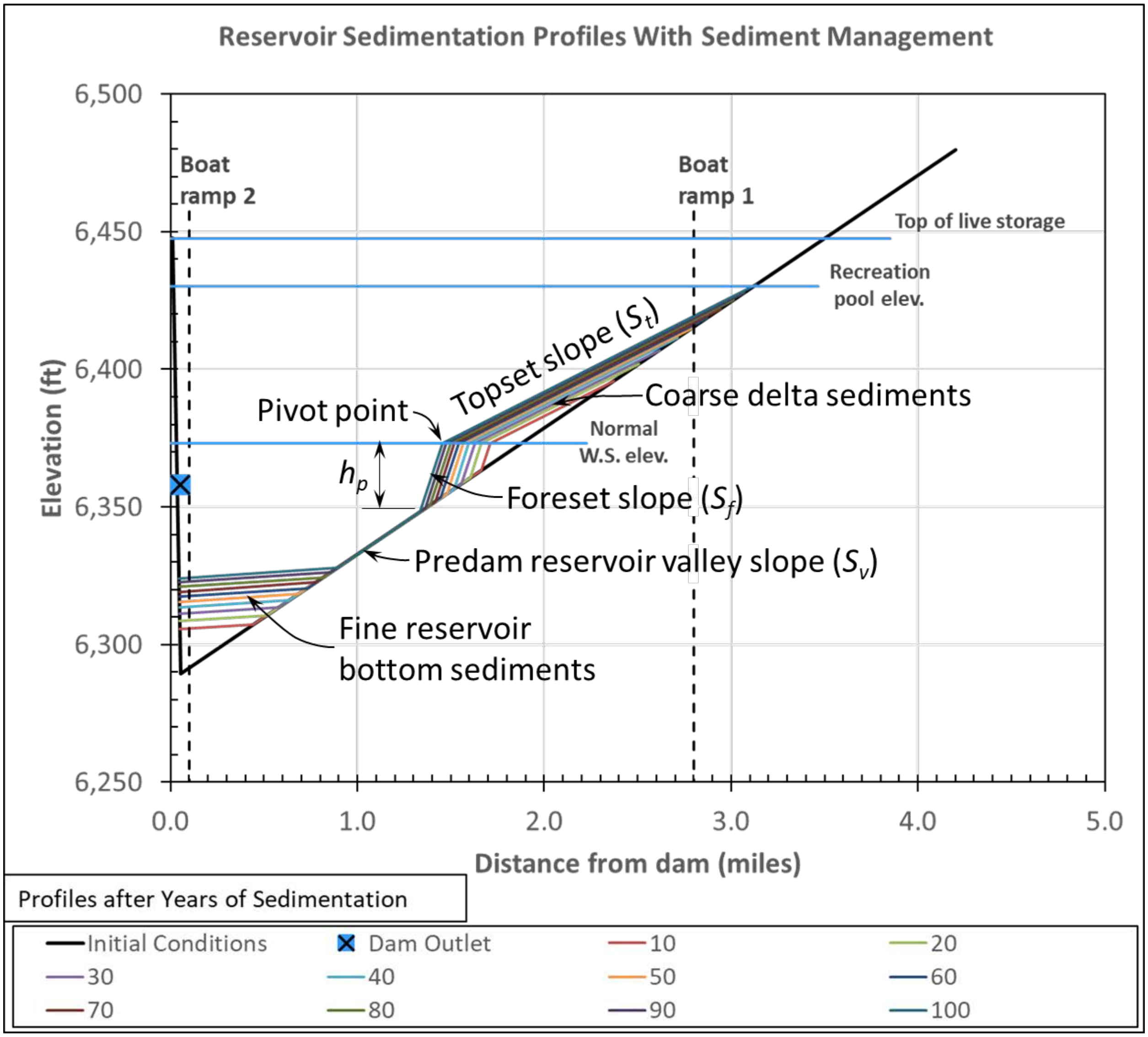


Figure 3-3.—Example reservoir sediment profiles simulated by RSEM.

For each year of simulation, the maximum delta thickness (h_p), at the pivot point, is computed from Equation 1. The units of Equation 1, and subsequent equations, must be consistent (e.g., either cubic feet [ft^3] and feet [ft] or cubic meters [m^3] and meters [m]). If the sediment volume is in acre-feet, then it must be converted to ft^3 (multiply by 43,560 square feet per acre [ft^2/acre]):

$$h_{p(n)_o} = \sqrt{\frac{2V_{c(n)}}{W_{S(n-2)}\left(\frac{1}{tan\left(R_{S_v} - R_{S_t}\right)} + \frac{1}{tan\left(R_{S_f} - R_{S_v}\right)}\right)}}S \qquad (1)$$

$$h_{p(n)} = \frac{h_{p(n)_0}}{\cos\left(R_{S_v}\right)}$$

Where:

$h_{p(n)}$ = maximum delta vertical thickness located at the pivot point, *p* during year *n*

$h_{p(n)o}$ = maximum delta orthogonal thickness located at the pivot point, *p* during year *n*

$V_{c(n)}$ = cumulative volume of coarse sediment deposition in the delta during year *n*

$W_{s(n-2)}$ = average width of reservoir sedimentation two years prior (during year *n-2*)

S_o = longitudinal predam channel slope

S_v = longitudinal predam reservoir valley slope

S_t = longitudinal delta topset slope = $a_s\ S_o$, where a_s is a user defined factor (e.g., 0.5)

S_f = longitudinal delta foreset slope = $b_s\ S_t$, where b_s is a user defined factor (e.g., 6.5)

$R_{S_v} = \tan^{-1}(S_v)$ = angle of reservoir valley slope in radians

$R_{S_t} = \tan^{-1}(S_t)$ = angle of reservoir topset slope in radians

$R_{S_f} = \tan^{-1}\left(S_f\right)$ = angle of foreset slope in radians

RSEM needs a sedimentation width ($W_{s(n-2)}$) that is averaged over the length and depth of the reservoir sediment. RSEM uses the sedimentation width from two years prior to avoid a circular reference. For each year of simulation, the average sedimentation width is linearly interpolated (or extrapolated), based on the total sedimentation volume, average reservoir widths at the top of live storage and dead storage, and the original storage capacities at the top of live storage and dead storage (Equation 2).

$$W_{s(n-2)} = \left(\frac{W_L - W_D}{C_L - C_D}\right)V_{T(n-2)} + \left[W_D - \left(\frac{W_L - W_D}{C_L - C_D}\right)C_D\right] \qquad (2)$$

Where:

$W_{s(n-2)}$ = average width of reservoir sedimentation (integrated over length and depth) two years prior (during year *n-2*)

W_L = average reservoir width (integrated over length and depth) associated with the original top of live storage capacity (at top of the live storage pool) (Equation 3)

W_D = average reservoir width (integrated over length and depth) associated with the original dead storage capacity (at top of dead storage pool) (Equation 4)

C_L = original total reservoir storage capacity (at the top of the live storage pool)

C_D = original dead reservoir storage capacity (at the top of the dead storage pool)

$V_{T(n-2)}$ = the total sedimentation volume two years prior (during year *n*-2)

$$W_L = \frac{2C_L}{L_L H_L} = \frac{2C_L S_v}{H_L^2} \tag{3}$$

Where:

L_L = reservoir valley length along the maximum pool elevation

H_L = hydraulic height of the dam for the original full reservoir pool

$$W_D = \frac{2C_D}{L_D H_D} = \frac{2C_D S_v}{H_D^2} \tag{4}$$

Where:

L_D = reservoir valley length along the original dead storage pool

H_D = hydraulic height of the original dead storage pool

The cumulative volume of coarse sediment comprising the delta is computed from the average annual rate of coarse sediment inflowing to the reservoir times the age of the reservoir, minus the annual rate of any forced or planned sediment management times the coarse portion of sediment removed (Equation 5).

$$V_{c(n)} = R_c T - S_{MGT} P_c \tag{5}$$

Where:

$V_{c(n)}$ = Cumulative coarse sediment volume comprising the delta in year *n*

T = time, in years since original filling of the reservoir

R_c = annual rate of coarse sediment inflow

S_{MGT} = annual rate of forced or planned sediment management removal

P_c = coarse portion of reservoir sediment that is removed

The delta topset and foreset lengths are computed using Equations 6 and 7:

$$L_{t(n)} = \frac{\left[\dfrac{-h_{p(n)}}{tan\left(R_{s_t}\right)}\right]}{\left[1 - \dfrac{tan\left(R_{s_v}\right)}{tan\left(R_{s_t}\right)}\right]} \tag{6}$$

Where: $L_{t(n)}$ = the delta topset length in year *n*

$$L_{f(n)} = L_{t(n)} = \frac{\left[\dfrac{-h_{p(n)}}{tan\left(R_{s_f}\right)}\right]}{\left[1 - \dfrac{tan\left(R_{s_v}\right)}{tan\left(R_{s_f}\right)}\right]} \tag{7}$$

Where: $L_{f(n)}$ = the delta foreset length in year *n*

The pivot point location is computed from Equation 8 or Equation 9:

$$P_{sta(n)} = \frac{H_d D_\alpha - h_p}{S_v}; \quad when\ H_d D_\alpha > h_p \tag{8}$$

$$P_{sta(n)} = 0.99\ P_{sta(n-1)}; \quad when\ H_d D_\alpha \leq h_p \tag{9}$$

Where:

$P_{sta(n)}$ = stationing or distance from the dam to delta the pivot point in year n

H_d = hydraulic height of dam

D_α = dimensionless depth of the normal reservoir water surface at the dam relative to dam’s hydraulic height (Equation 10)

$$D_\alpha = \frac{(El_{NWS} - El_o)}{(El_L - El_o)} \tag{10}$$

Where

El_{NWS} = normal reservoir water surface elevation

El_L = top of live reservoir pool elevation

El_o = elevation of original streambed at dam

The elevation of the pivot point is initially equal to the normal reservoir water surface elevation, which is a user input in RSEM. As the bottomset volume becomes large enough to merge with the delta, RSEM sets the elevation of the delta foreset to match the upstream elevation of the bottomset. If the bottomset elevation of a previous year exceeds the normal water surface elevation, RSEM sets the elevation of the delta pivot point to match the bottomset elevation of the previous year, which is also the same as the delta foreset elevation of the previous year. RSEM uses the previous year to avoid a circular reference. Therefore, the pivot point elevation is set equal to the maximum of normal water surface elevation or the delta foreset elevation of the previous year (Equation 11).

$$P_{El(n)} = \max\left\{El_{NWS},\ \ El_{f(n-1)}\right\} \tag{11}$$

Where:

$P_{El(n)}$ = elevation of delta pivot point in year n

$El_{f(n-1)}$ = elevation of the delta foreset from the previous year (see Equation 22 described later)

The cumulative volume of fine sediment comprising the reservoir bottom (V_f) is computed from the fine sediment volume from the previous year, plus the average annual rate of fine sediment inflowing to the reservoir times the sediment trap efficiency for that year, minus the annual rate of any forced or planned sediment management times the fine portion of fine sediment removed (Equation 12).

$$V_{f(n)} = V_{f(n-1)} + R_f T_{eff(n)} - S_{MGT} P_f \qquad (12)$$

Where:

$V_{f(n)}$ = cumulative fine sediment volume comprising the reservoir bottom in year *n*

$V_{cfn-1)}$ = cumulative fine sediment volume in the previous year (*n*-1)

R_f = annual rate of fine sediment inflow

$\mathrm{T}_{\mathrm{eff(n)}}$ = reservoir sediment trap efficiency in year *n*

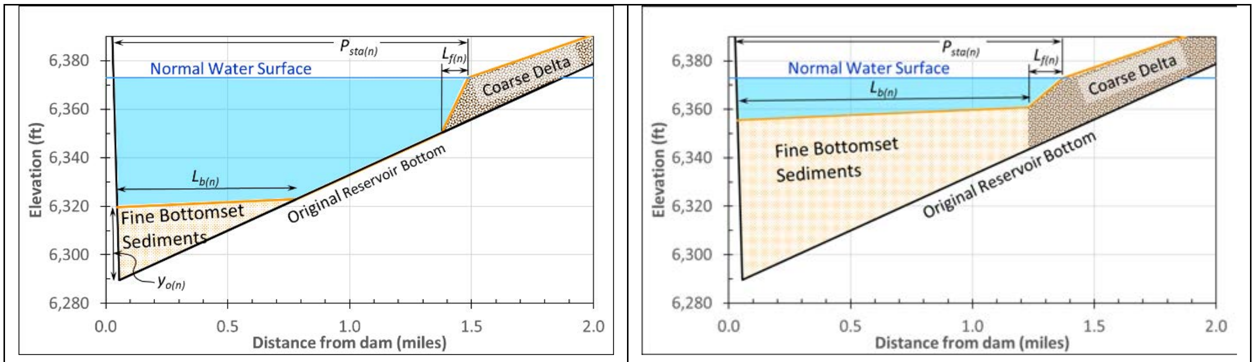
S_{MGT} = annual rate of forced or planned sediment management removal

P_f = fine portion of sediment removed from the reservoir

Once the delta dimensions (height, $h_{p(n)}$, and lengths of topset, $L_{t(n)}$ and foreset, $L_{f(n)}$) have been computed for given year, RSEM computes the stations and elevations of the reservoir sediment profile for the bottomset, foreset, and topset.

RSEM allows the fine sediment to deposit along the reservoir bottom at a different longitudinal slope (Bottomset slope, S_b) than the original streambed slope (S_o). When the two longitudinal slopes are the same, the sediment deposition thickness will be the same everywhere. However, when the slopes are not the same, two different fine sediment profile cases need to be considered:

1. Sedimentation is thickest at the dam and has a zero thickness at the upstream extent of the deposit, which has not yet reached the delta foreset (Figure 3-4, Case 1).
2. Sedimentation is thickest at the dam, but the bottomset has reached the upstream delta foreset and has a thickness greater than zero (Figure 3-4, Case 2).



Case 1 **Case 2**

Figure 3-4.—Bottomset sediment profiles: Case 1, where bottomset sediments have not yet reached the upstream delta and Case 2, where bottomset sediments have reached the upstream delta foreset.

For Case 1, where bottomset sediments have not yet reached the upstream delta foreset, the thickness of fine sediment against the dam is computed from the fine sediment volume, sedimentation length, and average reservoir width (Equation 13). The sedimentation length is also computed from these same variables and the longitudinal slopes of the original reservoir valley bottom (Equation 14).

$$y_{o(n)} = \frac{2\,V_{f(n)}}{L_{b(n)}\,W_{s(n-2)}} \quad < y_{o(max)} \tag{13}$$

Where:

$y_{o(n)}$ = fine sediment thickness at the dam, at year n

$L_{b(n)}$ = longitudinal length of fine sediment deposit, at year n

$y_{o(max)}$ = maximum allowable sediment deposition thickness at the dam (user defined)

$$L_{b(n)} = \left[\frac{2 \quad V_{f(n)}}{W_{s(n-2)}(S_v - S_b)}\right]^{0.5} \quad \le \left(P_{sta(n)} - L_{f(n)}\right) \tag{14}$$

Where:

S_b = longitudinal bottomset slope = $c_s S_o$, where c_s is a user defined coefficient (Table 3-8)

$L_{f(n)}$ = delta foreset length

When the longitudinal bottomset slope is significantly less than the original reservoir valley bottom slope, RSEM would apply Case 1 so long as the fine sedimentation volume does not extend all the way to the upstream delta. RSEM uses Equation 15 for each year of the simulation to determine when Case 1 applies. Otherwise, Case 2 applies.

$$\text{Case 1 when:} \quad \frac{S_b}{S_v} \geq \left(1 - \frac{y_{o(n)}}{S_v\, L_{b(n)}}\right); \quad \text{Otherwise, Case 2} \tag{15}$$

For case 2, where fine sediment deposition extends the entire distance between the dam and delta foreset, the thickness of fine sediment against the dam is computed from the fine sediment volume, sedimentation length, average reservoir width, original streambed slope, and bottomset slope (Equation 16).

$$y_{o(n)} = \frac{V_{f(n)}}{L_{b(n)}\, W_{s(n-2)}} - \frac{(S_b - S_v)L_{b(n)}}{2} < y_{o(max)} \tag{16}$$

Where:

$y_{o(n)}$ = bottomset sediment thickness at the dam

$L_{b(n)}$ = longitudinal length of bottomset sediment between dam and delta foreset (Equation 17)

$$L_{b(n)} = P_{sta(n)} - L_{f(n)} \tag{17}$$

The bottomset sediment thickness at the delta foreset is computed from thickness at the dam and the longitudinal slopes of the original streambed and bottomset (Equation 18).

$$y_{Delta(n)} = y_o + (S_v - S_b)L_f \tag{18}$$

Where:

$y_{Delta(n)}$ = bottomset sediment thickness at the delta foreset

The station for the bottomset sediment against the dam is always set to zero. The elevation of sediment against the dam is computed using Equation 19:

$$El_{Dam(n)} = Y_{o(n)} + El_o \tag{19}$$

Where:

$El_{Dam(n)}$ = elevation of sediment against the upstream face of the dam

The station for the upstream end of bottomset ($Bottomset_{Sta(n)}$) is set equal to the length of the bottomset ($L_{f(n)}$). The elevation for this bottomset is location is computed using Equation 20:

$$El_{b(n)} = El_{Dam(n)} + L_{f(n)}\, S_b \tag{20}$$

Where:

$El_{b(n)}$ = elevation of bottomset sediment at or near the delta foreset toe

If the computed station, or elevation, for the toe of the delta foreset is less than the upstream end of the bottomset, then the station, or elevation, of the delta foreset toe is set equal to the bottomset station or elevation.

The station and elevation for the toe of delta foreset is computed using Equations 21 and 22:

$$Foreset_{Sta(n)} = P_{sta(n)} - L_{f(n)} \tag{21}$$

$$El_{f(n)} = \left(Foreset_{Sta(n)}\right) S_v + El_o \tag{22}$$

The station and elevation for the upstream-most portion of the delta topset (Figure 3-3), where it intersects the predam reservoir valley, is computed using Equations 33 and 24:

$$Topset_{Sta(n)} = P_{sta(n)} + L_{t(n)} \tag{23}$$

$$El_{t(n)} = \left(Topset_{Sta(n)}\right) S_v + El_o \tag{24}$$

Where:

$Topset_{Sta(n)}$= station of delta topset where it intersects the original reservoir valley bottom in year *n*

$El_{t(n)}$= elevation of delta topset, where it intersects the original reservoir valley, in year *n*

3.1.6 Reduced Surface Area over Time

Delta sedimentation will reduce the surface area for recreation over time and, without intervention, will eventually bury reservoir boat ramps or marinas. Initially, delta sedimentation may be entirely contained within the reservoir pool and mostly below the water surface elevations normally used for recreation.

For each year of the simulation, RSEM computes the surface area of the recreation pool and chooses the appropriate equation, depending on the pool elevation relative to the reservoir delta. In the case where the recreation pool is above the delta topset, RSEM assumes that the original surface area of the recreation pool remains unchanged ($A_{R(n)} = A_{Ro}$).

In the case where the recreation pool intersects with the delta topset (i.e., above the pivot point, $El_R > P_{El(n)}$, and below the upstream end of the delta topset, $El_R < El_{t(n)}$), RSEM uses Equation 25 to compute the surface area of the recreation pool:

$$A_{R(n)} = \left\{\left[\frac{\left(El_R - P_{El(n)}\right)}{\left(El_{t(n)} - P_{El(n)}\right)}\right]\left(Topset_{sta(n)} - P_{sta(n)}\right) + P_{sta(n)}\right\} W_R \tag{25}$$

Where:

$A_{R(n)}$ = reservoir surface area at the recreation pool in year *n*

$A_{R(o)}$ = original reservoir surface area at the recreation pool when the reservoir was new

El_R = elevation of the typical reservoir recreation pool

$P_{El(n)}$ = elevation of delta pivot point in year *n*

$P_{sta(n)}$ = station of delta pivot point in year *n*

$El_{t(n)}$ = elevation of the delta topset at the upstream most extent in year *n*

$Topset_{sta(n)}$ = station of the delta topset at the upstream most extent in year *n*

W_R = Reservoir average surface width at the recreation pool elevation (Equation 28)

In the case where the recreation pool intersects the delta foreset (i.e., below the delta pivot point, $El_R < P_{El(n)}$ and above the foreset toe, $El_R > El_{f(n)}$), RSEM uses Equation 26 to compute the surface area of the recreation pool:

$$A_{R(n)} = \left\{\left[\frac{\left(El_R - El_{f(n)}\right)}{\left(P_{El(n)} - El_{f(n)}\right)}\right]\left(P_{sta(n)} - Foreset_{sta(n)}\right) + Foreset_{sta(n)}\right\} W_R \tag{26}$$

In the case where recreation pool intersects the original reservoir valley bottom below the delta foreset and above the bottomset (i.e., below the delta foreset ($El_R < El_{f(n)}$ and above the bottomset, $El_R > El_{b(n)}$), RSEM assumes that the original surface area of the recreation pool remains unchanged ($A_{R(n)} = A_{Ro}$).

In the case where the recreation pool intersects the bottomset sediments ($El_R < El_{b(n)}$), RSEM uses Equation 27 to compute the surface area of the recreation pool:

$$A_{R(n)} = \left\{\left[\frac{\left(El_R - El_{Dam(n)}\right)}{\left(El_{b(n)} - El_{Dam(n)}\right)}\right]\left(L_{b(n)}\right)\right\} W_R \tag{27}$$

The average reservoir surface width corresponding recreation pool is computed using Equation 28.

$$W_R = \frac{\left[\frac{(El_R - El_{Dead})}{(El_L - El_{Dead})}(W_L - W_D) + W_D\right] W_{SL}}{W_L} \tag{28}$$

Where:

W_{SL} = average reservoir surface width at top of live storage

RSEM assumes that reservoir boat ramps or marinas are no longer useable when the sedimentation level reaches the elevation of the recreation pool at the location of a given boat ramp or marina. RSEM checks for this condition each year.

3.1.7 Sediment Trap Efficiency

The reservoir sediment trap efficiency is a metric for the portion of inflowing fine sediments that are trapped within the reservoir during a particular time period (Morris and Fan 1998). All sediment particles are heavier than water and will tend to settle over time. However, flow turbulence, even in a reservoir, can keep fine sediment particles in suspension for a finite period. In reservoirs, there normally isn't enough turbulence to keep coarse sediment particles in suspension, so these particles tend to settle along the delta at the upstream end of the reservoir.

RSEM applies the sediment trap efficiency to the annual volume of inflowing fine sediment to determine the portion that will deposit within the reservoir and the remaining portion that will transport through the reservoir to the downstream channel. As the reservoir fills with sediment over time, the remaining storage capacity and trap efficiency reduce.

Each year of the simulation, RSEM estimates the trap efficiency for fine sediment based on the ratio of the remaining reservoir storage capacity to the mean annual stream inflow and the trap efficiency curve presented by Morris and Fan (1998) (Figure 3-5). The capacity to inflow ratio has units of years and is computed using Equation 29.

$$\text{Capacity to Inflow Ratio} = \frac{\text{Remaining Storage Capacity}}{\text{Mean Annual Inflow}} \tag{29}$$

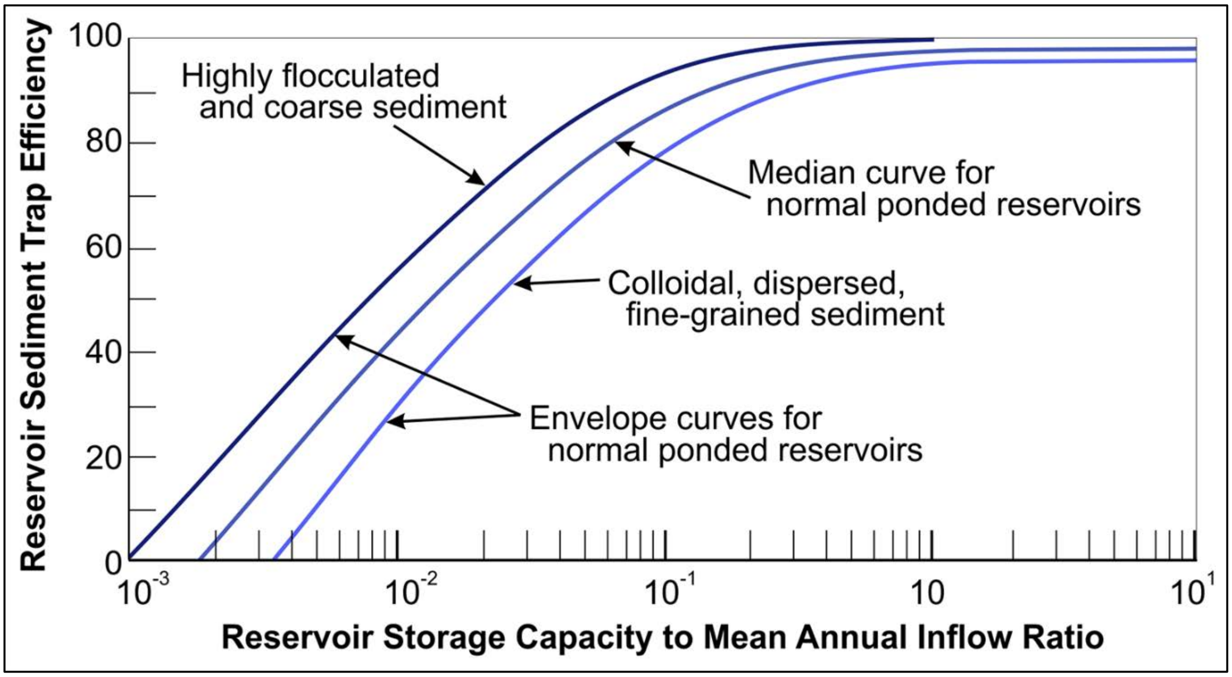


Figure 3-5.—Reservoir sediment trap efficiency curve modified from Morris and Fan (1998).

After severe sedimentation, RSEM eventually precludes the deposition of additional coarse or fine sediment. RSEM assumes the reservoir can no longer trap sediment once the sedimentation level at the dam exceeds the user-defined top limit of sedimentation. In this case, RSEM passes all inflowing coarse or fine sediments through the reservoir and past the dam site.

3.2 Upstream Sedimentation Modeling

Reservoir delta sedimentation typically extends upstream from the full reservoir pool and may impact upstream property, highways, railroads, and the passage of fish and boats. Sedimentation increases flood stage and groundwater elevations of surrounding lands. The thickness of upstream sedimentation is greatest at the reservoir interface and decreases in the upstream direction (Figure 3-6).

Upstream delta sedimentation may affect fish and boat passage when surface-water stream flows infiltrate the coarse sediments (alluvium) and continue downstream as groundwater (instead of surface flow) during periods of reservoir drawdown. Fish and boat passage is also affected when waterfalls form over bedrock ledges or steep rapids form over erosion-resistant surfaces. Sedimentation can force river channels to the far margins of the valley. If these realigned channels incise during reservoir drawdown, they may encounter bedrock ledges or erosion-resistant surfaces.

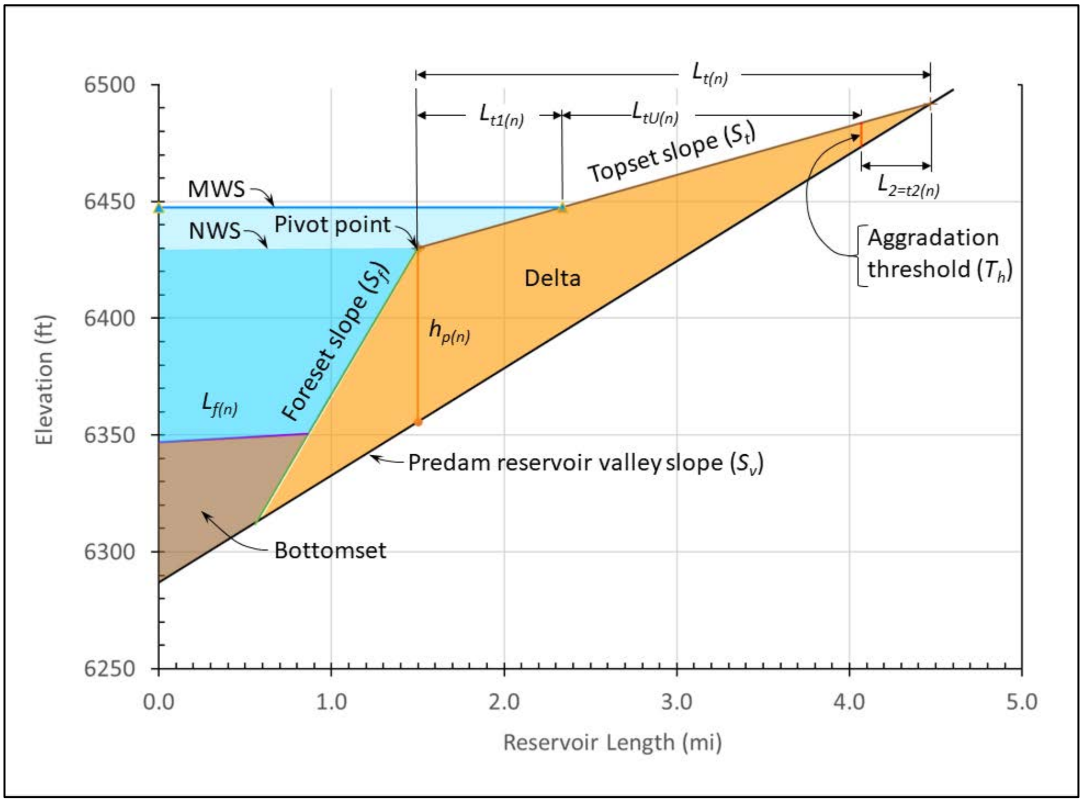


Figure 3-6.—Upstream delta aggradation beyond the full reservoir pool.

For some reservoirs (particularly in mountainous areas), the upstream river channel may flow through an unhabituated canyon without highways or railroads. However, human development may exist along river channels upstream of reservoirs and may be vulnerable to impacts from sedimentation.

The longitudinal distance of upstream sedimentation depends on the reservoir sedimentation volume (which tends to increase over time), normal elevation of the reservoir water surface, and the longitudinal slopes of the upstream river valley and delta topset (Figure 3-6). For each year of simulation, RSEM computes the upstream length of sedimentation beyond the full reservoir pool, but not counting the upstream-most portion of the delta where the thickness is less than the user-defined threshold. This threshold is defined as the vertical limit before aggradation impacts along the upstream channel become significant to property or infrastructure.

The model first tests to see if the upstream end of the delta is above the full-pool elevation of the reservoir (maximum water surface). If not, then the distance of upstream sedimentation is zero. If the delta topset extends above the top of live storage (full reservoir pool), then Equation 30 is used to compute the length of delta from the pivot point the intersection with the top of live storage.

$$L_{t1(n)} = \frac{\left(El_L - P_{El(n)}\right)}{tan\left(R_{s_t}\right)}; \qquad L_{t1(n)} \geq 0 \tag{30$$

Where:

$L_{t\ 1(n\ )}$ = Longitudinal length between the delta pivot point and where the delta topset intersects the full reservoir pool (top of live storage) in year *n*

If the upstream extent of the delta is above the full reservoir pool, RSEM computes the distance along the upstream-most portion of the delta where the thickness is less than the user-defined threshold.

$$L_{\ t2} = \frac{\left[\frac{-T_h}{tan\left(R_{s_t}\right)}\right]}{\left[1 - \frac{tan\left(R_{s_v}\right)}{tan\left(R_{s_t}\right)}\right]} \tag{31}$$

Where:

T_h = User-defined threshold where aggradation does not cause significant impacts to property or infrastructure

The length of delta causing significant upstream channel aggradation is computed from the delta topset length, less the distance between the pivot point and the full reservoir pool elevation (top of live storage), less the distance along the upstream portion where the sedimentation thickness is less than the user-defined threshold (equation 32).

$$L_{tU(n)} = L_{t(n)} - L_{t1(n)} - L_{t2}\ ; \qquad L_{tU(n)} \geq 0 \tag{32}$$

Where:

$L_{tU(n)}$ = longitudinal length of delta causing significant aggradation upstream from and above the full reservoir pool (top of live storage) in year *n*.

The area of upstream aggradation is computed as the product of the distance along the upstream delta and the depth-average width of the full reservoir (Equation 33).

$$\text{Area}_{U(n)} = \left(L_{tU(n)}\right)\left(W_{LS}\right) \tag{33}$$

Where:

$Area_{U(n)}$ = horizontal surface area of delta causing significant aggradation upstream from and above the full reservoir pool (top of live storage) in year *n*.

The economic costs of upstream channel aggradation are a function of both the longitudinal distance ($L_{tU(n)}$) and area ($\text{Area}_{U(n)}$). Computation of these economic costs are described in Section 4.4.8. Reservoir Sediment Management Costs).

3.3 Downstream Channel Degradation Modeling

The cost of downstream channel degradation has historically not been accounted for in the economic analyses of dams and reservoirs. However, channel degradation and subsequent bank erosion impacts the economic value of fish and wildlife habitat, vulnerable streamside infrastructure, and property. The value of habitat, any streamside infrastructure, and property is highly variable and may be difficult to quantify.

RSEM assumes that channel degradation, beyond a user-defined threshold, will eventually lead to streambank erosion. The model estimates the quantities and costs of rock riprap required to prevent the bank erosion. The model assumes that the cost of the streambank protection would be less than the value of any streamside infrastructure or property that would be lost without the streambank protection.

However, even with streambank protection, channel degradation would still impact fish and wildlife habitat due to a coarser streambed and greater flow magnitude to inundate the floodplain. Therefore, the model accounts for the cost of habitat degradation as a function of the cost for streambank protection.

For some reservoirs, only a small portion of the natural stream flows are released to the downstream channel and aggradation may occur due sediment supplied by downstream tributaries. RSEM does not simulate this condition.

3.3.1 Channel Degradation

RSEM uses the methodology described by Pemberton and Lara (1984) to simulate the channel degradation profile after each year of reservoir operations. The model assumes that the downstream channel degrades each year as coarse sediment is trapped within the upstream reservoir. The degradation progresses both vertically and downstream over time. Channel degradation may be limited by the armoring of the streambed by gravel, cobbles, or boulders, if enough armoring size sediment is available, or until a stable longitudinal slope is achieved.

The maximum degradation depth that may be limited by armoring is computed by Equation 34 as depicted in Figure 3-7 and described in Table 3-9 (Lara and Pemberton, 1984):

$$y_d = y_a \left(\frac{1}{\Delta \mathrm{p}} - 1\right) \tag{34}$$

Where:

y_d = depth of degradation limited by armoring (depth from predam streambed to top of armoring layer)

y_a = armor layer thickness (e.g., 0.5 ft, 0.15 m)

Δp = portion of original streambed material larger than the armor gain size, D_c (e.g., 10%)

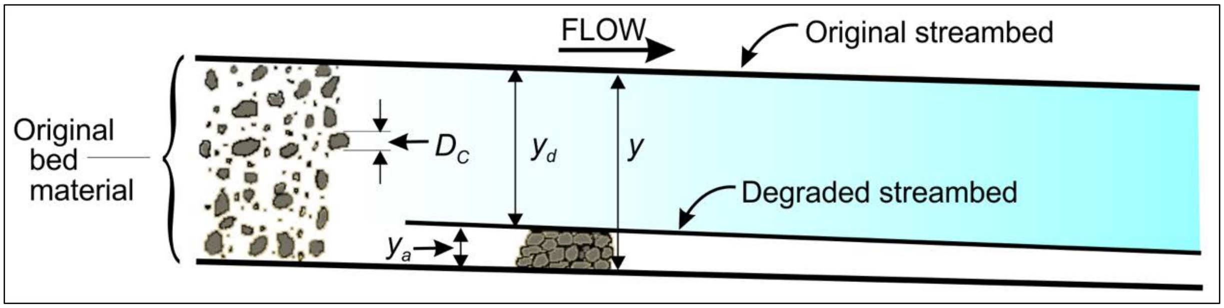


Figure 3-7.—Channel degradation limited by armoring (modified from Pemberton and Lara, 1984).

When there is insufficient armor size material in the streambed, channel degradation will continue until a stable longitudinal slop is reached. The longitudinal profile area of degradation is between the predam streambed and the degraded streambed (Figure 3-8) and computed by Equation 35:

$$a_g = \frac{V_g}{B_d} \tag{35}$$

Where:

a_g = longitudinal area of channel degradation

V_g = volume of channel degradation, which is equal to the volume of coarse reservoir sedimentation ($V_{c(n)}$) (see Equation 5)

B_d = width of degraded channel

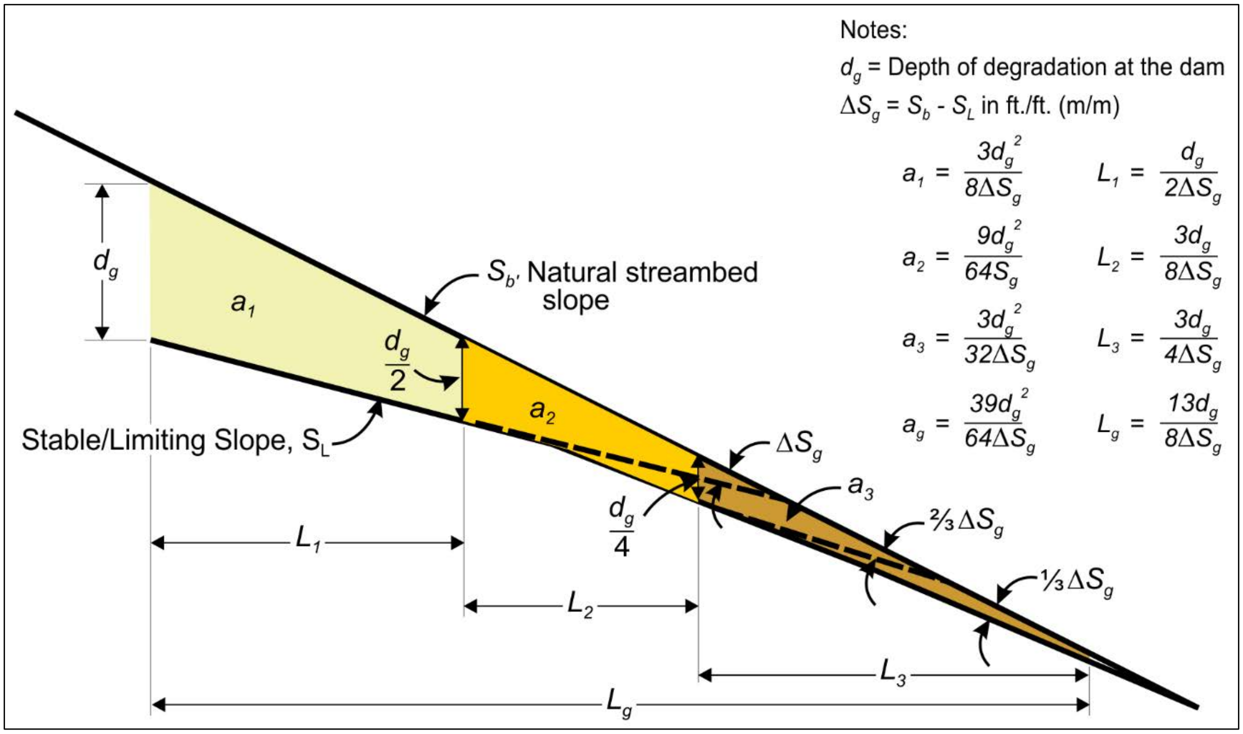


Figure 3-8.—Channel degradation limited by a stable slope (modified from Pemberton and Lara, 1984).

The channel degradation depth just downstream from the dam is computed using Equation 36:

$$d_g = \left[\frac{64}{39}\, a_g\, \Delta S_g\right]^{0.5} \quad \leq y_d \tag{36}$$

Where:

dg = channel degradation depth just below the dam

ΔSg = longitudinal slope difference between the predam channel and stable slope channel

The stable slope of a degraded river channel can be computed using a sediment transport equation so that the bed-material load is zero for the hydraulics of a bankfull discharge and given grain size distribution (Lara and Pemberton, 1984). RSEM uses a more simplified approach and computes the stable slope as a percentage of the predam slope. The difference in longitudinal slopes is computed from Equation 37:

$$\Delta S_g = S_o\,(1 - \beta) \tag{37}$$

Where: β = the portion that the predam slope would be reduced by to achieve the stable slope

S_o = predam longitudinal channel slope

For a given year, the channel degradation depth diminishes with the distance downstream. RSEM uses Equations 38 through 41 to estimate the distances where the degradation depth just below the dam has diminished to one-half (Equation 38), one-quarter (Equation 39), and near zero (Equation 40):

$$\mathrm{L}_1 = \frac{d_g}{2\,\Delta S_g} \tag{38}$$

$$L_2 = \frac{3 \quad d_g}{8\,\mathit{\Delta} S_g} \tag{39}$$

$$L_3 = \frac{3 \quad d_g}{4\,\mathit{\Delta} S_g} \tag{40}$$

$$L_g = \frac{13 \quad d_g}{8\,\mathit{\Delta} S_g} \tag{41}$$

Where:

L_1 = Length of channel degradation from the dam downstream to where the degradation has diminished to one-half the upstream amount

L_2 = Length of channel degradation from where the degradation has diminished from one-half to one-quarter of the amount below the dam

L_3 = Length of channel degradation from where the degradation has diminished from one- quarter the amount below the dam to near zero

L_g = Total length of channel degradation downstream from the dam

3.3.2 Bank Stabilization Design and Cost

While many types of streambank protection could be employed, including bio engineering, RSEM estimates bank stabilization costs by using a single streambank concept design for streambank protection based on using rock riprap. Users define the unit cost for materials and installation, and RSEM multiplies these costs to estimate the cost of streambank protection. The incremental quantities and costs are computed each year to simulate how the costs associated with channel degradation may change over time. For gravel and cobble-bed streams, the channel may be limited by armoring.

A key part of the concept design for riprap is estimating the median rock size based on the mean stream velocity for the bankfull discharge calculated in Equation 42 and shown in Figure 3-9.

$$d_{50} = 2.510 \times 10^{-3} \quad V_m^{2.620} \tag{42}$$

Where:

d_{50} = median rock riprap size (feet)

V_m = mean channel flow velocity (ft/s) at the bankfull discharge in Equation 43:

$$V_m = \frac{1.486}{n} \times R_h^{2/3} \quad S_o^{0.5} \tag{43}$$

Where:

n = Manning's roughness coefficient

R_h = hydraulic radius of the channel (feet), which can be assumed equal to the bankfull depth or bank height (H_{Bank})

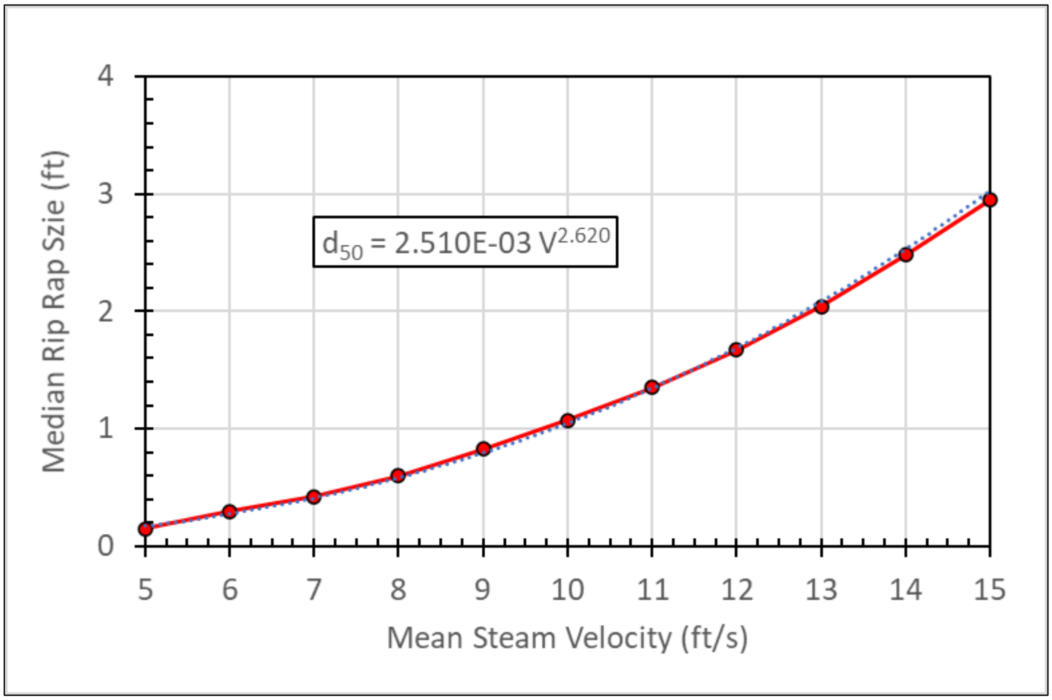


Figure 3-9.—Median riprap size as a function of mean stream velocity (modified from Baird et al. 2015).

The streambank protection concept design is presented in Figure 3-10. The top elevation of the rock riprap does not need to be as high as the top of the streambank, but the riprap needs to extend below the streambed to protect against channel degradation and local toe scour caused by the riprap.

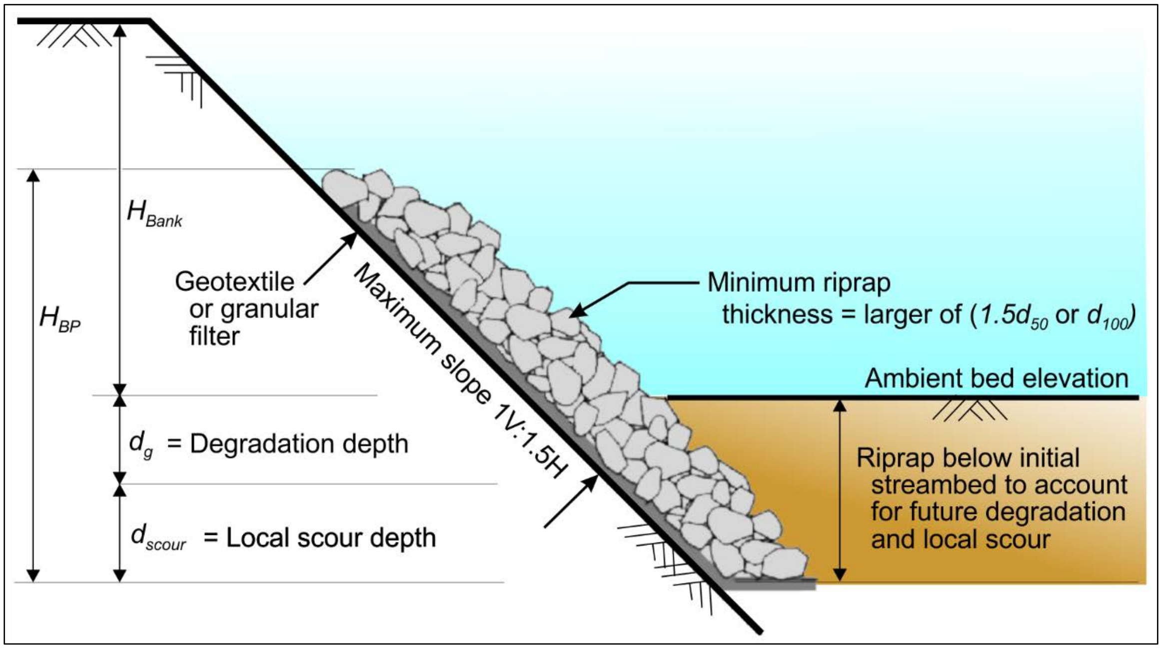


Figure 3-10.—Streambank protection concept design for riprap (modified from Baird et al. 2015).

RSEM estimates the vertical height of streambank protection as 30% of the bankfull height plus the estimated scour depth and degradation depth (Baird, personnel communication, 2022), Equation 44. The scour depth is estimated as 5% of the bankfull depth and is calculated using Equation 45. Equations 44 and 45 are combined to produce Equation 46.

$$H_{BP(m)} = 0.30\ H_{Bank} + d_{scour} + d_{g(m)} \tag{44}$$

$$d_{scour} = 0.05\ H_{Bank} \tag{45}$$

$$H_{BP(m)} = 0.35\ H_{Bank} + d_{g(m)} \tag{46}$$

Where:

$H_{PB(m)}$ = vertical height of streambank protection which extends below the streambed for reach *m*

H_{Bank} = channel bankfull height

$d_{g(m)}$ = average degradation depth in reach *m* is computed as a fraction of the degradation depth below the dam (d_g) (see Figure 3-8)

d_{scour} = depth of local scour caused by the riprap

The cross-sectional length of streambank protection depends on the vertical height and the bank slope (Equation 47).

$$SL_{BP(m)} = \left[\left(z\, H_{BP(m)}\right)^2 + \left(H_{BP(m)}\right)^2\right]^{0.5} \tag{47}$$

Where:

$SL_{BP(m)}$ = the slope length of rock riprap for reach *m*

z = horizontal component of the channel bank slope (z:1)

The cross-sectional area of rock riprap is computed from the slope length and thickness, where the thickness is assumed to equal 2 times the median riprap size (d_{50}) (Equation 48).

$$A_{BP(m)} = SL_{BP(m)}(2\, d_{50}) \tag{48}$$

Where: $A_{BP(n)}$ = cross-sectional area of stream bank protection for reach *m*

The volume of rock riprap is computed from the cross-sectional area and longitudinal length for each of three reaches (Equations 49 through 52). These equations account for the average degradation depth in each of three reaches (Figure 3-8)

$$V_{BP} = F_{BP}[L_1 A_{BP1} + L_2 A_{BP2} + L_3 A_{BP3}] \tag{49}$$

$$A_{BP1} = 2\, d_{50} \left\{ \left[z\left(0.35\, H_{Bank} + \frac{3}{4} d_g\right)\right]^2 + \left[\left(0.35\, H_{Bank} + \frac{3}{4}\, d_g\right)\right]^2 \right\}^{0.5} \tag{50}$$

$$A_{BP2} = 2\, d_{50} \left\{ \left[z\left(0.35\, H_{Bank} + \frac{3}{8} d_g\right)\right]^2 + \left[\left(0.35\, H_{Bank} + \frac{3}{8}\, d_g\right)\right]^2 \right\}^{0.5} \tag{51}$$

$$A_{BP3} = 2\, d_{50} \left\{ \left[z\left(0.35\, H_{Bank} + \frac{1}{8} d_g\right)\right]^2 + \left[\left(0.35\, H_{Bank} + \frac{1}{8}\, d_g\right)\right]^2 \right\}^{0.5} \tag{52}$$

Where:

V_{BP} = volume of streambank protection along reaches 1, 2, and 3 (Figure 3-8)

F_{BP} = streambank protection factor to account for protection along the left and right channel banks and habitat degradation ($1 \leq F_{BP} \leq 4$)

A_{BP1} = area of streambank protection for reach 1

A_{BP2} = area of streambank protection for reach 2

A_{BP3} = area of streambank protection for reach 3

The volume of rock riprap is computed for each year and used to estimate the economic costs of downstream channel degradation (see Section 4.4.7 Downstream Channel Degradation Costs).

4 Economic Modeling

This chapter describes the methods used by RSEM to estimate the economic costs and benefits under the sediment management scenarios. In general, the reservoir sedimentation modeling outputs drive the economic costs and benefits. All economics inputs should be entered at a common price level. RSEM will calculate the present value of costs and benefits based on the dollar values and temporal data provided by the user. RSEM estimates the annual economic costs and benefits based on the annual estimates for water storage yield, reservoir surface area, sediment removal requirements, upstream channel aggradation, and downstream channel degradation.

The following sections describe the model methodology and user inputs. For details on how to specify user input data, please see Appendix A – Reservoir Sedimentation Economics Model (RSEM) User Guide.

4.1 Considerations for Time-Equivalent Economic Evaluation

This section provides an understanding of several economic concepts and techniques to accommodate the time-equivalent estimation of the costs and benefits across the evaluated alternatives. The user specifies the base year for analysis (BYA), price level year, and the present dam and reservoir age to facilitate time-equivalent economic evaluation (Table 4-1). Note that Table 4-1 replicates Table 3-1, though with economics-specific context.

Table 4-1.—User inputs of base year, price level, and reservoir age

Reservoir Age Inputs	Units	Notes
Base year for economic analysis (BYA)	year	The year to be used as the first year of analysis. Generally, this is the current calendar year, but this is not required. Note that this is not necessarily the same as the price level for cost and benefit inputs but should be as close as possible.
Year that all dollar value inputs are indexed to (price level)	year	This is often one year prior to the base year of analysis because cost indexing may not yet be available for BYA.
Present Dam and Reservoir Age	years	The age of the reservoir at the BYA (0 indicates a new dam and reservoir).

RSEM’s treatment of these inputs, and the conceptual underpinnings, are described in the following sections, including an overview of:

- Period of analysis
- Specification of the base year for analysis
- Price level and conversion of nominal dollars to real dollars
- Accounting for the time-value of money

4.1.1 Period of Analysis (POA)

The period encompassing all modeled costs and benefits, associated with a sediment management alternative, is referred to as the *period of analysis* (POA). In accordance with Reclamation guidance, economic costs and benefits should be computed for the life of an asset not to exceed 100 years (DOI, 2015). RSEM developers recognize that large dams are built with the expectation of a service life beyond 100 years, and thus RSEM accommodates POAs greater than 100. RSEM displays results for four POAs for economic comparison: 50 years, 100 years, 200 years, and 500 years.

4.1.2 Base Year for Economic Analysis

The base year for economic analysis (BYA) is the first year of the POA and the base year for which dam age is calculated. In general, the BYA should be the current calendar year, but this is not a necessary requirement.

4.1.3 Price Level and Conversion of Nominal Dollars to Real Dollars

Past expenditures reported in the year they were incurred are stated in *nominal* dollars (actual prices that exist at the time). Comparison of costs and benefits requires that nominal dollars be adjusted to a common price level. Indexing is the technique used to convert nominal dollars to *real* dollars at a common price level based on empirical evidence (historical indices). Conversion to real dollars attempts to account for the change in the purchasing power of a dollar over time. RSEM uses real dollar values to compare costs and benefits across time.

Price level is the year that all dollar values are indexed to and is generally the most recent year for which applicable indices are available. Price level does not have to be the same as the BYA but should be as close as possible. Note that RSEM will not convert nominal dollars to a common price level for the user. All indexing must be performed outside of RSEM.

Useful resources for indexing past dam and reservoir-related costs to real dollars are Reclamation's quarterly publication *Construction Cost Trends* (CCT) (Reclamation, 2021a), Reclamation's Operations and Maintenance (O&M) Index (Reclamation, 2019), and the Engineering News Record Construction Cost Index (ENR CCI) (Zevin, 2021). The Reclamation CCT consists of numerous categories and subcategories, including indices for different dam types and structures.

Figure 4-1 displays index values for the Reclamation O&M Index, the Reclamation CCT – Earth Dams Index, the Reclamation CCT – Concrete Dams Index, and the ENR CCI for the years 1984 through 2020. The four indices are normalized to index value 100 in 1984 (the earliest common year among the four indices) to improve comparative visualization. For each cost input, the model user should use the most appropriate index for that cost category (e.g., earth dams, concrete dams, ENR general construction, O&M, etc.).

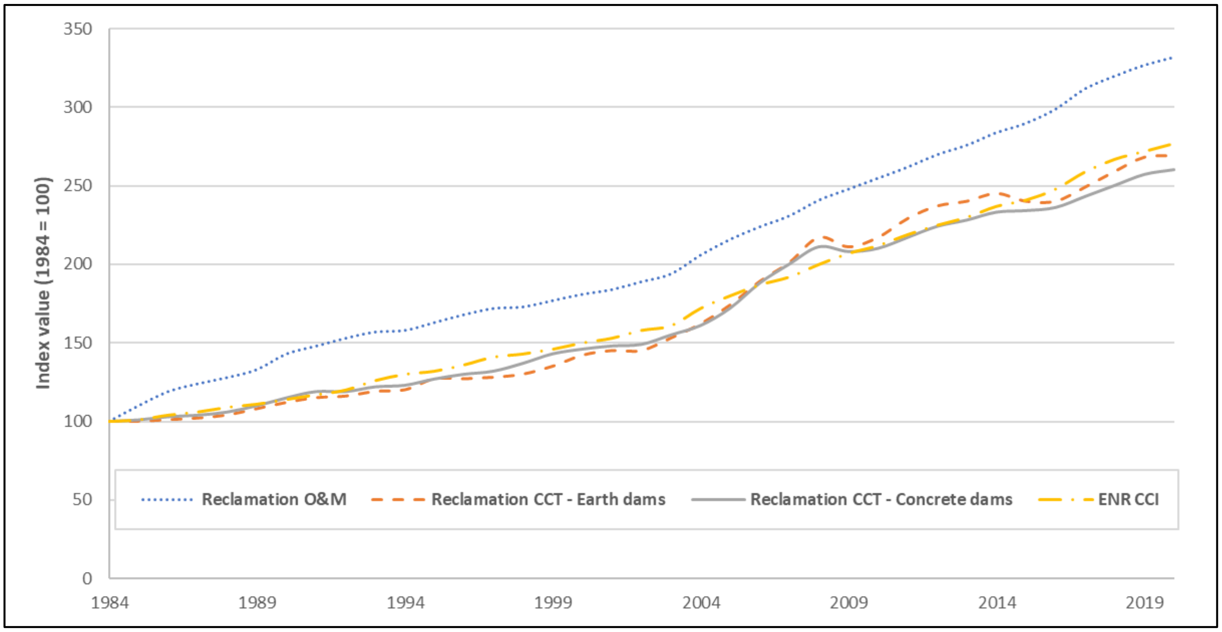


Figure 4-1.— Presentation of four dam construction and OM&R-related cost indices from 1984–2020.

4.1.4 Reconciling BYA, Price Level, and Dam Age

While RSEM simulates sedimentation from the first year the reservoir was placed in service—regardless of the current age—economic modeling always begins in the BYA. RSEM allows the user to conduct an economic analysis from two general perspectives:

- An economic comparison of without and with sediment management for an existing reservoir (i.e., dam age is greater than zero).
- An economic comparison of without and with sediment management for a new reservoir (i.e., dam age equals zero).

Example scenario for an existing dam and reservoir

An analysis is to be performed in 2022 on a dam that is 30 years old. The most recent indices available provide cost data through 2021. For this scenario:

BYA = 2022
Price level = 2021
Present dam age = 30

Example scenario for a new dam and reservoir

> An analysis is to be performed in 2022 for a new dam. The most recent indices available provide cost data through 2021. For this scenario:
>
> BYA = 2022
> Price level = 2021
> Present dam age = 0

4.1.5 Accounting for the Time Value of Money

The timing of costs and benefits is central to economic analyses of investment decisions. Costs and benefits attributable to a given dam and reservoir are incurred at different times over long horizons. A fundamental concept in economics is that the timing of benefits and costs makes a difference in the attractiveness of an investment. All other things being equal, one would prefer to receive benefits now and pay the costs of an investment as far out into the future as possible. Given the choice between paying out $100 today or one year from now, most of us would prefer the latter. The opposite is generally true for benefits, with most preferring to receive $100 today versus one year from now (accounting for price levels, i.e., inflation).

To be able to add and compare costs and benefits realized at different times over the POA, they must be made time equivalent. To make dollars time equivalent, they are converted to present dollars by compounding (past) or discounting (future) values to a common point in time—in this case the base year for analysis—a concept known as *present valuation*. Anticipated future costs and benefits are *discounted* back to their present value to account for the opportunity cost associated with tying up those dollars in the investment. Current spending incurs an opportunity cost relative to delayed spending because an investment generally yields a real rate of return, meaning there is a cost to spending that money in the present. The opposite holds true for benefits, with an opportunity cost from delayed benefits versus receiving them in the present, again due to the potential for resources to generate a real return across time.

An interest rate is typically employed to calculate the present value of future dollars referred to as the *discount rate*. This rate is intended to capture the forgone real rate of return and will differ for a private versus public entity due to differences in opportunity cost. For example, private entities often invest with higher risk and return, meaning they have a higher opportunity cost. The chosen rate can have a significant impact on the results of an economic analysis and its selection should therefore be made carefully. For Reclamation economic evaluations, costs and benefits are converted to present dollars using the rate prescribed each fiscal year (FY) by the U.S. Department of Treasury for federal agencies in the formulation and evaluation of plans for water and related land resources (Federal Planning Rate). This rate is intended to capture the opportunity cost for federal investments related to water and land resources. The Federal Planning Rate is employed as a real discount rate and Reclamation economic analyses therefore report results in real dollars (i.e., in today’s price level, excluding changes from inflation). The FY 2022 Federal Planning Rate is 2.250 percent, which is the lowest Federal Planning Rate on record. The highest on record is 8.875 percent, which was first used in FY1987 and then matched in FY1990. The Federal Planning Rate has declined over time due to a lower return on federal investments and greater societal preference for protecting natural resources for future generations.

The approach to discounting required under Reclamation guidance can generally be termed “exponential” discounting. However, there are a number of alternative discounting approaches that also could be considered for research or comparative purposes. RSEM allows the user to choose from a selection of seven alternative different discounting approaches, which are detailed in Section 4.4.1 of this report.

4.2 Economic Benefits

Most Reclamation dam and reservoir projects (projects) were built with the primary purpose to provide irrigation water supply (irrigation) to western agriculture. Additional beneficiaries often include municipal and industrial (M&I) water supply, hydropower production, recreation, fish and wildlife habitat enhancement (F&W), and flood risk reduction (flood control). RSEM accommodates benefit estimation for six beneficial use categories: irrigation, M&I, hydropower, recreation, F&W, and flood control. Table 4-2 summarizes how a reservoir provides economic benefits for each of the beneficial use categories included in the model. Although society may derive benefits from reservoir storage capacity, not all benefits produce financial income. For example, lost benefits do not necessarily imply the incurrence of financial expenditures. However, benefits and costs (or lost benefits) do affect society.

Table 4-2.—Generation of reservoir-based economic benefits

Benefit category	Benefits depend on:
Irrigation	Irrigation deliveries from live storage
M&I	M&I deliveries from live storage
F&W	Instream flows and water quality downstream of dam
Flood control	Total reservoir capacity space allocated for flood events
Hydropower	Hydraulic head and water availability for optimizing generation
Recreation	Reservoir surface area and boat ramp accessibility

A foundational concept for establishing the economic benefits provided by a dam and reservoir project is the comparison of the with- versus without-project conditions. In short, the net difference in economic output accrued to a given use with the project in its current condition versus economic output accrued to that use in the absence of the project. For example, irrigation benefits are often evaluated by comparing the net farm income of lands irrigated by a water project and the net farm income for the same lands in the absence of the project—which is often dryland (precipitation-dependent) farming. The difference between the two conditions, for a given use, is the total economic benefit provided by the dam and reservoir to that use. Dividing the total economic benefit by the volume of project water provided to that use gives an approximation of the marginal benefit provided or lost by one additional, or one less, unit volume of water. The unit of measure most commonly used is dollars per unit volume of stored water, though this is not consistent across all beneficial uses.

4.2.1 Consumptive versus Non-Consumptive Beneficial Use

For RSEM, a useful delineation of the economic benefits provided by a reservoir is consumptive versus non-consumptive beneficial use. In general, a non-consumptive beneficial use is one that does not impact other beneficial uses of the water. Whether a use is consumptive or non-consumptive can depend on the timing and location of the use. Consumptive beneficial uses simulated by RSEM include irrigation, M&I, and F&W because these uses often influence the quantity and/or quality of water resources available for other uses. Non-consumptive beneficial uses simulated by RSEM include recreation, hydropower, and flood control because these benefits generally do not affect other water uses.

Consumptive uses preclude the use of the same unit of water by another beneficial use. For example, if a unit volume of water is applied to irrigate a field, it cannot be delivered to a city to provide M&I benefits. An exception to this pertains to water reuse, which may allow a portion of consumptive water use to be used again, but this often requires water quality treatment.

Non-consumptive uses, on the other hand, do not preclude the same unit volume of water from providing benefits to more than one purpose. For example, a unit volume of water might support recreation and F&W at the reservoir, then pass through a hydropower turbine to generate energy, and then be delivered to a downstream irrigator to provide irrigation benefits.

It is important to note that non-consumptive uses can still compete with consumptive uses due to the importance of timing. For example, if the system demands a particular output of hydropower, and the water required to generate that hydropower exceeds the demand of downstream irrigators, then the irrigators have effectively lost the ability to put that excess water to beneficial use. Complex timing impacts should be modeled outside of RSEM using a dedicated water operations model, such as RiverWare, as RSEM is not equipped to simulate this.

RSEM models F&W as a consumptive use, but this is context dependent. There are scenarios where F&W benefits might be accrued in the reservoir, and therefore would be a non-consumptive use. A more common scenario for Reclamation reservoirs is that F&W requires a minimum level of downstream flows, and this water cannot be diverted for irrigation or M&I and is therefore in direct competition with these other consumptive uses. Likewise, river-based recreation downstream of the dam is akin to a consumptive use, but most recreation benefits dependent on Reclamation reservoirs are flatwater-based and therefore are modeled as non-consumptive.

Consumptive versus non-consumptive beneficial use is an important distinction for the purposes of RSEM, as the model will not allow for the sum of stored reservoir water utilized by all consumptive uses to exceed the modeled reservoir yield. In short, consumptive uses are constrained by one another, while non-consumptive uses are not.

The consumptive beneficial uses modeled in RSEM (irrigation, M&I, and F&W) each require the user to input the proportion of available water supply dedicated to that use, and the sum of all three should equal, and cannot exceed, 100%. Total available water supply for consumptive use is represented by water yield as a percentage of storage capacity, which is calculated by RSEM based on the reservoir storage capacity, mean annual inflow, and standard deviation (coefficient of variation) of the annual inflows. These inputs are described in the first five rows of Table 4-3. Once the unit values for consumptive benefits are estimated and input to the model, it calculates the weighted benefit of storage capacity (row 11 of Table 4-3).

The following sections provide some conceptual background and common techniques for unit value benefit estimation for the beneficial uses modeled in RSEM. Each of the required inputs and calculations are summarized in Table 4-3.

Table 4-3.—User inputs for reservoir benefits

Reservoir Benefits	Units	Notes
Water Yield as a Percentage of Storage Capacity*	Dimensionless	This yield is computed by RSEM and determines the amount of water that economic benefits for consumptive uses are based on.
Percentage of Consumptive Uses		This is the proportional distribution of available water for generation of benefits by consumptive uses. Consumptive uses are treated as mutually exclusive, so the sum of all three consumptive uses should always be 100%.
Agricultural irrigation use	Dimensionless	The proportion of annual water releases, on average, provided to irrigated agriculture
M&I water use	Dimensionless	The proportion of annual water releases, on average, provided to municipal and industrial water users
Fish and wildlife and other*	Dimensionless	The proportion of annual water releases, on average, provided to fish and wildlife enhancement, or other consumptive purposes not explicitly listed
Unit Values for Consumptive Use Benefits		The benefit per acre-foot for each of the consumptive uses. Specifically, this is the marginal benefit, i.e., the benefit attributable to an additional unit volume of water.
Agricultural irrigation use	$/acre-foot/yr	The benefit per acre-foot of water delivered to irrigated commercial agriculture from the reservoir, adjusted to the price level specified for the analysis.
M&I water use	$/acre-foot/yr	The benefit per acre-foot of water delivered to municipal and industrial water users from the reservoir, adjusted to the price level specified for the analysis.

Table 4-3.—User inputs for reservoir benefits

Reservoir Benefits	Units	Notes
Fish and wildlife and other	$/acre-foot/yr	The benefit per acre-foot of water delivered downstream to fish and wildlife habitat from the reservoir, adjusted to the price level specified for the analysis.
Flood Risk Reduction	$/acre-foot/yr	The annual flood control benefit depicted as the benefit per acre-foot of storage capacity, adjusted to the price level specified for the analysis.
Weighted Average Benefit of Storage Capacity*	$/acre-foot/yr	Calculated as the sum of the weighted benefit per acre-foot of each consumptive use and the benefit per acre-foot of flood control. Result is the weighted benefit per acre-foot of reservoir storage at the specified price level.
Hydropower Production		Estimation of the benefits attributable to hydropower
Average annual energy production	MWh/yr	The MWh of energy generated in the average year. For existing Reclamation facilities, this can be found on the agency website.
Average energy benefit rate	$/MWh	The average dollar per MWh the specific facility accrues, adjusted to the price level specified for the analysis. The Energy Information Administration provides regional market rates that are useful for this purpose.
Annual hydropower energy benefit*	$/ yr	The product of annual energy production and the energy benefit rate.
Recreation Use Benefits in Base Year		
Average annual visitor days*	Visitor days/yr	The number of recreation visitor days for the base year of analysis. One visit is equal to 12 hours.
Benefit per visitor day (consumer surplus)	$/day	Equal to the difference between what consumers are willing to pay for a recreation experience and what they actually pay for that experience.
Benefit dependent on ALL boat ramps/marinas*	Dimensionless	The proportion of recreation benefits dependent on the existence of the reservoir's boat ramps.
Benefit reduction from loss of 1 boat ramp/marina*	Dimensionless	The proportion of recreation benefits lost with the loss of one boat ramp. Note that if there are 2 boat ramps, this value is likely not 50% of boat-based recreation, as some of the loss at a single boat ramp can be substituted with the 2nd ramp.
Maximum Annual Benefits Based on Inputs*	$/yr	The total benefits attainable in the first year after the reservoir is filled to the full pool and prior to impacts from sedimentation. This value is used as the baseline for calculating lost economic benefits due to sedimentation.

*Parameters computed by RSEM. These parameters may be overridden by the user.

4.2.2 Irrigation Water Supply

A common and widely accepted methodology for estimating the value of water supply to irrigated agriculture is the change in net income approach. This is generally done by a farm budget analysis and is described conceptually below. Farm budget analyses by Reclamation economists are often conducted using Reclamation's Farm Budget Tool, but there is a variety of tools and techniques available for estimating irrigation benefits.

Net farm returns (NFR) reflects the difference between farm revenues and costs. In general, as irrigation water supply increases, NFR is expected to increase. The curve demonstrating this relationship is shown in Figure 4-1 (A). The convex length of the curve, denoted by bracket "A", indicates increasing marginal returns, attributable to factors such as yield increases, cropping pattern shifts to more valuable commodities, and cost savings resulting from efficiency in irrigation water use as well as optimal response to changes in water supply like decreased groundwater pumping. These factors are not mutually exclusive. As a full irrigation supply is achieved, there are diminishing marginal returns per additional acre-foot (AF) of water due to the positive and diminishing marginal productivity of irrigation water, as denoted by bracket "B"—the concave length of the curve. In summary, when irrigation water is scarce, each additional unit is increasingly valuable, and when irrigation water is plentiful, each additional unit is decreasingly valuable.

Figure 4-1 (B) depicts irrigation water supply under the with- and without-project conditions. Note that cropland might receive some irrigation water under the without-project condition, such as groundwater or river pumping, so the without-project condition does not necessarily indicate zero AF of any irrigation water—rather, it indicates zero AF of Project irrigation water. In the example illustrated in Figure 4-1 (B), the with-project condition represents a full water supply; however, a full water supply may not be available in all irrigation projects.

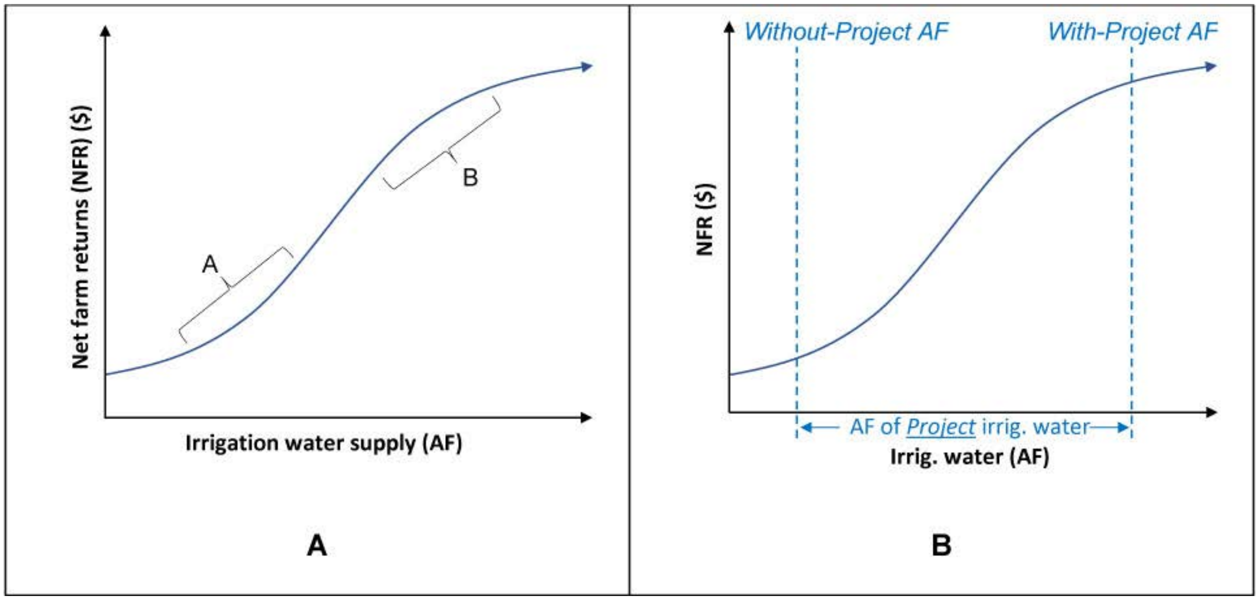


Figure 4-1.—Conceptual relationship between irrigation water supply and NFR.

The Project irrigation benefit is equal to the difference in NFR under the with- and without-project conditions, as shown on the y-axis of Figure 4-2 (A). This can be stated as the total economic benefits accrued to irrigated agriculture due to the existence of the project.

It is also necessary to estimate a unit value for the irrigation water, i.e., the marginal benefit attributable to one AF of Project irrigation water. This metric helps estimate economic impacts due to changes in irrigation water supply under evaluated alternatives, such as decreased supply under a reservoir restriction, or a reoperation to increase supply.

The marginal value of irrigation water is dependent on which length of the curve is being solved for. Estimation of the actual curve is prohibitively time and data intensive, and often not possible. Rather, two solvable points along the curve are estimated: (1) the with-project condition, and (2) the without-project condition, as shown in Figure 4-2 (A). The slope of the linear curve intersecting these solvable points is an approximation of the marginal benefit attributable to one additional AF of Project irrigation water—depicted in Figure 4-2 (B).

The marginal benefit per AF of Project irrigation water, adjusted to the appropriate price level, should be used as the input for RSEM (Table 4-3).

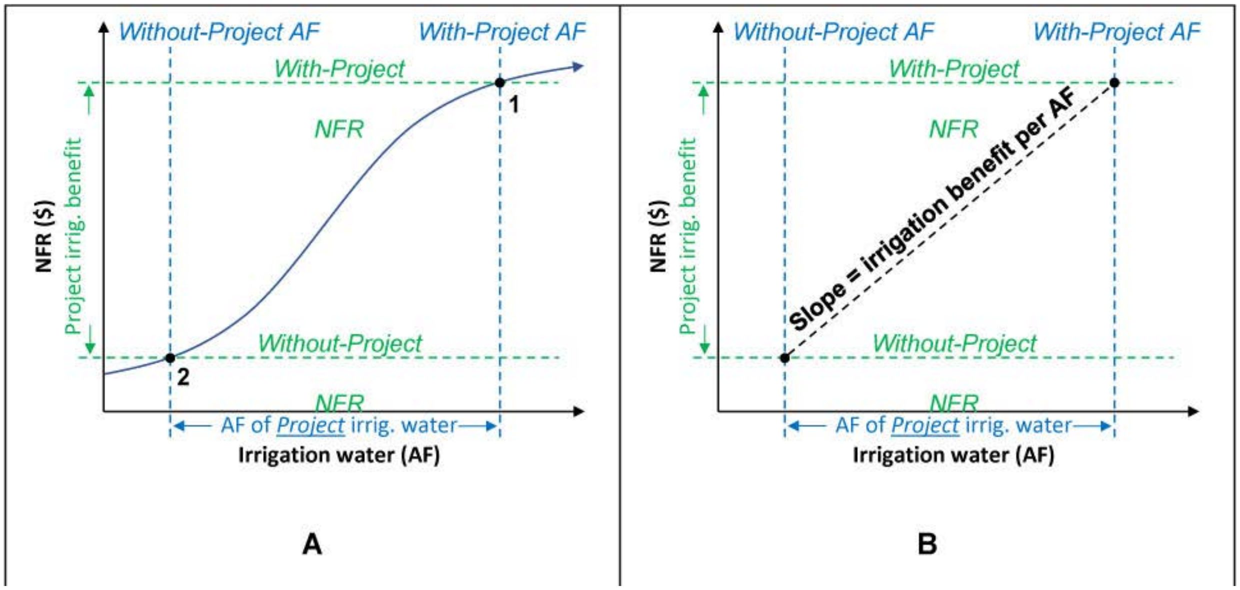


Figure 4-2.—Estimating the Project irrigation benefit and the marginal benefit per acre-foot of water delivered from the Project.

4.2.3 Municipal and Industrial Water Supply

For federal water projects, the conceptual basis for evaluating the benefits from M&I water supplies is society's willingness to pay (WTP) for improvements attributable to the water supply. If the price of water reflects the marginal cost of water in the area under consideration, the price can be used to calculate the willingness to pay for additional water supplies. In the absence of a direct measure of WTP, the *cost of the most likely alternative* can be used to estimate benefits. The price charged for water is generally not a reflection of marginal cost because water utilities do not typically operate in a competitive environment and because most utilities use average cost pricing. Therefore, the cost of the most likely alternative method is the often used for evaluating federal water projects—generally measured as the cost for procuring an alternative raw water supply.

A related method is the *revealed preference* approach (RPA), where actual observed market behavior is analyzed to derive the value of project M&I water supply. In the absence of an active market, RPA is dependent on a limited number of transactions and will not reflect the true WTP but most often a conservative estimate of WTP. The price that an entity actually pays is by definition equal to or less than their WTP, so true WTP could be considerably higher.

Reclamation Technical Memorandum Number EC-2009-02 (Piper 2009) provides a comprehensive discussion of the methods for valuing M&I water. This memorandum takes a closer look at five valuation methods and provides a matrix ranking the approaches by complexity and accuracy. This matrix is reproduced in Table 4-4.

Table 4-4.—Valuation methods ranked by complexity and accuracy

Valuation method	Complexity[a]	Accuracy[b]
Stated Preference - Contingent Valuation Method	5	4
Revealed Preference - Demand Curve Estimation	4	4
Use of Price Elasticity Estimates	3	3
Benefits Transfer	2-3	2-3
Cost of Most Likely Alternative Without Project	1	1

[a] **Complexity is based on the following scale:**

1 – Requires only cost data, assumes project goal is met, rigorous economic analysis not required, simple to apply.
2 – Requires only very basic secondary data (including at least valuation estimate from a previously completed study) and basic socio-economic data depicting conditions in the study area.
3 – Requires secondary data (including results from previously completed studies relevant to the study area), understanding of basic economic principles, and general socio-economic information for the study area.
4 – Requires secondary economic data, rigorous modeling and economic analysis, and site-specific information.
5 – Requires potentially time consuming and complicated primary data collection, rigorous modeling and economic analysis, and site-specific information.

[b] **Accuracy is based on the following scale:**

1 – Not a consistently reliable or accurate measure of benefits.
2 – Estimates are based on general economic theory, but accuracy is reduced by limited data and/or by many potential sources of measurement error.
3 – Estimates are representative and accurate within a range of values. Estimates tend to apply to regional characteristics and are not necessarily site specific.
4 – A greater level of precision than for 3, but still uncertainty due to data errors, errors in data gathering, and errors in modeling. Sources of error can be identified but are not fully accounted for. Results are site specific.
5 – Very accurate and site-specific results.

Source: Reproduction of Table ES-1 “Method Advantages/Disadvantages” from Reclamation TM EC-2009-02

Once the unit value of M&I water supply is estimated in dollars per AF and adjusted to the appropriate price level it can be used as the input for RSEM (Table 4-3).

4.2.4 Fish and Wildlife Enhancement

There are a number of considerations when estimating the benefits for fish and wildlife enhancement (F&W). Recreational fishing is typically non-rival (i.e., success of one angler does not diminish the utility of other anglers) and valued with recreation. Commercial fishing is rivalrous (i.e., multiple fishing operations competing for the same limited resource) and can be valued by the change in net income. Lastly, F&W may provide non-use values (cultural, spiritual, bequest, etc.) which can only be valued with stated preference methods.

F&W is a benefit often quantified in the economic justification of Reclamation water projects. Reclamation economic studies generally assume that a significant portion of the quantifiable benefits associated with fish and wildlife are captured by the recreation benefits through recreation-based visitation (see Section 4.2.6)—especially for reservoir-based F&W benefits. Any residual fish and wildlife benefits may be quantified through non-market valuation techniques. For example, people might be willing to pay for fish and wildlife habitat provided by a reservoir if it helped endangered species. RSEM models F&W benefits as a consumptive use, but this is context dependent. There are scenarios where F&W benefits might be accrued in the reservoir, and therefore would be a non-consumptive use. A more common situation for Reclamation reservoirs is that F&W requires a certain level of downstream flows, and this water cannot be diverted for irrigation or M&I and is therefore in direct competition with these other consumptive uses. As explained above, the portion of F&W benefits accrued in the reservoir—the non-consumptive portion—is assumed to be captured by the recreation benefits analysis. The model user should work with an economist to determine the appropriate F&W benefit inputs for RSEM.

F&W benefits could be realized through minimum streamflow maintenance, pulse events, or reservoir habitat. The non-recreation portion of F&W benefits are generally quantified based on nonuse values. Nonuse, intrinsic, or passive use values, reflect an individual’s WTP for a unique resource even if they never intend to physically use it. If threatened and endangered (T&E) species are involved, people may be willing-to-pay to ensure preservation of those species through maintenance flows released from the dam.

Nonuse values generally fall into three primary categories: existence value, option value, and bequest value. Existence value is derived from the satisfaction of knowing that a particular resource/habitat/species exists even if no onsite use is ever expected. Option value reflects satisfaction associated with maintaining a resource for some future use, including recreational, medicinal, and other purposes. Bequest values reflect satisfaction individuals receive from knowing a resource will be preserved for future generations.

Oftentimes, nonuse values are one of the primary benefit components associated with dam removal. There can be a high WTP for returning a river to a free-flowing state. Dam removal is typically expected to help improve damaged habitats thereby aiding in the recovery of dependent T&E species. The species that might be maintained and valued with the dam in place could be different than the species that would thrive in the absence of the dam, so the F&W benefits analysis might be distinctly different between the two sediment management alternatives. It is quite likely that there would be an increased measure of net F&W benefits under a scenario that a dam is decommissioned due to sedimentation, and native habitat is restored. The passage of reservoir sediments to the downstream river channel, through regular sediment management, may also benefit native and endangered species. For example, native and endangered fish in the Grand Canyon evolved under high sediment concentrations and would likely benefit from sediment being supplied from Lake Powell (Randle et al., 2007).

For most uses of RSEM, it is reasonable to assume that F&W benefits provided by the dam are captured by the recreation benefits analysis. In those cases where an independent F&W benefit analysis is warranted, nonuse valuations should be conducted with caution and conducted by a knowledgeable economist. Once the value of F&W water is estimated in dollars per unit of water and adjusted to the appropriate price level it can be used as the input for RSEM (Table 4-3).

4.2.5 Flood Risk Reduction

Flood risk reduction (flood control) is a basic function of most dams. The main purpose of flood risk reduction is to reduce flood hazard in terms of both flood damages and loss of life. Flood reduction benefits are the reduction in all forms of damage from inundation (including sedimentation) of property, disruption of business and other activity, hazards to health and security, and increase in net return from higher value use of property made possible as a result of lowering the flood hazard. Preventing loss of life is a clear benefit of flood risk reduction, however, Reclamation does not assign a monetary benefit to a human life.

Flood control benefits are generally estimated as the flood-related economic damages prevented due to the existence of the dam. The US Army Corps of Engineers provides prevented economic damages calculations annually for most large US dams based on the reservoir inflow flood magnitude and probability and the available reservoir flood storage capacity. As sedimentation decreases reservoir storage capacity (especially in the upstream delta), there is less volume to store inflowing floods and, therefore, more of the flood (both volume and peak discharge) is passed downstream. Even though reservoir sedimentation does not change the magnitude and probability of floods entering the reservoir, sedimentation does decrease the capacity to store floods entering the reservoir.

The historic average of prevented annual flood damages represents the total annual flood reduction benefits provided by the project.

Dividing the total flood reduction benefit by the available live reservoir storage capacity (at the time the benefits were determined) approximates the benefit per unit volume of storage. Once indexed to the base price level it can be used as the input for RSEM (Table 4-3). This unit flood risk reduction benefit remains constant over time. Annual flood risk reduction benefits decrease over time as sedimentation reduces the live reservoir storage capacity.

4.2.6 Hydropower

Most dams do not have a powerplant to produce hydroelectric power, but for dams with powerplants, the hydroelectric benefits from energy and capacity are often significant. For Reclamation dams with powerplants, hydropower production is often not one of the primary project purposes and is often generated as an incidental benefit, meaning that the production of hydropower is not the first priority of reservoir operations. For example, hydropower operations typically do not influence annual flow release volumes, but may influence the timing of hourly releases within a month and may have some influence on the monthly release volumes within a year. Even so, hydropower production can make up a significant portion of facility revenue and is an important component of a reservoir economic analysis.

A few practical measurement approaches for hydropower benefits include:

- Additional cost of replacement power as measured by long-term market price or the least cost alternative. The additional cost of replacement power is equal to the cost of the replacement power minus the costs which would have been incurred to generate the lost hydropower.
- Cost of Energy Efficiency Programs
- Cost of Air Quality Treatment

The energy produced at a hydroelectric powerplant is primarily a function of the reservoir head and the water discharge passed through the powerplant. The reservoir head is the elevation difference between the reservoir water surface the river surface below the dam. The economic value of the energy depends on the amount of energy produced and the time and day that it is produced. When the reservoir water surface elevation is held constant (run-of-the river operation), the head is constant and the rate that energy is produced depends on the rate that water is discharged through the powerplant. For powerplant peaking operations, more water is released through the powerplant during times of peak energy demand (e.g., Mondays through Saturdays and between 7 AM and 11 PM) and less water is released during times of low energy demand (e.g., 11 PM to 7 AM and on Sundays and holidays). Peaking operations depend on capacity of the reservoir to store and subsequently release water.

For a run-of-the river operation, reservoir sedimentation would not change the reservoir head available to a downstream powerplant. As sedimentation reduces storage capacity, the capacity for hydroelectric peaking operations also may be reduced. However, reduced storage capacity would cause the reservoir to fill quicker and more frequently. More head will be available when the reservoir is at or near full. As sedimentation at the dam reaches the power penstock elevation, sediments will be entrained into the penstock and turbines. Coarse sediments have the potential to rapidly damage the turbines by abrasion (within hours of operation).

RSEM is not able to simulate all these complexities of hydroelectric power generation. Rather, RSEM assumes that hydroelectric benefits are constant each year until the dam is decommissioned due to severe sedimentation.

RSEM requires the user to input the average annual energy production in the units of megawatt hours (MWh) per year. This should be the historic average for the subject powerplant as a whole, rather than per unit (if there are multiple units). The user also provides the dollars per MWh for the region of interest in the latest year for which data is available. This can be found using the spot market price for the closest energy hub on the Energy Information Administration’s website. RSEM then calculates the annual gross hydropower benefit as the product of these inputs (see

Table 4-3). Hydropower-related OM&R expenses should be captured in the annual and periodic OM&R costs, so RSEM effectively nets out these expenses to provide an approximation of net hydropower benefits. This is a simplified estimation of the economic benefits for hydropower. If the user has access to more advanced estimation techniques (such as production cost modeling or expansion cost modeling) they can directly input this value as the annual hydropower benefit, and it will override the two component variables described above.

Hydropower production is essentially a binary function in RSEM. Hydropower production is not incrementally impacted as sediment levels rise, but once the sediment reaches hydropower intake structures, the benefits drop to zero. This is because hydraulic head can be maintained even as reservoir storage capacity is drastically decreased. There might be other marginal impacts before intakes are sedimented, such as fine sediments entering hydropower infrastructure and causing damage, but these impacts are not captured in the current version of RSEM.

4.2.7 Recreation

Reclamation guidance (Reclamation, 2011) recognizes that reservoir recreation is a significant beneficial use at many Reclamation projects, and that impacts to reservoir elevation and surface area may also impact project benefits. Recreation benefits associated with a dam and reservoir are generally limited to those water and land-based recreation opportunities that exist, or are enhanced, due to the existence of the reservoir. Recreation analyses generally involve a process of developing and multiplying activity-specific visitation and economic value estimates together to calculate total recreation value by activity. The total recreation values by activity are summed to obtain total recreational site value. Separate and external analyses of recreation visitation and net economic benefits are needed to provide the necessary input to RSEM.

RSEM estimates recreation benefits as the product of annual recreation visitor days and the consumer surplus per visitor day. The consumer surplus of a recreation visitor day is equal to recreation consumer surplus of a visit under the with-project condition minus recreation consumer surplus of a visit under the without-project condition. The with-project condition assumes the presence of the dam, reservoir, and affiliated recreation facilities in their current condition, while the without-project condition assumes the *absence* of the dam and reservoir.

Note that one visit is equal to one day (12 hours) and that consumer surplus is equal to the difference between what consumers are *willing* to pay for a recreation experience and what they *actually* pay for that experience.

Visitor days are recalculated annually within the model, while consumer surplus per visitor day is held constant over time. The quality of a recreation visit could decrease, in a given wetted area, as the reservoir becomes shallower due to sedimentation. However, RSEM assumes the recreation quality of a wetted area remains the same until the area is no longer wetted.

The primary variable for estimating changes in recreation visitation is reservoir surface area. Previous work has found reservoir recreation visitation to have a strong, positive correlation to reservoir surface area with a roughly linear relationship (Neher, Duffield, & Patterson, 2013; Reclamation, 2000; 2016a). In short, greater reservoir surface area results in greater recreation visitation, while less reservoir surface area results in less recreation visitation. For example, if at reservoir age 10, RSEM estimates that the reservoir has lost 17% of surface area compared to the baseline (new reservoir), then RSEM calculates recreation visitation in that year as 83% of the user-defined baseline visitation (see Table 4-3).

The secondary variable for estimating changes in recreation visitation is boat ramp/marina accessibility. RSEM accommodates up to two boat ramps/marinas. The user defines the percentage of recreation visitation dependent on accessibility to all reservoir boat ramps/marinas and the percentage of visits lost due to losing one boat ramp/marina (the model only uses this variable if there are two boat ramps/marinas). A boat ramp/marina is lost to sedimentation when sediment elevation equals boat ramp/marina elevation at the point upstream from the dam where the boat ramp/marina is located.

In the case with one boat ramp/marina

- In the year that the boat ramp/marina is lost due to sedimentation, visitation is reduced from that year on by the user-defined percentage of benefits dependent on all boat ramps/marinas.
- This lost visitation is in addition to any reductions in visitation up to that point due to lost surface area.

In the case with two boat ramps/marinas

- In the year that the first boat ramp/marina is lost due to sedimentation, visitation is reduced from that year on by the user-defined percentage of benefits lost from the loss of one boat ramp/marina.
- In the year that the second boat ramp/marina is lost due to sedimentation, visitation is reduced from that year on by the user-defined percentage of benefits dependent on all boat ramps/marinas.
- This lost visitation is in addition to any reductions in visitation up to that point due to lost surface area.

When there are two boat ramps/marinas, it is generally assummed that the loss of one can be at least partially substituted through increased use of the second, hence, the two different parameter inputs (see Table 4-3).

Recreation consumer surplus under the without-project condition is not necessarily zero. A portion of recreator consumer surplus could be retained through substitution with a less desirable recreation site and/or recreation activity. The example methodology provided here accounts for the effects of substitution, as should any recreation economic analysis.

Mathematically, the annual net recreation benefit of a reservoir in year j can be expressed as Equation (53). Equation (54) shows the calculation of consumer surplus of a recreation visit to affected recreation areas for activity i in year j. Equation (55) shows the calculation of consumer surplus under the without-project condition for activity i—equal to the consumer surplus of activity *i* under the with-project condition less the proportion of consumer surplus lost if the reservoir ceased to exist. For example, if consumer surplus for one day of activity *i* at the reservoir in its current condition were equal to \$40, and 60 percent of consumer surplus would be lost if the reservoir ceased to exist (due to having to recreate at a further and/or less desirable location), then the substitution factor for activity *i* is 0.4 (the proportion of consumer surplus *retained*) and $CS_{Without,in}$ equals \$40 x 0.4, or \$16.

$$NRB_n = \sum_{i=1}^{k} CS_{Net,in} \times V_{in} \tag{53}$$

$$CS_{Net,in} = CS_{With,in} - CS_{Without,in} \tag{54}$$

$$CS_{Without,in} = CS_{With,in} \times SF_{in} \tag{55}$$

Where:

NRB_n = Net recreation benefit for affected areas in year *n*

$CS_{Net,in}$ = Consumer surplus of a visitation day in year *n* at Project-affected areas for recreation activity *i*

$CS_{With,in}$ = Consumer surplus of a visitation day in year *n* at Project-affected areas for recreation activity *i* under the with-project condition

$CS_{Without,in}$ = Consumer surplus of a visitation day in year *n* at Project-affected areas for recreation activity *i* under the without-project condition

V_{in} = Annual recreation visits in year *n* to Project-affected areas for recreation activity *i*

k = Number of different recreation activities at Project-affected areas

SF_{in} = Substitution factor: the proportion of recreation activity *i* consumer surplus retained through substitution with a less desirable recreation site and/or activity in the absence of the subject reservoir in year *n*

For simplification, this methodology develops a consumer surplus value for a typical visitor day, weighted by the participation rates of each recreation activity. By weighting the consumer surplus value by participation rate per activity, participation rates are, therefore, implicitly accounted for in annual visitation and the substitution factor. Modifying Equations (53), (54), and (55) to accommodate the typical visitor day yields Equations (56), (57), and (58).

$$NRB_n = CS_{Net,n} \times V_n \tag{56}$$

$$CS_{Net,n} = CS_{With,n} - CS_{Without,n} \tag{57}$$

$$CS_{Without,n} = CS_{With,n} \times SF_n \tag{58}$$

Where:

NRB_n = Net recreation benefit for Project-affected areas in year *n*

$CS_{Net,n}$ = Consumer surplus of a typical visitor day in year *n* at Project-affected areas

$CS_{With,n}$ = Consumer surplus of a typical visitor day in year *n* at Project-affected areas under the with-project condition

$CS_{Without,n}$ = Consumer surplus of a typical visitor day at in year *n* at Project-affected areas under the without-project condition

V_n = Total recreation visits in year *n* to Project-affected areas

SF_n = Substitution factor: the proportion of consumer surplus for a typical visitor day at Project-affected recreation areas retained through substitution with a less desirable recreation site and/or activity in the absence of subject reservoir in year *n*

Consumer surplus can be estimated by conducting a site-specific recreation benefit study for the subject reservoir, adapting a past site-specific study, or (most commonly) by employing the *benefit transfer approach* based on published recreation economics literature for similar recreation settings. An excellent resource for identifying relevant recreation economic analyses is the 2016 meta-analysis *Recreation Use Values Database for North America* (Rosenberger, 2016). Visitation by recreation activity and substitution effects are most often based on historical visitation data and estimates provided by local experts knowledgeable about regional recreation, such as the reservoir recreation manager.

Recreation visitation is seasonally dependent. The typical Reclamation reservoir sees more than half of annual recreation visitation in the months of June, July, and August. The shoulder months of April/May and September/October generally see a steep decline compared to the summer highs, while the winter months see the lowest visitation rates. For some reservoirs in the northern U.S., and some at higher elevations, there can be a moderate increase in visitation in the coldest winter months from ice fishing participation. To account for any seasonal effects, it is preferable to obtain historical visitation and activity participation rate data at the monthly timestep rather than annual timestep. Monthly participation rate data, if available, would be compiled to provide the annual participation rate data needed for RSEM.

Once consumer surplus per visitor day is established and adjusted to the appropriate price level it can be used as the input for RSEM along with the baseline visitation and boat ramp/marina recreation dependency values (Table 4-3). The model user should work with an economist to determine the appropriate unit recreation benefit inputs for RSEM (i.e., consumer surplus).

4.3 Lost Economic Benefits

When comparing benefits and costs, lost benefits impact the final result equivalent to an additional cost. This is to say that lost benefits can be treated as a cost in the same way that a decreased cost can be treated as a benefit. If lost benefits and decreased costs are accounted for accurately the net result is indifferent to their characterization as costs or benefits. This distinction will be further clarified in the economic results section of the report (Section 4.4).

Table 4-5 reports the hydrologic mechanism for benefits generation and the mechanism for loss of benefits in the presence of sedimentation. The sediment load is recalculated each year for the POA and then the impact of this sediment load is applied to the economic benefit categories in an annual recalculation of benefits for each. Irrigation, M&I, and F&W benefits are dependent on reservoir storage capacity, so as water storage capacity is reduced due to sedimentation, water supply to these beneficiaries is reduced. Flood control benefits are also dependent on reservoir storage capacity, but for the storage and regulation of flood events rather than for providing supply. When sediment decreases storage capacity, flood control benefits are consequently reduced. Hydropower benefits are dependent on hydraulic head and RSEM treats the benefit production as constant until the intake structure is sedimented in or the dam is decommissioned, whereby all hydropower benefits are lost. Recreation is dependent on reservoir surface area and accessibility to boat ramps/marina. As sedimentation fills the reservoir surface area and render boat ramps/marinas unusable, recreation benefits are decreased.

Table 4-5.—Mechanism for lost economic benefits due to sedimentation

Benefit	Benefits depend on:	Mechanism for lost benefits due to sedimentation
Irrigation	Irrigation deliveries from live storage	Decreased storage and therefore decreased irrigation deliveries
M&I	M&I deliveries from live storage	Decreased storage and therefore decreased M&I deliveries
F&W	Instream flows and water quality downstream of dam	Decreased storage and therefore decreased deliveries and less flexible timing for maintaining downstream volume and quality
Flood control	Total reservoir capacity space allocated for flood events	Decreased total capacity and therefore decreased capacity to regulate flood events.
Hydropower	Hydraulic head and water availability for releases	Sedimentation of outlet works fully depleting production and/or creating penstock and turbine damage
Recreation	Reservoir surface area and boat ramp accessibility	Sedimentation of facilities and increasing delta and sandbars decrease accessibility and reservoir surface area.

As impounded sediment can diminish the quantity of stored water, at some sites the sediment can be harmful and degrade water quality. When levels exceed background values for a particular period of time, this accumulated sediment can impact on reservoir operation, water release, sediment management, site desirability for recreational users, and survival and well-being of aquatic organisms within the reservoir.

Moreover, fine sediments such as silt and clay carry nutrients needed by aquatic organisms downstream of the reservoir. When downstream sediment discharge is discontinued, fewer or even no sediment are released downstream that affects nutrients, fishery habitat and populations, channel degradation and probably desirability of site for recreational users.

These lost benefits due to water quality are not accounted explicitly in RSEM, however, at some events they can be considered by reducing other categories of benefits, for example, considering the percentage reduction in recreation benefits.

4.4 Economic Costs

The economic benefits of a project need to be compared with the costs. RSEM evaluates costs for the following categories:

- Dam and reservoir planning, design, land acquisition, and construction costs.
- Dam and reservoir operations, maintenance, and replacement (OM&R) costs.

- Eventual dam decommissioning costs, including removal of the dam and management of the reservoir sedimentation.

- Upstream costs to property, infrastructure, and fish and boat passage due to sedimentation (aggradation) along the upstream river valley. Property and infrastructure may be impacted by increased groundwater and flood levels. Fish and boat passage may be impacted on the lower reservoir delta when surface stream flows seep into the groundwater or when delta channels form waterfalls over bedrock or erosion resistant surfaces.

- Downstream costs to property, infrastructure, and fish and wildlife habitat due to erosion (degradation) of the downstream river channel. These costs are incurred because the river's sediment supply is being trapped within the reservoir.

- Forced sediment management costs (e.g., dredging or flushing) to keep a dam outlet or reservoir water intake functioning.

- Planned sediment removal or avoidance costs. This would include any capital expenditures and unit costs during sediment removal or avoidance. Capital expenditures may include sediment sluiceways at the dam, reservoir bypass tunnels, dredging equipment, slurry pipelines, pumping stations, mechanical equipment, check dams, etc.

Some costs are incurred regardless of how reservoir sedimentation may be managed (e.g., dam construction, dam and reservoir operations). Other costs vary in magnitude and timing depending on the sediment management alternative (e.g., upstream and downstream impacts, forced sediment management, planned sediment management, and dam decommissioning). In general, costs are incurred each year to continually manage reservoir sedimentation, but the costs associated with reservoir sedimentation impacts may be avoided or delayed.

As a reservoir accumulates sediment over time, benefits that depend on the reservoir storage capacity, and benefits that depend on the wetted surface area, all decrease over time. Reservoir water storage benefits for agricultural irrigation use, M&I water use, and fish and wildlife use all decrease with reservoir sedimentation. Reservoir recreation benefits that depend on the wetted surface area also decrease with reservoir sedimentation. These diminishing benefits can be considered a cost. RSEM directly accounts for these reductions in benefits over time. Each year, the total diminished reservoir benefits are computed as the difference between benefits with and without sediment management as described above in Section 4.3 Lost Economic Benefits.

4.4.1 Cost Estimating

Site-specific cost estimates depend on engineering designs and determination of the construction means and methods. The services of a cost estimating engineer are needed to provide cost estimates that are appropriate for the level of investigation (preliminary, appraisal, feasibility, and final design). Costs are a function of the project scope, engineering design, means and methods of construction, quantities, unit costs, contingencies, overhead, and profit. The project scope determines what is needed. Engineering designs specify what will be accomplished. The construction means and methods are determined by the design, project requirements, and constraints. Quantities are determined by the project scope and engineering design. Unit costs are a function of material types, construction means and methods, transportation, and local prices. Without knowledge of the design and the construction means and methods, cost estimates may only have order-of-magnitude accuracy. RSEM assumes that cost estimates have been prepared external to the model.

4.4.2 Dam & Reservoir Planning, Design, and Construction Costs

RSEM asks the user to input the costs to construct a dam and the costs to operate and maintain it. The model considers these costs to be common to both alternatives (without and with sediment management). The additional capital costs and operation, maintenance, and replacement costs for sediment management are considered separately under the with sediment management alternative.

For an existing dam and reservoir, the previous costs to build the dam are considered sunk (non-recoverable) and are not considered in the economic analysis. For a new reservoir, the costs to plan, design, purchase land, and a construct the dam must be considered. The model user may enter the total cost to plan, design, purchase land, and construct the dam. Alternatively, the use may enter the costs for each of these categories and let RSEM compute the total (Table 4-6). The model can estimate the planning and design costs as percentages of the construction cost, or the user can directly enter the planning and design costs. The land acquisition cost is also entered for the dam, the full reservoir pool, and any other land needed for reservoir facilities (e.g., water intakes, boat ramps, marinas, campgrounds). The construction costs are entered for the dam and all reservoir facilities. The cost of dam construction generally depends on the site location and topography, the type of dam (earth, rockfill, concrete gravity, concrete arch, concrete buttress), construction methods, cost of materials, and transport of materials to the construction site.

The planning, design, land purchase, and construction of a dam is typically a multi-year effort. The costs for each of these activities need to be indexed to the common price-level year chosen for the analysis (see Section 4.1.2 Base Year for Economic Analysis). For a new dam and reservoir, the BYA should represent the year that the dam and reservoir are placed into service. The costs accrued up to that point should be compounded up to the common price-level year and stated as their present value. For RSEM, the user expected to ensure that all past construction costs, specific to the dam and reservoir, are accounted for and input to the model after being adjusted to the price level consistent with the base year for analysis. There are multiple approaches to accommodate past expenditures. Reclamation’s typical approach is to estimate opportunity costs by applying interest during construction to all related costs before the dam and reservoir are placed in service. The user will have to consistently perform these calculations outside of RSEM.

Table 4-6.—User cost inputs for dam & reservoir planning, design, and construction

Dam & Reservoir Planning, Design, and Construction Costs	Units	Notes
Planning cost as percentage of construction cost	dimensionless	The actual planning costs may be difficult to estimate, but can be expressed as a percentage of the total construction cost (e.g., 1%)
Design cost as percentage of construction cost	dimensionless	The actual design costs may be difficult to estimate, but can be expressed as a percentage of the total construction cost (e.g., 5%)
Planning cost*	$	The planning cost can be provided directly, otherwise, RSEM will estimate the cost as a percentage of the total construction cost
Design cost*	$	The design cost can be provided directly, otherwise, RSEM will estimate the cost as a percentage of the total construction cost
Land acquisition cost	$	Cost to purchase land for the dam, reservoir, and any related facilities
Construction cost	$	Total cost to construct the dam and reservoir facilities
Additives for design and construction cost contingencies *	$	Cost additives to account for unlisted items, mobilization, demobilization, contingencies, procurement, overhead, and profit (Table 4-7)
Total of Planning, Design, Acquisition and Construction Cost*	$	Total cost including contingencies for design, construction, and contracting

*Parameters computed by RSEM. These parameters may be overridden by the user.

4.4.3 Design, Construction, and Contract Contingencies Cost Additives

Once costs are estimated for materials and labor, additional costs are estimated to account for unlisted items, mobilization, demobilization, contingencies, procurement, overhead, and profit (table 4 3). These additional costs are typically estimated as percentages of the combined cost of materials and labor:

- *Unlisted Items* include minor items required to construct a project for which it is not practical to develop designs and quantities during early stages of a project.
- *Mobilization & Demobilization* costs include contractor bonds and mobilizing (and de-mobilizing) contractor personnel and equipment to and from the project site, including initial project startup.
- *Design Contingencies* to account for the cost of minor design and cost estimating refinements which are not practical to anticipate early in the project but typically arise as the project advances through final design.
- *Allowance for Procurement Strategy* to account for the additional cost when solicitations will be advertised and awarded without full and open competition. Examples of these

practices include Hub-zone, 8(a) competitive and negotiated procurement[2], small business set aside[3], Public Law 93-638 Indian Self-Determination Act[4], or Request for Proposal[5] where award may be based on technical considerations.

- *Contractor Overhead and Profit* to account for the additional cost necessary to attract construction contractors for assuming the risk of performing the scope of work.
- *Construction Contingencies* to cover minor differences in actual and estimated quantities, unforeseeable difficulties at the site, changed site conditions, possible minor changes in plans, and other uncertainties.

Table 4-7.—User Percentage Inputs for Design, Construction, and Contract Contingencies Cost Additives

Design, Construction, and Contract Contingencies Cost Additives	Units	Notes
Increase for unlisted items	dimensionless	Minor items required to construct a project
Increase for mobilization and demobilization	dimensionless	Contractor bonds and mobilizing (and de-mobilizing) contractor personnel and equipment to and from the project site
Increase for design contingencies	dimensionless	Minor design and cost estimating refinements
Increase for procurement strategy	dimensionless	Cases when solicitations will be advertised and awarded under other than full and open competition
Increase for overhead and profit	dimensionless	Attraction of construction contractors for assuming the risk of performing the scope of work
Increase for construction contingencies	dimensionless	Site conditions, possible minor changes in plans, and other uncertainties
Total design, construction, and contracting increase*	dimensionless	Sum of all percentages above to account for uncertainty, overhead, and profit

*Parameters computed by RSEM. These parameters may be overridden by the user.

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[2] The HUB Zone program fuels small business growth in historically underutilized business zones with a goal of awarding at least 3% of federal contract dollars to HUB Zone-certified companies each year. The program also gives preferential consideration to those businesses in full and open competition.

[3] The federal government limits competition for certain contracts to small businesses to help provide a level playing field. Those contracts are called "small business set-asides," and they help small businesses compete for and win federal contracts.

[4] The 1975 Indian Self-Determination and Education Assistance Act, Pub. L. 93-638, gave Indian tribes the authority to contract with the Federal government to operate programs serving their tribal members and other eligible persons.

[5] A request for proposal (RFP) is a business document that announces a project, describes it, and solicits bids from qualified contractors to complete the project.

4.4.4 Dam and Reservoir OM&R Costs

For the dam and reservoir OM&R costs, RSEM considers both annual costs and costs that recur every 5 years (Table 4-8). These OM&R costs are the non-sediment related costs to operate the dam and reservoir facilities and apply to both the without-and with sediment management alternatives. RSEM assumes that present OM&R costs remain the same throughout the life of the dam and reservoir. Any future forced sediment management costs to keep the dam outlet functioning are considered separately under the without sediment management alternative. Some OM&R costs are significant and do not occur every year. For example, coating of spillway gates, rewinding of powerplant generators, replacement of valves, etc. The model user is free to annualize all OM&R costs or partition them as desired between annual costs and 5-year recurring costs.

Table 4-8.—User Costs Inputs for Operations, Maintenance, and Replacement (OM&R)

Operations, Maintenance, and Replacement (OM&R) Costs	Units	Notes
Annual OM&R cost	$	Annual OM&R costs to operate and maintain the dam and reservoir facilities, independent of any sediment management costs
5-year recurring costs	$	Additional and periodic OM&R costs to maintain the dam and reservoir facilities, independent of any sediment management costs

4.4.5 Dam Decommissioning Costs and Benefits

The financial cost of dam decommissioning can be high for a reservoir full of sediment. Because of discounting, the economic cost from today’s perspective will depend on how far into the future the dam might be decommissioned. RSEM assumes that high and significant hazard dams will eventually be removed if their reservoirs experience severe sedimentation. With sediment management, dam decommissioning may be avoided or occur much later than without sediment management.

There is generally little concern when sediment or woody debris deposits within the reservoir’s dead storage pool (below the elevation of lowest dam outlet) because that portion of the reservoir storage can’t be used anyway. However, after the end of the sediment design life, when sediment has filled the dead storage pool, some sediment will begin passing through the dam outlet. Without intervention, continued sedimentation, along with wood debris, will eventually burry and plug the dam outlet or reservoir water intake, if present. Plugging may occur soon after the dead storage pool has filled with sediment or after a few more decades of sedimentation. Forced and localized sediment management (e.g., dredging, flushing) will be required to maintain a functioning dam outlet. However, even with forced sediment management, the sedimentation level near the dam eventually will be high enough above the dam outlet that maintaining the outlet will no longer be practical and dam decommissioning will be necessary.

Actual removal of a dam with severe sedimentation may require multiple years to plan and implement. However, dam decommissioning is typically accomplished many decades into the future, so the exact distribution of costs that are incurred over a period of a few years is not so important and can be simulated to occur in a single year. Therefore, RSEM assumes that all costs related to dam decommissioning occur during a single year of decommissioning. The decommissioning of Reclamation dams is decades away, so assigning costs to a single year is a reasonable approximation. However, the years that dam decommissioning costs are incurred would be significant when decommissioning would occur during the near term. The model user would have to input an equivalent cost in a certain year that accounts for the actual time period of decommissioning. For RSEM, the dam age at decommissioning is based on the sediment design life plus the additional years until the outlet becomes unreliable and decommissioning can be planned.

RSEM estimates the dam decommissioning costs as the sum of the costs to remove the dam structure, manage the reservoir sediment, temporarily divert the river (e.g., coffer dam construction), and river restoration, less any salvage value of equipment and materials as calculated in Equation 59.

$$C_{DC} = V_{Dam}\, U_{DR} + V_{Sed}\ \ U_{SM} + C_{RD} + C_{CD} + C_{RR} - Salvage \qquad (59)$$

Where:

C_{DC} = total cost of dam decommissioning

V_{Dam} = volume of dam material to be removed

U_{DR} = unit cost to remove dam materials

V_{Sed} = volume of reservoir sediment at time of dam removal

U_{SM} = unit cost to manage sediment volume

C_{RD} = cost of river flow diversion around construction area

C_{CD} = cost of possible coffer dam construction, and subsequent removal, to dewater construction area

C_{RR} = cost of river habitat restoration related to dam removal, such as establishing a river channel past the dam site, care of endangered species during construction, and habitat enhancement

Salvage = Salvage value from any removed dam materials or reservoir sediment

The user needs to specify the unit costs related to dam decommissioning along with costs for river diversion, coffer dam construction, river diversion, and any salvage benefits (Table 4-9).

Table 4-9.—User inputs of dam decommissioning costs

Dam Decommissioning	Units	Notes
Dam removal unit cost	$/yd^3	Unit cost of removing the material composing the dam (e.g., concrete, earth, rock)
Sediment management unit cost	$/yd^3	Unit cost of managing or mitigating the reservoir sediment upon dam decommissioning. This could include sediment removal or stabilization, or downstream mitigation for releasing the sediment.
River diversion cost	$	Cost to divert reservoir inflows through or around the construction site
Coffer dam cost	$	Cost to construct, and subsequently remove, any coffer dams that might be needed to dewater construction areas
Salvage benefits	$	Value of any dam materials that may be salvaged. This will depend on the market value of reusable dam material or sediment.
Other river restoration costs	$	Costs for any river restoration activities associated with dam decommissioning (e.g., constructed stream channel past dam site, engineered riffles, log jams)
Dam decommissioning cost before additives*	$	Total dam decommissioning cost before additives for design, construction, and contracting
Dam decommissioning cost with additives*	$	Total dam decommissioning cost after the addition of costs for design, construction, and contracting
Annual dam removal benefit	$	Annual river restoration benefit for decommissioning the dam (may be determined from non-use economic study)

*Parameters computed by RSEM. These parameters may be overridden by the user.

RSEM assumes that all economic costs associated with operating and maintaining the dam and reservoir cease the year that dam decommissioning begins. This is also assumed for all economic costs related to reservoir sedimentation impacts upstream and downstream of the reservoir and for all economic benefits associated with water storage, recreation, and hydropower.

The annual economic benefits associated with dam removal and river restoration begin the year after dam decommissioning. These restoration benefits will be site specific and could be small or quite substantial. For example, the removal of two dams on the Elwha River (Elwha Dam and Glines Canyon Dam) allowed salmon to reestablish their spawning routes, resulting in increased salmon runs. This improvement in fishing provided direct values for tourism and food production, and indirect values for ecosystem restoration and species restoration. Loomis (1996) estimated the “range in benefits to Washington residents from a minimum of $94 million to $138 million annually. The range in national benefits ranges from a lower bound estimate of $3.47 billion to $6.275 billion as our best estimate based on the sample response.”

4.4.6 Upstream Sedimentation Costs

RSEM simulates the potential upstream inundation of lands and costs associated with the purchase of property, relocation of highways and railroads, and improvement of fish and boat passage. The unit costs for land purchase and highway and railroad relocation, and the annual costs for fish and boat passage may be the same under alternatives without and with sediment management. However, the annual costs will be larger and occur sooner without sediment management and may not occur with sediment management. The costs for lands, highways, and railroads are assumed to be a function of length, area, and thickness of the upstream delta sedimentation, which tends to increase over time (see Section 3.2 Upstream Sedimentation Modeling). For reservoirs in steep and remote locations, upstream sedimentation costs may be low or zero.

RSEM assumes that the incremental cost of these impacts is assigned in each of the years that they occur. Even though inundated land might be purchased, and highways and railroad relocated, once every 5 or 10 years, RSEM assumes that incremental costs are assigned each year (while the reservoir continues to exist) so that costs are spread out over the period of upstream delta sedimentation. The annual costs for fish and boat passage are assumed to be constant over time. The formulas used to compute these costs are presented below:

$$C_{Up(n)} = C_{Land(n)} + C_{Road(n)} + C_{FB} \tag{60}$$

Where:

$C_{Up(n)}$ = incremental cost of sedimentation upstream from the full reservoir pool in year n

$C_{Land(n)}$ = incremental cost of impacts to upstream lands from rising water table and flood stage

$C_{Road(n)}$ = incremental cost of impacts to upstream highways or railroads from rising water table and flood stage and lateral delta channel migration

C_{FB} = annual mitigation cost to enable fish and boat passage along the upstream delta (includes design, construction, and contracting additive costs)

When the stream flows along delta channels become very low or even dry, during low-flow seasons, there may be a need to improve fish or boat passage. This might be accomplished by increasing flows from upstream dams, excavating a deeper channel through the reservoir delta, or lining the channel to prevent seepage of surface water into the ground water of the delta. For example, a delta channel on Box Canyon Creek, flowing into Lake Kachees, WA, is periodically lined with polyethylene plastic sheeting to enable endangered bull trout migration (https://www.youtube.com/watch?v=fvZDVZ4_Xvk). RSEM assumes that these activities, if necessary, will be accomplished every year on a seasonal basis and that the mitigation cost (C_{FB}) will be the same each year.

Equations 61 and 62 are presented to compute the incremental cost of impacts to upstream lands and highways or railroads from rising water table and flood stage and lateral delta channel migration.

$$C_{Land(n)} = \left(Area_{U(n)} - Area_{U(n-1)}\right)(V_{Land}) \tag{61}$$

Where:

$Area_{U(n)}$ = horizontal surface area of delta causing significant aggradation upstream from and above the full reservoir pool (top of live storage) in year *n*

V_{Land} = Lost value per unit area of land when rendered unusable due to inundation

$$C_{Raod(n)} = \left(L_{tU(n)} - L_{tU(n-1)}\right)(V_{Road}) \tag{62}$$

Where:

$L_{tU(n)}$ = longitudinal length of delta causing significant aggradation upstream from and above the full reservoir pool (top of live storage) in year n.

V_{Road} = Unit highway or railroad relocation cost due to inundation (includes design, construction, and contracting additive costs)

Input parameters utilized by RSEM are presented in Table 4-10.

Table 4-10.—User inputs for upstream sedimentation costs

Upstream Sedimentation Costs	Units	Notes
Sedimentation threshold that would cause upstream land impacts	feet	Sedimentation thicknesses below this threshold may be measurable, but do not cause significant impacts
Lost value per unit area of land when rendered unusable due to inundation	$/acre	Unit value includes the land, buildings, and any infrastructure on these lands (except for highways and railroads)
Unit highway/railroad relocation cost due to inundation	$/mile	Unit cost to relocate highways or railroads away from or above upstream delta sedimentation
Annual fish and boat passage cost due to sedimentation	$/yr	Average annual cost to enable fish and boat to pass along delta channels upstream of the reservoir pool (assumed to be the same each year)

4.4.7 Downstream Channel Degradation Costs

When coarse sediment is trapped within a reservoir, the downstream release of clear water tends to degrade the downstream channel and lead to streambank erosion. If sediment management is employed to allow coarse sediment to pass downstream of the reservoir, then channel degradation can be avoided or reduced.

RSEM simulates downstream channel degradation and costs associated with streambank protection. RSEM assumes that rock rip rap would be used to prevent streambank erosion after the occurrence of channel degradation. The volume of rock required is estimated as a function of the stream velocity and predicted channel degradation depth.

Rock rip rap is a very common form of bank protection, and a design template is available (Baird, et al, 2015). Other bank stabilization methods include preservation, restoration of channel and floodplain function, enhance or plant riparian vegetation, construct log jams (large woody debris), and construct bendway weirs or spur dikes. Designs for these other methods are very site specific and not easily adopted to RSEM.

RSEM estimates the annual cost of downstream channel degradation as a function of the annual cost of installing streambank protection to mitigate the impacts (see Section 3.3 Downstream Channel Degradation Modeling). Channel degradation will be significantly greater for sand-bed rivers than for gravel-bed rivers. The cost of streambank protection is used as a proxy for damages to land, streamside infrastructure, and habitat that would occur in the absence of mitigation. Even though streambank protection might not be installed every year that degradation continues, RSEM assumes annual incremental installation so that costs are spread out over the period of channel degradation.

RSEM assumes that rock riprap would be the chosen method to protect streambanks from erosion caused by channel degradation (see Section 3.3.2 Bank Stabilization Design and Cost). Each year, the model estimates the annual increase in vertical degradation, and its downstream progression, along with the annual volume of rock riprap needed to mitigate the degradation impacts. The unit cost of rock riprap installation (supplied by the model user) is multiplied by the annual volume of rock needed for installation. The unit installation cost includes materials, delivery, and labor. Additional factors are applied to account for one or both stream banks, habitat degradation, and contingencies (Equation 63).

$$Cost_{BP(n)} = \left(V_{BP(n)}\ UC_{BP}\right)(SB_F)\ (1 + UI)\ (1 + MD)\ (1 + DC + PS)\ (1 + OP)\ (1 + CO) \quad (63)$$

Where:

$Cost_{BP(n)}$ = Cumulative cost of streambank protection at year *n* since the beginning of reservoir sedimentation

$V_{BP(n)}$ = Cumulative volume of streambank protection at year *n* needed for one streambank

UC_{BP} = unit cost for streambank protection materials, delivery, and installation labor

SB_F = stream bank protection factor to account for one or both streambanks and habitat degradation (typical values range from 1 to 4)

UI = increase to account for unlisted items (e.g., 0.10)

MD = increase to account for mobilization and demobilization (e.g., 0.05)

DC = increase to account for design contingencies (e.g., 0.20)

PS = increase to account for procurement strategy (e.g., 0.05)

OP = increase to account for overhead and profit (e.g., 0.15)

CO = increase to account for construction contingencies (e.g., 0.20)

For a given year, the annual cost of streambank protection is computed as the cumulative cost for that year less the cumulative cost for the preceding year.

Table 4-11.—User inputs for downstream channel degradation costs

Downstream Channel Degradation Costs	Units	Notes
Median riprap rock size*	feet	Rock rip rap size necessary to prevent erosion of the channel banks (computed by RSEM as a function of stream velocity)
Degradation threshold (min. vertical erosion when economic impacts begin)	feet	Channel degradation depths less than this threshold are considered insignificant
Streambank side slope (*z*:1)	dimensionless	The side slope is expressed as the ratio of horizontal (H) distance, *z*, to a unit increase in vertical (V) rise (*z*H:1V). A 2:1 side slope is the same as a 50% slope (2ft H : 1ft V or 2m H : 1m V)
Streambank protection factor	dimensionless	Factor between 1 and 4 to account for protection along the left and right channel banks and habitat degradation. For example, a value of 1 is for protection of one streambank. A value of 2 is for the protection of both streambanks. A value of 3 or 4 accounts the protection of one or both streambanks and habitat loss.
Unit cost of streambank protection before additive costs	$\$/yd^3$	Unit cost to purchase and place rock rip rap along the channel streambanks (before cost additives)
Unit cost of streambank protection with additive costs*	$\$/yd^3$	Unit cost to purchase and place rock rip rap along the channel streambanks (after cost additives)

*Parameters computed by RSEM. These parameters may be overridden by the user.

4.4.8 Reservoir Sediment Management Costs

The costs of reservoir sediment management are described in Chapter 5 Sediment Management Alternatives. The costs are different under the without and with sediment management alternatives. RSEM considers sediment management costs under the three categories listed below:

- Forced sediment management costs (e.g., dredging or flushing) to keep a dam outlet or reservoir water intake functioning. Under the without sediment management alternative, sediment and woody debris may eventually block the dam outlet forcing emergency action and often at a higher cost than under planned sediment management. This category does not apply to the with sediment management alternative because actions would already in place to prevent dam outlets from becoming blocked or respond quickly if they should become blocked.

- Capital expenditures associated with planned sediment management. Such expenditures could include construction of sediment sluiceways at the dam; construction of a reservoir bypass tunnel; purchase of dredging equipment and construction of slurry pipelines, and pumping stations; purchase of mechanical equipment; construction of check dams.

- Annual reservoir sediment removal or avoidance costs associated with the planned sediment management activities. RSEM computes these annual costs based on the unit costs ($\$/yd^3$), supplied by the user, for the management of fine and coarse sediment. For reservoir sluicing or flushing, costs are primarily associated with low-level dam outlets and any water-injection systems that assist sediment transport through the reservoir. For dredging alternatives, costs are primarily associated with dredging equipment and supporting systems such as slurry pipelines, pumping plants, conveyor belts, or trucking. For watershed sediment management alternatives, costs might be associated with removing sediment from behind check dams, promoting vegetation growth, and maintaining erosion control protection measures.

The existing OM&R cost allocation agreements with stakeholders could be applied to the repayment of sediment management costs to maintain reservoir storage capacity.

4.5 Economic Results

This section describes the economic results reported by RSEM. The model calculates and reports a series of economic outputs for both the without and with sediment management alternatives and then provides direct comparisons of the competing alternatives. The RSEM simulation of alternatives is described in Chapter 5. Sediment Management Alternatives.

All reported economic outputs are discounted to their present value for time-equivalent comparison. Discounting benefits and costs is discussed in detail in Section 4.4.1, while Economic outputs, comparisons, and additional decision support metrics are presented in sections 4.4.2, 4.4.3, and 4.4.4.

4.5.1 Discounting Benefits and Costs

There are two inputs that dictate how RSEM accounts for the time value of money, the discounting approach and the discount rate. The discounting approach affects the shape of the discount factor curve, while the rate affects the slope of the discount factor curve, as illustrated in Figure 4-4 comparing an exponential discounting approach to a gamma discounting approach, using different discount rates. The discount factor is a measure of the discounting effect at a given point in time. The interaction of different discounting approaches and rates will result in a different discount factor in a given analysis year.

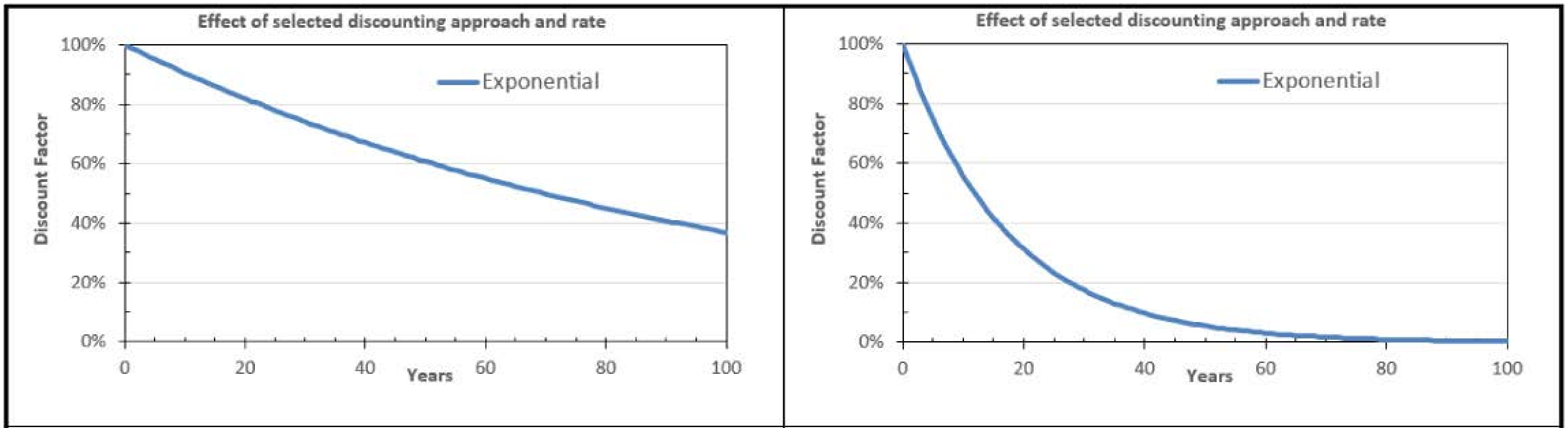
The approach to discounting required under Reclamation guidance can generally be termed exponential (classic or standard) discounting. Exponential discounting is the approach traditionally used by economists and engineers and is the most widely used approach today. When any discounting approach is employed, costs and benefits occurring several decades into the future, even dam decommissioning cost, have reduced influence on the initial investment decision. Exponential discounting does this in a fixed and indifferent manner. The method is straightforward and has time-consistent properties. Projects can be economically justified without sediment management, but this can lead to integrational inequity (i.e., future generations bear the lion’s share of costs and minimal project benefits).

Several alternative discounting approaches have been described in recent years that arguably better represent future economic uncertainty, regional and intergenerational equity, and sustainability considerations (Harpman 2014). Many of these new discounting approaches result in declining discount rates (DDRs) over time and may be better suited for the analysis of long-lived infrastructure and environmental investments (National Center for Environmental Economics 2014). DDRs have also been used by World bank group projects (Annandale et al. 2016). Figure 4 5 illustrates the temporal differences across a selection of discounting approaches over a 150-year period.

Reclamation guidance also provides direction regarding the use of real versus nominal discount rates: “Where not precluded from doing so, real interest rates should be used” (DOI, 2015). This is consistent with RSEM’s assumption of no inflation and reporting of results in real dollars.

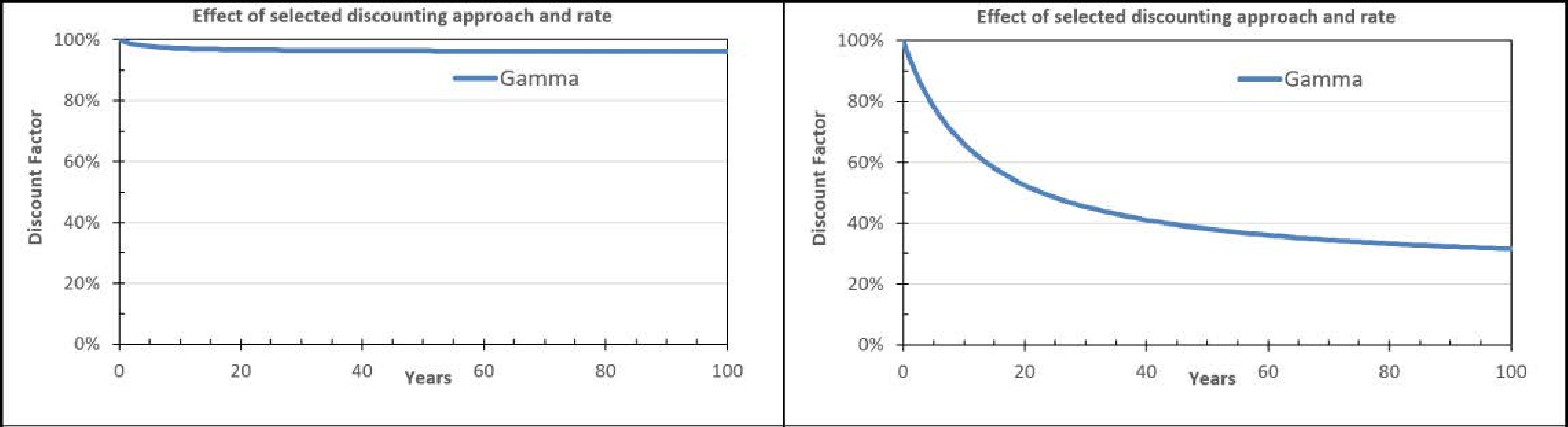
Considering Reclamation’s guidance, and the fact that results generated using the exponential approach will generate results most readily comparable with other models, the exponential discounting approach should be treated as the default for RSEM. Alternative discounting approaches may be appropriate, depending on decision process needs, time preference, consideration of intergenerational equity, and available knowledge concerning approaches.

Alternative discounting approaches could be used for comparison, sensitivity analysis, or research purposes and these interpretations would require knowledge of economics or collaboration with an economist to meaningfully apply and interpret results. Note that these approaches require additional parameters to be defined, and there is a lack of consensus on the appropriate values these parameters should assume.



(A) Exponential discounting approach using 1.0% discount rate

(B) Exponential discounting approach using 6.0% discount rate



(C) Gamma discounting approach using 1.0% discount rate

(D) Gamma discounting approach using 6.0% discount rate

\Figure 4 4.—Discount factor over 100 years using the exponential and Gamma approaches and two different rates. The approach affects the curve's shape, while the rate affects the curve's slope.

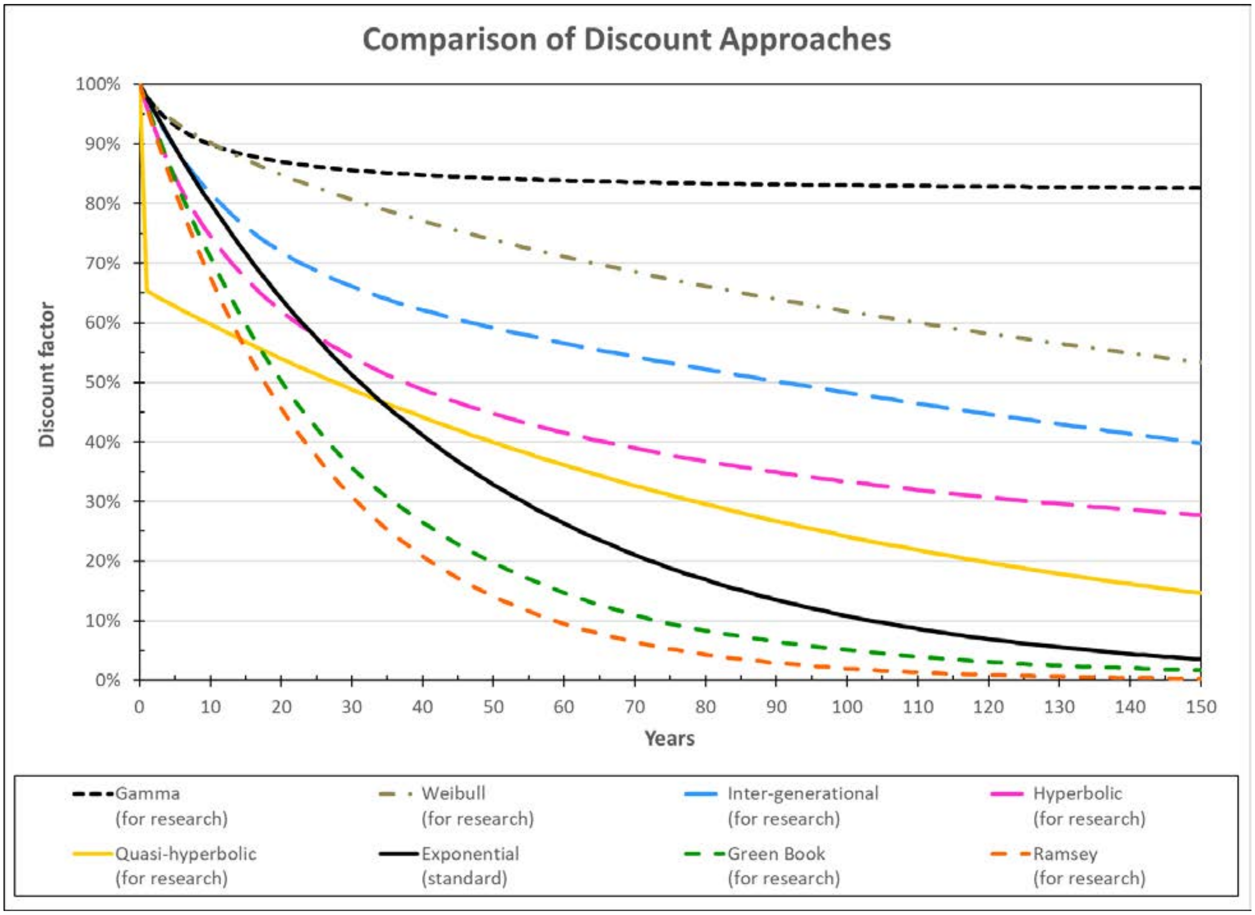


Figure 4-5.—Relationships between discount factors and time under the various discounting approaches available in RSEM based on Harpman, 2014 (modified from Anari et al, 2023). Discount factors for the exponential discounting approach assume a discount rate of 2.5%.

In summary, the user should always start with the exponential discounting approach, and in most cases should conduct all their modeling and report results using this approach. There is a lack of consensus surrounding the suitability of, and parameter definition for, most of the seven alternative discounting approaches. For economists interested in further investigating the suitability and parameter definition for alternative discounting approaches, RSEM can serve as a useful tool. RSEM will allow the investigating economist to develop any number of real-world scenarios and then conduct wholesale changes of discounting approach and sensitivity analysis of individual parameters to contribute to the body of knowledge around non-exponential discounting.

Among the eight discounting approaches depicted in Figure 4-5, two are investigated in Chapter 6. Example Case Study: exponential and intergenerational. The equations expressing these discounting approaches, as well as a brief description of each, are provided in the following section. For alternative discounting approaches, the user is encouraged to study the cited references to better understand the applicability of these methods.

4.5.1.1 *Exponential Discounting*

Discounting future benefits or costs by a fixed rate, for each unit of time, is the basis of exponential discounting, and it is the standard and most commonly used approach by economists and engineers today. Guerriero and Pacelli (2020) indicate that exponential discounting can be problematic and inappropriate for investments that are to be judged over longer periods of time since future generations will bear costs (or benefits) from actions of previous generations.

Exponential discounting:

$$W_t = \left(\frac{1}{1+r}\right)^t \tag{64}$$

Where:

W_t = discount factor, or weight at time t

r = (constant) discount rate

t = time period index

4.5.1.2 *Ramsey Discounting*

The Ramsey discounting reflects a social planner prospective to maximize social welfare. The project’s cash flows are discounted to the rate of consumption at which a society is willing to postpone a unit of current consumption in exchange for more future consumption. This rate can be estimated through the Ramsey formula (Nesticò, 2019). The Ramsey discount rate accounts for people’s impatience (ρ) and the growth rate of future (per capita) consumption (product of η and g) (Pearce and Groom, 2003).

Ramsey discounting:

$$W_t = \left(\frac{1}{1+r}\right)^t \tag{65}$$

$$r = \rho + \eta g_t \tag{66}$$

Where:

W_t = discount factor, or weight at time t

r = discount rate

ρ = pure rate of time preference

η = elasticity of marginal utility of consumption

g_t= growth of consumption

Pearce and Groom (2003) state that η presents the percentage change in the well-being derived from a percentage change in consumption (or income). People in the future will (almost certainly) be richer and hence the 'utility' they attach to one more dollar of income is likely to be lower than that attached to the same dollar today. If future generations are richer, then η might be less than 1.0. However, RSEM has η set equal to 1.0 as the default, as used by Johnson and Hope (2012) and Cowell and Gardiner (1999), but the user can override this value. An assumption of 1 implies the utility of a dollar is the same today as in the future, while a value less than 1 implies the utility of a dollar is less in the future than today.

The pure rate of time preference (ρ) is generally set to zero when considering intergenerational equity, and a positive value implies a greater preference for the current generation relative to future generations.

The greatest difficulty in implementing the Ramsey Discounting method might be the estimation of the growth rate of consumption (g_t) since it is influenced by economic shocks and uncertainty (Nesticò, 2019). There exist two types of approaches for providing values to the parameters of this equation: a descriptive and a prescriptive approach. Interested readers are referred to Guerriero & Pacelli (2020).

It can be argued that estimating the elasticity of consumption is equally (if not more) challenging than estimating the growth rate of consumption, as there is no agreement on what this should be, while the growth rate is more objective and can be based on past observations. Basic economic theory for diminishing returns in consumption would imply using an elasticity less than 1, but the choice from 0-1 is an open question, especially since this is supposed to represent preferences for all of society (Matthew Elmer, written communication, December 2022).

4.5.1.3 *Hyperbolic Discounting*

More generally, the rate at which people discount future benefits and costs decline as the length of the delay increases (Redden 2007). Hyperbolic discounting is an alternative discounting approach that decreases the rate of discounting as the delay occurs further in the future. Hyperbolic discounting will generally discount future benefits and costs more than Exponential discounting for short delays, and less than exponential discounting for long delays (Redden 2007).

Hyperbolic discounting:

$$W_t = \left(\frac{1}{1+kt}\right)^{h/k} \tag{67}$$

Where:

W_t = discount factor, or weight at time t

k = degree to which hyperbolic discount weight differs from exponential discount weight ($k > 0$)

h = effect of time perception ($h > 0$)

t = time period index

The parameters *h* and *k* influence the degree to which the Hyperbolic discount factor differs from the Exponential discounting (Harpman 2014).

4.5.1.4 *Quasi-Hyperbolic Discounting*

The hyperbolic discounting curve decreases steeply in the immediate future and then more gently over the long term. This function is described as present-biased (Robinson and Hammitt, 2010). In contrast, the Quasi-Hyperbolic discounting approach (or β-δ preferences) includes the parameters β (short-term discount factor) and δ (long-term discount factor) (Ida 2014).

The Quasi-Hyperbolic discounting approach is a simpler version of hyperbolic discounting. For Quasi-Hyperbolic discounting, the discount weight (W_t) is defined as shown in Equation (68), where the parameters β and δ are time invariant constants and t can take on only discrete values (Harpman, 2014).

$$W_t = \begin{cases} 1 & \text{For t} = 0 \\ \beta\,\delta^t & For\ t > 0 \end{cases} \tag{68}$$

Where:

W_t = discount factor or weight at time t

$0 < \beta < 1$

$0 < \delta < 1$

t = time period index

Van de Ven and Weale, (2014) noted β ranging from 0.296 to 0.825. Harpman (2014) applied β = 0.660 and δ = 0.990 and compared Quasi-Hyperbolic approach with the Exponential (with r = 0.08) and Hyperbolic discounting approaches. With these parameters, the Quasi-Hyperbolic discounting curve is lower than exponential discounting curve during the initial period, but then is higher, and similar to the hyperbolic curve during the later period.

4.5.1.5 *Gamma Discounting*

Gamma discounting is an approach developed mainly by Weitzman (2001) and is based on the argument there are huge uncertainties about the magnitude of future discount rates (Sumaila and Walters, 2005 and Weitzman, 2001). The gamma discounting approach uses a discount rate which varies with each time period, Equation 69, (Harpman, 2014).

$$r_t = \frac{\mu}{1 + t\sigma^2 / \mu} \tag{69}$$

Where:

r_t = certainty equivalent discount rate at time

σ = standard deviation of the Gamma distribution

μ = mean of the Gamma distribution

t = time period index

Using the time-varying gamma discount rate (Equation 69), Gamma discount weights can be characterized as shown in Equation 70.

$$W_t = \left(\frac{1}{1 + r_t}\right)^t \tag{70}$$

Where:

W_t = discount factor or weight at time (t)

r_t = the gamma discount rate at time (t) from Equation 69

t = time period index

In the case of Gamma discounting, the discount weight (W_t) decreases over time (t) but at a rate which is less than the exponential (classic) discount factor. As a consequence, the net values (V) which occur in later in the analysis period would be expected to be more important in the calculation of NPV (Harpman, 2014).

4.5.1.6 *Weibull Discounting*

Weibull discounting approach considers an extra parameter for time perception by slowing down or speeding up the influence of time (Jamison and Jamison 2010) (Equation 71). When the parameter, $s = 1$, the Weibull discount weight collapses to Exponential discount weight with the same annual (constant) discount rate. When $s > 1$, time perception slows down and the Weibull weight lies everywhere above the Exponential discount weight. If $s < 1$, time perception is speed up and the Weibull weight lies below the plot of the Exponential weight (Harpman, 2014).

$$W_t = \left(\frac{1}{1+r}\right)^{t^{\frac{1}{s}}} \tag{71}$$

Where:

W_t = discount factor or weight at time (t)

r = the constant annual discount rate

s = a parameter affecting time perception

t = a time period index

4.5.1.7 *Green Book Discounting*

The Green Book discount rate, known as the Social Time Preference Rate (STPR), for use in UK government appraisal, is set at 3.5% in real terms. This rate has been used in the UK since 2003.

The approach is similar to the Ramsey discounting approach considering the time preference (ρ), the marginal utility of consumption (η), and growth of consumption (g). However, there are a range of estimates of the individual components of the discount rate (Spackman, M., 2016)

The standard STPR of 3.5% applied in a UK government appraisal declines over the long term due to uncertainty about future values of its components. Table 4-12 presents the standard STPR and a reduced STPR (excludes the pure social time preference - $\rho = 0$) (Green Book 2022).

When applying this approach, the NPV using the standard STPR and the reduced rate STPR should both be included in the results of the appraisal and explained clearly. (Green Book 2022). The difference between these two estimates of NPSV provides an estimate of the intergenerational wealth transfer attributable to pure social time preference which should be part of the explanation of the approach. (Lowe 2008).

Table 4-12.—Green Book long-term discount rates

Period of years	0-30	31–75	76–125	126–200	201–300	301+
Standard rate as published in the Green Book	3.5%	3%	2.5%	2%	1.5%	1.00%
Reduced rate where; pure social time preference - $\rho = 0$	3.00%	2.57%	2.14%	1.71%	1.29%	0.86%

4.5.1.8 *Intergenerational Discounting*

Preferences can change over time, and this characteristic makes it difficult for economists to assess whether current generations' preferences reflect those of communities that are not born yet (Guerriero and Pacelli 2020). An alternate method of incorporating intergenerational impact is to consider the timespan of future generations. Intergenerational discounting accomplishes this by requiring two different discount rates and an assumed generation timespan (Harpman 2014; Sumaila and Walters 2005).

Intergenerational discounting:

$$W_t = \left(\frac{1}{1+r_a}\right)^t + \frac{\left(\frac{1}{1+r_{fg}}\right)\left(\frac{1}{1+r_a}\right)^{t-1}}{G}\left[\frac{1-\Delta^t}{1-\Delta}\right] \tag{72}$$

$$r_{fg} = \frac{\left(1-\sqrt[G]{\frac{1}{1+R_{fg}}}\right)}{\sqrt[G]{\frac{1}{1+R_{fg}}}} \tag{73}$$

$$\Delta = \frac{1/(1+r_{fg})}{1/(1+r_a)} \tag{74}$$

Where:

W_t = discount factor, or weight at time *t*

r_a = present generation annual discount rate

r_{fg} = future generation annual discount rate

G = the assumed length of a generation

R_{fg} = generational discount rate

t = time period index

4.5.2 Economic Outputs for Without and With Sediment Management

The following economic outputs are reported for both the without and with sediment management alternatives over four different POAs—50 years, 100 years, 200 years, and 500 years. These outputs include cumulative and annualized economic benefits, costs, and lost benefits. However, the cumulative and annualized lost benefits are only provided for informational purposes as they are already accounted for as reduced benefits. Lost benefits are not added to the costs.

All annualized values are calculated using an exponential discounting approach, regardless of the discounting approach selected for present valuation. For alternative approaches, the annualized values represent the cumulative value amortized at a fixed rate over the POA, effectively applying an exponential amortization to the declining discounting approach.

- Present valuation over the POA of:
    - Cumulative benefits
    - Cumulative costs
    - Cumulative lost benefits due to sedimentation
- Annualization over the POA of:
    - Cumulative benefits
    - Cumulative costs
    - Cumulative lost benefits
- Calculation of the following comparative metrics over the POA:
    - Benefit-cost ratio (BCR)
    - Net present value (NPV)
    - Annualized net benefits

The outputs listed above are presented in a matrix to facilitate comparison between the without and with sediment management alternatives. RSEM then provides a table that identifies the alternative with the greater BCR and greater NPV for each of the four POAs.

Annualized values are computed using the exponential discounting approach, regardless of the discounting approach selected for present valuation. Alternative discounting approaches have dynamic inconsistency and discount rates that change over time. When alternative discounting approaches are used, only the present values results are valid over the POA and not the annualized values. The authors are not aware of any published method for annualizing time-inconsistent discounting approaches. The present value calculations are used for all comparative results and metric reporting, including the BCR, NPV, and the break-even and retirement fund analyses.

The BCR describes the benefit per dollar of cost which is the preferred metric when multiple alternatives can be selected, as it will identify the combination of choices that maximizes the net benefit for society. In general, when selecting a single alternative, NPV is the preferred metric because it identifies the alternative with the greatest net benefit for society. For a given POA the alternative with the greater BCR won’t necessarily have the greater NPV. This is because BCR is calculated as a unitless ratio and is therefore indifferent to the magnitude of the input values while NPV is calculated as the difference between benefits and costs and is therefore sensitive to the magnitude of the input values. Table 4-13 provides a simple example to demonstrate two competing alternatives (1 and 2) where Alternative 1 has a greater BCR (2.5 versus 1.6) and Alternative 2 has a greater NPV ($350 versus $300).

Table 4-13.—Simplified example comparing BCR and NPV

	Alt. 1	Alt. 2
Economic outputs		
PV of benefits	$500	$900
PV of costs	$200	$550
Comparative metrics		
BCR (PV benefits / PV costs)	2.5	1.6
NPV (PV benefits – PV costs)	$300	$350

As indicated above, RSEM displays a dedicated line item reporting the lost benefits due to sedimentation under a given alternative. This value is not used in the calculation of BCR, NPV, or PV but rather is an independent output provided for user insight. Lost benefits due to sedimentation under a given POA are calculated as the difference between the benefits estimated during the reservoir's first year of full capacity (calculated in the Inputs worksheet in the row labeled "Maximum Annual Benefits Based on Inputs") and the benefits estimated under the given POA.

4.5.3 Breakeven Analysis

In addition to direct comparisons of BCR and NPV over the fixed POAs, RSEM conducts a breakeven analysis to provide the year at which the NPV of the with sediment management alternative exceeds the NPV of the without sediment management alternative. This can be interpreted as the minimum POA for which sediment management is economically preferred and therefore "breaks even."

RSEM reports the breakeven analysis results using a dam age basis and an analysis year basis. If the analysis is conducted for a new dam and reservoir, then there will be no difference in the calculations. However, if the analysis is conducted for an existing dam and reservoir then the calculation based on the analysis year will indicate a shorter period to break even, all else being equal.

4.5.4 Retirement Fund Analysis

The final decision-support metric provided by RSEM is a retirement fund analysis. In short, this is an estimate of the of funding that should be set aside annually to pay the dam decommissioning costs in the estimated year of decommissioning. This mechanism for financing eventual dam decommissioning, if implemented upon dam construction or relatively early in the dam's service life, can help to achieve intergenerational equity. Contributions to the fund should be paid by project beneficiaries and would be calculated as the cost of decommissioning (in present dollars) amortized over the remaining years of dam life. Such a mechanism ensures that the totality of decommissioning and mitigation costs do not fall to the later generation(s) who derive little or no benefit from the dam and reservoir. This fund could also serve to offset the cost of any emergency actions required as the dam and reservoir age.

An additional consideration is the comparison of the annualized cost of sustainable sediment management to the annual contribution calculated for a retirement fund. If the comparison indicates that the sustainable sediment management costs less than decommissioning fund contributions, this bolsters the economic case for sediment management. Note that for most scenarios the annual contribution to a dam retirement fund will be less under the sediment management alternative, as costs are amortized over a longer service life. Annual contributions to a retirement fund may approach zero under a comprehensive sediment management program that begins with a new dam. If sediment management annually removed the entire inflowing mass or volume of sediment, then dam decommissioning would not be needed due to severe sedimentation.

RSEM conducts the retirement fund analysis for both the without and with sediment management alternatives using two different year bases: (1) dam age equals zero (new dam and reservoir), and (2) analysis year equals zero (existing dam and reservoir). For a new dam and reservoir (dam age equals zero), the analysis assumes that annual contributions are made to the retirement fund beginning in the first year of the dam's service life. For an existing dam and reservoir (analysis year equals zero), the analysis assumes that annual contributions are made to the retirement fund beginning in the BYA. The year of dam decommissioning is the same regardless of the year basis. If the analysis is conducted for a new dam and reservoir then dam age and BYA both will be equal to zero in the same year, and there will be no difference in the calculations. However, if the analysis is conducted for an existing dam and reservoir then the BYA will necessarily be after dam age equals zero, and the calculation based on analysis year equals zero will be amortized over a shorter period, resulting in a greater required annual contribution.

Contributions to the retirement fund could utilize existing cost allocation principles and frameworks. For example, federal water projects are authorized for specific project beneficiaries who are responsible for a portion of project repayment based on the "beneficiary pays" principle, i.e., repayment of project costs in proportion to benefits received. Existing cost allocations for project repayment could serve as the basis for proportional retirement fund contributions for a dam and reservoir.

5 Sediment Management Alternatives

RSEM always simulates and compares two alternatives at a time: one, without sediment management and another alternative with sediment management. The model can be run multiple times to simulate a range of sediment management alternatives (one additional model run for each additional sediment management alternative or scenario).

The following sections describe the model methodology and user inputs. For details on how to specify user input data, please see Appendix A – Reservoir Sedimentation Economics Model (RSEM) User Guide.

5.1 Without Sediment Management Alternative

This alternative assumes there is no planned reservoir sediment management. However, forced sediment management is assumed to keep the dam outlet functioning if the dam outlet should become plugged with sediment.

5.1.1 Dam Age at Decommissioning

There is generally little concern when sediment or woody debris deposits within the reservoir's dead storage pool (below the elevation of lowest dam outlet) because that portion of the reservoir storage can't be used anyway. However, after the end of the sediment design life when sediment has filled the dead storage pool, some sediment will begin passing through the dam outlet. Without intervention, continued sedimentation, along with any wood debris, may eventually bury and plug the dam outlet. Plugging may occur anytime and within a few decades after the dead storage pool has filled with sediment. Forced and localized sediment management (e.g., dredging, flushing) will be required to maintain a functioning dam outlet. However, even with forced sediment management, the sedimentation level near the dam eventually will be high enough above the dam outlet that maintaining the outlet will no longer be practical and dam decommissioning may be necessary.

RSEM simulates when the dam will be decommissioned based on the simulated sediment design life plus the additional years until dam decommissioning (Table 5-1). After the dead storage has filled with sediment, the additional years until dam decommissioning are a function of the sedimentation rate at the dam outlet and the decades of planning, design, and permitting required to develop a decommissioning plan that is accepted by decision-makers and stakeholders.

Table 5-1.—User inputs of dam decommissioning parameters without sediment management

Dam Decommissioning Age	Units	Notes
Planned sediment design life	years	Planned number of years before the dead storage would completely fill with sediment
Simulated sediment design life[a]	years	Simulated number of years for the dead storage to completely fill with sediment
User-defined sediment design life	years	User-defined number of years for the dead storage to become filled with sediment
Additional years until dam decommissioning (engineering, public involvement, & financing)	years	Number of years after the dead storage has completely filled with sediment and until the dam would need to be decommissioned
Dam age when sediment is at height limit above outlet[a]	Years	Simulated age of the dam after sediment has accumulated to a certain height limit above the dam outlet
Dam decommissioning age[a]	years	Age of dam when decommissioned (equal to the simulated sediment design life plus the additional years until decommissioning)
Year of dam decommissioning[a]	year	Calendar year the dam is decommissioned

[a] Parameters computed by RSEM. These parameters may not be changed.

5.1.2 Forced Sediment Management

Without planned sediment management, forced sediment management would be required to maintain the dam outlet once sedimentation begins to impair the operations. The user needs to specify when forced sediment management would begin as the number of years after the dead storage has filled with sediment (Table 5-2). RSEM assumes the volume of reservoir sediment removed to keep the outlet functioning will be initially small and then increase at a linear rate each year until dam decommissioning. The user specifies the maximum volume of forced sediment removal in the last year before dam decommissioning and the model interpolates the annual sediment removal rate for the intervening years. The maximum volume removed in the last year is specified as a percentage of the average annual reservoir sediment inflow. The unit costs for the forced removal of fine and coarse sediment removal are also specified. These unit costs for forced sediment removal could be higher than for planned sediment removal because of the emergency nature of the actions.

Table 5-2.—User inputs for forced sediment management

Forced Sediment Management Parameters	Units	Notes
Begin forced sediment removal	years	Number of years after dead storage has filled with sediment until the beginning of forced sediment management
Maximum percentage of sediment inflow that will be removed in the year prior to dam decommissioning	dimensionless	Portion of annual sediment inflow than needs to be removed in the last year prior to dam decommissioning
Forced fine sediment removal unit cost	$/yd^3	Cost to remove a cubic yard of fine sediment
Forced coarse sediment removal unit cost	$/yd^3	Cost to remove a cubic yard of coarse sediment
Annual forced sediment management cost before additive costs*	$/yr	Computed maximum annual cost of forced sediment management based on the unit costs, annual sedimentation rates, and the maximum portion of sediment removed
Annual forced sediment management cost with additive costs*	$/yr	Computed maximum annual cost of forced sediment management with additive costs

*Parameters computed by RSEM. These parameters may be overridden by the user.

Forced sediment management is not applied to the sediment management alternative because this alternative already includes management actions that could be adapted to keep the dam outlet and any reservoir water intakes or boat ramps functioning. Also, the sediment management actions that are already part of this alternative may prevent sedimentation impacts to these dam and reservoir facilities.

5.1.3 Loss of Boat Ramps and Marinas

Boat ramps and marinas are an important aspect of recreation benefits because they provide visitors with access to the reservoir surface area. Without the boat ramps or marinas, recreation access is more limited to the reservoir shoreline. For example, if a boat ramp or marina is buried by sedimentation, recreation benefits might be reduced by 20 percent (down to 80 percent). If a second boat ramp or marina is buried by sedimentation, then recreation benefits might be reduced to just 50 percent. The user provides the percentage losses for the specific reservoir. This percentage loss is combined for all recreation activities (e.g., fishing, canoeing, kayaking, swimming).

For each year of the simulation, RSEM reduces the recreation benefit by the same proportion that the recreation surface has reduced. In addition, RSEM tests to see if the sedimentation level has reached the recreation pool elevation at either boat ramp or marina (Figure 3-3). RSEM estimates the dam age that each boat ramp or marina may be lost to sedimentation (Table 5-3). Upon loss of a boat ramp or marina, recreation benefits are additionally reduced according to the percentage specified by the model user. Another approach would be to estimate the cost of relocating a boat ramp if one were lost to sedimentation. However, the relocated boat ramp may eventually become buried in sediment as well. For some reservoirs, the geology and steep topography will make the relocation of a boat ramp very difficult and expensive. At this time, RSEM is not able to automatically account for the cost and frequency of relocating boat ramps and the recreation benefits that would be maintained.

Table 5-3.—User inputs for boat ramps or marinas lost

Boat Ramps or Marinas Lost	Units	Notes
Dam age when boat ramp / marina #1 is lost*	Years	Dam age when sedimentation has buried boat ramp / marina #1
Dam age when boat ramp / marina #2 is lost*	Years	Dam age when sedimentation has buried boat ramp / marina #2

*Parameters computed by RSEM. These parameters may be overridden by the user.

5.2 With Sediment Management Alternative

This alternative includes planned sediment management to help preserve the reservoir storage capacity and provide sediment continuity to the downstream river channel. The range of possible sediment alternatives is described in Section 5.2.2 Range of Sediment Management.

5.2.1 Dam Age at Decommissioning (If Applicable)

Even a modest sediment management program can extend the life of the reservoir. When sediment management annually prevents all the inflowing sediment from depositing in the reservoir or annually removes the amount of sedimentation, there will be no need for dam decommissioning. However, dam decommissioning eventually may need to be considered if the annual rate of sediment prevention or removal still allows for significant rates of sedimentation to occur. The sedimentation level near the dam eventually could be high enough above the dam outlet that maintaining the outlet will no longer be practical and dam decommissioning will be necessary.

According to American Rivers (2022), 1,951 dam have been removed in the United States between 1912 and 2021. These dams were removed for environmental (e.g., fish passage, water quality), dam safety, and economic reasons. Most all of these dams (97%) were small (less than 23 feet high). Removing dams to alleviate safety concerns often occurred when the dams were not well maintained or were abandoned (Randle et al., 2021). Severe reservoir sedimentation was a reason for removing a few large dams such as San Clemente Dam and Matilija Dam, both in California.

Because of robust dam safety programs for federal agencies, RSEM only evaluates dam decommissioning in the context of severe reservoir sedimentation. The model otherwise assumes that dams will be maintained and operated indefinitely. If a dam were to be removed for other reasons (e.g., environmental, dam safety) and independent of sedimentation, then the economic analysis would have to be accounted for this external to RSEM.

RSEM simulates when the dam will be decommissioned based on the simulated sediment design life plus the additional years until dam decommissioning (Table 5-4). After the dead storage has filled with sediment, the additional years until dam decommissioning are a function of the sedimentation rate near the dam, any sediment sluicing or flushing operations, and the decades of planning, design, and permitting required to develop a decommissioning plan that is accepted by decision-makers and stakeholders.

Table 5-4.—User inputs of dam decommissioning parameters with sediment management

Dam Decommissioning Age	Units	Notes
Simulated sediment design life*	years	Simulated number of years for the dead storage to completely fill with sediment
Dam age when sediment is at height limit above outlet[a]	Years	Simulated age of the dam after sediment has accumulated to a certain height limit above the dam outlet
Additional years until dam decommissioning (engineering, public involvement, & financing)*	years	Number of years after the dead storage has completely filled with sediment and until the dam would need to be decommissioned
Dam decommissioning age[a]	years	Age of dam when decommissioned (equal to the simulated sediment design life plus the additional years until decommissioning)
Year of dam decommissioning[a]	year	Calendar year the dam is decommissioned

*Parameters computed by RSEM. These parameters may be overridden by the user.

[a] Parameters computed by RSEM. These parameters may not be changed.

5.2.2 Range of Sediment Management Alternatives

As stated in Section 1.2, reservoir sediment management alternatives may be classified into four categories:

- Implement watershed management practices to reduce soil erosion closer to natural levels and reduce the sediment yield entering the reservoir (e.g., soil erosion control, forestation, construction of check dams)
- Route sediments through or around the reservoir to avoid deposition within the reservoir (e.g., sluicing, turbidity current venting, tunnel bypassing)
- Remove sediments that have already deposited within the reservoir (e.g., flushing, dredging)
- Use adaptive strategies to slow and cope with sedimentation impacts until eventual dam decommissioning (e.g., improve operational efficiency, modify dam intakes, raise dam height, water conservation, relocation of boat ramps)

Specific alternatives under each of these four categories are presented in Figure 5-1 (same as Figure 1-1 and repeated here for convenience). RSEM is designed to simulate the sediment management alternatives that belong in the first three categories listed above. The fourth category, adaptive strategies, are not sustainable but attempt to prolong the life or usefulness of the reservoir. RSEM is not really designed to simulate these strategies, but the model input: "additional years until dam decommissioning," could be used to account for any additional years of reservoir service life resulting from adaptive strategies.

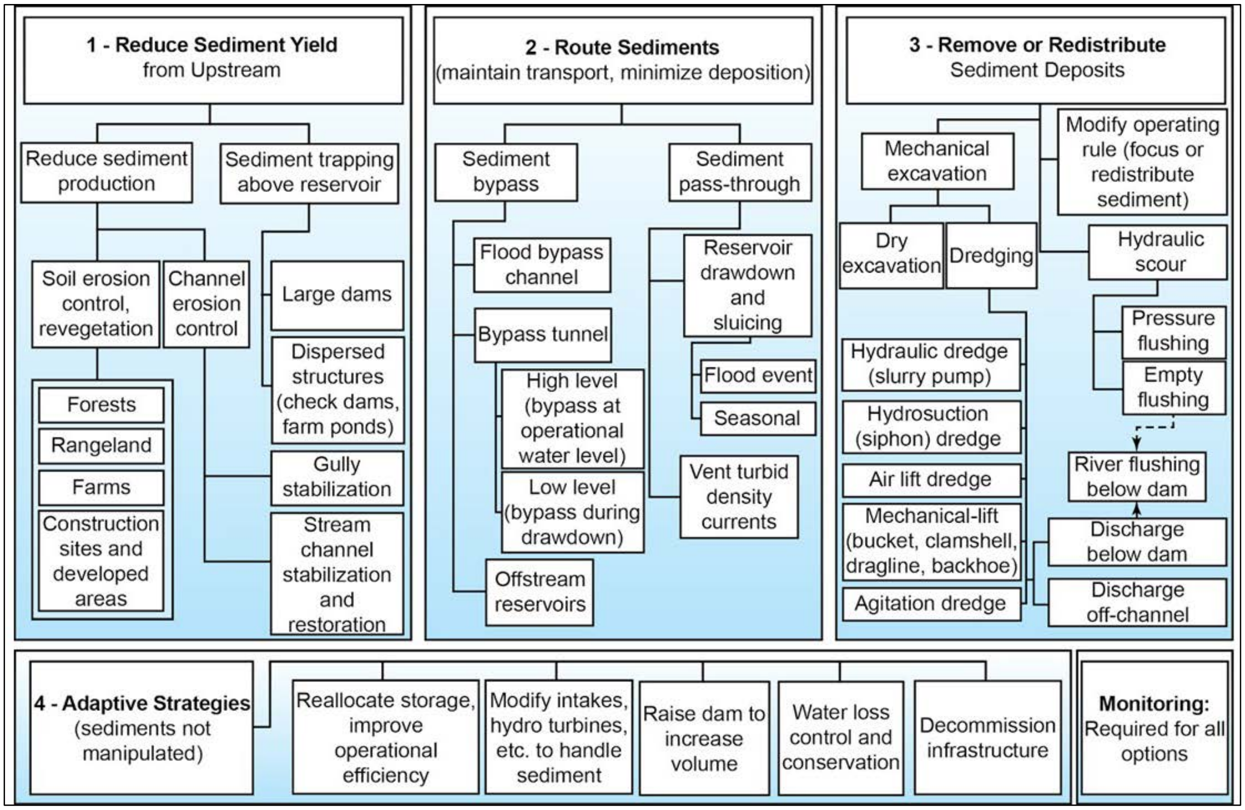


Figure 5-1.—Reservoir sediment Classification of methods to manage reservoir sedimentation (Morris, 2015).

Specific reservoir sediment management templates are not provided in this first version of RSEM. However, RSEM can simulate a specific sediment management alternative (for comparison without sediment management). For RSEM, the basic characteristics needed to define a specific sediment management alternative include the following parameters:

- Percentage reduction in the rate of reservoir sedimentation
- Capital cost and service life of equipment or infrastructure
- Dam age when sediment management begins,
- Unit costs of sediment avoidance or removal
- Percentage of reservoir water storage used for sediment management

The input data needed for RSEM are presented in Table 5-5.

Table 5-5.—User inputs for reservoir sediment management parameters

With Sediment Management Alternative	Units	Notes
Annual fine sediment removal	dimensionless	Percent of annual fine sediment inflow volume
Annual coarse sediment removal	dimensionless	Percent of annual coarse sediment inflow volume
Capital cost before additives	$	cost of equipment or infrastructure required (before additives) to remove reservoir sediment
Capital cost with additives*	$	cost of equipment or infrastructure required (after additives) to remove reservoir sediment
Equipment life	years	Time period after which equipment or infrastructure would have to be replaced
Sediment management begins at dam age*	years	Dam age when sediment management is scheduled to begin
Unit cost for fine sediment removal or avoidance	$/yd^3	Unit cost to remove fine sediment from the reservoir or prevent it from depositing within the reservoir
Unit cost for coarse sediment removal or avoidance	$/yd^3	Unit cost to remove coarse sediment from the reservoir or prevent it from depositing within the reservoir
Annual sediment management cost before additives*	$/yr	Annual cost (exclusive of capital costs) to implement sediment management
Annual sediment management cost with additives*	$/yr	Annual cost (exclusive of capital costs) to implement sediment management
Percentage of live reservoir storage used only for sediment management	dimensionless	Portion of stored reservoir water used for sediment management
Annual downstream sediment mitigation cost (if sed. passed downstream)*	$/yr	Annual cost to mitigate impacts from the downstream release of reservoir sediment (e.g., pump intakes, canals)

*Parameters computed by RSEM. These parameters may be overridden by the user.

The percentage reduction in the rate of reservoir sedimentation could be applied to the portion of sediment yield annually eroded from the upstream watershed, the portion of inflowing sediments annually depositing within the reservoir, or the portion of sedimentation annually removed from the reservoir. The percentage reductions for both fine and coarse sediment are specified. If 100 percent of the inflowing fine and coarse sediments are avoided or removed annually, then the reservoir storage capacity, at the time of implementation, may be sustained indefinitely. If 50 percent of the inflowing sediments are annually avoided or removed, then the life of a new reservoir, or the remaining life of an existing reservoir, would be doubled. If more than 100 percent of the inflowing sediments are annually removed from an existing reservoir, then some storage capacity lost to past sedimentation could be reclaimed. However, RSEM has not been fully tested to simulate the recovery of lost storage capacity (i.e., annually removing more than 100 percent of the inflowing sediments).

The capital cost and service life of equipment or infrastructure could apply to vehicles, machines, and materials used in watershed management activities, construction of tunnels and gates for sediment bypass operations, construction of sediment sluice gates in the dam, or acquisition of a dredge and construction of sediment slurry pipelines. The average equipment or infrastructure life is used by RSEM to periodically repeat the capital cost so that equipment or infrastructure may be replaced, and operations maintained indefinitely.

Sediment management could begin as soon as a new reservoir is placed in service (year 0) or some years or decades after the reservoir is placed in service. For an existing reservoir, sediment management cannot begin sooner than the first year of economic analysis. For example, if the reservoir is already 30 years old, then sediment management cannot begin sooner than the 31st year of dam age.

The unit costs of fine and coarse sediment avoidance or removal could be applied to watershed management activities, reservoir sediment pass-through or bypass operations, or reservoir dredging or flushing activities. In the case of sediment removal, the unit costs need to account for all aspects of transporting and managing the removed sediment, including any long-term storage.

The percentage of reservoir water storage used for sediment management is specified to estimate any reduction in reservoir water storage yield and related benefits. RSEM will reduce the water volume, or yield, delivered to water users by the portion of live storage needed for sediment management. Some sediment management alternatives may not change the volume and timing of reservoir water that is released downstream, while other alternatives may reduce the volume of live storage available for other beneficial uses. For example, a hydraulic dredge might discharge water and sediment through a slurry pipeline to the downstream channel. The water portion of this sediment slurry could be considered part of the minimum water release rates from the dam. In contrast, periodic reservoir drawdown for sediment sluicing or flushing could preclude the use of live storage for other benefits, but only if there were not enough inflows to refill the reservoir prior to when water for those benefits would be needed.

Some management strategies like sluicing may be less expensive than other strategies like dredging, but sluicing could use a significant portion of the reservoir water with a corresponding decrease in live storage benefits. Watershed management strategies might reduce reservoir inflows during floods, but this might be offset by an increase in base flows. Bypassing water inflows through or around the reservoir may result in less reservoir storage and a corresponding reduction in storage benefits. Reservoir water used for drawdown for sluicing or flushing would tend to empty the reservoir, which may decrease the likelihood of refilling the reservoir for later water storage use. The volume of water used for dredging is typically small relative to the reservoir water storage and could be considered part of the volume of water normally released downstream from the reservoir.

Sediment released downstream from a reservoir may provide less than desirable water quality for non-native sport fish, cause increased water treatment costs for downstream users, and cause additional operations and maintenance costs for irrigation facilities. RSEM includes an input parameter "Annual downstream sediment mitigation costs (if sediment is passed downstream)." This input parameter can be used to account for the net cost of water quality changes caused by the downstream release of sediment.

5.2.3 Beneficial Use of Removed Reservoir Sediment

Reservoir sediment that is passed to the downstream channel may slow, stop, or reverse degradation and restore habitats (e.g., floodplains, spawning gravels). There may be other beneficial uses for sediment that is removed from the reservoir and river system. For example, cohesive sediments might be used to make bricks, clay linings of ponds or canals, or creation of wetlands. Fine sediment also might be used to amend topsoil. Coarse sediments might be used for aggregate or construction of roads, embankments, and general fill.

For model simulation, the user specifies the portions of fine and coarse sediment removed from the reservoir and the benefit unit values of fine and coarse sediments. RSEM then estimates the annual benefit of using removed sediment which may be overridden by the user (Table 5-6). The unit cost of any sediment removal should already account for all transport and management aspects of the sediment removed, especially long-term storage. The benefit unit values for removed sediment should account for any beneficial uses that may be derived.

Table 5-6.—User inputs for beneficial use of removed sediment

Percentage of removed fine sediments put to beneficial use	%	Portion of fine sediment removed for things like brick making, waterbody linings, topsoil, wetland creation, etc.
Percentage of removed coarse sediments put to beneficial use	%	Portion of coarse sediment removed for things like aggregate, or construction of roads, embankments, and general fill
Unit value of fine sediment	$\$/yd^3$	Unit value of fine sediment used
Unit value of coarse sediment	$\$/yd^3$	Unit value of coarse sediment used
Annual benefit of using removed sediment*	$/yr	Annual beneficial use of sediments removed from the reservoir.

*Parameters computed by RSEM. These parameters may be overridden by the user.

5.2.4 Loss of Boat Ramps and Marinas

As stated in Section 5.1.3, boat ramps and marinas provide visitors with important access to the reservoir surface area and the resulting recreation benefits. For each year of the simulation, RSEM reduces the recreation benefit by the same proportion that the recreation surface has reduced. In addition, RSEM tests to see if the sedimentation level has reached the recreation pool elevation at either boat ramp or marina (Figure 3-3). RSEM estimates the dam age that each boat ramp or marina may be lost to sedimentation (Table 5-7). Upon loss of a boat ramp or marina, recreation benefits are additionally reduced according to the percentage specified by the model user. As previously stated, another approach would be to estimate the cost of relocating a boat ramp if one were lost to sedimentation. However, the relocated boat ramp may eventually become buried in sediment as well. For some reservoirs, the geology and steep topography will make the relocation of a boat ramp very difficult and expensive. At this time, RSEM is not able to automatically account for the cost and frequency of relocating boat ramps and the recreation benefits that would be maintained.

Table 5-7.—User inputs for boat ramps or marinas lost

Boat Ramps or Marinas Lost	Units	Notes
Dam age when boat ramp / marina #1 is lost*	Years	Dam age when sedimentation has buried boat ramp / marina #1
Dam age when boat ramp / marina #2 is lost*	Years	Dam age when sedimentation has buried boat ramp / marina #2

*Parameters computed by RSEM. These parameters may be overridden by the user.

6 Example Case Study

Muddy Reservoir, the hypothetical case study under consideration, is introduced in Section 2.2. In this section, seven scenarios were created to assess their economic performance using RSEM. The seven scenarios evaluate and compare three sediment management alternatives: (1) without sediment management, (2) with sediment sluicing, and (3) with sediment dredging. These alternatives were evaluated for both new and existing reservoirs (Table 6-1). The first scenario (Alt 1a) was created to evaluate the economics of a new reservoir when the impacts of reservoir sedimentation are not considered to match historic practices. The other six scenarios were created to compare economic results without and with reservoir sediment management for different period of analysis and different discounting approaches.

Table 6-1.—Defined alternatives and scenarios in RSEM for the Muddy Reservoir Example

Alternative	Reservoir age	Sediment management	Description	Economic Metric
Alt 1a	New	Without	Costs and lost benefits due to sedimentation are not considered	Benefit-cost Ratio
Alt 1b	New	Without	Costs and lost benefits due to sedimentation are considered	Benefit-cost Ratio
Alt 2a	New	With	Sluicing as sediment management technique	Benefit-cost Ratio
Alt 2b	New	With	Dredging as sediment management technique	Benefit-cost Ratio
Alt 3	Existing*	Without	Costs and lost benefits due to sedimentation are considered	Net Present Value
Alt 4a	Existing*	With	Sluicing as sediment management technique	Net Present Value
Alt 4b	Existing*	With	Dredging as sediment management technique	Net Present Value

*Existing 30-year-old reservoir

6.1 Case Study Inputs

The scenarios presented differ in reservoir age, sediment management method, and the metrics used to evaluate their economic performance. All required data to define the scenarios are presented in Table 6-2 (more information about the input data categories is available in Appendix A Reservoir Sedimentation Economics Model (RSEM) User Guide). The data presented in the table include all input values used by RSEM. Some input values specific to the case study, some values are the model default values, and some values are computed by RSEM based on other input values.

All benefit and cost input data for the example case study were estimated at the 2020-price level. The methods for estimating benefit and cost input data are not provided for this hypothetical example. Information on cost estimating is provided by the American Society of Professional Estimators (2012); Anchor QEA (2020); D. C. Baird et al. (2015); PR&Gs (2014); The Los Angeles County Flood Control District (2013); USEPA 2000; and WEDA (2021). For the Muddy Reservoir example, professional judgement and the model's default input values were used to prepare the input data for this hypothetical case study. For this case study example, the costs of upstream sedimentation or downstream channel degradation are small (less than 5%). The greatest effects of sedimentation (without management) are from the diminishing reservoir storage benefits and the eventual cost of dam decommissioning.

Each RSEM simulation can analyze a maximum of two alternatives: without sediment management and with sediment management. Multiple model runs may be performed to simulate additional sediment management alternatives. Users should be aware of the similarities and differences between their alternatives or scenarios in terms of reservoir age, geometry, storage, sedimentation, and considered benefits and costs.

Table 6-2.—Input Data Values Used in the Case Study Economic Assessment

Parameter	Value			
Base year for economic analysis (BYA)*	2023			
Year that all dollar value inputs are indexed to (price level)*	2020			
Present reservoir age	0 years for new reservoir 30 years for existing reservoir			
Reservoir Elevation Inputs				
Top of live storage	6447.5	ft	1965.2	m
Top limit of sedimentation	6440.0	ft	1962.9	m
Recreation pool elevation	6430.0	ft	1959.8	m
Normal W.S. elevation	6373.0	ft	1942.5	m
Incremental sedimentation height limit above dam outlet	20.0	ft	6.1	m
Sedimentation elevation limit for dam outlet function[a]	6378.0	ft	1944.0	m
Top of dead storage	6358.0	ft	1937.9	m
Original streambed elevation	6287.0	ft	1916.3	m
Original reservoir storage capacity input				
Total storage volume at top of live storage	20,950	acre-ft	25.84	Mm^3
Dead pool volume	2,800	acre-ft	3.5	Mm^3
Live storage volume[a]	18,150	acre-ft	22.4	Mm^3
Reservoir inflow characteristics				
Mean Annual Reservoir Inflow	99,800	acre-ft/year	123	Mm^3/year
Standard deviation of mean annual inflow[b]	5129	acre-ft/year	6.33	Mm^3/year
Reservoir live storage capacity to inflow ratio	18.2%			
Annual coefficient of variation[a]	0.05			
99% reliable yield (% of mean annual flow)*	97%			
Annual water volume delivered at 99% reliable yield*	97,101	acre-ft/year	120	Mm^3/year

Table 6-2.—Input Data Values Used in the Case Study Economic Assessment

Parameter	Value			
Original reservoir dimensions				
Reservoir valley length at full pool	3.5	mi	6	km
Reservoir surface area at full pool[b]	296	acre	120	ha
Reservoir average surface width at the top surface of a full pool[b]	1,056	ft	322	m
Reservoir average depth at full pool*	71	ft	22	m
Reservoir average surface width at recreation pool*	991	ft	302	m
Reservoir surface area at the recreation pool elevation*	374	acres	151	ha
Boat Ramps / Marinas				
Number of boat ramps/marinas	2			
Boat ramp/marina #1 length from dam*	2.8	mi	4.5	km
Boat ramp/marina #2 length from dam*	0.1	mi	0.2	km
Dam characteristics				
Dam type		Earth		
Volume of dam material[b]	1,302,000	yr^3	995,500	m^3
Hydraulic height*	161	ft	48.9	m
Dam crest length across river	770	ft	234.7	m
Reservoir Sedimentation Characteristics				
Sediment Inflow Rate Inputs				
Annual storage percent loss[b]	0.51%	per year		
Fine sediment portion (clay and silt)		70%		
Coarse sediment percentage (sand and gravel)[a]		30%		
Initial fine sediment trap efficiency percentage[a]		92%		
Annual total sedimentation rate*	101.1	acre-feet/yr	0.125	Mm^3/yr
Annual fine sedimentation rate*	69	acre-feet/yr	0.085	Mm^3/yr
Annual coarse sedimentation rate*	32.1	acre-feet/yr	0.04	Mm^3/yr
Reservoir Sedimentation Profile Slope Inputs				
Delta topset slope factor			0.75	
Delta foreset slope factor			6.0	
Bottomset slope factor			0.1	
Reservoir profile plotting interval			10	

Table 6-2.—Input Data Values Used in the Case Study Economic Assessment

Parameter	Value			
Predam River Channel and Degradation Inputs				
Channel sinuosity		1.0		
Channel slope*		0.00869		
Average bank full channel width	125	ft	38.1	m
Average bank height	3	ft	0.9	m
Average channel roughness (Manning's n coefficient)		0.022		
Age streamflow velocity*	13.1	ft/s	4.0	m/s
Bankfull discharge[a]	4910	ft^3/s	139	m^3/s
Percentage of bed material that is armor size or coarser			15%	
Armor layer thickness	0.5	ft	0.15	m
Percentage reduction in the original downstream channel slope needed to achieve stability			5%	
Percentage of original downstream channel slope that would remain after stability has been achieved[a]			95%	
Reservoir benefits for consumptive use				
Water Yield as a Percentage of Storage Capacity			100%	
Percentage of Consumptive Uses:				
Agricultural irrigation use			60%	
M&I water use			30%	
Fish & wildlife and other			10%	
Unit Values for Consumptive Use Benefits				
Agricultural irrigation use	250	$/acre-ft/yr	202,678	$/ Mm^3/yr
M&I water use	450	$/acre-ft/yr	364,821	$/ Mm^3/yr
Fish & wildlife and other	100	$/acre-ft/yr	81,071	$/ Mm^3/yr
Flood risk reduction	40	$/acre-ft/yr	32,429	$/ Mm^3/yr
Weighted Benefit of Storage Capacity*	335	$/acre-ft/yr	271,589	$/ Mm^3/yr
Hydropower production				
Average annual energy production			0	MWh/yr
Average energy benefit rate			$0	$/MWh
Annual hydropower benefit			$0	/year

Table 6-2.—Input Data Values Used in the Case Study Economic Assessment

Parameter	Value			
Recreation Use Benefits in Base Year				
Average annual visitor days[b]	26,000	visitor days/year		
Benefit per visitor day (net consumer surplus)			45.00	$/day
Benefit dependent on ALL boat ramps/marinas			50%	
Benefit reduction from loss of 1 boat ramp/marina			20%	
Maximum Annual Benefits Based on Inputs[a]			7,250, 250	$/yr
Dam & Reservoir Planning, Design, and Construction Costs				
Total construction cost[b]			$119,480,000	
Design, Construction, and Contract Contingencies Cost Additives				
Increase for unlisted items			10%	
Increase for mobilization and demobilization			5%	
Increase for design contingencies			20%	
Increase for procurement strategy			5%	
Increase for overhead and profit			15%	
Increase for construction contingencies			20%	
Total design, construction, and contracting increase*			75%	
Operations, Maintenance, and Replacement (OM&R) Costs				
Annual OM&R cost			$450,000	
5-year recurring costs			$100,000	
Dam Decommissioning Costs and Benefits				
Dam removal unit cost	3.0	$\$/\text{yr}^3$	3.9	$\$/\text{m}^3$
Sediment management unit cost	8.0	$\$/\text{yr}^3$	10.46	$\$/\text{m}^3$
River diversion cost			$6,000,000	
Coffer dam cost			$600,000	
Salvage benefits			$0	
Other river restoration costs			$0	
Dam decommissioning cost before additives*			$125,960,127	
Dam decommissioning cost*			$220,430,222	
Annual dam removal benefit			$10,000	

Table 6-2.—Input Data Values Used in the Case Study Economic Assessment

Parameter	Value			
Upstream sedimentation costs[2]				
Deposition threshold for land impacts	3.0	ft	0.91	m
Unit land devaluation cost	5,000	\$/acre	12,355	\$/ha
Unit highway/railroad relocation cost	0	\$/mi	0	\$/km
Unit fish & boat passage cost	0	\$/mi/year	0	\$/km/year
Downstream channel degradation costs				
Median riprap rock size	2.1	ft	0.65	m
Degradation threshold (min. vertical erosion when economic impacts begin)	2.0	ft	0.61	m
Streambank side slope (1:z)		2		
Streambank protection factor		3		
Unit cost of streambank protection before additive costs*	50	\$/yd^3	65.40	\$/m^3
Unit cost of streambank protection with additive costs[b]	75	\$/yd^3	98.10	\$/m^3
Without sediment management alternative				
Dam Decommissioning Age				
Planned sediment design life			100	years
Simulated sediment design life (years to fill dead storage with sediment)[a]			40	years
User-defined sediment design life (years to fill dead storage with sediment)[b]			71	years
Add'l years until dam decommissioning (engineering, public invol., & financing)			20	years
Dam age when sediment is at height limit above outlet[a]			61	years
Dam decommissioning age[a]			91	years
Year of dam decommissioning[a]			2114	
Forced sediment management parameters				
Begin forced sediment removal (years after end of sediment design life)			10	years
Maximum portion of sediment inflow that will be removed in the year prior to dam decommissioning				50%
Forced fine/coarse sediment removal cost	8.00	\$/yd^3	10.46	\$/ m^3
Annual forced sediment management cost before additive costs*			652,335	\$/yr
Annual forced sediment management cost with additive costs*			1,141,586	\$/yr
Boat Ramps or Marinas Lost				
Dam age when boat ramp / marina #1 is lost*			60	years
Dam age when boat ramp / marina #2 is lost*			91	years

Table 6-2.—Input Data Values Used in the Case Study Economic Assessment

Parameter	Value			
With Sediment management alternative				
Dam Decommissioning Age				
Simulated sediment design life*			329	years
Dam age when sediment is at height limit above outlet[a]			472	years
Additional years until dam decommissioning*			143	years
Dam decommissioning age[a]			472	years
Year of dam decommissioning*			2495	
Sediment Management Parameters				
Annual fine sediment removal			90%	
Annual coarse sediment removal			75%	
Sediment management capital cost before additives	$6,000,000 for sluicing		$600,000 for dredging	
Capital cost with additives*	$10,500,000 for sluicing		$1,050,000 for dredging	
Equipment life	100 years for sluicing		30 years for dredging	
Sediment management begins at dam age	2 years for sluicing		5 years for dredging	
Fine sediment removal cost	0.5 (sluicing) 4.0 (dredging)	$\$/\text{yd}^3$	0.65 (sluicing) 5.23 (dredging)	$\$/\text{m}^3$
Coarse sediment removal cost	0.5 (sluicing) 4.0 (dredging)	$\$/\text{yd}^3$	0.65 (sluicing) 5.23 (dredging)	$\$/\text{m}^3$
Annual sediment management cost before additives*	$69,718 for sluicing		$557,746 for dredging	
Annual sediment management cost with additives*	$122,007 for sluicing		$976,056 for dredging	
Percentage of live reservoir storage used only for sediment management			0%	
Annual downstream sediment mitigation cost (if sed. passed downstream)[b]			0	$/yr
Beneficial Use of Removed Sediment (revenue generation for use as road base, soil augmentation, brick production, etc.)				
Percentage of removed fine sediments put to beneficial use			0%	
Percentage of removed coarse sediments put to beneficial use			0%	
Unit value of fine sediment			0	$\$/\text{yd}^3$
Unit value of coarse sediment			0	$\$/\text{yd}^3$
Annual benefit of using removed sediment			0	$\$/\text{yd}^3$

Table 6-2.—Input Data Values Used in the Case Study Economic Assessment

Parameter	Value	
Boat Ramps / Marinas Lost		
Dam age when boat ramp / marina #1 is lost*	292 for sluicing	284 for dredging
Dam age when boat ramp / marina #2 is lost*	472 for sluicing	451 for dredging

*Parameters computed by RSEM. These parameters may be overridden by the user.
[a]Parameters computed by RSEM. These parameters may not be changed.
[b]Parameters computed by RSEM. These values were overridden for this case study.
1 Note: for Alternative Alt 1a, costs and lost benefits due to sedimentation are not considered to match historic practices.
2 Note: For the example case study, upstream aggradation impacts are not discernible, but they may be important for other reservoirs

A benefit-cost ratio was utilized to compare economic results from the four new reservoir scenarios (Alt 1a, Alt 1b, Alt 2a, and Alt 2b). The benefit-cost ratio is a useful parameter for evaluating the economic feasibility of a new dam construction project where not building the project is the no action alternative (Anari et al, 202).

Net present value requires the same model inputs as the benefit-cost ratio. For an existing reservoir, the no action alternative (without planned sediment management) will eventually require some future action to manage reservoir sedimentation, unless the sedimentation rate is extremely slow. Net present value provides a useful metric to identify which sediment management alternative has the maximum economic benefit to society. Detailed explanation of these metrics is provided in Section 4.5.2 Economic Outputs for Without and With Sediment Management.

Moreover, RSEM computes net present value and a benefit-cost ratio for a range of discounting approaches (see Section 4.2) and discount rates that users can select in “Economic Summary Results”. For this example, the exponential discounting approach (at a rate of 2.5%) and the intergenerational discounting approach were applied. For the intergenerational discount approach, all required parameters as presented by Harpman (2014) were used (see model worksheet “Discount Approaches & Factors” – the present generation annual discount rate and the generational discount rate= 8%, length of generation=20 years).

6.2 Case Study Results Summary

Benefit-cost ratios were simulated for the four new reservoir scenarios (Alt 1a, Alt 1b, Alt 2a, and Alt 2b) using both the exponential and intergenerational discounting approaches (Table 6-3). The intergenerational discounting approach discounts costs and benefits more slowly and typically simulates higher benefit-cost ratios than the exponential discounting approach. For the alternatives without sediment management (Alt 1a and Alt 1b), dam decommissioning is simulated at a dam age of 91 years.

Table 6-3.—Example benefit-cost ratios for alternatives without and with sediment management using both the exponential and intergenerational discounting approaches

	Discounting approach	
Alternative / POA (years)	**Exponential**	**Intergenerational**
Alt 1a: Without sediment management (ignoring sedimentation and dam decommissioning costs)		
50	1.53	1.87
100	1.94	3.04
200	Not considered in historical economic analyses	
300		
Alt 1b: Without sediment management (considering sedimentation and dam decommissioning costs)		
50	1.47	1.79
100*	1.48	1.40
200	BCR remains constant after dam decommissioning	
300		
Alt 2a: With sediment management (sluicing)		
50	1.36	1.66
100	1.71	2.63
200	1.82	3.66
300	1.83	4.18
Alt 2b: With sediment management (dredging)		
50	1.26	1.48
100	1.51	2.09
200	1.60	2.67
300	1.60	2.91

* Dam decommissioned at dam age of 91; year 100 reported for continuity across alternatives.

The simulated benefit-cost ratio results are presented in Table 6-3 for the first four scenarios. For scenario Alt 1a (without sediment management), the economics were simulated while ignoring the impacts of reservoir sedimentation to match historic practices used during the 20th century. This scenario produced the highest benefit-cost ratios through 100 years period of analysis.

However, the simulated benefit-cost ratios under scenario Alt 1b were lower for all comparative periods of analysis and discounting approaches. Under scenario Alt 1b, the economic simulation of all costs and benefits, related to reservoir sedimentation, is considered to be more comprehensive than the simulation of scenario Alt 1a.

The alternatives considering sediment management for a new Muddy Reservoir (Alt 2a: sediment sluicing, and Alt 2b: sediment dredging) have a lower benefit-cost ratio over a 50-year period of analysis than the comparable without sediment management alternative that considers the impacts of sedimentation (Alt 1b). This is true for both discounting approaches. However, for the 100-year period of analysis, the alternatives that consider sediment management have greater benefit-cost ratios for either discounting approach. Without sediment management (scenario Alt 1b), sedimentation produces a continuous loss of benefits and additional costs related to upstream and downstream sedimentation and eventual dam decommissioning. Example results from the case study indicate that sustainable reservoir sediment management is more economically justified than an alternative without sediment management when a long period of analysis is considered. Furthermore, when compared to exponential discounting, the application of the intergenerational discounting approach continues to produce significantly greater benefit-cost ratios for periods of analyses beyond 100 years.

The economics of a 30-year-old existing Muddy Reservoir is simulated without sediment management in scenario Alt 3. The 30-year-old existing reservoir was also simulated under two sediment management alternatives: sluicing (Alt 4a) and dredging (Alt 4b). For these two alternatives, sediment management begins well before the dead storage has filled with sediment: dam age of 32 years for the sluicing alternative and dam age of 35 years for the dredging alternative. The benefits and costs are discounted applying exponential and intergenerational discounting approaches. The net present value results for these alternatives are plotted in Figure 6-1 and Figure 6-2.

As illustrated in Figure 6-1, sediment sluicing (Alt 4a) has a lower net present value than without sediment management (Alt 3) for analysis years 0 through 40 (dam ages 30 through 70). However, by the time the dam is decommissioned at age 91, the net present values for Alt 4a significantly increases in comparison to Alt 3 for both discounting approaches. In contrast to exponential discounting (Figure 6-1a), the net present value for Alt 4a under intergenerational discounting (Figure 6-1b) substantially increases by analysis year 200. Regardless of the discounting approach, comprehensive economic analysis reveals sediment management as the economically preferred alternative (compared to without sediment management) when the period of analysis is long enough to capture sedimentation costs.

Figure 6-2 indicates that until dam decommissioning at age 91, the sediment dredging alternative (Alt 4b) has a lower NPV than without sediment management (Alt 3) for both discounting approaches. However, the NPV for dredging (Alt 4b) continues to significantly increases over the longer period of analysis while NPV for the alternative without sediment management (Alt3) decreases upon dam decommissioning. As in the case of sediment sluicing, the net present value associated with dredging continues to substantially increases over the long-term using intergenerational discounting.

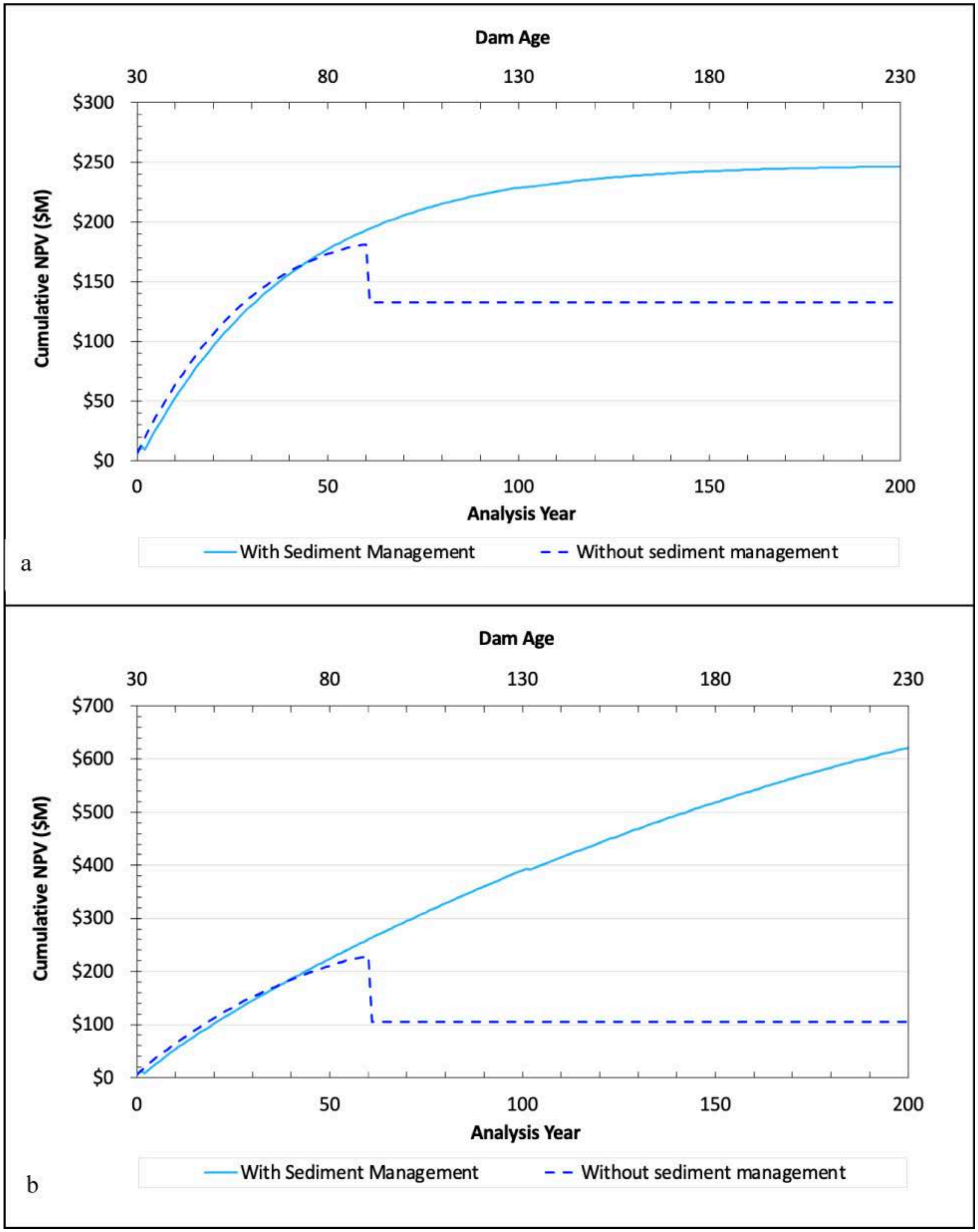


Figure 6 1.—Net present values of Alt 3 (without sediment management) and Alt 4a (with sediment sluicing) for an existing Muddy Reservoir; a) Exponential b) Intergenerational.

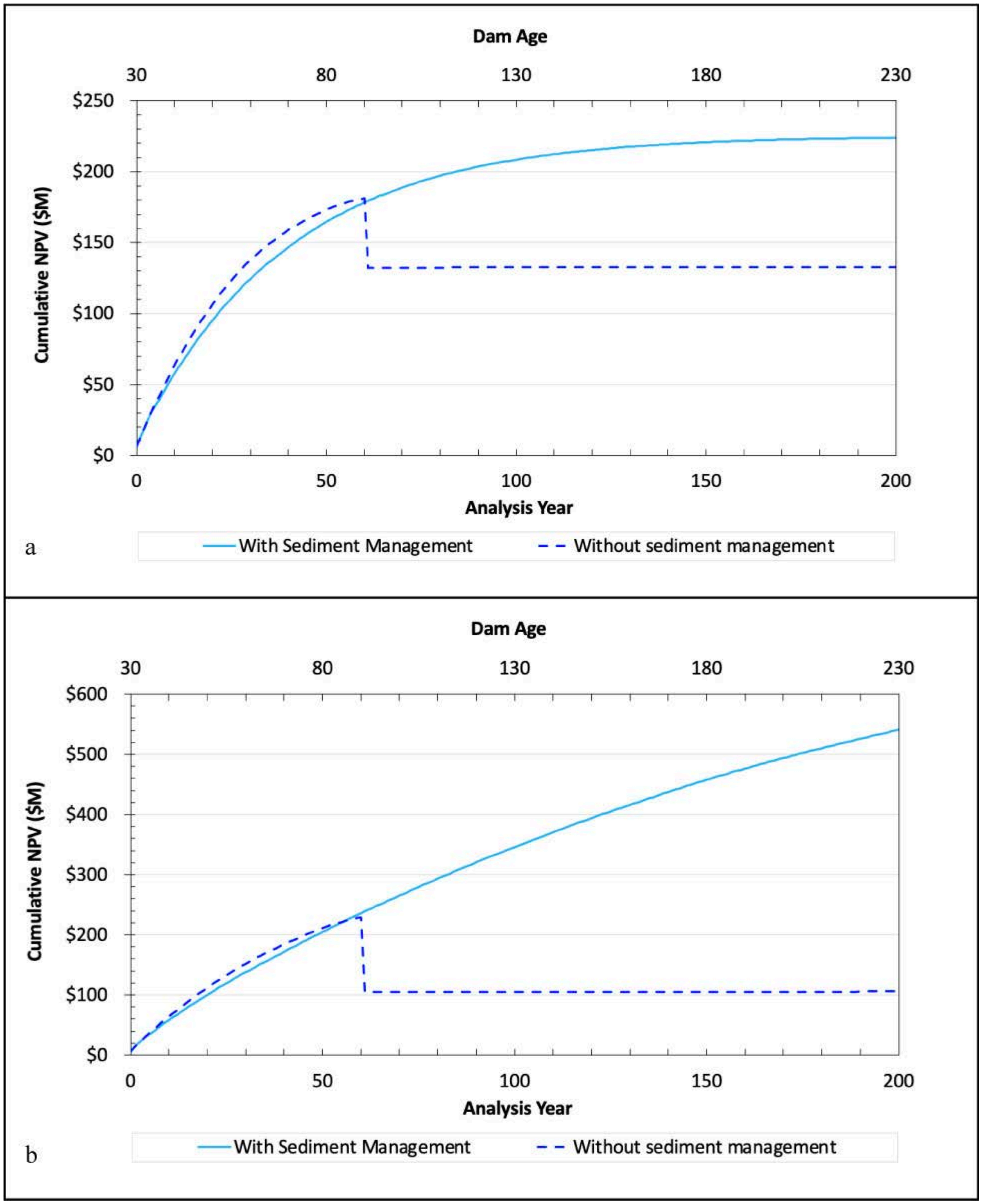


Figure 6 2.—Net present values of Alt 3 (without sediment management) and Alt 4b (with sediment dredging) for the existing Muddy Reservoir; a) Exponential b) Intergenerational.

For both new and existing reservoirs, case study results indicate that additional costs associated with sustainable sediment management eventually could be compensated for by the preserved economic benefits, avoided upstream and downstream sedimentation costs, and avoided dam decommissioning costs. These example case study results indicate that sustainable sediment management is more economic than without sediment management, for both new and existing reservoirs, sediment management approach (sluicing or dredging), or the discounting approach if the period of analysis is long enough to capture sedimentation costs. This finding may also be true for other reservoirs, but site-specific analysis would be required to determine the most economical alternative, and RSEM provides a framework and tool to accommodate that analysis. However, not properly accounting for sedimentation and decommissioning generally leads to a higher BCR and the implication of this is that some projects (for example without sediment management) may not have been considered economically justified if these factors were accounted for.

As illustrated in Figure 6-1and Figure 6-2, modeling results are highly sensitive to the choice of discounting approach. Exponential discounting, even when employing a historically low discount rate of 2.5 percent, tends to produce economic results that favor the present generation over future generations. On the other hand, intergenerational discounting produces significantly greater benefit-cost ratios (Table 6-3) and net present values (Figure 6-1 and Figure 6-2), in particular as the period of analysis increases. A comprehensive economic analysis of all costs and benefits is necessary to determine the economic viability of sediment management. Extending the life of a reservoir through sediment management, has the potential to provide greater economic production and social well-being for future generations, more than offsetting the cost of sediment management.

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