Reservoir Sedimentation Economics Model (RSEM) Extended Abstract

Timothy J. Randle, PhD, PE, D.WRE, Civil Engineer (Hydraulics), Bureau of Reclamation, Denver, Colorado, tim.j.randle@gmail.com
Todd Gaston, MS**,** Senior Associate (Economist), WestWater Research, LLC, Denver, Colorado, gaston@waterexchange.com
Razieh Anari, PhD, Civil Engineer (Hydraulics), SNC-Lavalin, Montreal, Canada, razieh.anari@snclgroup.com

Introduction

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 model and its use are more fully described in Randle, Gaston, and Anari (2023). Comparative model simulations can be used to help determine where reservoir sediment management is economically preferred to a no action alternative where the reservoir sedimentation is ignored until actions must eventually be taken. RSEM can be applied to both new and existing reservoirs. RSEM was developed and applied in support of the work by Anari et al. (2023).

Background

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; and fish and wildlife. 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 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 would be difficult and expensive for large reservoirs because of the very large sedimentation volumes (millions to billions of cubic yards) and cost. However, sustaining the remaining storage capacity by managing inflowing sediment loads on an annual basis may be economically viable.

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 costs considered related to upstream sedimentation, downstream degradation, and dam decommissioning (Anari et al. 2023).

Model Approach

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.

RESM annually simulates a comprehensive set of economic benefits and costs over future decades and centuries. Annual benefits are estimated under six 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, and 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 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.

The model uses exponential discounting as the standard approach. The user may also select other discounting approaches for research or comparison purposes (seven other 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.

Example Results

Example RSEM results for sedimentation and economics are compared in a series of figures for alternatives without and with sediment management. Example simulation of reservoir sedimentation profiles are compared in Figure 1 for alternatives without and with sediment management (reservoir sediment sluicing). After 100 years, simulation without sediment management indicates severe reservoir sedimentation, obstruction of the dam outlet, and the need for dam decommissioning. In contrast, annual sediment management preserves much of the reservoir storage capacity after 100 years of operation and sedimentation has not obstructed the dam outlet.

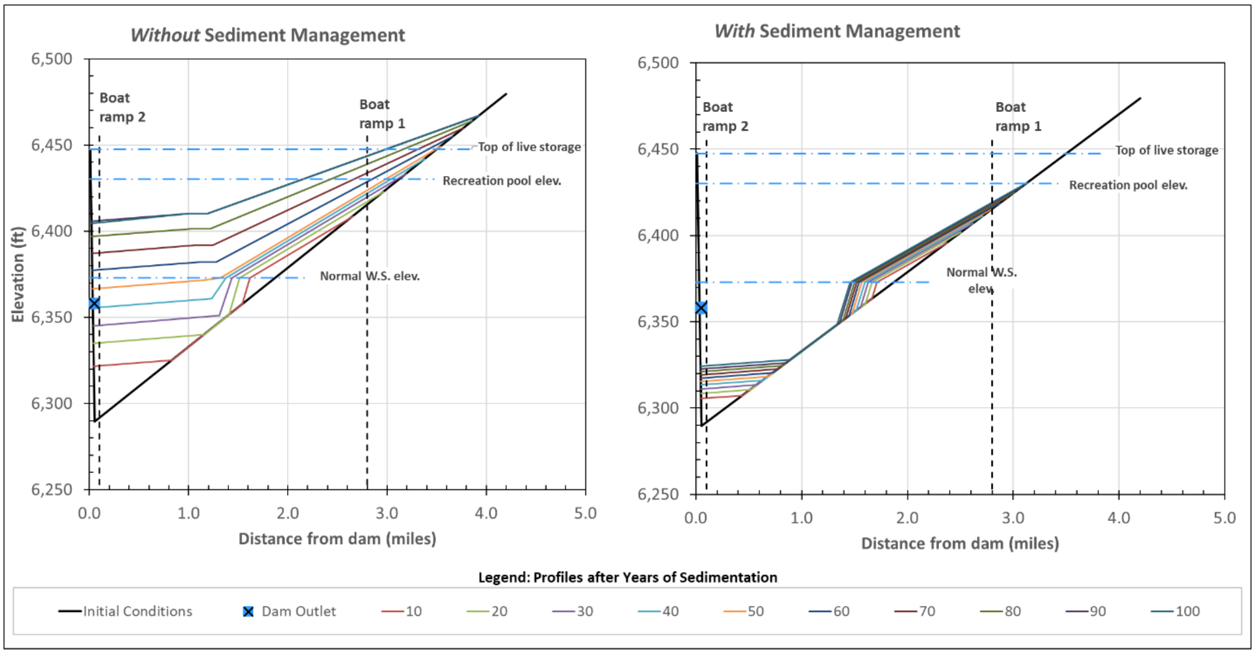

Figure 1. Example reservoir sedimentation profiles simulated by RSEM over the first century of dam operations for alternatives without and with sediment management.

Example economic compilation of benefits and costs, before discounting, is presented in Figure 2 for alternatives without and with sediment management. Both alternatives have capital costs to initially construct the dam and annual costs to operate the dam and reservoir. Both alternatives have annual benefits. Under the alternative without sediment management, reservoir benefits reduce over time until dam decommissioning with a large cost after 91 years (assumed dam decommissioning age). Annual reservoir benefits cease after dam decommissioning, but river restoration benefits emerge after that time. Under the alternative with sediment management, there is an annual sediment management cost, but the reservoir benefits continue over the long term.

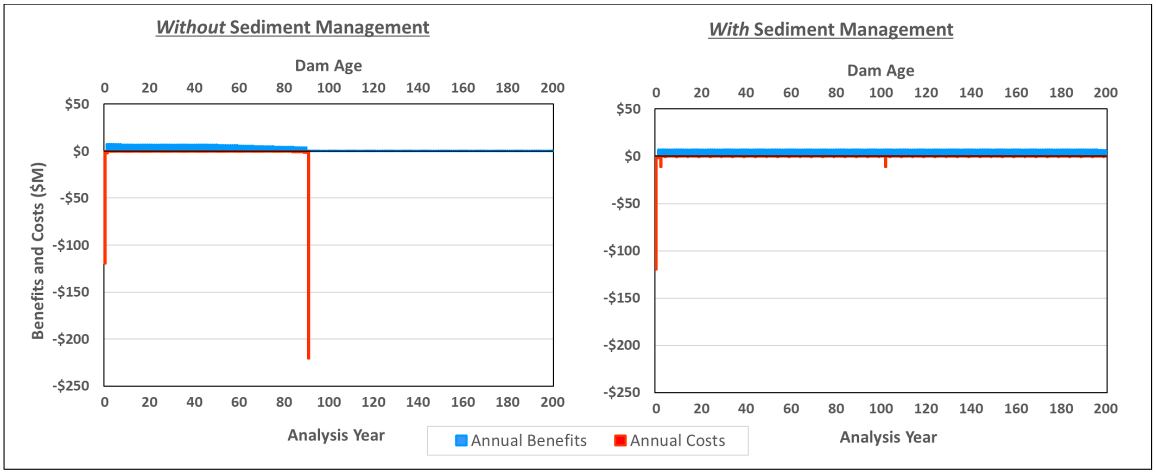

Figure 2. Example annual benefits and costs compiled by RSEM, before discounting, over 200 years for alternatives without and with sediment management.

The simulation of discounted benefits and costs is presented in Figure 3 for alternatives without and with sediment management. Exponential discounting significantly reduces benefits and costs over time, but the dam decommissioning cost is still significant at 91 years in this example. Because of discounting, cumulative benefits increase most rapidly during the early years, but the rate of increase slows over time. After dam decommissioning, the cumulative benefits and costs change little over time (Figure 4). However, with sediment management, cumulative benefits continue to increase over time.

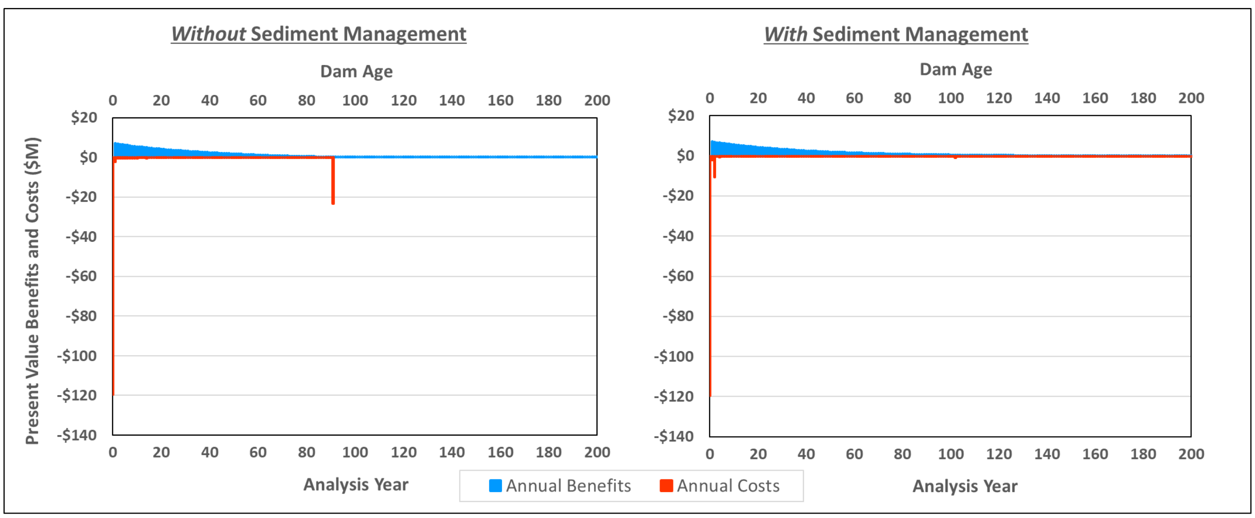

Figure 3. Example economic simulation of annual discounted benefits and costs over 200 years for alternatives without and with sediment management.

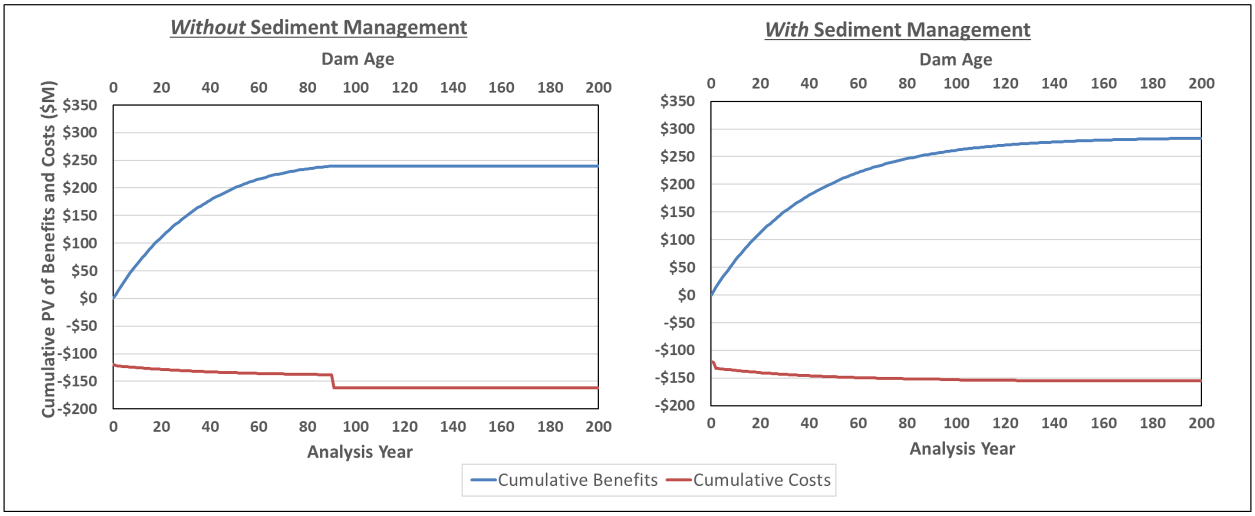

Figure 4. Example economic simulation of cumulative discounted benefits and costs over 200 years for alternatives without and with sediment management.

The simulation of cumulative net present values over time is presented for alternatives without and with sediment management (Figure 5). Initially, cumulative net present values are greater under the alternative without sediment management than under the alternative with sediment management. However, the cumulative net present value for both alternatives become nearly equal after 86 years in this example. After that year, cumulative net present values are greater under the alternative with sediment management and the difference become more significant after dam decommissioning.

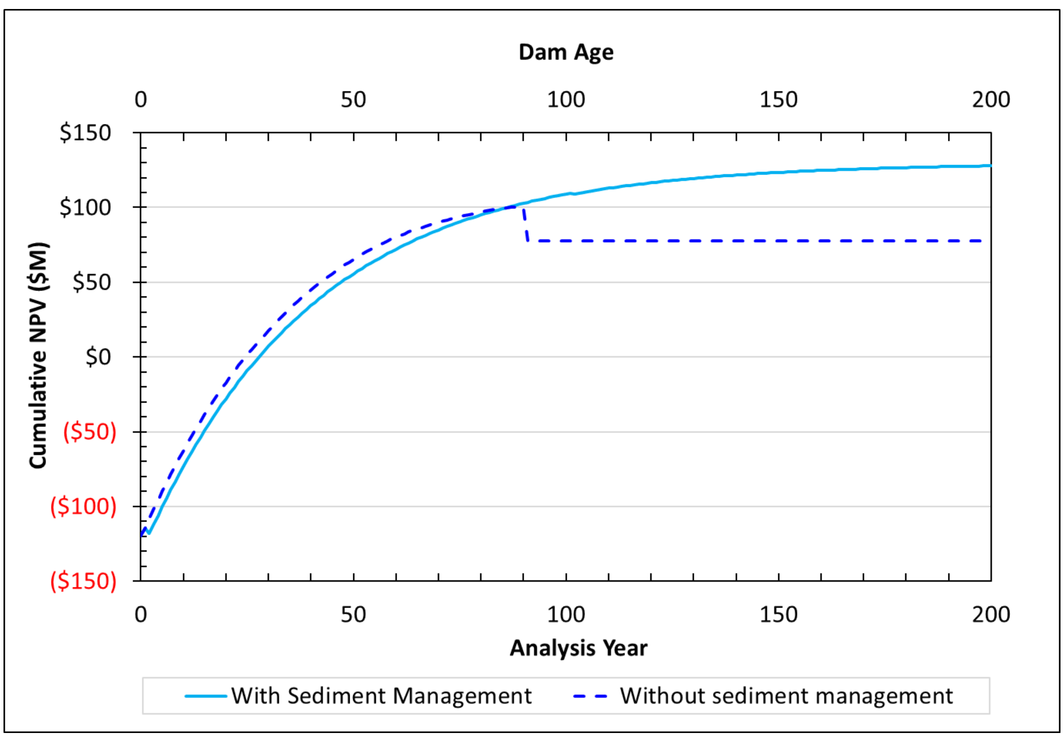

Figure 5. Economic simulation of cumulative net present values (NPV) for alternatives without and with sediment management.

RSEM also provides comparative tables of present and annualized values of benefits, costs, lost benefits, benefit-cost ratios, and net present values. Comparative values are presented for alternatives without and with sediment management after 50, 100, 200, and 500 years. In addition, RSEM provides decision support metrics:

- A break-even analysis (identifies the year where the cumulative net present values for both alternatives are nearly equal).
- A retirement fund analysis (estimate of the annual payment into a dam retirement fund to cover dam decommissioning cost in the year needed).

Conclusions

RSEM is a useful tool to help guide comprehensive and comparative analyses of sedimentation and economics for reservoirs without and with sediment management. Without sediment management, the model simulates how sedimentation may reduce reservoir storage benefits over time, incur costs from aggradation upstream, degradation downstream, and eventual dam decommissioning after severe sedimentation. The model also helps simulates the economic costs of sediment management over time and how that alternative can help preserve reservoir storage benefits and avoid dam decommissioning. These economic analyses can help determine where reservoir sediment management is the economically preferred alternative.

References

Anari, R., Gaston, T., Randle, T., Hotchkiss, R.H. 2023. "New Economic Paradigm for Sustainable Reservoir Sediment Management," *J. Water Resources Planning and Management*, Volume 149, Issue 2 - February 2023.

Annandale, G., 2013. *Quenching the Thirst, Sustainable Water Supply and Climate Change*, Create Space Independent Publishing Platform, North Charleston, SC, 231 pages.

Annandale, G.W., Morris, G.L., Karki, P. 2016. *Extending the life of reservoirs, sustainable sediment management for dams and run-of-river hydropower*. International Bank for Reconstruction and Development / The World Bank, Washington, DC.

Morris, G.L., Fan, J. 1998. *Reservoir Sedimentation Handbook*, McGraw-Hill Book Co., New York, New York, https://reservoirsedimentation.com/.

Morris, G., Annadale, G., and Hotchkiss, R. 2008. "Reservoir Sedimentation," chapter 12 (pp. 579-612) of *Sedimentation engineering: processes, measurements, modeling, and practice*, ASCE Manuals and Reports on Engineering Practice No. 110, American Society of Civil Engineers.

Randle, T.J., Yang, C.T., Daraio, J. 2006. "Chapter 2, Erosion and Reservoir Sedimentation" in *Erosion and Sedimentation Manual*, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado. https://www.usbr.gov/tsc/techreferences/mands/mands-pdfs/Erosion%20and%20Sedimentation%20Manual.pdf

Randle, T., Morris, G., Whelan, M., Baker, B., Annandale, G., Hotchkiss, R., Boyd, P., Minear, J.T., Ekren, S., Collins, K., Altinakar, M., Fripp, J., Jonas, M., Kimbrel, S., Kondolf, M., Raitt, D., Weirich, F., Eidson, D., Shelley, J., Vermeeren, R., Wegner, D., Nelson, P., Jensen, K., Tullow, D., 2019. *Reservoir sediment management: building a legacy of sustainable water storage reservoirs*. National Reservoir Sedimentation and Sustainability Team White Paper, June 12,

2019. https://www.sedhyd.org/reservoir-sedimentation/National%20Res%20Sed%20White%20Paper%202019-06-21.pdf.

Randle, T. J., G.L. Morris, D. Tullos, F. H. Weirich, M. G. Kondolf, D. N. Moriasi, G.W. Annandale, J. Fripp, M. J. Toby, and D. L. Wegner. 2021. "Sustaining United States Reservoir Storage Capacity: Need for a New Paradigm." *Journal of Hydrology*, 126686.

Randle, T.J., Gaston, T., Anari, R. 2023. *Reservoir Sedimentation Economics Model Description*, U.S. Department of the Interior, Bureau of Reclamation, Water, Environmental, & Ecosystems Division, Denver, Colorado, https://www.usbr.gov/tsc/techreferences/computer%20software/compsoft.html.

Strand, R.I., Pemberton, E.L. 1982. *Reservoir Sedimentation*, Bureau of Reclamation, Sedimentation and River Hydraulics Section, Hydrology Branch, Denver, CO.