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Managing Water in the West

The Economics of Reservoir Sedimentation & Remediation

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This study provides an overview of reservoir sedimentation, an analysis of sediment management costs, and an economics case study of sedimentation management at a hypothetical western US reservoir. The case study demonstrates an approach for quantitatively estimating the economic impacts of sedimentation and the cost-effectiveness of sediment removal. The results indicate that it is economical to mechanically remove the annual sediment inflow to the hypothetical reservoir at per-unit costs falling within the range of reasonable cost estimates compiled for such removal.

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Acronyms and Abbreviations

$M	Millions of dollars
AF	Acre-foot/feet – measure of volume equal to 325,851 gallons
CS	Consumer surplus – the difference between what consumers are willing to pay for a good/service and what they actually pay
FMCRC	Fire Mountain Canal and Reservoir Company
FY2018 Planning Rate	Fiscal Year 2018 Plan Formulation and Evaluation Rate of 2.750
M&I	Municipal and industrial – a beneficial purpose of water projects
MSL	Mean sea level
MWh	Mega-watt hour – a unit of power
NFR	Net farm returns – an intermediate farm income measure in the estimation of irrigation water supply benefits
NFWCD	North Fork Water Conservancy District
NPV	Net present value
NRB	Net recreation benefits
OM&R	Operations, maintenance, and replacement
Reclamation	US Department of the Interior, Bureau of Reclamation
UC Region	Reclamation's Upper Colorado Region

Executive Summary

Reclamation operates 338 reservoirs with a total storage capacity of 140 million AF, contributing more than $48 billion in economic output and supporting nearly 388,000 jobs (Reclamation, 2018a). Reservoir sedimentation threatens the continued viability of these economic benefits and reactionary measures to address reservoir sedimentation are generally prohibitively expensive. Therefore, proactive economic management of reservoir sedimentation should be a priority for Reclamation.

This scoping-level study provides an overview of reservoir sedimentation, a description of the costs associated with reservoir sedimentation, and concludes with a benefit-cost analysis case study for sediment management at a hypothetical western US reservoir typical of those existing in the Mountain West. The case study demonstrates an approach for quantitatively estimating the economic impacts of sedimentation and comparative cost-effectiveness of sediment removal. The case study concludes by identifying the break-even per unit cost for economical sediment removal subject to several no action future scenarios. The results of the case study indicate that mechanical sediment removal is within reasonable per unit cost estimates identified for such removal efforts. The finding that mechanical sediment removal is a potentially economic alternative was unexpected—as this alternative is generally assumed it to be prohibitively expensive—but comprehensively quantifying the costs of no action bring mechanical removal into the margins of economic feasibility.

Next steps include further research on the interrelated topics of intergenerational equity with regards to long-lived infrastructure, non-traditional discounting methods, and alternative discount rates. Future work products include the development of sediment management cost and reservoir benefit value databases and elevating the scoping-level (effectively pre-appraisal-level) economic analysis of sediment removal to the feasibility-level for a western US reservoir confronting severe sedimentation.

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Background

Sediment accumulation in storage reservoirs (sedimentation) is a predictable process that was anticipated upon the construction of the nation's large storage dams. In planning the installation of these dams, storage capacity was generally designed to accommodate expected sediment deposition over a 100-year design life from the time of construction. Some of the nation's dams are approaching this centennial milestone, and many others have accumulated sediment at much faster than anticipated rates, rendering them nearly inoperable after only 50 or 60 years. There is no coherent strategy to cope with this looming predicament, yet there is little appetite to forego the economic benefits these dams provide.

A glaring oversight in the economic evaluation of these projects when in the planning phase was the omission of perennial sediment management costs, or, in cases when sediment management was deemed infeasible, dam removal costs upon attainment of the sediment design life. These unaccounted costs have effectively accrued and compounded over time in the form of sediment deposition. The challenge for Reclamation and other water management agencies is to determine the most economically efficient way to pay this cost down.

Numerous publications have documented the impending crisis regarding the sedimentation of reservoirs in the United States and around the world, and the technologies that might be employed to remedy the problem. Some publications have addressed the costs of these technologies, but there is a dearth of literature addressing the *cost-effectiveness* of such undertakings, and more so, a dearth of literature comparing the benefits provided by a given dam to the most cost-effective sediment control measures.

This study first provides an overview of the reservoir sedimentation problem, the costs associated with the problem, and discusses the technologies commonly proposed (and sometimes employed) to remedy or mitigate the problem. Secondly, this study documents the costs of the remediation technologies. Finally, this study provides a cursory benefit-cost analysis for sediment management at a hypothetical western US reservoir—demonstrating an approach for quantitatively estimating the economic impacts of sedimentation and comparative cost-effectiveness of sediment removal. This study discusses reservoir sedimentation in general but focuses primarily on the western United States—where Reclamation manages many of the large dams and reservoirs—due to the accessibility of Reclamation-specific data and expertise.

Selection of Literature Reviewed

A selection of the literature reviewed in conducting this study is summarized below. The literature is broken-out into two categories: (1) literature that evaluates reservoir sedimentation and the need for management from an engineering perspective (i.e., what is technically possible); and (2) literature that evaluates reservoir sedimentation management from an economic perspective (i.e., what is economically feasible). Much of the literature reviewed overlaps these two designations, but in general, fall within one or the other. A comprehensive listing of literature reviewed can be found in the References section of this report.

Sedimentation Management and Reservoir Sustainability

There is a wealth of literature expounding on the issue of reservoir sedimentation and the need for sustainable sediment management. Kondolf, et al. (2014) assess these issues at the largest scale—the breadth of their research including case studies on five continents and involved an international team of 19 authors. The study provides an overview of reservoir sediment management strategies, upstream and downstream considerations, and some specific recommendations. The study concludes that "…the most important consideration in sediment management through reservoirs is getting it right from the start.", though they do acknowledge that existing reservoirs are consigned to less enviable management options.

Sankey, et al. (2017) delve into the primary driver of reservoir sedimentation: upstream erosion. Specifically, they evaluate the increased wildfire frequency and intensity forecasted by climate change ensemble models and predict a significant uptick in erosion-induced sedimentation in the western US. This is an important consideration, as the sediment design life for dams built in decades past used historical sedimentation rates in their capacity calculations.

Randle, Ekren, Hanson, & Ramsdell (2018) make a compelling case for the need for long-term sustainable reservoir management and provides a detailed examination of dredging as a candidate for achieving this. The study concedes that past decades of sedimentation would likely have to be accepted in large reservoirs, but a long-term program could be employed to maintain existing storage capacity by dredging the annual sediment load. Further, if the dredged sediment is delivered to the downstream river channel—where they would have been naturally transported without the dam and reservoir—there would be a mitigation of the downstream sediment deprivation impacts. The study considers the impacts of multiple variables, including: specific location and topography, sedimentation volume and grain size, reservoir depths, disposition of the dredged sediment, slurry pipeline length and alignment, permits, mobilization, and power for the dredge and pumps. Especially applicable to the case study featured in this report, Randle, Ekren, Hanson, & Ramsdell acknowledge that the cost of dredging should be compared with the cost of other sediment management options, the cost of eventually losing the reservoir benefits, and the cost of dam decommissioning in the absence of sediment management.

Economic Considerations of Reservoir Sedimentation

George, Hotchkiss, & Huffaker (2016) make a case conventional cost-benefit analyses (CBAs) cannot adequately account for sustainable reservoir life spans nor intergenerational equity, as a conventional CBAs render all benefits and costs projected to occur more than several decades into a project as negligible. The article goes on to discuss some alternatives to the traditional application of the CBA, such as dam owners instituting retirement funds or insurance policies, beneficiaries paying for rehabilitation or maintenance, and economists incorporating infrastructure damages and potentially logistic discount rates into their analyses. The article includes a brief case study of Gavins Point Dam that demonstrates that damages due to a lack of sediment management account for at least 70% of the actual construction cost. In summary, the article recommends integrating alternative economic analyses for reservoirs that will lead to more accurate costs estimates, account for reservoir sustainability, and lessen the economic burdens placed on future generations.

Two papers that present methodologies for quantitatively estimating the cost-effectiveness of sedimentation management are *Conserving reservoir water storage: An economic appraisal* (Kawashima, 2007) and *A method for evaluating the economic benefit of sediment control in irrigation systems* (Chancellor, Lawrence, & Atkinson, 1996). Kawashima (2007) analyzes reservoir level sediment management from a benefit-cost perspective and uses dynamic programming simulation to evaluate the long-term consequences of dam management decisions regarding reservoir sedimentation. The methodology includes a sensitivity analysis that varies, the value of stored water, the discount rate, and the annual sediment load. The results indicate that doing nothing is likely to lead to inefficiencies and reduce the social welfare in the long run, while sediment management can mitigate the economic loss due to reservoir sedimentation. The paper develops a useful—albeit generic—economic analysis framework and acknowledges several of its limitations, including the lack of site specificity and the omission of accounting for the potential impacts (both environmental and economic) of sediment disposal.

Chancellor, Lawrence, & Atkinson (1996) present the most specific prescription for an economic analysis of sediment management. Specifically, they evaluate the economic benefits of sediment control in irrigation systems. This niche analysis is an excellent resource for approaching the topic of agricultural impacts due to sedimentation, but—as expected—lacks the wider applicability of Kawashima (2007). Most Reclamation storage reservoirs have an irrigation component, which makes this study especially applicable for this agency and the case study featured in this report.

Overview of Reservoir Sedimentation

The Problem of Reservoir Sedimentation

All rivers transport sediment (e.g., clay, silt, sand, gravel, and cobble) in widely varying amounts, and reservoirs tend to trap all or a portion of these sediment loads (Randle, Ekren, Hanson, & Ramsdell, 2018). Unless dams are designed and operated to pass the incoming sediment load downstream, they are not sustainable (Hotchkiss, 2018). The nation’s 90,000 dams and reservoirs are continually filling with sediment and some are reaching their sedimentation design life (the sediment load expected to accumulate over the design life of the structure). More alarming, some reservoirs are experiencing higher sedimentation rates than were forecasted in the dam planning phase, which is depleting economic benefits and escalating costs in an abbreviated timetable. Sustainable sediment management solutions are needed to preserve the economic benefits provided by dams and reservoirs and to minimize the costs associated with their sedimentation.

The Costs of Reservoir Sedimentation

The costs attributed to reservoir sedimentation can be classified into five general categories: (1) a depletion of economic benefits dependent on reservoir and dam features impacted by sedimentation; (2) increased operations, maintenance, and replacement (OM&R) costs attributed to sedimentation; (3) the cost of dam removal if accrued sediment makes this an inevitability; (4) downstream costs incurred due to sediment deprivation, and (5) the costs upstream attributed to increased groundwater tables and increased flood stage.

Economic Benefits Impacted by Reservoir Sedimentation

In the western US, the economic benefits provided by dams generally fall within the following six categories (known as "beneficial purposes"):

1. Irrigation water supply;
2. Municipal and industrial (M&I) water supply;
3. Flood control;
4. Hydropower generation;
5. Recreation; and
6. Fish and wildlife enhancement (including environmental instream flows).

A dam and reservoir provide economic benefits to beneficial purposes through different means, including: actual storage, total capacity, reservoir forebay elevation, and reservoir surface area. Irrigation and M&I water supply benefits are dependent on actual storage that can be delivered through the dam outlet works or reservoir water intake structure. Flood control benefits are dependent on the proportion of total reservoir capacity that is available to capture flood flows. Hydropower generation benefits are dependent on hydraulic head, directly related to reservoir forebay elevation and operational powerplant turbines. Recreation benefits are dependent on the reservoir surface area available for recreation activities. Finally, fish and wildlife benefits can be dependent on reservoir volume (maintenance of reservoir habitat), or releases from the dam (maintenance of downstream habitat). Timing is a key aspect for any of the beneficial purposes. For example, storage for irrigation deliveries can only generate benefits if available during the irrigation season and flood control benefits can only accrue if the capacity is available during storms.

No beneficial purpose is spared from the impacts of dam sedimentation. Sedimentation can decrease overall capacity and actual storage; clog outlet works, water intakes, and turbines; decrease hydraulic potential; decrease reservoir surface area and depth; decrease reservoir fisheries habitat; increase turbidity in the reservoir; degrade downstream habitat; and bury upstream habitat.

The metric used to quantify the benefits to a purpose depends on the means through which that purpose is realized. Irrigation and M&I water supply benefits are generally reported as benefits per acre-foot (AF) of delivered water. Flood control benefits are generally reported based on the average annual flood damages prevented (reported for most large dams by the US Army Corps of Engineers). Hydropower benefits are reported as benefits per megawatt hour (MWh) generated. Recreation benefits are generally reported as benefit per recreation visit. Fish and wildlife benefits can be quantified through non-market valuation techniques—such as existence value estimates—and the metrics for reporting can vary widely based on the employed technique.

Benefit values can vary drastically by region and even by site. For example, irrigation water supply benefits are generally estimated at a higher value in California and the Pacific Northwest than in the Great Plains. This is primarily due to the high value fruit and nut orchards being irrigated in California and the Pacific Northwest versus the irrigated grains and pasture that dominate the Great Plains.

Increased OM&R Costs due to Reservoir Sedimentation

Sediment can have a significant impact on dam and reservoir infrastructure. Coarse sediment (generally sand and gravel) can significantly decrease the service life of outlet works, hydropower penstocks and turbines, and other infrastructure through abrasive deterioration of protective coatings and the structures themselves. This decreases the maintenance intervals, increases material and labor costs, and can impede optimal operation of outlet works and hydropower production.

Coarse sediment generally falls out of the water column quickly and in the early stages of reservoir sedimentation will have minimal impact on infrastructure. However, as sedimentation continues, and the deposition increases in thickness and breadth, coarse sediment comes into increasing contact with dam and reservoir infrastructure. In some extreme cases, the thickness of the sediment can completely overtake dam outlet works, essentially burying the structure.

Finer sediment, such as clay and silt, are more easily passed through dam and reservoir infrastructure and aside from their contribution to sediment deposition, generate comparatively less OM&R costs than coarse sediment.

Dam Removal Costs due to Reservoir Sedimentation

If reservoir sedimentation accumulates to the point that the dam and reservoir are no longer functional and able to provide benefits, this can be a significant safety hazard and the dam may need to be removed. Without functioning outlet works, sediment and water will continue to build behind the dam, and if the dam were to be topped by this accumulation, or a flood, a catastrophic failure could be imminent.

Nationwide, 1,492 dams have been removed during the period 1912 through 2017 (American Rivers, 2018). The costs of some dam removals have been extraordinary. For example, the removal, related property and facilities purchases and installation, and continued ecological restoration of Elwha and Glines Canyon Dams in 2012—which once stood on the Elwha River in Clallam County, Washington—are estimated to have a combined cost of $324.7 million (NPS, 2015). Note that these dams were not removed solely due to sedimentation, but sedimentation was becoming an insurmountable problem and one of the largest costs related to the removal projects is the management of the residual sediment load.

Downstream Costs due to Reservoir Sedimentation

Sediment trapped behind reservoirs causes downstream sediment deprivation, impacting downstream habitats and features that depend on the natural process of sediment replenishment. Notable downstream impacts that can lead to considerable costs include: river channel incision or degradation, floodplain detachment from incised river channels, and reduction of sediment delivery to coastal deltas (Randle, Ekren, Hanson, & Ramsdell, 2018). These impacts can lead to collapse of structures built on or near riverbanks, depleted fish and wildlife habitat, and increased coastal shoreline erosion—all of which involve substantial costs to repair, mitigate, or manage.

Upstream Costs due to Reservoir Sedimentation

Reservoir sedimentation can generate upstream costs attributed to increased groundwater tables and increased flood stage. Increased groundwater tables and flood stage can lead to increased flood severity and frequency, resulting in significant flood damages to upstream farm fields, residential property, and commercial property.

Management and Remediation of Reservoir Sedimentation

There are several approaches to managing and remediating reservoir sedimentation. Kondolf, et al. (2014) exhaustively catalogs sedimentation management strategies and provides detailed descriptions and implemented examples for each. In summary, the strategies include:

- Sediment Bypassing and Off-Channel Reservoir Storage
- Sediment Sluicing
- Drawdown flushing
- Pressure flushing;
- Turbidity current venting; and
- Dredging and mechanical removal of accumulated sediments.

Kondolf, et al. (2014) also provides descriptions of upstream sediment management approaches (including catchment erosion control, checkdams, sediment traps, and warping) and sediment augmentation strategies downstream of dams (including addition of sediment to the downstream channel).

In cases where dams were built without any bypass feature, existing outlet works can sometimes be operated to pass through a portion of the sediment load. However, this can have a deleterious effect on outlet works not intended for this purpose and can lead to significantly higher OM&R costs. In such cases, a retrofitting of bypass features can be considered, or, if such a retrofit is prohibitively expensive, the dam operator may be relegated to mechanical removal of sediment.

> Dredging of sediment from reservoirs is one option for recovering or maintaining reservoir storage capacity, especially in cases where the reservoir cannot be drawn down for sediment management purposes. Recovery of water storage capacity lost to past decades of sedimentation would be most economically viable for small reservoirs where dredged sediment could be delivered to nearby disposal areas (Randle, Ekren, Hanson, & Ramsdell, 2018).

This report focuses primarily on mechanical removal of sediment, notably dredging, as a sediment management strategy. The next section concerns the costs of dredging.

Cost Data for Mechanical Sediment Removal

Extensive research was done to compile non-coastal dredging cost data. The dataset compiled for this analysis includes 33 dredging costs line items, including 26 estimates, four awarded contracts, two final contracts, and one submitted bid—all for reservoir or lake dredging costs. The dataset includes cost items for 13 states and the costs span the years 1979 through 2017. All cost data was converted to dollars per AF of sediment removed and indexed to 2017 dollars using the Engineering News-Record's Construction Cost Index Construction cost index (ENR, 2018). Summary statistics for the database are presented below in Table 1. Note the large range in cost per AF for sediment dredging. This might be due to several factors, including: accessibility (mountain canyon reservoir versus a prairie lake), sediment type, geographic proximity to dredging assets, the nature of the contract (bid versus final contract), and the amount of sediment to be removed (in general, the more sediment removed, the lower the cost per AF).

Table 1. Dredging cost database summary

Number of cost items	33
Number of states included in dataset	13
States included	CA, CO, IA, IL, KS, MA, MD, MI, MN, NY, TX, WA, WI
Date range for cost items	1979–2017

		Cost per AF of sediment removed (2017$)			
Contract type	**Count**	**Min**	**Median**	**Average**	**Max**
Awarded contract	4	$12,052	$11,806	$46,829	$94,298
Final contract	2	$15,094	$80,935	$80,935	$146,776
Estimate	26	$1,186	$6,854	$22,812	$111,307
Submitted bid	1	$236,936	$236,936	$236,936	$236,936
All contracts	33	$1,186	$11,806	$36,138	$236,936

Case Study: Muddy Reservoir

This case study is conducted for Muddy Reservoir, a hypothetical western US reservoir typical of those existing in the Mountain West, where high sediment load is a persistent, and often pressing, issue.

The Hypothetical Dam and Reservoir

The hypothetical Muddy Dam impounds the hypothetical Muddy Reservoir, both of which are the principal features of Reclamation's hypothetical Muddy Project. The Muddy Project was commissioned 60 years ago and falls within Reclamation's Upper Colorado Region (UC Region).

Economic Benefits Provided by the Muddy Project

The Muddy Project was authorized primarily to provide irrigation water supply to Project lands. Other beneficial purposes included in the Project authorization are flood control and recreation. The economic benefits generated owing to these three beneficial uses are described and quantified in this section. Due to the limited scope of this analysis, simplified assumptions—based on the best data readily accessible for comparable existing projects—are employed to estimate the benefits provided by the Muddy Project.

The estimation of economic benefits is consistent with the *Principles, Requirements and Guidelines for Water and Land Related Resources Implementation Studies* (PR&Gs) (DOI, 2015). Annual benefit values are estimated for each beneficial purpose. Annual benefits are discounted over a 50-year planning horizon at the Fiscal Year 2018 Plan Formulation and Evaluation Rate (FY2018 Planning Rate) of 2.750 percent to determine their present value (U.S. Department of the Treasury, 2017).

Irrigation Water Supply

The Muddy Project provides full and supplemental irrigation water supplies for 15,300 acres of irrigable lands in the Mountain West. Approximately 80 percent of Muddy Project irrigation water is applied to crop land and 20 percent to pasture land. The crop land consists of high-value fruit orchards (namely apples, peaches, cherries, pears) and some smaller plots of vegetables.

Irrigation Diversions

All Muddy Project irrigation water is diverted through the Muddy Mountain Canal which is managed by the Muddy Mountain Canal and Reservoir Company. On average, total annual diversions through Muddy Mountain Canal are 47,303 AF, with 34,104 AF (or approximately 72 percent) coming from direct streamflow and the remaining 13,198 AF (or approximately 28 percent) coming from Muddy Reservoir storage. As is typical of Mountain West irrigation projects, headgate diversions usually begin in mid-April and end from early September to mid-October. The canal turn-off date is dependent upon storage releases from Muddy Reservoir and annual climate conditions.

Irrigation Water Supply Benefit Methodology

Reclamation estimates irrigation water supply benefits using a with-without project methodology. In summary, irrigation benefits are calculated as the difference in net farm returns (NFR) to project-irrigated lands with the project in its current state (with-project condition) and the same lands in the absence of the project (without-project condition). The with-without methodology is applied to a model farm that is representative of the cropping patterns and agricultural practices in the project area. The NFR of the model farm is estimated for both the with- and without- project conditions using a farm budget analysis. The difference in NFR yields the irrigation benefit to the model farm. Dividing this irrigation benefit by the AF of project irrigation water delivered to that farm yields the benefit per AF of project irrigation water. Multiplying this value by total project irrigation deliveries returns the irrigation benefits provided by the project.

Irrigation Water Supply Benefits

Even an appraisal-level irrigation benefits analysis requires data and labor inputs beyond the scope of this study. A proxy is therefore used for the benefit per AF value that is representative of the Muddy Project area. The proxy used is $93.05 per AF (2017 dollars) of irrigation water and is the median value of UC Region benefits per AF based on an analysis of 20 irrigation benefit studies conducted by Reclamation since 2012. The dataset demonstrates a wide range of values, introducing skewness to the mean, and therefore the median is determined to be a better indicator of central tendency.

As explained above, an average of 13,198 AF of irrigation diversions per year were provided by the Muddy Project. Multiplying 13,198 AF by $93.05 per AF per year yields an annual irrigation water supply benefit of approximately $1.23 million (2017 dollars). If this stream of benefits were to be preserved, this is the equivalent of approximately $33.15 million in present benefits—discounted over a 50-year planning horizon at the FY 2018 Planning Rate of 2.750 percent.

Recreation

This section estimates the economic value that water availability and reliability contribute to recreation opportunities in the region. Muddy Reservoir has a water surface area of approximately 334 acres and the adjacent lands make up Muddy State Park. Reservoir and park recreation are managed by the state under agreement with Reclamation. The park offers picnic areas and 15 semi-primitive campsites.

Recreation Benefit Methodology

The annual economic benefits of recreation are estimated as the net consumer surplus of a recreation visit multiplied by total annual recreation visitation. 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. Net consumer surplus of a recreation visit is equal to recreation consumer surplus of a visit under the With-Project condition less 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.

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. This analysis accounts for the effects of substitution.

Mathematically, the annual net recreation benefit of a reservoir in year j can be expressed as Equation (1), below. Equation (2) shows the calculation of net consumer surplus of a recreation visit to affected recreation areas for activity *i* in year j. Equation (3) 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 $CS_{Without,ij}$ equals $40 x 0.4 = $16.

$$NRB_j = \sum_{i=1}^{n} \left[CS_{Net,ij} * V_{ij} \right] \tag{1}$$

$$CS_{Net,ij} = CS_{With,ij} - CS_{Without,ij} \tag{2}$$

$$CS_{Without,ij} = CS_{With,ij} * SF_{ij} \tag{3}$$

Where:

NRB_j = Net recreation benefit for affected areas in year *j*

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

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

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

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

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

SF_{ij} = 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 Muddy Reservoir in year *j*

For simplification, this study develops a “typical” visitor day net consumer surplus value—weighted by the participation rates of each recreation activity. By weighting the net consumer surplus value by participation rate per activity, participation rates are therefore implicitly accounted for in (now aggregate) annual visitation and the substitution factor. Modifying equations (1), (2), and (3) to accommodate the typical visitor day yields equations (4), (5), and (6), below.

$$NRB_j = CS_{Net,j} * V_j \tag{4}$$

$$CS_{Net,j} = CS_{With,j} - CS_{Without,j} \tag{5}$$

$$CS_{Without,j} = CS_{With,j} * SF_j \tag{6}$$

Where:

NRB_j = Net recreation benefit for Project-affected areas in year *j*

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

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

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

V_j = Total recreation visits in year *j* to Project-affected areas

SF_j = 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 Muddy Reservoir in year *j*

Consumer surplus is derived using the *benefit transfer approach* based on published literature, while visitation by recreation activity and substitution effects are based on historical data and estimates provided by the recreation manager.

Recreation Activities

Recreation activities at Muddy State Park include wildlife viewing, water sports, recreational vehicle use, picnicking, hunting, fishing, camping, and boating. Correspondence with park officials indicates that boating, camping, and fishing are the most popular activities at the reservoir, making up about 50 percent, 20 percent, and 20 percent of all recreation activity, respectively. The final 10 percent of activity consists of other recreation activities. Park officials further elaborated that there are very few trails for hiking, biking, or horseback riding and muddy water can sometimes prevent activities such as swimming and fishing.

Substitutability

Muddy Reservoir is unique for the recreation opportunities and facilities it provides within a 50-plus-mile radius. According to park officials, the closest substitutes that provide a similar quality experience are four reservoirs between 35 and 120 miles driving distance from Muddy Reservoir, with drive times between one hour and three hours, and travel is difficult from the Muddy area due to the mountainous terrain.

Due to the relative isolation (and thus minimal substitutability) of Muddy Reservoir, this analysis assumes that in the absence of Muddy Dam and Reservoir (the Without-Project condition), 50 percent of recreator consumer surplus is lost and 50 percent of recreator consumer surplus is retained through substitution from a less desirable site and/or activity. Therefore, the substitution factor to be used in calculating recreator consumer surplus under the Without-Project condition—denoted as variable SF_j in Equation (6)—is 0.5.

Consumer Surplus of Recreation at Muddy Reservoir

The consumer surplus of a recreation visit to Muddy Reservoir is determined using a *benefit transfer approach.* The consumer surplus values for the primary recreation opportunities provided by Muddy Reservoir were deduced using primarily the *Recreation Use Values Database for North America* (Rosenberger, 2016). This database contains 421 economic valuation studies that estimate the use value of recreation activities, measured in net economic value (consumer surplus) for recreational access in the U.S. and Canada from 1958 to 2015. In an effort to increase the accuracy of benefit values and obtain values that are more site specific, the recreation benefit values estimated in this analysis employed only a subset of the aforementioned database—only those economic valuation studies conducted after 1980 in the Western Census Region for recreation sites where the primary environment type was lake or reservoir. Further, the median consumer surplus values are used to avoid potential skewness and distortion from outliers. All consumer surplus values are indexed to 2017 dollars using the US Bureau of Labor Statistics' CPI Inflation Calculator (BLS, 2018).

For simplification, this study develops a "typical" visitor day consumer surplus value based on the participation rates of each primary recreation activity. As stated above, participation rates for the recreation activities practiced at the reservoir were estimated to be 50 percent boating, 20 percent camping, 20 percent fishing, and ten percent general recreation. The typical visitor day consumer surplus value is weighted by these participation rates. Table 2 displays the median recreation consumer surplus per visit for the primary recreation activities at Muddy Reservoir, and the derivation of net consumer surplus for a "typical" visitor day.

Table 2. Calculation of net consumer surplus per recreation day

Recreation activity[a]	CS per recreation visit (2017 $'s)[b]	Participation rate[c]	CS weighted by participation rate
Boating	$117.65	50%	$58.83
Fishing	$72.94	20%	$14.59
Camping	$41.39	20%	$8.28
General recreation	$31.25	10%	$3.13
CS of "typical" visitor day under With-Project condition[d]			$84.83
Substitution factor[e]			0.5
CS of "typical" visitor day under Without-Project condition[f]			$42.42
Net consumer surplus of "typical" visitor day[g]			**$42.42**

[a] Primary recreation activities at Muddy Reservoir.

[b] Median of consumer surplus values for identified primary recreation activities (Rosenberger, 2016); indexed to 2017 dollars.

[c] Participation rate for each recreation activity practiced at Muddy Reservoir and State Park.

[d] Calculated as the sum of the participation-weighted recreation activity consumer surplus values (variable $CS_{With,j}$ in Equation (5)).

[e] The proportion of consumer surplus retained in the absence of Muddy Reservoir (variable SF_j in Equation (6)).

[f] Calculated as: $CS_{Without,j} = CS_{With,j} * SF_j$ per Equation (6).

[g] Calculated as: $CS_{Net,j} = CS_{With,j} - CS_{Without,j}$ per Equation (5).

Recreation Visitation to Muddy Reservoir and State Park

Muddy State Park officials indicate that on average there are 26,000 annual recreation visits to Muddy Reservoir and State Park. The park manager further stated that visitation is highly dependent on reservoir water levels.

Recreation Benefits

To estimate recreation benefits owing to Muddy Reservoir, average annual recreation visitation to the reservoir is multiplied by the net consumer surplus per visit. As stated earlier in this section, Muddy Reservoir receives approximately 26,000 annual recreation visits. Table 2 shows that each recreation visit has a net consumer surplus of $42.42. Multiplying 26,000 by $42.42 yields a net recreation benefit of approximately $1.10 million annually (2017 dollars). If this stream of benefits were to be preserved, this is the equivalent of approximately $29.78 million in present benefits—discounted over a 50-year planning horizon at the FY 2018 Planning Rate of 2.750 percent.

Flood Control

Muddy Reservoir has 2,280 AF of capacity assigned to flood control. The Muddy Project has provided an accumulated $253,000 in flood control benefits from since its inception to 1999, or an average of $6,657 in flood control benefits annually (1999 dollars). This is the equivalent of $9,841 per year when indexed to 2017 dollars (BLS, 2018). If this stream of benefits were to be preserved, this is the equivalent of approximately $0.27 million in present benefits—discounted over a 50-year planning horizon at the FY 2018 Planning Rate of 2.750 percent.

Summary of Muddy Project Economic Benefits

As displayed below in Table 3, annual total economic benefits provided by Muddy Dam and Reservoir are approximately $2.34 million (in 2017 dollars). If this stream of benefits were to be preserved, this is the equivalent of more than $63 million in present benefits—discounted over a 50-year planning horizon at the FY 2018 Planning Rate of 2.750 percent.

Table 3. Total benefits provided by Muddy Dam and Reservoir

Project purpose	Annual Project benefits (2017 $'s)	Present Value (million $'s)[a]
Irrigation water supply	$1,228,074	$33.15
Recreation	$1,102,790	$29.78
Flood control	$9,841	$0.27
Total	**$2,340,705**	**$63.20**

[a] Discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750% and rounded to the nearest $1,000.

Sedimentation of Muddy Reservoir

The watershed upstream of Muddy Dam lies on geologic formations presenting highly erodible hillslopes and landslides within the watershed, delivering a large sediment load to Muddy Reservoir. The most recent bathymetric survey of the entire reservoir, conducted in June 2016, indicates that the average annual rate of sedimentation has been approximately 100 AF per year, decreasing capacity by nearly 26 percent since 1962 (see Table 4 below). According to the study *Muddy Reservoir Sediment Management Planning Alternatives* (2018 Sediment Management Study):

> At the current rate of storage loss, and assuming that all sediment is trapped in the reservoir in the future, the reservoir would completely fill with sediment in approximately 150 years, gradually reducing the available pool over time and reducing water supply reliability downstream. However, long before sediment completely fills the reservoir, the reservoir space below the outlet works intake elevation, known as the "dead pool", generally fills first with sediment, impacting outlet works intakes and adversely impacts project operations and downstream water deliveries.

Table 4 displays the results of eight reservoir surveys complete for Muddy Reservoir between 1961 and 2016. Note the decreasing capacity and resulting storage loss over time due to sedimentation. Figure 1 presents the decrease in capacity over time due to sedimentation in graphical form. All capacity values in Table 4 and Figure 1 are reported for the full pool elevation of 6450.

Table 4. Muddy Reservoir surveyed capacity versus time

Survey date	Total capacity (AF)[a]	Total capacity loss (AF)	% storage loss
12/5/1961	20,950	-	-
2/19/1969	20,214	736	3.5%
6/29/1988	17,461	3,489	16.7%
6/15/2002	15,977	4,973	23.7%
6/12/2013	15,776	5,174	24.7%
11/18/2014	15,690	5,260	25.1%
7/1/2015	15,550	5,400	25.8%
6/15/2016	15,521	5,429	25.9%

[a] All survey results reported at full pool (elevation 6450)

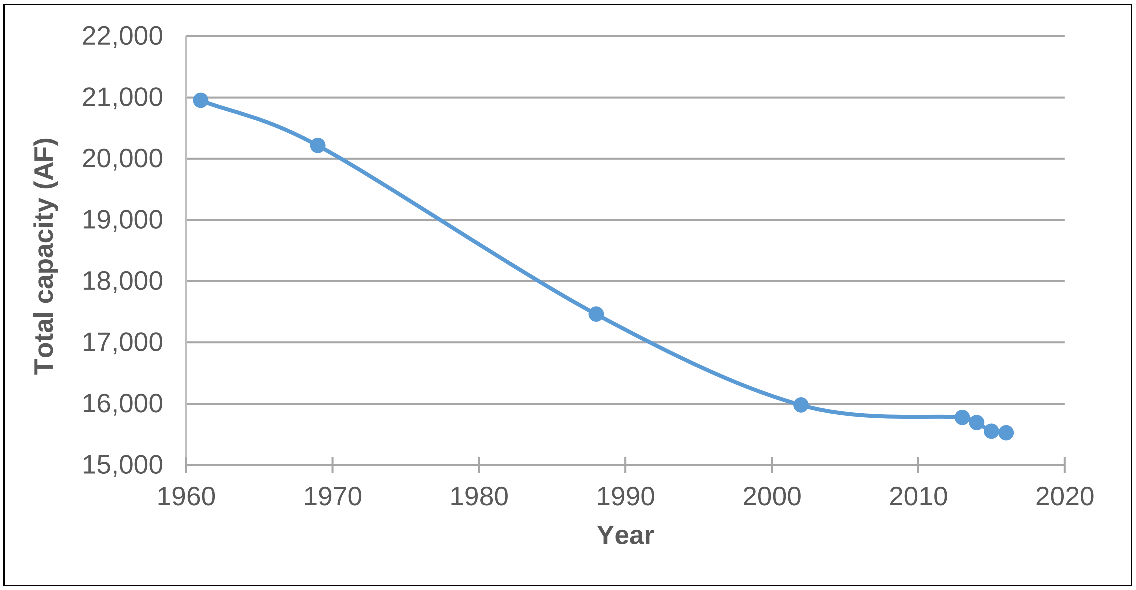


Figure 1. Muddy Reservoir full pool capacity (elevation 6450) versus time

Sedimentation has also decreased Muddy Reservoir surface area over time. This effect has been especially pronounced at the upstream end of the reservoir, where sediment falls out as the velocity of the primary tributary slows considerably as it meets the reservoir. Figure 2 displays the reservoir surface area across the full range of reservoir elevations based on five surveys spanning 1962 through 2016.

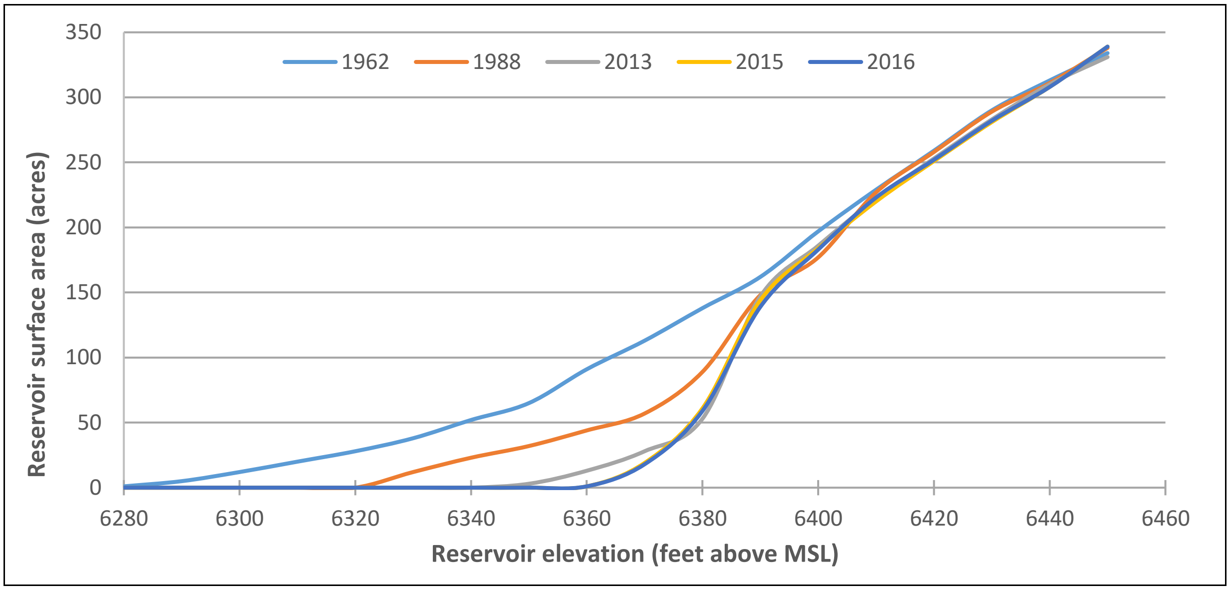


Figure 2. Muddy Reservoir surface area versus elevation from 1962–2016

Sediment Management at Muddy Reservoir

The 2018 Sediment Management Study describes short- and long-term sediment management plans for the continued operation of Muddy Dam and Reservoir. In the short-term, the study recommends that Muddy Reservoir maintain a minimum pool restriction to keep incoming sediment deposition upstream of the outlet works to prevent plugging and burial. The study notes that this short-term alternative allows for the continuance of reservoir operations and water supply delivery, but does not minimize reservoir storage loss, and a separate long-term sediment management alternative must be implemented to do so.

The study identifies four potential long-term sediment management plans for further investigation:

1. Build an access road to modified intake tower to improve sediment/debris removal and maintenance;
2. Modify and extend the existing intake to nearby access to improve sediment/debris removal and maintenance;
3. Construct an additional intake and tunnel for sediment sluicing; and
4. Implement permanent mechanical (dredging/hydrosuction) sediment removal capabilities.

Multiple analyses have been conducted to assess the feasibility of mechanical sediment removal at Muddy Reservoir (identified in the fourth long-term plan listed above), notably dredging. These analyses describe multiple dredging scenarios and accompanying cost estimates specific to Muddy Reservoir, while there is more limited cost data available for other long-term sediment management plans. Therefore, the economic analysis proceeds using a dredging alternative as the long-term sediment management alternative.

Economic Analysis of Muddy Reservoir Sediment Management

A cursory economic analysis is conducted to evaluate the cost-effectiveness for a dredging alternative as a long-term sediment management solution for the sedimentation problem at Muddy Reservoir. The stream of costs and benefits under a dredging alternative (Dredging) and a no action alternative (No Action) are detailed and evaluated to determine the economic feasibility of Dredging. Due to the limited scope of this analysis, simplified assumptions—based on the best data readily accessible for comparable existing projects—are employed to estimate the economic benefits and costs under each alternative. Note that this is an economic analysis, not a financial analysis, and thus, this analysis can demonstrate whether an alternative is economically justified from the national perspective (i.e., benefits to the nation) but does not evaluate whether beneficiaries can afford to fund the alternative. Per Reclamation policy, all benefits and costs are evaluated over a planning horizon of 50 years and discounted using the FY2018 Planning Rate of 2.750 percent (DOI, 2015) (U.S. Department of the Treasury, 2017).

Alternatives Evaluated

The dredging alternative is based on cost estimate data for seven sediment dredging scenarios prepared for comparable existing projects. Each scenario involves a variation of regular dredging of the annual sediment load to maintain the reservoir in its current operable condition. Note that these scenarios do not call for dredging beyond the annual sediment deposition. The dredging cost estimates include annualized capital costs and operation and maintenance costs and are indexed to 2017 dollars using the Engineering News-Record's Construction Cost Index Construction cost index (ENR, 2018) for use in this analysis. The minimum cost dredging scenario is approximately $3,500 per AF of material removed (2017 dollars), while the maximum cost dredging scenario is approximately $27,500 per AF of material removed (2017 dollars). The average cost across all seven dredging scenarios is approximately $11,000 per AF of material removed (2017 dollars). In summary, Dredging calls for the removal of the 100 AF average annual sediment load each year into perpetuity.

The no action alternative (No Action) models operations and outcomes at Muddy Dam and Reservoir under current operations (i.e., no long-term sediment management plan). The sedimentation projections and resulting impacts are based on discussions with sediment experts who have studied the issue at comparable existing reservoirs. The impacts captured by No Action include the degradation of economic benefits due to the continuing sediment deposition of 100 AF per year and the eventual necessary decommissioning and removal of Muddy Dam due to sediment build-up and resulting inoperability of the outlet works.

Table 5 shows the direct sedimentation impacts and construction cost ranges expected under the two alternatives. The lost benefits due to continuing sedimentation under No Action are an additional cost that must be accounted for and are evaluated in the following section of this report.

Table 5. Impacts and construction costs under No Action and Dredging alternatives

	No Action	Dredging
Sedimentation impacts		
Lost storage/capacity at full pool	~100 AF per year	0 AF per year
Lost surface area at el 6430[a]	~0.17 acres per year	0 acres per year
Construction cost estimates		
Dredging cost	$0 per AF (no dredging)	$3,648–$27,181 per AF
Dam removal cost[b]	$50M–$100M, 30–40 years out	$0 (no dam removal)

[a] Estimated based on historical elevation-area curves developed in 1962, 1988, 2013, 2015, and 2016.

[b] Based on discussions with Reclamation sediment specialists.

Benefits Analysis under No Action and Dredging Alternatives

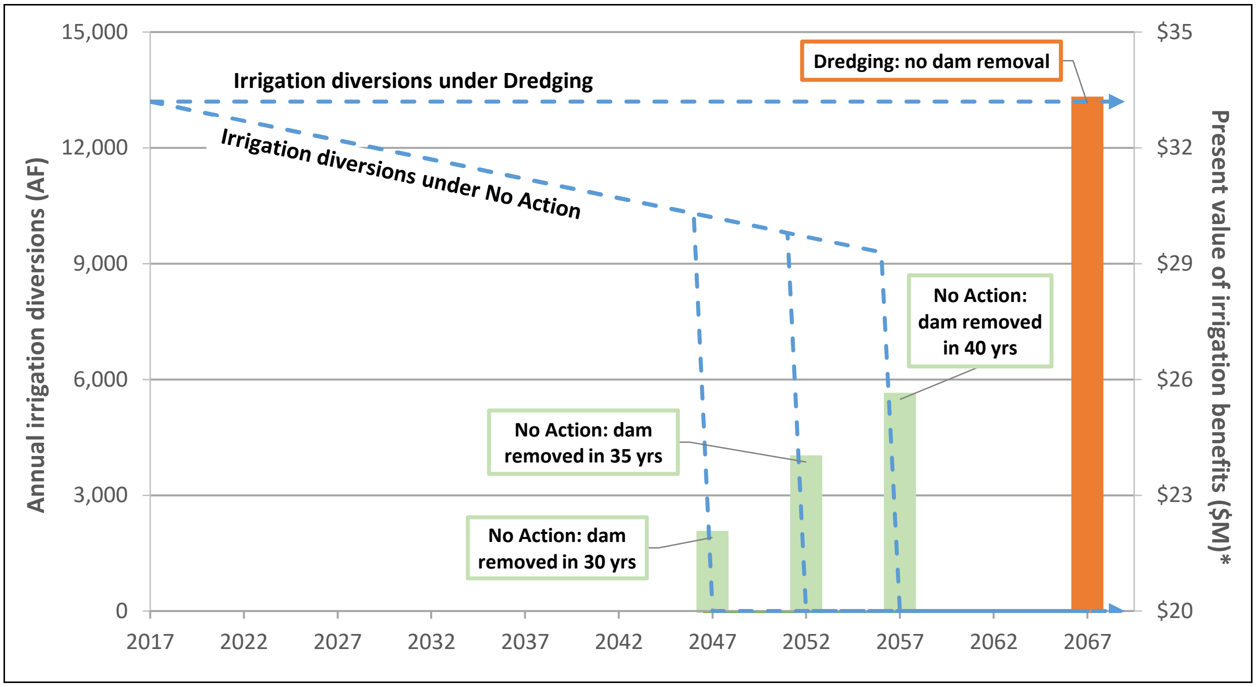
The stream of economic benefits under No Action and Dredging is dependent on the impacts of sedimentation to the three primary beneficial uses of Muddy Project water: irrigation, recreation, and flood control.

Irrigation Water Supply Benefits under No Action and Dredging Alternatives

Under No Action, the economic benefits dependent on irrigation water supply from Muddy Dam storage are impacted by sedimentation through lost reservoir capacity. In a given year, diversions might be adjusted such that average irrigation demand is met, but as storage steadily decreases, so will operational flexibility. On average, diversions are expected to decrease equal to the sedimentation rate, or about 100 AF per year. This has a significant cumulative impact over time.

Further, the accumulation of sediment under No Action leads to the inevitable removal of Muddy Dam within 30 to 40 years. Dam removal is not only a significant cost, but upon removal the stream of annual irrigation benefits due to the existence of the dam are fully depleted. Due to the uncertainty regarding the exact year in which a dam removal would be required under No Action, irrigation benefits are estimated under three removal scenarios that encompass the likely range of removal: 30, 35, and 40 years from present. Under the Dredging alternative, irrigation diversions are maintained at the historical average of 13,198 AF across the 50-year planning horizon, as the dredging activity removes the annual sediment load.

Figure 3 displays expected irrigation diversions and the present value of benefits over a 50-year planning horizon under the No Action and Dredging alternatives. Irrigation benefits in a given year are calculated based on the expected irrigation diversions in that year multiplied by the irrigation benefit per AF value of $93.05 (2017 dollars). The present value of irrigation benefits is equal to the sum of discounted dollars over the planning horizon. Note that the present values depicted in Figure 3 do not include dredging or dam removal costs.



*Present value of benefits discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750%.

Figure 3. Irrigation diversions (dashed lines) and present value of irrigation benefits (solid bars) under No Action and Dredging

Table 6 reports the present value of irrigation benefits under the No Action and Dredging alternatives, discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750 percent. Note that the present values reported in Table 6 do not account for dredging or dam removal costs.

Table 6. Present value of irrigation benefits under No Action and Dredging

	No Action			Dredging
Years until dam removal	30	35	40	No removal
Annual rate of change to irrigation diversions (AF/yr.)	-100	-100	-100	No change
Present value of irrigation water supply benefits ($M)[a]	$21.91	$23.86	$25.48	$33.15

[a] Discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750%.

Recreation Benefits under No Action and Dredging Alternatives

There is inadequate visitation data to develop a rigorous model establishing the impacts of reservoir sedimentation on recreation visitation. This analysis, therefore, assumes Muddy Reservoir recreation visitation to be directly proportional to reservoir surface area; a methodology detailed in *Reclamation Technical Memorandum EC-2000-02* (EC-2000-02) (Reclamation, 2000). Surface area as a directly proportional proxy for recreation visitation rates does not account for a degraded recreation experience (e.g., hindrances to boating due to more sand bars, shallower water, etc.), but that is beyond the scope of this analysis.

Five reservoir surveys conducted between 1962 and 2016 demonstrate the rate of decreasing reservoir surface area due to sedimentation (see Figure 2 above). From 1975 through 2017 during the primary recreation season (May through September), reservoir elevation ranged from 6359 (in September of 2012) to 6449 (multiple instances in both June and July over the 43-year data period). The average reservoir elevation during the primary recreation season across the data period is approximately 6430. Based on the 1962 survey, reservoir elevation 6430 equates to 290 acres of reservoir surface area, while the 2016 survey indicates that elevation 6430 equates to 282 acres of surface area. A regression analysis of reservoir surface area at elevation 6430 indicates a loss of 0.17 acres per year from 1962 through 2016 (see Figure 4 below). This rate of surface area loss is forecasted over a 50-year planning horizon to estimate recreation benefits under No Action.

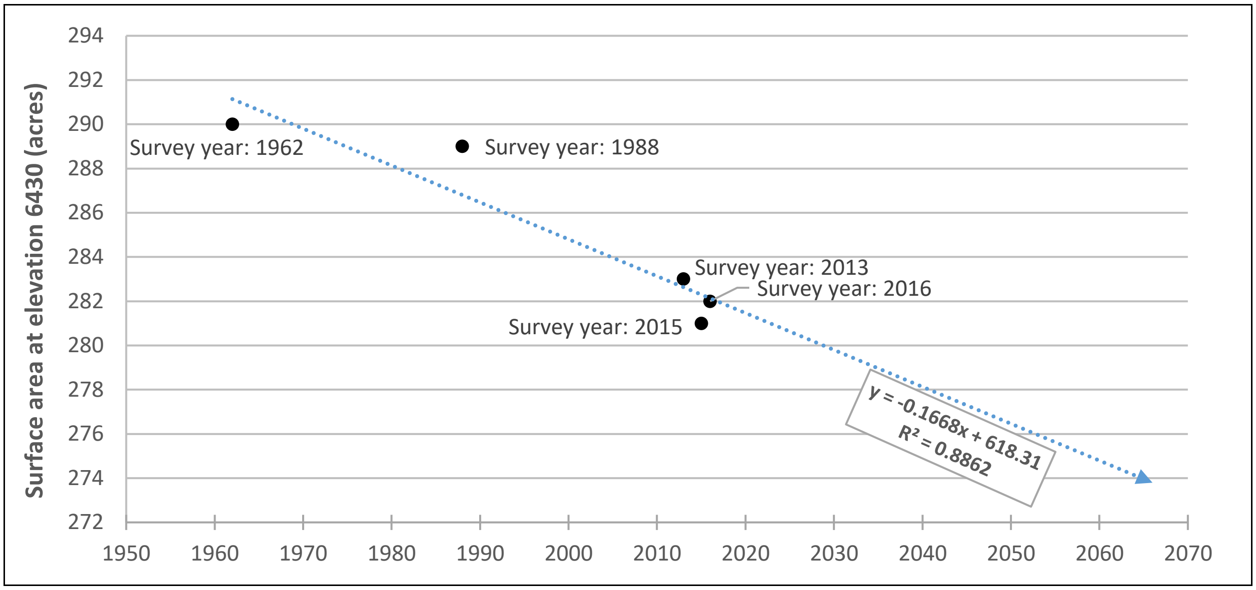


Figure 4. Declining trend of Muddy Reservoir surface area at elevation 6430

Under No Action, the economic benefits dependent on Muddy Reservoir recreation are impacted by sedimentation through lost surface area. In a given year, higher inflows will provide a higher reservoir water surface elevation but will also deliver more sediment to the reservoir. On average, surface area is expected to decrease at 0.17 acres per year. This has a significant cumulative impact over time.

Like irrigation benefits, upon dam removal the stream of annual recreation benefits is fully depleted. Due to the uncertainty regarding the exact year in which a dam removal would be required under No Action, recreation benefits are estimated under three removal scenarios that encompass the likely range of removal: 30, 35, and 40 years from present. Under the Dredging alternative, reservoir surface area remains at the 2016 value of 282 acres across the 50-year planning horizon, as the dredging activity removes the annual sediment load.

Table 7 reports the present value of recreation benefits under the No Action and Dredging alternatives, discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750 percent. Note that the present values reported in Table 7 do not account for dredging or dam removal costs.

Table 7. Present value of recreation benefits under No Action and Dredging

	No Action			Dredging
Years until dam removal	30	35	40	No removal
Annual rate of change in reservoir surface area (acres/yr.)	-0.17	-0.17	-0.17	No change
Present value of recreation benefits ($M)[a]	$21.67	$23.94	$25.92	$29.78

[a] Discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750%.

Flood Control Benefits under No Action and Dredging Alternatives

Under No Action, flood control benefits provided by Muddy Dam are impacted by sedimentation through lost reservoir capacity. On average, reservoir capacity is expected to decrease equal to the sedimentation rate, or about 100 AF per year (see Figure 1 above). This has a significant cumulative impact over time.

Like irrigation and recreation benefits, upon dam removal the stream of annual flood control benefits is fully depleted. Due to the uncertainty regarding the exact year in which a dam removal would be required under No Action, flood control benefits are estimated under three removal scenarios that encompass the likely range of removal: 30, 35, and 40 years from present. Under the Dredging alternative, reservoir capacity is maintained at the historical average of 14,130 AF across the 50-year planning horizon, as the dredging activity removes the annual sediment load.

Table 8 reports the present value of flood control benefits under the No Action and Dredging alternatives, discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750 percent. Note that the present values reported in Table 8 do not account for dredging or dam removal costs.

Table 8. Present value of flood control benefits under No Action and Dredging

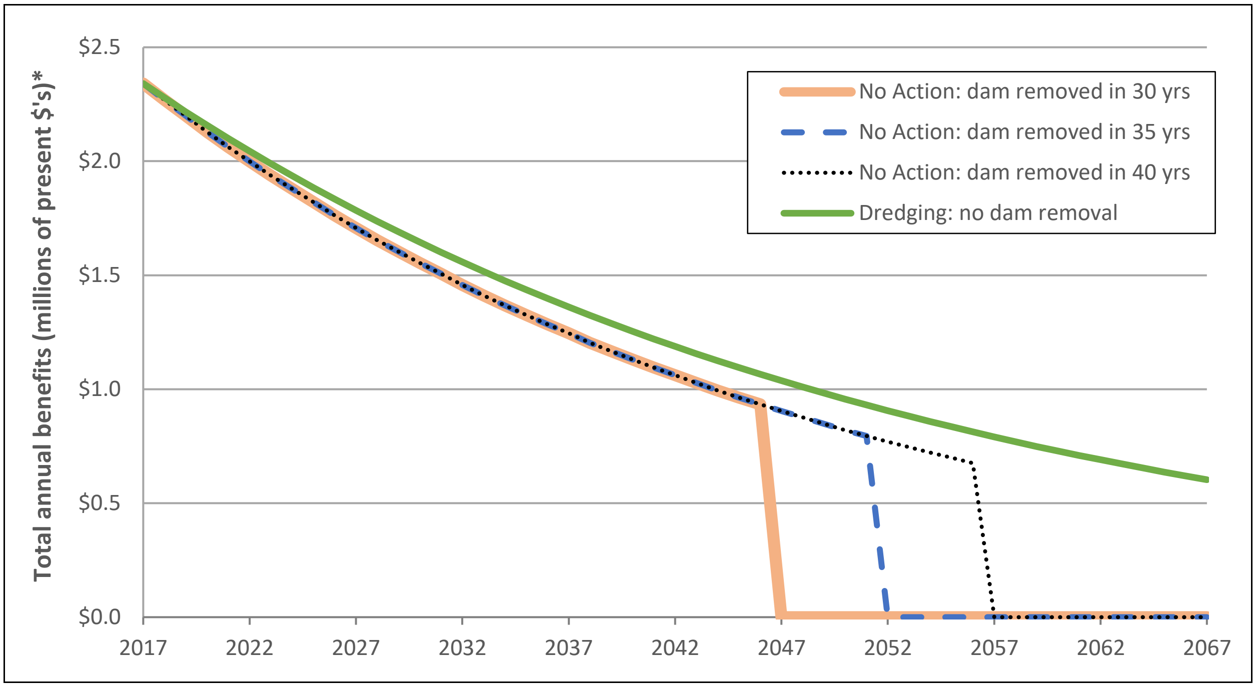
	No Action			Dredging
Years until dam removal	30	35	40	No removal
Annual rate of change in reservoir capacity (AF/yr.)	-100	-100	-100	No change
Present value of flood control benefits ($M)[a]	$0.18	$0.19	$0.21	$0.27

[a] Discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750%.

Summary of Economic Benefits under No Action and Dredging Alternatives

Figure 5 displays the stream of total annual economic benefits under the No Action and Dredging alternatives. Total benefits in year zero of the planning period (2017) are calculated based on the historical average of irrigation diversions, recreation visits, and flood control capacity under both alternatives. Beginning in year one (2018), these variables begin to diminish under No Action, while they are maintained at historical averages under Dredging.

Future benefits are discounted back to present dollars to account for the time-value of money, explaining a portion of the decrease in benefits in future years under all alternatives depicted in Figure 5. However, benefits under Dredging in future years decline in present dollars *exclusively* due to the effects of discounting; while benefits under the No Action scenarios decline at a higher rate than under Dredging due to the effects of discounting *and* the compounding diminishment of benefit-dependent variables. Figure 5 also illustrates that for each dam removal scenario under No Action, the benefit stream is fully depleted upon the year of removal. Note that the benefit streams depicted in Figure 5 do not include dredging or dam removal costs.



*Annual present benefits are discounted at the FY2018 Planning Rate of 2.750%.

Figure 5. Stream of total annual economic benefits under No Action and Dredging

Table 9 reports the present value of total economic benefits under the No Action and Dredging alternatives, discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750 percent. Note that the present values reported in Table 9 do not account for dredging or dam removal costs. The Dredging alternative provides nearly $12 million more in benefits than the most optimistic No Action scenario (dam removal in 40 years), and nearly $20 million more in benefits than the most dire No Action scenario (dam removal in 30 years).

Table 9. Summary of benefits under No Action and Dredging

	No Action			Dredging
Years until dam removal	30	35	40	No removal
Irrigation water supply benefits ($M)[a]	$21.91	$23.86	$25.48	$33.15
Recreation benefits ($M)[a]	$21.67	$23.94	$25.92	$29.78
Flood control benefits ($M)[a]	$0.18	$0.19	$0.21	$0.27
Present value of all benefits ($M)[a]	**$43.76**	**$47.99**	**$51.61**	**$63.20**

[a] Discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750%.

Costs Analysis under No Action and Dredging Alternatives

This analysis accounts for the primary cost drivers under the No Action and Dredging alternatives. Dam removal, an inevitability under the No Action alternative, is expected to be required in 30 to 40 years at an estimated cost of $50 to $100 million dollars (2017 dollars). Note that the year in which the cost is incurred has a significant impact on the present value, due to the time value of money (i.e., the longer a cost is delayed, the lesser the present value of that cost). Due to the uncertainty regarding the exact year of removal and the cost of removal under No Action, three removal scenarios are developed that establish the likely bounds of time equivalent costs. The most dire removal cost scenario is dam removal 30 years from present at $100 million (2017 dollars), while the most optimistic scenario is dam removal 40 years from present at $50 million (2017 dollars). A third, “middle ground”, scenario is developed that assumes dam removal 35 years from present at $75 million (2017 dollars).

Under the Dredging alternative, reservoir volume is maintained at the historical average through dredging of the annual sediment load (100 AF per year) at cost of $3,500 to $27,500 per AF of sediment removed (2017 dollars) (see *Alternatives Evaluated* section on page 29). Due to the uncertainty regarding the dredging cost, three dredging scenarios are developed that establish the likely bounds of this cost. The high-end Dredging cost scenario is dredging of 100 AF of sediment per year at a cost of $25,000 per AF of dredged material (2017 dollars), while the most optimistic scenario is dredging of 100 AF of sediment per year at a cost of $3,000 per AF of dredged material (2017 dollars). A third, “middle ground”, scenario is developed that assumes dredging of 100 AF of sediment per year at a cost of $11,000 per AF of dredged material (2017 dollars)—approximately the average expected cost of dredging at Muddy Reservoir as reported in the *Alternatives Evaluated* section of this report.

Figure 6 displays the expected cost ranges under the No Action and Dredging alternatives over a 50-year planning horizon discounted at the FY2018 Planning Rate of 2.750 percent. Note that dam removal costs are incurred in the year of removal, and displayed as such in Figure 6 (in present dollars), while dredging costs are incurred annually, and displayed in Figure 6 as cumulative present dollars in a given year.

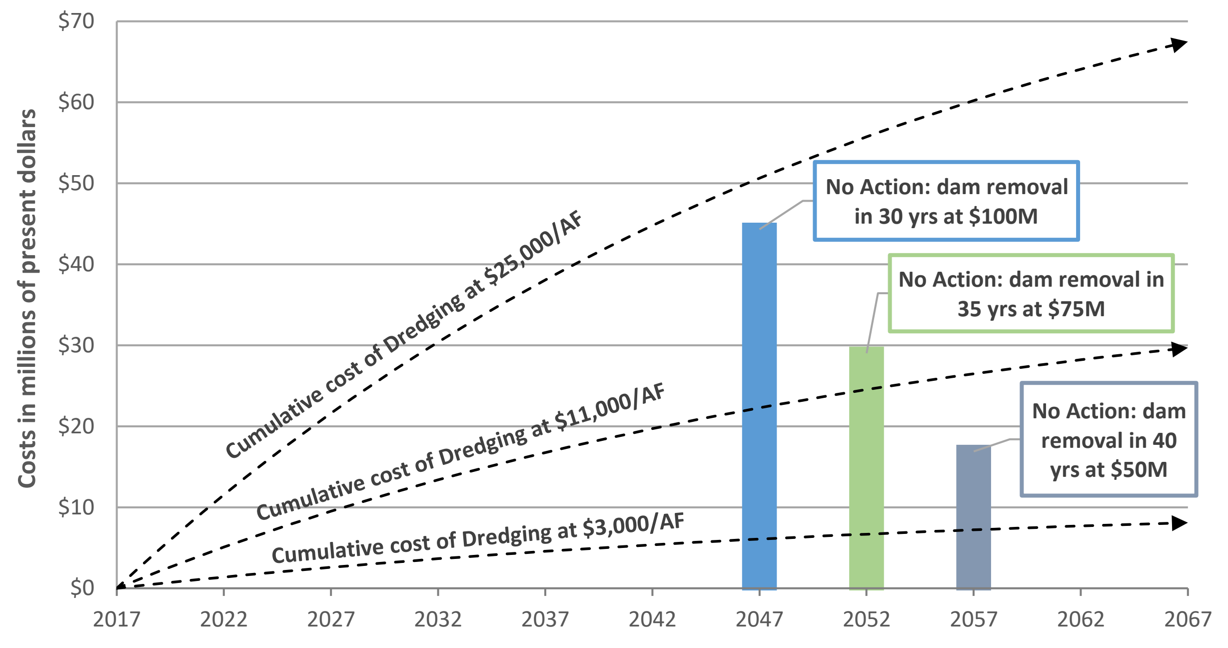


Figure 6. Present value of costs under No Action and Dredging

Table 10 reports the present value of total economic costs under the No Action and Dredging alternatives, discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750 percent. Note that the present values reported in Table 10 do not account for lost benefits under the evaluated alternatives. Amongst the six scenarios evaluated and reported in Table 10, both the overall highest and lowest costs are variations of the Dredging alternative. The highest overall cost is for the removal of 100 AF of material per year at $25,000 per AF (2017 dollars), which equates to a present value of more than $67 million. The lowest overall cost reported is the dredging of 100 AF of material per year at $3,000 per AF (2017 dollars), which equates to a present value of more than $8 million. All No Action dam removal scenario costs fall between $16 million and $45 million in present value.

Table 10. Present value of costs under No Action and Dredging

	No Action			Dredging		
Years until dam removal	30	35	40	No dam removal		
Dam removal cost (M's 2017$)	$100	$75	$50	No dam removal costs		
Material dredged per year	No dredging			100 AF	100 AF	100 AF
Dredging cost/AF (2017$)	No dredging costs			$3,000	$11,000	$25,000
Present value of costs ($M)[a]	**$44.31**	**$29.02**	**$16.89**	**$8.10**	**$29.70**	**$67.49**

[a] Discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750%.

Net Present Benefits under No Action and Dredging Alternatives

The net present benefits under a given alternative scenario are calculated as the present value of benefits less the present value of costs under the defined scenario criteria. Table 11 reports the net present benefits under the No Action and Dredging alternatives, while Figure 7 displays these results graphically. Amongst the six scenarios evaluated and reported in Table 11, both the overall highest and lowest net present benefits are variations of the Dredging alternative. The highest overall net present benefits are realized for the removal of 100 AF of material per year at $3,000 per AF (2017 dollars), which equates to over $55 million in net present benefits. The lowest overall net present benefits are realized for the removal of 100 AF of material per year at $25,000 per AF (2017 dollars), which equates to -$4 million in net present benefits. All No Action dam removal scenarios fall between -$0.6 million and $35 million in net present benefits.

Table 11. Net present benefits under No Action and Dredging

	No Action			Dredging		
Years until dam removal	30	35	40	No dam removal		
Dam removal cost (M's 2017$)	$100	$75	$50	No dam removal costs		
Material dredged per year	No dredging			100 AF	100 AF	100 AF
Dredging cost/AF (2017$)	No dredging costs			$3,000	$11,000	$25,000
Present value of benefits ($M)[a]	$43.76	$47.99	$51.61	$63.20	$63.20	$63.20
Present value of costs ($M)[a]	$44.31	$29.02	$16.89	$8.10	$29.70	$67.49
Net present benefits ($M)[b]	**-$0.55**	**$18.97**	**$34.72**	**$55.10**	**$33.50**	**-$4.29**

[a] Discounted over a 50-year planning horizon at the FY2018 Planning Rate of 2.750%.

[b] Equal to the present value of benefits less the present value of costs under a given alternative/scenario.

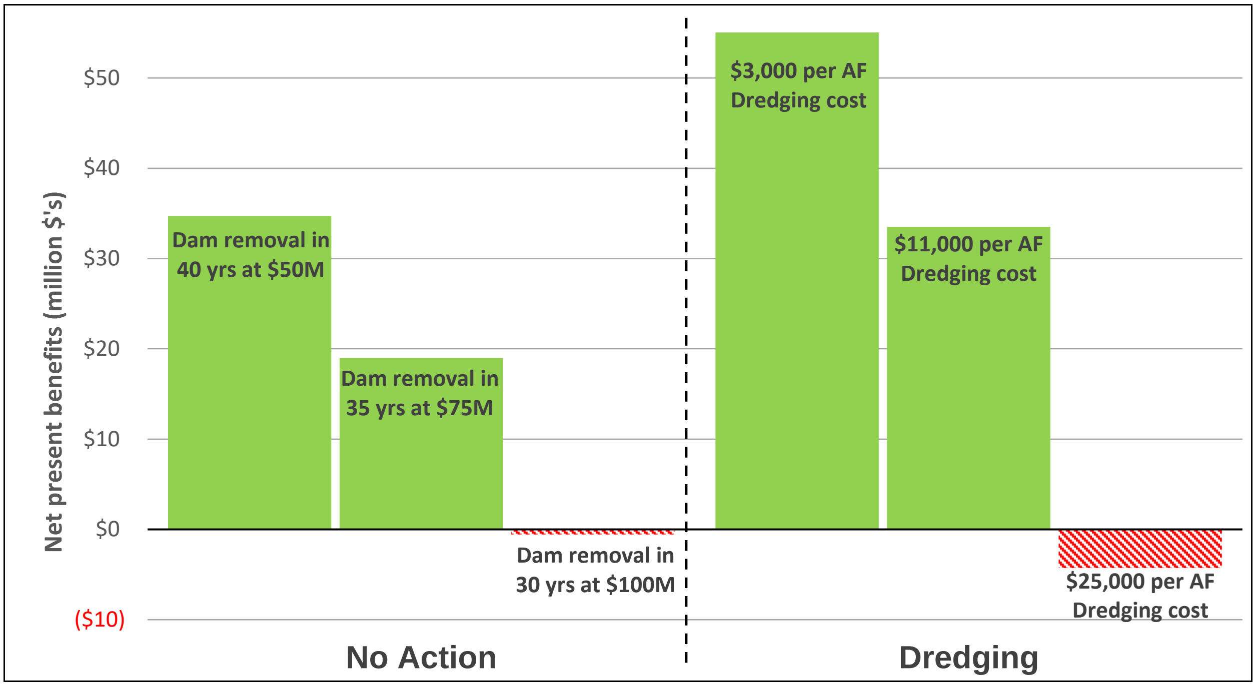


Figure 7. Net present benefits under No Action and Dredging

The Net Present Value of Sediment Removal

The net present value (NPV) of Dredging can be evaluated over a range of dredging costs. The difference between the net present benefits under a given Dredging scenario and the net present benefits under a given No Action scenario returns the NPV of Dredging at the respective unit cost of sediment removed. Table 12 reports the NPV of dredging based on the six primary scenarios evaluated for net present benefits.

Table 12. Net present value (NPV) of Dredging versus evaluated No Action scenarios

NPV of Dredging 100 AF annually at a cost of:[a]		Range of No Action scenarios		
		Dam removal in 30 yrs. at $100M	Dam removal in 35 yrs. at $75M	Dam removal in 40 yrs. at $50M
$3,000/AF	Calculation ($M)[b]	$55.10 - ($0.55)	$55.10 - $18.97	$55.10 - $34.72
	NPV ($M)	**$55.65**	**$36.13**	**$20.38**
$11,000/AF	Calculation ($M)[b]	$33.50 - ($0.55)	$33.50 - $18.97	$33.50 - $34.72
	NPV ($M)	**$34.05**	**$14.53**	**-$1.22**
$25,000/AF	Calculation ($M)[b]	($4.29) - ($0.55)	($4.29) - $18.97	($4.29) - $34.72
	NPV ($M)	**-$3.74**	**-$23.26**	**-$39.01**

[a] Dredging per unit costs and dam removal costs stated in 2017 dollars.

[b] NPV of Dredging calculated as the difference between the net present benefits of a given Dredging scenario and the net present benefits of a given No Action scenario. All net present benefits evaluated over a 50-year planning horizon at the FY2018 Planning rate of 2.750%.

Figure 8 displays the NPV of dredging across the entire range of per unit dredging costs ($3,000 through $25,000 per AF in 2017 dollars). At any per unit dredging cost equal to or less than the point at which a No Action scenario crosses the x-axis (where NPV equals $0), sediment removal is economically feasible. Figure 8 demonstrates that if the dam must be removed in 30 years due to sedimentation at a cost of $100 million (2017 dollars), annual removal of the sediment load of up to approximately $24,000 per AF of sediment removed (2017 dollars) is preferred from an economic perspective. Likewise, any cost per AF of sediment removed above approximately $24,000 per AF is not economical under this scenario and the preferred alternative from an economic perspective would be No Action. Thus, $24,000 per AF of sediment removed is the approximate *breakeven* cost for sediment removal under the specified No Action scenario. The breakeven cost for the No Action scenario of dam removal in 35 years at a cost of $75 million is approximately $16,000 per AF of material removed and the breakeven cost for the No Action scenario of dam removal in 40 years at a cost of $50 million is approximately $11,000 per AF of material removed (2017 dollars).

Note that NPV calculations are highly sensitive to inputs used for both benefits and costs, and therefore, such an analysis should be conducted at the feasibility-level before any decisions are made about the most economical way to approach sedimentation at Muddy Reservoir.

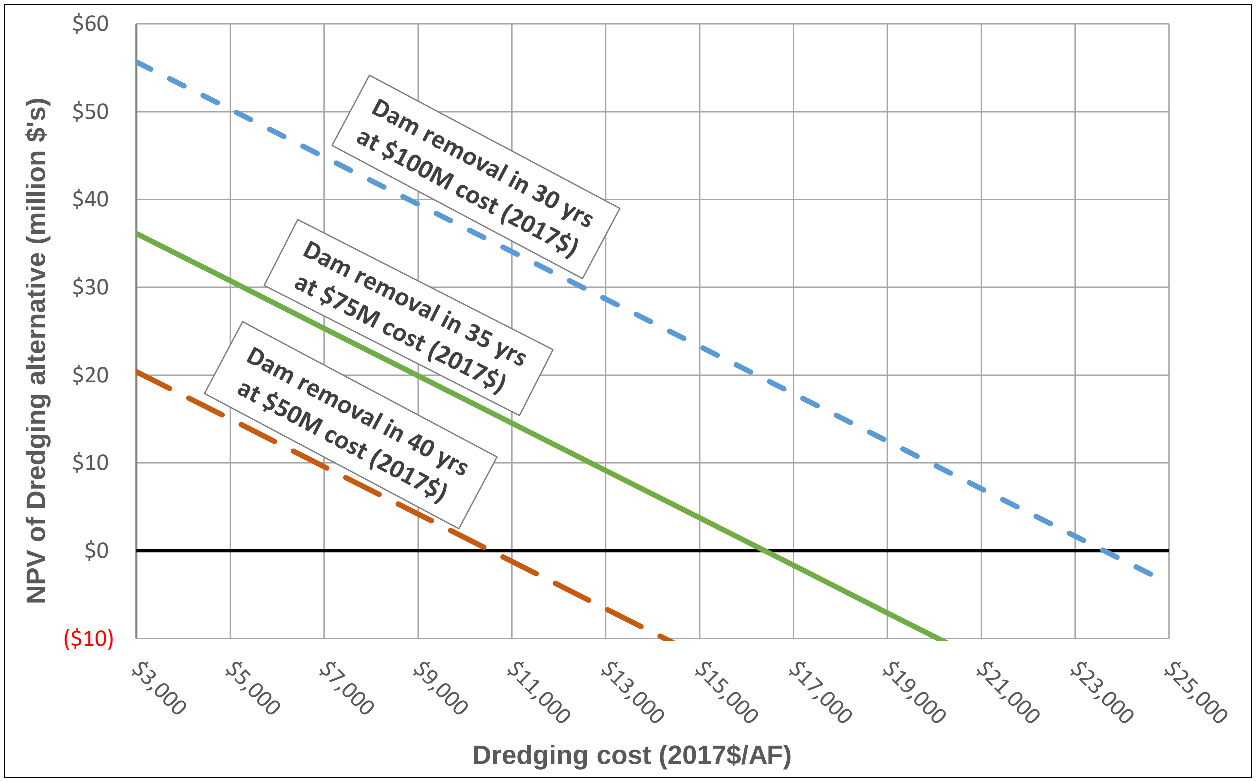


Figure 8. The net present value (NPV) of Dredging across a range of per unit costs

Results and Conclusions

Reclamation operates 338 reservoirs with a total storage capacity of 140 million AF, providing irrigation water supply for 10 million acres of farmland, M&I water supply to more than 31 million people, and recreation opportunities for 90 million visits annually (Reclamation, 2018a). Reclamation dams generate approximately 40 million MWh of hydropower annually and significant flood control benefits. Reservoir sedimentation threatens the continued viability of all these beneficial purposes and reactionary measures are generally prohibitively expensive. Therefore, proactive economic management of reservoir sedimentation should be a priority for Reclamation.

This study provides an overview of reservoir sedimentation, an analysis of sediment management costs, and a benefit-cost analysis for sediment management of a hypothetical reservoir in the western US. The case study demonstrates an approach for quantitatively estimating the economic impacts of sedimentation and comparative cost-effectiveness of sediment removal. The results indicate that it is economical (cost-effective) to mechanically remove the annual sediment inflow to the hypothetical reservoir at a cost per AF of $11,000–$24,000 or less (depending on the No Action future evaluated). This dredging cost per unit range is within reasonable estimates prepared for comparable existing reservoirs (see *Alternatives Evaluated* section of this report) and those estimates and awarded contracts for other locations around the US (see Table 1). Note that dredging is not the only sediment removal alternative at the hypothetical reservoir for which these findings are applicable—any sediment removal alternative that has an annualized per AF cost indicating a positive NPV per Figure 8 is a viable option.

Existing publications have presented conceptual methodologies for evaluating the cost-effectiveness of sediment management but use generic cost and benefit values that lack geographic and beneficial-use specificity. As demonstrated in the case study, the beneficial purposes served by a reservoir have a significant impact on the economic benefits the reservoir provides (e.g., irrigation water supply at the hypothetical Muddy Reservoir has an economic benefit of more than $1.2 million annually, while flood control at the same reservoir has an economic benefit of less than $10,000 annually). In cases where M&I water supply to large urban centers and/or hydropower generation are part of the benefit mix, the economic benefits of maintaining reservoir storage and outlet work operability can economically justify sediment management costs significantly higher than those reported in the case study.

The geographic location of a reservoir can be just as significant as the mix of beneficial purposes in determining the economic benefits provided by a reservoir—and thus the economic feasibility of sediment removal. As discussed above on page 16, benefit values for a given beneficial purpose can vary drastically by region and even by site. Likewise, sediment management costs can vary widely, as demonstrated in Table 1 of this report. An important conclusion drawn from this work is that a sediment management plan for an existing reservoir should be tailored to the specific site not just from an engineering standpoint, but from an economic standpoint (i.e., feasibility-level economic analysis of the benefits provided by the specific project).

A common oversight in the existing literature that attempt to quantify the benefits and costs of reservoir sedimentation management strategies is a comprehensive no action alternative—notably the inclusion of dam removal costs. If evaluating cost-effectiveness solely based on historical benefit streams and anticipated sediment management costs, the management costs in a given year will generally outweigh the benefits. However, if dam removal costs are incorporated into the no action alternative (as Reclamation sediment engineers warn is an inevitability in the absence of sediment management) cost-effective sediment management becomes attainable. Likewise, accounting for the degradation of benefits over time under no action is a cost omitted from some reviewed literature. The presented case study accounts for both variables and demonstrates that they can have a significant impact on the determination of sediment management economic feasibility.

It is important to note that an economic analysis—such as that presented in the case study of this report—can indicate whether an alternative is economically feasible (i.e., if the benefits outweigh the costs), but this does not measure *financial* feasibility, which would assess cashflows, indebtedness, etc. for the entity(ies) responsible for funding the implementation of an alternative. An economic analysis helps to determine what *should* be done, while a financial analysis helps to determine if an entity can afford to do it.

In summary, the case study presented in this report lays out a framework for comprehensively estimating the site-specific benefits and costs under a no action alternative and sediment management alternative. The case study also reveals that mechanical sediment removal is a potentially economic alternative at the hypothetical reservoir—an unexpected finding as this alternative is generally assumed to be prohibitively expensive—that merits further investigation at the feasibility-level for identified sedimentation-affected reservoirs. At the feasibility-level, the input data would be further researched and refined, and further cost and benefit considerations might be included, such as increased OM&R costs under No Action due to structural damage caused by the ever-accumulating sediment load, or a regional impact analysis that assesses agricultural and recreation dependent employment in the region. This study can serve as a template for Reclamation to assist in making the most economic reservoir sedimentation management decisions going forward.

Recommendations for Next Steps

Due to time and budget constraints, it was necessary for this scoping-level study to leave unaddressed several interrelated research topics that deserve further consideration. This section also discusses some omitted variables and concepts that should be considered in a feasibility-level economic analysis of reservoir sediment management and some future work products that would facilitate such analyses.

Research Topics for Further Consideration

An important research topic when considering the economic service life of major infrastructure is the concept of intergenerational equity (or inequity). For example, when a dam is designed with a 100-year service life, a life-cycle cost analysis would account for decommissioning costs to be incurred 100 years into the future (if at all). Typical discounting techniques render this cost nearly negligible in present dollars, making sediment management in the early and mid-years of a project economically unjustified. In the intervening years, the lion's share of project benefits has been realized by previous generations with minimal OM&R costs, while the last generation inherits a degraded benefit stream, increased OM&R costs, and the prospect of incurring dam decommissioning costs in present dollars. George, Hotchkiss, & Huffaker (2016) provide an excellent overview of this concept, though the topic deserves further treatment, especially from Reclamation, whose aging fleet of large infrastructure presents significant potential for intergenerational inequity.

Inseparable from the topic of intergenerational inequity is the concept of discounting and the choice of a proper discount rate. Merten, Gaston, Torrey, & Skaja (2017) demonstrate that when using traditional discounting methods, varying the discount rate between the Federal Planning Rate (treated as a real discount rate) and the real discount rate based on 30-year US Treasury bonds can change the economically preferred hydroelectric penstock lining alternative. Some economists propose non-traditional discounting techniques and even negative discount rates should be employed when evaluating long-lived infrastructure, and Reclamation has funded some interesting work in this area, notably Harpman (2014). However, infrastructure management agencies have yet to incorporate non-traditional discounting methods and there is no consensus amongst such agencies that this should be pursued. Research like the case study featured in this report subjected to alternative discounting techniques and incorporating a sensitivity analysis for different discount rates would shed some light on this topic.

Opportunities for Model Improvement and Future Work Products

Additional variables to be incorporated into a feasibility-level analysis of sediment removal at identified sedimentation-affected reservoirs include:

- Increased OM&R costs under No Action (e.g., repairing structural and coatings damage to outlet works due to sediment load)
- Detailed, site-specific, life-cycle costs for Dredging (e.g., incorporate expected service lives and OM&R costs for components such as pipes, pumps, etc.)
- Regional impact analysis to evaluate indirect economic benefits provided by the affected reservoir (e.g., employment in agricultural supplies sales and recreation sector)

Future work products that would facilitate the economic evaluation of reservoir sediment management include:

- Sediment management unit cost database with inclusion of multiple variables (e.g., sediment type, geography, accessibility, dam type, dam size, reservoir depth, etc.)
- Reservoir economic benefit unit value database sortable by multiple variables (e.g., by region, state, beneficial purpose, crop type, recreation activity, etc.)

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