Economic and Hydraulic Simulation Models for Evaluation of Sediment Management in a Reservoir

Razieh Anari
Brigham Young University

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Economic and Hydraulic Simulation Models for Evaluation of
Sediment Management in a Reservoir

Razieh Anari

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

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ABSTRACT

Economic and Hydraulic Simulation Models for Evaluation of Sediment Management in a Reservoir

Razieh Anari
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Doctor of Philosophy

Reservoir sedimentation is a serious problem that threatens the water storage capacities across the world. Extending a dam’s life requires adopting a new design and operational paradigm that focuses on managing the reservoir and watershed system to bring sediment inflow and outflow into balance by including reservoir sediment management facilities in dam and reservoir. However, the cost of methods that remove the sediment from reservoirs is usually prohibitive and is a serious factor preventing sustainable sediment management.

This thesis considered a case study, Paonia Reservoir in Colorado, to investigate two aspects of reservoir operation, sediment management and economic assessment. The purpose is to determine how sediment management (sluicing using a low-level gate) effectively reduces sedimentation and whether this management is economically viable. The SRH-1D will be implemented to model the reservoir sedimentation, and RSEM evaluate it economically.

The result comparison of current Paonia operation with hypothetical Paonia (added low-level gate) proved sluicing incoming sediment-laden flow effectively reduces sedimentation without interruption in the reservoir targeted functions like irrigating downstream. The deposited sediment volume could decrease more by monitoring the possible peak flow time and keeping the low-level gate open to pass high incoming flow downstream.

This thesis applied RSEM to evaluate and compare the benefits and costs of continued sedimentation and eventual dam decommissioning (the existing Reservoir condition) to sediment management costs and benefits (hypothetical Paonia Reservoir). The results illustrated that sediment removal is advantageous because it contributed to decrease rate of decline of reservoir capacity, which made this capacity, and the associated instantaneous net benefits exceed those in the without sediment management alternative. The preserved benefits from sustainable sediment management offset the additional costs of incorporating sediment management.

One of the key messages of this thesis is that incorporating sediment management into the planning and design phases of dam projects is essential for ensuring that the benefits of reservoir storage are sustained over the long term. This means fairness between current and future generations to enjoy the benefits of the facility while spreading the cost of ownership, operations, and maintenance over generations.

Keywords: Reservoir Sedimentation, Economic Evaluation, Paonia, SRH-1D, RSEM
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1 INTRODUCTION

Growing worldwide demands for fresh water and energy has resulted in rising scientific attention to water resource management in recent decades. Previous studies proved that reservoir management is of central importance for the sustainable use of fresh water and energy resources [1]. Furthermore, reservoir storage is becoming increasingly important as climate change-related stresses increase [2, 3].

On the other hand, dam construction dramatically alters the sediment inflow and outflow balance, creating a reservoir characterized by extremely low flow velocities and high sediment trapping [4]. Reservoir siltation and related issues are receiving growing attention due to the aging of water-storage infrastructures, particularly in North America and Europe, where most of the dam-building took place during the 1940-1970s [5].

The design of a reservoir project entails the determination of the required storage capacity [6]. The rate of storage loss due to sedimentation will vary widely because of differences in geographic features such as soils, land cover, and land use [4]. An average of up to 1% of global reservoir capacity is lost annually to sediment accumulation [7, 8]. Another study suggests that at prevailing rates of sedimentation, most parts of the world may lose 70%–80% of their currently installed reservoir capacity by 2080 or earlier [5].

Analysis of existing global datasets indicates that despite plans in some regions and countries to build more water storage dams, mainly for hydropower generation, there will not be
another "dam revolution" to reach the scale of the high-intensity dam construction in the early to middle 20th century [9]. At the same time, many of the constructed large dams are aging. In the United States, for example, the combined impacts of sedimentation and population growth have resulted in an estimated 35% decline in storage capacity per capita [10], and 80% of all dams catalogued in the National Inventory of Dams (NID) were built more than 50 years ago [9] as of 2020. This means reservoirs, as vital elements of our water infrastructure, are non-sustainable, and thus mitigation measures are urgently needed to extend the useful lifetime [5].

Dam construction does not only result in water storage loss. Dams trap eroded sediment from the watershed and cause aggradation upstream from the reservoir. That reduces the water-carrying capacity of the river channel and produces higher and more frequent flood level [11], elevated groundwater levels [12], navigation impairment, deposition from or into a tributary [13], and burial of boat ramps. Sedimentation upstream from reservoirs may also reduce conveyance of bridges. As the size of the bridge opening diminishes, the amount of water that can be passed by such a bridge will also decrease [14]

The environmental issues associated with dam projects are rarely treated with the seriousness they deserve [15]. Due to the binding characteristic of fine sediments (large surface areas compared to their volume) coupled with biostabilisation1, pollutants, nutrients, and organic matter accumulate in the reservoirs impairing water quality and leading to the production and

---

1 The operation of reservoirs can lead to significant accumulations of fine sediment and nutrients, which can result in formation and development of biofilms on the sediment surface. These microorganisms settled on fine sediments and are also known to glue sediment grains together and permeate their void space, which can alter sediment properties, e.g., density, morphology, size gradation, architecture, erosion and transport behavior of sediments and associated contaminants. The ability of biofilms to increase erosion thresholds by biological actions is named “biostabilisation” 16. Daus, M., K. Koberger, K. Koca, F. Beckers, J. Encinas Fernandez, B. Weisbrod, D. Dietrich, S. Gerbersdorf, R. Glaser, S. Haun, H. Hofmann, D. Martin-Creuzburg, F. Peeters, and S. Wieprecht, “Interdisciplinary reservoir management—a tool for sustainable water resources management”. Sustainability, 2021. 13: p. 4498. https://doi.org/10.3390/su13084498
emission of CO2 and CH4 [16]. Managing such sediment by downstream discharge can be challenging.

When reservoirs capture sediment, the sediment in the water released downstream is reduced. Since the quantities of in-and outflowing sediments are different, the morphology and ecology of downstream channels are also impacted [17]. The water downstream of the dam has been called “hungry water”. The implication is that the water flowing in the downstream river has a greater capacity to carry additional sediment. The net effect is that the river erodes and degrades [18]. That can cause immediate impacts on pre-project environment and tributary channels [19], downstream agricultural conditions [20], erosion of riparian habitat, undercutting of banks, abandoned water intakes [21], and bridge piers exposure [22]. Beach sand along coastlines consists principally of sediment discharged into oceans by rivers. The sediment discharging into oceans from rivers has been dramatically reduced in the last decades due to dam construction that has resulted in the shrinking of the world’s major river deltas [23].

Sedimentation and water infrastructure may also impoverish downstream aquatic ecosystems [24, 25]. Fine sediments such as silt and clay carry nutrients required to produce food consumed by fish. When such sediments are captured in reservoirs, fewer nutrients are released downstream [26]. Decreases in nutrients affect fishery populations and aquatic ecosystems [27]. In addition to the impact on food availability for fish, degradation due to sediment-hungry water can produce a coarser-grained streambed [28], rendering previously excellent fish spawning habitat useless [29].

1.1 Importance of Reservoir Sediment Management

The reservoir storage is a finite resource [30] critical for the sustainable use of water and energy resources. As such, the sediment must be managed for storage to be sustainable, and
preventative measures must be taken to alleviate the continual loss of reservoir storage space. Nevertheless, many reservoirs have neglected implementing sediment management practices to counteract the previously mentioned consequences [26] due to often misguided belief that sediment negatively affects water quality and increases risks to downstream communities [31]. Moreover, the cost of methods that remove the sediment from reservoirs is usually prohibitive and is a serious factor preventing sustainable sediment management in the United States and other countries with similar sediment reduction policies [32]. A warning in the Reservoir Sedimentation Handbook states that the “sudden loss of the world’s reservoir capacity would be a catastrophe of unprecedented magnitude, yet their gradual loss due to sedimentation receives little attention or corrective action [4].”

Extending the dam’s life entails adopting a new design and operational paradigm that focuses on managing the reservoir and watershed system to bring sediment inflow and outflow into balance by including reservoir sediment management facilities in the dam and reservoir. That gives the reservoir a greatly extended or even indefinite life [19] and helps restore downstream ecosystems [31].

The World Commission on Dams (WCD) stated that dams are a series of public infrastructure projects aimed at the economic development of a region, nation, or river basin and a crucial way to meet water, food, and energy demands [33]. Since water storage is a key factor for cost-effective water and energy production, sediment management sustains these resources for more prolonged periods [14, 34]. Moving sediment past the dam can also avoid costs of obstructed intakes and turbomachinery abrasion that occurs when sediment accumulates at the dam. Passing sediment downstream can reduce the impacts mentioned earlier.
Most of our presently functioning dams were approved using an economic analysis with a relatively short design life [35]. This custom and policy heavily favors projects that avoid high initial costs while promising short-term benefits, effectively eliminating multi-generation projects that require the installation of sediment management facilities as part of the capital cost [36]. A filled reservoir with minimal project benefits becomes an economic burden for future generations. A brief study of the Gavins Point Dam, for example, shows that available information on damages due to a lack of sediment management account for 70% of the original construction cost and would likely exceed construction costs if comprehensive damage information were available for downstream impacts [37].

The fairness between current and future generations is called intergenerational equity and is the core element of sustainable development [1]. The concept of intergenerational equity is derived from the Brundtland’s Commission definition of sustainability: “the ability to meet the needs and aspirations of the present without compromising the ability of future generations to do so” [38]. Intergenerational equity ensures that all generations will pay costs for and reap benefits from facilities [39]. Current economic policies based on the design life approach that neglect the impacts of sedimentation and even dam decommissioning ignore intergenerational equity.

1.2 Sediment Management Alternatives

The many methods of managing reservoir sedimentation are summarized in Figure 1-1. They are divided into four major categories: reducing sediment yield, routing sediments (minimize deposition), removing or redistributing deposited sediments, and adaptive strategies [40]. The cost and applicability of each alternative are a function of the site, reservoir geometry, incoming flow, and the volume of sediment accumulation. Figure 1-2 indicates the general range of applicability.
of different management techniques as a function of the reservoir’s hydrologic capacity and sediment loading.

Figure 1-1: Classification of Methods to Manage Reservoir Sedimentation [45]

1.2.1 Reduce Sediment Yield

Watershed management can reduce sediment yield through soil conservation activities such as upstream reservoirs, check dams [41], stabilizing eroding channels [42], and increasing vegetative cover or modifying agricultural practice [1]. Watershed management changes a community’s economic activities to create sustainable production systems that retain topsoil on the farm [43]. However, the downstream response to upstream land-use changes may experience a time lag of decades [43]. That delays benefit to a future decade.
The use of best management practices for land and streams throughout the watershed can reduce erosion to rates to close to natural background levels. Since, erosion and sediment yield are natural processes, neither will never (and should not) reach zero, even in undisturbed watersheds [44].

Figure 1-2: Applicability of Sediment Management Techniques Based on Hydrologic Capacity and Sediment Loading [1]
1.2.2 Route Sediment

Sediment routing includes any method to manipulate reservoir hydraulics, geometry, or both, to pass sediment through or around storage or intake areas while minimizing deposition [4].

Sediment bypassing means diverting the sediment-laden flood flows around the reservoir. Bypassing a reservoir using conveyance structures is only feasible when favorable hydrological and morphological conditions exist. The ideal geometry for sediment bypass is one where the river makes a sharp turn between the reservoir headwater (entrance) reach and the downstream from the dam because minimizes the length of the conveyance channel or tunnel and takes advantage of the relatively steeper gradient for gravity flow [26]. Overall, Japan [45] and Switzerland are the leading countries for sediment bypass tunnels [26]. Bypass tunnels are constructed to produce super critical flow with maximum velocities between 32–50 ft/s range, and to date tunnel lengths up to 2.7 mile have been constructed [43].

A bypass tunnel can also be used at existing dams. Because it is unnecessary to draw down the reservoir level to bypass sediment laden flow, there is no loss of storage.

Off-stream (off-channel) storage is constructed outside the main river channel by impounding a small tributary or constructing the impoundment in an upland area. Clear water is diverted into the off-stream reservoir by gravity or pumping, but large sediment-laden flows including coarse bedload remains in the river channel instead of being trapped in a reservoir.

Sediment sluicing is an operational technique in which sediment-laden inflows are released through a reservoir before the particles can settle, thereby reducing trap efficiency. The essential strategy for sediment sluicing is to maintain the passage of natural high-discharge flows through an in-stream reservoir pool, utilizing these high flows to pass the inflowing sediment load through the reservoir. In this approach, the reservoir is drawn down either seasonally or for specific events
and then refilled at the end of the event [26]. This is suitable for reservoirs with a small storage capacity compared to annual stream flow (capacity/ inflow < 0.1). The overall strategy can be summarized as, “Store clear water—release muddy water.” [43]. The scoured channel width within reservoirs increases with discharge [8], so a sluicing strategy with a large discharge flood will sustain more long-term reservoir capacity than sediment management with lower discharge [43].

*Density currents* can occur in reservoirs if the density of the sediment-laden inflow is significantly greater than the density of impounded clear water. Density currents plunge and flow along the bottom of a reservoir [4] and, if maintained to the dam, can be passed downstream through low-level outlets. By correctly forecasting density current onset and movement [46, 47], venting does not require reservoir drawdown or result in significant impact on reservoir operations [26].

*A compartmented reservoir* is a reservoir subdivided using structural barriers, to be treated as multiple separate reservoirs with water-level differences [43]. In one alternative, a larger seasonal-use on-stream impoundment can be constructed to receive a heavy sediment load with a smaller off-stream impoundment [4], or vice versa.

### 1.2.3 Remove Deposited Sediment

*Flushing* is a technique whereby the flow velocities in a reservoir are increased by drawing down the reservoir level such that deposited sediments are re-mobilized and transported through low-level outlets in the dam [8]. There is a distinction between sediment flushing and sediment sluicing. Sediment flushing is concerned with the removal of sediments that have settled in the reservoir at a previous time as well as passing through incoming sediments during the flushing event. In contrast, sediment sluicing is concerned mainly with passing sediments through the reservoir during floods [4].
Pressure flushing involves opening low level gates without drawing down the reservoir level and is a maintenance action that only removes sediment from the immediate vicinity of the outlet. Pressure flushing does not remove significant volumes of sediment from the reservoir. [48]

Hydraulic dredging refers to excavating material from beneath the water [1, 43] and is often used to remove sediment from specific areas near dam intakes [26] or from small to medium-sized reservoirs [49]. If a reservoir is completely drawn down, mechanical removal or dry excavation can be employed using scrapers, dump trucks, and other heavy equipment to remove accumulated sediments. Mechanical removal can remove coarser sediments but requires the reservoir to be drawn down far enough to expose the coarse deposits sediment [26]. Mechanical removal is best adapted to reservoirs that remain dry for parts of the year, such as flood control reservoirs [26, 41].

A static pipe on the reservoir bed can siphon water and sediment over the dam [50]. This hydrosuction sediment removal system (HSRS) is typically limited to reservoirs less than 1.8 mile in length, and is limited by atmospheric pressure to less than 33 feet of drop on the discharge side of the siphon [26].

There is a new approach water injection dredging that operates by injecting water to fluidize deposited sediment through the use of pumps and a series of nozzles located on a horizontal pipe positioned above the sediment bed [51]. This induces a density current which flows downslope and can be vented through low-level outlets. Water injection dredging has been applied in harbors and channels for many years but not in reservoirs. A pilot project using water injection dredging in Tuttle Creek Reservoir is planned for 2023 [52]. Since it hasn’t been proven yet in actual reservoir sediment management practice, we have excluded from the remainder of this thesis.
Implementation strategies will vary considerably, reflecting site specific factors including hydrology, sediment yield, sediment-sensitive downstream infrastructure and ecosystems, regulations, downstream users, operational constraints, dam design, value of storage, project costs and client’s financial capacity. For example, rapid reservoir emptying for flushing would be precluded at an earthen dam due to dam safety limits on reservoir drawdown and refill rates. However, it may be feasible at a concrete dam [10].

**1.2.4 Adaptive Strategies**

Adaptive strategies focus on techniques that seek to mitigate sedimentation impacts by methods other than adjusting the reservoir’s sediment balance. These strategies can be redistributing sediments, manipulating the geometry of delta deposits, raising the dam, abandoning low-value water-intensive activities [43] and changing reservoir operation to optimize benefits [53, 54].

**1.3 Comparison of Sediment Management Features**

Because of the various purposes for which dams are built, there are variations from one reservoir to another in appropriate sediment management, the amount and duration of downstream flow releases, incurred costs, and effects on the receiving stream. The best-suited application will depend on the ability to manage reservoir water levels [55] and reproducing natural sediment movement. If reservoir sediments can be delivered downstream, and then also naturally moved along in the stream, at rates similar to the inflow rates, the sediment load to the downstream river will be restored and the reservoir water storage capacity can be sustainable [56]. However, there are specific factors needed to be considered in costs and downstream impacts of reservoir sediment management alternatives as presented in Table 1-1.
Table 1-1: Comparison of Costs and Downstream Impacts of Reservoir Sediment Management Alternatives

<table>
<thead>
<tr>
<th>Sediment Management Alternative</th>
<th>Cost</th>
<th>Downstream Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reduce Sediment Yield</strong></td>
<td>This group of sediment management may be costly and require ongoing maintenance [43]. In areas of high sediment yield, trapping sediment in the upstream watershed due to this cost and the limited volumetric capacity of upstream sediment traps may not be a sustainable solutions [57].</td>
<td>This alternative does not address the issue of sediment starvation downstream of the reservoir in contrast to the remaining alternatives [26].</td>
</tr>
<tr>
<td><strong>Route Sediment Bypass</strong></td>
<td>Sediment bypass tunnels involve high cost caused by tunnel construction and can experience severe hydro abrasive invert wear [58]. However, it has advantages of passing sediment without interfering with reservoir beneficial operation [26].</td>
<td>Bypass can have less impact on the downstream environment [59] because the natural flood will be diverted the downstream simulating pre-dam discharge and sediment characteristics [60]. Investigations in Japan and Switzerland showed that long term sediment bypass can recover downstream invertebrates density [61].</td>
</tr>
<tr>
<td><strong>Off-stream (off-channel) Storage</strong></td>
<td>Since inflow can be controlled at the diversion point, an off-stream storage does not require a large and costly spillway structure. The reduced sediment loading can largely eliminate the need to provide a sediment storage pool and reduces future maintenance costs compared to other alternatives (such as dredging) [4].</td>
<td>This alternative can maintain downstream sediment transport with high geomorphic and ecological importance [43]. Moreover, the dam does not pose a barrier to migratory aquatic species [62].</td>
</tr>
<tr>
<td><strong>Sluicing</strong></td>
<td>At some sites, sluicing can be implemented at very low cost, such as operation cost [55], but at others costly modifications to the dam will be required to provide large-capacity low-level outlets [4]. This alternative is suitable for reservoirs that can be completely drawn down without impact on the reservoir storage benefit.</td>
<td>Sluicing as a sediment-management technique can maintain the equilibrium of sediment between the reservoir and downstream environment [59]. Impacts from sluicing operations on biological resources below the dam would vary, however, anticipated negative ecological impacts of the sluicing can be limited [4, 61].</td>
</tr>
<tr>
<td><strong>Density Currents</strong></td>
<td>Modern monitoring technology allows a cost-effective [4] and accurate forecasting density current onset and movement [46, 47]</td>
<td>Density current venting delivers fine suspended sediment to downstream reaches during floods and can simulate pre-dam conditions [47].</td>
</tr>
<tr>
<td>Sediment Management Alternative</td>
<td>Cost</td>
<td>Downstream Impact</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Compartmented Reservoir</td>
<td>Construction cost is higher than sediment sluicing method due to installation of closing levee, however, is less expensive than bypass method [63]</td>
<td>The basic operating strategy is to make downstream deliveries from the sediment storage reservoir, releasing as much sediment downstream as possible while conserving the water in the main storage reservoir [64]</td>
</tr>
</tbody>
</table>

Remove Deposited Sediment

| Flushing | Similar to sluicing, this alternative requires a low-level gate. However, it can be done when the river is at low-flow conditions so that drawing down the water level takes less effort and does not affect the water storage benefit [1] | Since flushing releases high sediment loads with limited water volumes, it frequently produces downstream environmental impacts such as low dissolved oxygen [55], clogging of river gravels with fine sediment and eliminating spawning sites and habitat (4), and impacts downstream density and diversity of macroinvertebrates [61]. High sediment concentrations can also affect downstream infrastructure such as irrigation canals, or causing issues at water purification plants with low capacities for suspended solids [4]. Generally, more frequent flushing (e.g., annually) has less downstream impacts because it delivers sediment to the downstream channel, where it is needed [26]. |

Hydraulic Dredging

| This alternative is expensive but effective solution to extreme storage loss in reservoirs [59]. In many cases in the United States, the removed sediment material is trucked or piped to (usually upland) confined disposal facilities. These methods have proven cost-prohibitive for long-term maintenance of reservoir storage [32]. | One main issue with dredging is the environmental impact of trapping several years of settled sediment [59]. However, in regions with high nutrient loads from fertilizers or other sources this trapping may be considered beneficial [55]. Uncontaminated dredged sediment can be added to downstream reach, habitat development, soil improvement for agriculture and forestry, and construction (for example, brick making) [55]. |

Mechanical Removal

| Mechanical removal is commonly less expensive than hydraulic dredging, but it is region specific, and depends on volume of removed material, and haul distance [55]. | Downstream impacts are similar to hydraulic dredging. |

HSRS

| Hydrosuction is significantly less expensive than traditional dredging with upland disposal because it eliminates the costs for external power, typically comprise 30% of the cost of dredging operation, as well as the costs for upland disposal of the sediments, typically comprise over 50% of the total cost of a dredging operation [65, 66] | This alternative is environmentally friendly and can transport, and discharge of sediment to the downstream channel [50]. |
1.4 Purpose of the Thesis

The purpose of this research is to combine physically based computer modeling of sediment management with economic analyses of the same to determine the feasibility of extending the useful life of existing reservoirs.

Chapter 2 describes the dominant physical processes of sediment management alternatives. Understanding the dominant physical processes for each alternative is the first step toward an efficient simulation. Moreover, a brief discussion of the equations of motion for water and sediment is presented. The equations follow with citations of successful simulation studies. Published reservoir sediment management simulations demonstrate which computer codes can be used for reservoir sediment simulation. Chapter 2 presents our contribution in R. Anari et al. (2020) [67] and also updated simulation studies published since then.

Evaluation of sediment management alternatives should include hydraulic and sedimentation analyses to model physical attributes and economic analysis to model benefits and costs. The purpose of Chapter 3 is to introduce a new economic paradigm for new and existing water storage reservoirs. This new economic paradigm encourages policymakers to consider a comprehensive economic evaluation and intergenerational equity to truly make water resources projects sustainable. Chapter 3 presents our contribution in R. Anari et al, 2022, [68], and uses a hypothetical “Muddy Reservoir” to test the concepts.

Chapter 4 evaluates sediment management efficiency in the selected case study (Paonia Reservoir). The existing dam will be compared to a hypothetical one that includes a low-level gate.
The SRH-1D model will be applied to simulate long-term reservoir operation since dam commissioning and compares reservoir sedimentation in the two alternatives. This comparison provides the connection to the economic analysis.

The sedimentation in Paonia Reservoir is then connected to an economic analysis. Chapter 5 applies a new developed model called the Reservoir Sedimentation Economics Model (RSEM) (Randle, T. J., T. L. Gaston, and R. Anari. Reservoir sedimentation economics model (RSEM), U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, CO, under writing) to evaluate and compare the benefits and costs of continued sedimentation and eventual dam decommissioning to sediment management costs and benefits (hypothetical Paonia Reservoir).

Finally, Chapter 6 presents a summary and recommendations for future work.
2 SEDIMENT MANAGEMENT MODELING

Sediment management alternatives have a common purpose: achieving sustainable reservoir storage by balancing inflowing with outflowing sediments. Each sediment management alternative has unique physical characteristics. Physical and computational models help to better understand the associated features for each alternative. Several considerations differentiate physical models from computational models. Physical models [69-72] are used to represent site-specific conditions. Computational models, however, can be adapted to different physical domains more easily than physical models without being subject to effects due to scale distortion in physical models [73]. With the rapid developments in numerical methods for fluid mechanics, computational modeling has become an attractive tool for studying flow and sediment transport.

This chapter aims to understand how physical characteristics of sedimentation in reservoirs can be simulated with available computer codes. “Code” in this study refers to the compiled program used to simulate sediment management alternatives. Such simulations are referred to as models. Incorporating sediment prediction and management correctly into the planning, design, and operational phases of dam projects is essential for ensuring that the benefits of reservoir storage are sustained well into the future.
Physical processes of sediment management alternatives will be described first, followed by the governing equations that describe the physical processes and the commonly available computer codes for simulating them. Results cite successful simulation studies, and published reservoir sediment management simulation studies demonstrate which computer codes can be used for reservoir sediment simulation. The chapter summarizes the main findings relevant for all the management alternatives and their unique features.

2.1 Physical Processes Associated with Sediment Management Alternatives

Successfully simulating reservoir sediment management alternatives requires relevant and comprehensive knowledge about the reservoir performance and the physical processes that govern each technique. For example, reservoir pool elevation has a major influence on hydraulic behavior and the pattern of sediment deposition in reservoirs [4] or a mistake in estimating sediment inflow into a reservoir, especially during flood events, produces incorrect bed elevations in the reservoir and an incorrect simulation of sediment flushing [74]. Operational conditions for each alternative are also crucial. For example, according to the feasibility study carried out by Consorcio PCA (2012), the minimum outflow from a bottom outlet to achieve efficient flushing should be at least twice the annual mean flow [75].

Moreover, every computer code has assumptions, advantages, and constraints, which may impact accuracy. Thus, users must recognize the primary and governing physical processes
underlying sediment management techniques to select the appropriate computer code to simulate the desired condition.

Table 2-1 presents the dominant physical processes for alternatives in Categories 2 and 3 of Figure 1-1, transporting sediments downstream of the dam. Category 1 and 4, reducing sediment yield and adaptive strategies, are beyond the scope of this thesis.

A summary and a brief discussion of the equations of motion for water and sediment that describe the physical processes of Table 2-1 is discussed next, followed by a description of codes found capable of solving such equations.

<table>
<thead>
<tr>
<th>Sediment Management Alternative</th>
<th>Sediment Management Category and Dominant Physical Processes to be Simulated by Computer Codes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route Sediments</td>
<td></td>
</tr>
<tr>
<td>Sediment bypass tunnel</td>
<td>Sediment distribution in water column, wear on tunnel perimeter, sediment transport in supercritical flow, splitting sediments at intake</td>
</tr>
<tr>
<td>Sediment pass-through</td>
<td></td>
</tr>
<tr>
<td>Drawdown and sluicing</td>
<td>Sediment suspension, multiple grain size sediment transport, time-dependent gate operation</td>
</tr>
<tr>
<td>Turbidity current</td>
<td>Hyper-concentrated flow, vertical sediment entrainment and deposition, plume momentum, diffusion and arrival time</td>
</tr>
<tr>
<td>Hydrosuction Sediment Removal System (HSRS)</td>
<td>Sediment entrainment, slurry transport in pipes, sufficient head difference</td>
</tr>
<tr>
<td>Remove Deposits</td>
<td></td>
</tr>
<tr>
<td>Flushing</td>
<td>Sediment entrainment, multiple grain size sediment transport, bank erosion, water surface variation, incipient motion</td>
</tr>
<tr>
<td>Pressure flushing</td>
<td>Incipient motion, cohesive sediment transport</td>
</tr>
<tr>
<td>Hydraulic dredging</td>
<td>Sediment cohesion, slurry transport in pipes</td>
</tr>
<tr>
<td>HSRS</td>
<td>Sediment entrainment, slurry transport in pipes, incipient motion, sufficient head difference</td>
</tr>
</tbody>
</table>
2.2 Equations of Water and Sediment Motion

Two mathematical approaches can be used to describe water and sediment transport. One is the two-fluid model that considers water and sediment as two fluids and uses the continuity and momentum equations for each fluid. However, the two-fluid model is quite complex [76] and will not be considered here. The other approach is the diffusion model that evaluates the transport and dispersion of sediment particles in the water column and uses the continuity and momentum equations for the sediment-laden flow and the diffusion equation for sediment grains [76]. The flow and sediment transport equations presented here are based on the diffusion model. All variables are defined in the Notation at the end of this section.

2.2.1 Three-Dimensional Equations

The equations governing bottom adjustment and the turbulent transport of a water and sediment mixture with density $\rho$ and velocity $\vec{u} = (u, v, w)$ vector in a Cartesian coordinate system $(x, y, z)$ over time $t$ are given below.

Mass Conservation:
\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]  

(2-1)

Momentum Conservation:
\[
\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial uv}{\partial y} + \frac{\partial uw}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\frac{u_t}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{u_t}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{u_t}{\partial z}\right)
\]

(2-2)
\[
\frac{\partial v}{\partial t} + \frac{\partial uv}{\partial x} + \frac{\partial vv}{\partial y} + \frac{\partial vw}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left(\frac{v_t}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{v_t}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{v_t}{\partial z}\right)
\]

(2-3)
\[
\frac{\partial w}{\partial t} + \frac{\partial u w}{\partial x} + \frac{\partial v w}{\partial y} + \frac{\partial w w}{\partial z} = -g - \frac{1}{\rho} \frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left( v_t \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left( v_t \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z} \left( v_t \frac{\partial w}{\partial z} \right)
\]  \tag{2-4}

where \( p \) is pressure, \( v_t \) is eddy viscosity, and \( g \) is gravitational acceleration. Note, that the gravity force is the only external body force considered in the above equation.

\textbf{Sediment Advection-Diffusion Transport:}
\[
\frac{\partial c}{\partial t} + \frac{\partial u c}{\partial x} + \frac{\partial v c}{\partial y} + \frac{\partial w c}{\partial z} - \frac{\partial w f c}{\partial z} = \frac{\partial}{\partial x} \left( \epsilon_s \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( \epsilon_s \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left( \epsilon_s \frac{\partial c}{\partial z} \right)
\]  \tag{2-5}

where \( c \) is volumetric sediment concentration, \( w_f \) is sediment particle fall velocity, and \( \epsilon_s \) is eddy diffusivity of sediment particles. The net flux of sediment particles between the flow and bottom \((D - E), \text{where} \ D = c_b w_f \) is deposition rate of sediment onto the bed, \( c_b \) is the near-bed sediment concentration, \( E = c_{be} w_f \) is entrainment rate of sediment from the bed, and \( c_{be} \) is the equilibrium near-bed sediment concentration) is imposed as a boundary condition.

\textbf{Bed Sediment Mass Conservation:}
\[
(1 - \eta) \frac{\partial Z_b}{\partial t} + E - D = 0
\]  \tag{2-6}

where \( \eta \) is \( c \) and \( Z_b \) is bottom elevation.

\textbf{2.2.2 Two-Dimensional Equations}

The equations describing the transport of water and sediment in two dimensions are derived by integrating the above three-dimensional Equations (2-1)–(2-5) across the water depth \( h \). Depth-averaged variables are indicated by an overbar.
Mass Conservation:
\[
\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = 0
\]  
\begin{equation}
(2-7)
\end{equation}

Momentum Conservation:
\[
\begin{align*}
\frac{\partial \bar{u}}{\partial t} &+ \frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = -gh \frac{\partial (Z_b + h)}{\partial x} - \frac{gh^2}{2\rho} \frac{\partial \rho}{\partial x} - \frac{\bar{u}}{\rho} \left( \frac{\partial \bar{u}}{\partial x} \right) + \frac{\bar{v}}{\rho} \left( \frac{\partial \bar{v}}{\partial y} \right) + \tau_{sx} - \tau_{bx} \quad (2-8) \\
\frac{\partial \bar{v}}{\partial t} &+ \frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = -gh \frac{\partial (Z_b + h)}{\partial y} - \frac{gh^2}{2\rho} \frac{\partial \rho}{\partial y} - \frac{\bar{u}}{\rho} \left( \frac{\partial \bar{v}}{\partial x} \right) + \frac{\bar{v}}{\rho} \left( \frac{\partial \bar{u}}{\partial y} \right) + \tau_{sx} - \tau_{by} \quad (2-9)
\end{align*}
\]

where \( \tau_s \) and \( \tau_b \) are the shear stresses acting on the water surface and channel bottom, respectively. The subscripts \( x \) and \( y \) indicate the components in \( x \)- and \( y \)-direction, respectively.

Sediment Advection-Diffusion Transport:
\[
\frac{\partial \bar{c}}{\partial t} + \frac{\partial \bar{u}}{\partial x} + \frac{\partial \bar{v}}{\partial y} = \frac{\partial}{\partial x} \left( \varepsilon_s h \frac{\partial \bar{c}}{\partial x} \right) + \frac{\partial}{\partial y} \left( \varepsilon_s h \frac{\partial \bar{c}}{\partial y} \right) + E - D
\]  
\begin{equation}
(2-10)
\end{equation}

Bed Sediment Mass Conservation:
\[
(1 - \eta) \frac{\partial Z_b}{\partial t} + E - D = 0
\]  
\begin{equation}
(2-11)
\end{equation}

The net flux of sediment between flow and bottom can also be written as:
\[
E - D = \frac{\partial (h\bar{c})}{\partial t} + \nabla \cdot (\bar{q}_b + \bar{q}_s)
\]  
\begin{equation}
(2-9)
\end{equation}

where \( \bar{q}_b \) and \( \bar{q}_s \) are the vectorial bed load and suspended load transport rates, respectively.

### 2.2.3 One-Dimensional Equations

The equations describing the transport of water and sediment in one dimension along the downstream direction (\( x \)) are derived by integrating the above two-dimensional Equations (2-7)–(2-10) across the flow width. Cross sectional-averaged variables are indicated by a double overbar.
Mass Conservation:

\[ \frac{\partial \rho A}{\partial t} + \frac{\partial \rho Q}{\partial x} = 0 \]  

(2-13)

where \( A \) is flow area and \( Q \) is discharge.

Momentum Conservation:

\[ \frac{\partial Q}{\partial t} + \frac{\partial \bar{u}Q}{\partial x} = gA(S_0 - S_f) - gA \frac{\partial \rho h}{\partial x} \]  

(2-14)

where \( S_0 \) and \( S_f \) are bed slope and friction slope, respectively.

Sediment Advection-Diffusion Transport:

\[ \frac{\partial \bar{c}}{\partial t} + \bar{u} \frac{\partial \bar{c}}{\partial x} = \frac{\partial}{\partial x} \left( \bar{c}_s \frac{\partial \bar{c}}{\partial x} \right) - \alpha \omega \left( \bar{c} - \bar{c}_s \right) \]  

(2-15)

where \( \alpha \) is a dimensionless coefficient that characterizes the rate at which the new carrying capacity \( \bar{c}_s \) is attained.

Bed Sediment Mass Conservation:

\[ (1 - \eta) \frac{\partial Z_b}{\partial t} + \frac{\partial A \bar{c}}{\partial t} + \frac{\partial Q_b}{\partial t} + \frac{\partial Q_s}{\partial x} = 0 \]  

(2-16)

where \( Q_b \) and \( Q_s \) are bed load and suspended load transport rate, respectively.

### 2.2.4 Notation

All the variables are presented here:

- **A** flow area
- **c** volumetric sediment concentration
- **c_b** near-bed sediment concentration
- **c_{be}** equilibrium near-bed sediment concentration
- **\bar{c}** depth averaged concentration
- **\bar{c}_s** cross sectional-averaged concentration
- **\bar{c}_*,** new carrying capacity
- **D** deposition rate of sediment onto the bed
Codes Used for Reservoir Sediment Management: Capabilities and Limitations

A summary of the features of commonly available computer codes is presented below.

2.3.1 One-Dimensional Models

Most of the sediment transport models used for long-term simulation of a long river reach are one-dimensional [77]. One-dimensional models generally require the least field data for
calibration and testing. Numerical solutions are more stable [77], and require the least amount of
computer time and capacity, are appropriate for narrow reservoirs and multiple alternative analyses
[78].

In one-dimensional modeling, the solution of the sediment continuity equation provides a
change in the cross-sectional area at each cross-section. It allocates changes to each wetted
coordinate point across the cross-section. Different computational models approach the allocation
calculation differently. Consequently, the shape of the cross-section is not a question to address
with a one-dimensional sediment model [62].

One-dimensional models are more stable than the 2-D and 3-D models. But 1-D models
cannot show lateral variations of currents and patterns of lateral sedimentation in cross-sections of
rivers. Also, some of these models can simulate lateral erosion[79]. Modeling lateral variations
can be approximated with quasi 2-D models [80].

A horizontal deposit is more likely in reservoir delta deposition with the bed material load
that first deposits in the original channel section. After filling the submerged channel feature, the
water-sediment mixture expands laterally outwards. When the reservoir level falls, the channel
will cut through the delta deposit, perhaps some new location [62]. However, the width and depth
of the new channel will be very similar to that of the original channel, unless there is a major
change in the inflow. Consequently, a carefully constructed one-dimensional model is able to
predict delta growth and the resulting water surface elevations even though it does not mimic the
deltaic channel avulsion process [62].
One of the most widely used one-dimensional computer codes is the U.S. Army Corps of Engineers Hydrologic Engineering Center-River Analysis System (HEC-RAS) [81]. Key advantages of this code include extensive documentation, continuing support and development by the Hydrologic Engineering Center [82-85], a long history of use, familiarity to many reviewing agencies, and availability of training by the engineering community [86]. This computer code can simulate steady, unsteady, and quasi-steady flow with various features to model sediment and reservoir operation [87].

The Generalized Stream Tube model for Alluvial River Simulation (GSTARS) code, developed by the U.S. Bureau of Reclamation\(^1\) [88], can predict channel geometry in a quasi-two-dimensional manner by using the stream tube concept [89]. GSTARS hydraulic calculations can be done in either a steady or unsteady mode. However, the hydraulic and sediment transport calculations are performed in an uncoupled manner [90]. GSTARS does not consider flow interchange between stream tubes.

The Rhone 1-D model was developed by Irstea (National Institute for Environmental and Agricultural Science and Research) as part of the OSR (Observatory sediments Rhone) program in France to understand the spatial and temporal variability of the suspended sediment dynamics along the river [91].

\(^1\)“developed by the U.S. Bureau of Reclamation” added posted publication
Sedimentation and River Hydraulics – 1D (SRH-1D) is a hydraulic and sediment transport model for use in natural rivers and manmade canals. This model is able to simulate steady or unsteady flows, internal boundary conditions, cohesive and non-cohesive sediment transport, consolidation, fractional sediment transport, bed sorting, and armoring [92, 93]. Specific applications demonstrate potential uses of the model in estimation of channel change in a river system caused by dam construction, dam removal, or sediment sluicing [93]. The Environmental Protection Agency (EPA) and Bureau of Reclamation (Reclamation) were funding partners in the original development of the SRH-1D model which can be downloaded freely [93].

2.3.2 Two-Dimensional Models

Huang et al. (2018) [69] discussed 2-D models can reasonably simulate lateral but hardly simulate vertical particle movements in a reservoir as the fall velocity term is ignored in Equation 2-7. All 2-D models can predict the total sediment transport load; but few models, e.g., MOBED2 (Mobile BED), USTARS (Unsteady Sediment Transport models for Alluvial Rivers Simulations;), FLUVIAL 12, DELFT-2D, and CCHE2D (The National Center for Computational Hydroscience and Engineering) can separate the total sediment load into bedload and suspended load. However, some of those are limited to uniform sediment sizes [73].

The traditional approach in sediment transport models has been to calculate the transport rate using a single characteristic grain size, such as the median. This calculation should be used carefully since this approach does not account for the transport of sediment particles with different
sizes (or density), it is likely to underpredict or overpredict the transport rate of sediment fractions [73].

A significant advantage of multi-dimensional models over one-dimensional models is that they provide more details within an area of interest by their gridding capabilities. For example, one of the major features of SRH-2D (Sedimentation and River Hydraulics) is the adoption of an unstructured mesh, based on the arbitrarily shaped element method of Lai (1999) [94] for geometric representation. This meshing strategy allows for greater modeling details in areas of interest that ultimately leads to increased modeling efficiency through a compromise between solution accuracy and computing demand [95].

Iber is a depth-averaged two-dimensional hydraulic model for the simulation of free-surface flow in rivers and estuaries. The equations are solved with an unstructured finite volume solver of triangle and quadrilateral elements. Dam break, sediment transport considering both bed and suspended loads, GIS (Geographic information system) integration, and mass conservative wetting and drying algorithm are some of the main current features of Iber [96].

TELEMAC-2D and 3D are used to simulate free-surface flows with computation mesh of triangular elements. TELEMAC offers the user a set of FORTRAN subroutines that can be modified to meet the specific requirements of each model: specification of initial conditions or complex boundary conditions, link-ups with other modeling systems, or introduction of new functions [97]. Modelling vertical stratification is also possible [98].
The numerical software BASEMENT (Basic Simulation Environment) for simulation of hydro- and morpho-dynamics is available free of charge. Two maintained versions of the software are currently available, which differ in their key features, such as arbitrary combination of 1-D and 2-D model domains and different performance capabilities [99].

The two-dimensional physiographic soil erosion–deposition (PSED) can accurately estimate discharge hydrographs and suspended sediment transport rates from a watershed to compute sediment yield. This information can quantify the value of sediments to be flushed and estimate the resulting bed evolution. Since the model utilizes GIS, the hydrological and physiographical factors are processed instantaneously [74, 93, 100].

RAS 2D is another widely used computer codes developed in the U.S. Army Corps of Engineers Hydrologic Engineering Center-River Analysis System (HEC-RAS) [81] that allows the user to perform 2D or combined 1D/2D modeling. The software was designed to use unstructured computational meshes but can also handle structured meshes [101]. Recently two-dimensional (2D) sediment transport option officially released in Version 6.1. HEC-RAS that allows users to add sediment data to new or existing 2D hydraulic models[1] [102].

2.3.3 Three-Dimensional Models

One-dimensional models are not suitable for simulating local two- or three-dimensional phenomena [77]; an example is local scour, the process which involves three-dimensional

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1 Added posted publication
 accelerations, pressure fluctuations, and gravity forces on the sediment particles [62]. Turbulence is essentially a three-dimensional phenomenon, and three-dimensional models are particularly useful for simulating turbulent heat and mass transport. These models are usually based on the Reynolds-averaged form of the Navier–Stokes (RANS) equations (Equations (2-1, 2-2) [103, 104], and using additional equations with varying degrees of complexity for the turbulence [77]. Although a 3-D numerical model can practically describe the flow, it requires significant computing resources and data [69]. When the reservoir pool is wide and without a clear single flow direction, multi-dimensional models should be used [78].

A 3-D simulation can better evaluate flushing operations, especially its early phases [75]. Two-dimensional models may not properly simulate: (1) the deltaic sediment dynamics and therefore the movement sediments that could eventually block the bottom outlets; nor (2) the initial pressurized flow in the bottom outlets that occurs during the flushing.

Among the three-dimensional models, the commercial codes ANSYS FLUENT and FLOW-3D have been used to simulate reservoir sedimentation. ANSYS FLUENT is a powerful CFD (Computational fluid dynamic) tool, based on the finite volume method with a wide range of applicability laminar-turbulent, incompressible-compressible, steady-transient, and sediment transport [98]. The FLOW-3D code solves the (RANS) equations discretized by finite differences. It incorporates various turbulence models, a sediment transport model, and an empirical bed erosion model with a method for calculating the free surface of the fluid [75].
Freely available codes have also been used to evaluate reservoir sediment management practices. The disadvantages of such codes are that they are not well supported and therefore have limited user adoption—for example, SSIIM (Sediment Simulation in Intakes with Multiblock option). Generally, the released manuals and documentation only provide help. SSIIM (2-D or 3-D) is a finite volume hydrodynamic and sediment transport model based on an unstructured grid system with the ability to simulate sediment transport in a movable riverbed with complex geometries. The model has been extended to other hydraulic engineering applications such as spillway modeling, head loss in tunnels, meandering in rivers, and turbidity currents [73].

Delft3D is a multi-dimensional (2-D or 3-D) hydrodynamic and morpho-dynamic model for riverine flows, simulations in deep lakes and reservoirs, stratified and density-driven flows, thermal stratification in lakes, and reservoirs and transport of dissolved material [105].

MIKE 3 builds on the same solid technology as MIKE 21. Applications include assessment of hydrodynamics for design, construction, and operation of structures and plants in stratified waters, coastal, and oceanographic circulation studies, including fine sediment dynamics, lake hydrodynamics, and ecology [106].

2.4 Published Simulations of Reservoir Sediment Management

This section describes published simulations of alternatives in Categories 2 and 3 of Figure 1-1 during the last 20 years. The simulation of watershed sediment yield is beyond the scope of this thesis. There are multiple sources that detail this alternative [71, 107-114].
Two criteria were used to select eligible studies: (1) success in simulating the sediment management alternative, and (2) current availability of the computer code. Some studies are based on computer codes that are no longer available, and some are developed for specific purposes of the authors [104, 115, 116].

HSRS an alternative in the third category, does not require computer simulation and is not included in this section. A summary of the cited simulations is found in Table 2-2.

2.4.1 Simulation of Longitudinal Sediment Profile in Reservoirs

A longitudinal profile is very useful for visualizing and understanding the sedimentation processes in a reservoir [19]. Both 1-D and multidimensional codes have been used for this purpose. Regarding 1-D applications Gibson and Pridal (2015) used HEC-RAS 1D to simulate a 50-year bed elevation profile [117]. Moreover, Amini et al. (2014) [118], Mohammad et al. (2016) [119], and Shelley et al. (2015) [54] used HEC-RAS 1D to examine deposition and transport of the sediment load [54]. The required time for sediment to reach the bottom outlet elevation can be estimated by considering the downstream delta movement as Castillo et al. (2014) modeled using HEC-RAS 1D [120]. Gibson and Boyd (2014) demonstrated the advantage of using operational rules in HEC-RAS 1D for modeling reservoir sediment management practices [121]. In addition, other codes such as GSTARS3 have been successfully used to simulate the long-term longitudinal profile by Nohani and Afrous (2015) [122]. Launay et al. (2019) simulated the spatial and temporal dynamics of suspended particulate matter during floods using the Rhone 1-D model [123].
Hobi (2014) used SSIIM (2D) to simulate the formed channel in the delta deposits in Haditha Reservoir, Iraq [124], and Lai (2012) applied the SRH-2D to model ten years of channel morphology for upstream from the Elephant Butte Reservoir on the Rio Grande [125].

Omer et al. (2015) Predicted the long-term evolution of the bed topography using the multidimensional model, Delft3D [126]. They simulated the fate of incoming sand and silt of Roseires Reservoir (Sudan).

2.4.2 Route Sediments to Maintain Transport and Minimize Deposition

During periods of high inflows to the reservoir, the discharging of the high flows through the bottom outlets at the dam is performed with the objective of permitting the sediment to be transported through the reservoir as rapidly as possible while minimizing deposition [26]. This alternative is described in case studies by Huang et al. (2019) [127], and Kimbrel and Greimann (2016) [128] using SRH-1D.

Venting of turbid density currents through a low-level outlet have been simulated by Mohammadnezhad et al. (2010) using Mike 3 [129]. An and Julien (2014) used a particle dynamics algorithm in FLOW-3D to simulate 3-day turbidity current movement in Imha reservoir [130], while Georgoulas et al. (2012) similarly used the 3-D multiphase numerical modelling within FLUENT [131]. Moreover, Huang et al. (2019) applied SRH-2D to simulate a density current [132].
Sediment-laden flows can be bypassed around a reservoir. Lai and Wu (2018) used a 2-D layer-averaged version of SRH-2D to simulate various bypass tunnel plans [133]. The SRH-2D code was also used to simulate the bypass tunnel for the Yellowstone River intake by Sixta et al. (2015) [95].

2.4.3 Remove or Redistribute Sediment Deposits

Gibson and Boyd (2016) simulated an unsteady flushing event at Spencer Dam [134] and Rashid et al. (2021) in Tarbela Reservoir [135] with HEC-RAS 1D. Tagavifar and Adib (2010) selected GSTARS3 to simulate flushing through successive Dez dams in Iran [13]. To identify when flushing should be conducted based on the inflow hydrograph, Shooshtari et al. (2010) used GSTARS3 [80]. GSTARS3 was also used to simulate reservoir sedimentation and flushing by Ahn and Yang (2011) [90].

The influence of lowering the reservoir and increasing discharge from upstream on the relocation of fine sediments was addressed using the Iber code by Castellet et al. (2019) [136]. Chen and Tsai (2017) applied PSED for computing sediment flushing efficiency [74]. Removing deposited sediment requires the correct simulation of bed shear stress. Amini et al. (2014) used BASEMENT 2D to compute bed-level shear stress for different reservoir water surface elevations during flushing [118]. Furthermore, Ermilov et al. (2018) simulated flushing by TELEMAC [98].
Scheuerlein et al. (2004) used the 3-D code SSIIM [98, 137] and Rodriguez et al. (2018) applied FLOW-3D for simulating flushing around a bottom outlet [138]. Harlan et al. (2018) applied FLOW-3D to simulate flushed sediment from an off-reservoir sedimentation basin [139].

Simulating dredging deposited sediments was done by reshaping topography at given points using HEC-RAS and a precursor, HEC-6 by USSD (2015) [78].

2.5 Discussion

The complexity and capability of morpho dynamic codes can vary with the code’s ability to simulate processes such as unsteady flows, bed load, suspended load, sediment exchange processes, type of sediment (cohesive versus non-cohesive), and multi-fractional sediment transport.
### Table 2-2: Published Simulations of Reservoir Sediment Management

<table>
<thead>
<tr>
<th>Dimensionality</th>
<th>1-D</th>
<th>2-D</th>
<th>3-D</th>
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<tr>
<td><strong>Process</strong></td>
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<tr>
<td>Simulation of Longitudinal Sediment Profile in Reservoirs</td>
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<tr>
<td>Shelley et al. (2015) [54]</td>
<td>HEC-RAS</td>
<td>GSTARS3</td>
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<td>Nohani and Afrous, (2015) [122]</td>
<td>HEC-RAS</td>
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<td>Gibson and Pridal (2015) [117]</td>
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<td>Gibson and Boyd, (2014) [121]</td>
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<td>Amini et al. (2014) [118]</td>
<td>HEC-RAS</td>
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<tr>
<td>Castillo et al. (2014) [120]</td>
<td>HEC-RAS</td>
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<tr>
<td><strong>Process</strong></td>
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<tr>
<td>Route Sediments (Maintain Transport, Minimize Deposition)</td>
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<tr>
<td>Sluicing</td>
<td>Huang et al. (2019) [127]</td>
<td>SRH-1D</td>
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<tr>
<td>Kimbrel and Greimann (2016) [128]</td>
<td>SRH-1D</td>
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<tr>
<td>Turbidity current</td>
<td>Huang et al. (2019) [132]</td>
<td>SRH-2D</td>
<td>An and Julien, (2014) [130]</td>
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<td>Georgoulas et al. (2012) [131]</td>
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<td>Mohammadnezhad et al. (2010) [129]</td>
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<tr>
<td>Bypass Tunnel</td>
<td>Lai and Wu (2018) [133]</td>
<td>SRH-2D</td>
<td>FLOW-3D</td>
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<td></td>
<td>Sixta et al. (2015) [95]</td>
<td>SRH-2D</td>
<td>Fluent</td>
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<td>Mike 3</td>
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<td><strong>Process</strong></td>
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<tr>
<td>Remove or Redistribute Sediment Deposits</td>
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<tr>
<td>Flushing</td>
<td>Rashid (2021) [135]</td>
<td>HEC-RAS</td>
<td>IBER</td>
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<td>Gibson and Boyd, (2016) [134]</td>
<td>HEC-RAS</td>
<td>TELEMAC</td>
<td>Harlan et al. (2018) [139]</td>
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<td>Ahn and Yang, (2011) [90]</td>
<td>GSTARS3</td>
<td>PSED</td>
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<tr>
<td>Shooshhtari et al. (2010) [80]</td>
<td>GSTARS4</td>
<td>2D</td>
<td>Scheuerlein et al. (2004) [98, 137]</td>
</tr>
<tr>
<td>Dredging</td>
<td>USSD, (2015) [78]</td>
<td>HEC-RAS</td>
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The selection of a computer code for a given problem is a critical issue, depending on different criteria. Although each sediment management technique has specific features, there are some common considerations between all kinds of reservoir sedimentation.

- Caution should be used when applying riverine transport models to reservoir transport as some of them ignore the finest size fractions, which are important for reservoir transport [78].

- Selecting dimensionality is related to spatial and temporal desired solution resolutions. One-dimensional codes are suitable for long-term simulation. The excessive run time for multi-dimensional codes limits their application to short-term simulation or where the detailed solutions for critical points within the reservoir is more important than computational cost.

- Appropriate determination of reservoir geometry, sediment grain size distribution, type of sediment (cohesive versus non-cohesive) and sediment transport formula influence the accuracy of results. For example, erosion and deposition prediction for multi-sized sediment is more realistic than using only the median size, which can lead to overprediction or underprediction of the transport of the fine or coarse fraction of a sediment mixture.

- Beyond the mentioned characteristics, user friendliness, support, and access are important to select a code.

However, each sediment management alternative has crucial considerations described below.
2.5.1 Route Sediments (Maintain Transport, Minimize Deposition) model selection

Routing of sediment through the reservoir pool is somewhat more complex as the erosion, transport, and deposition processes will need to be simulated, and these will change in space and time during the simulation.

Simulating sediment sluicing requires routing the rising limb of the hydrograph and storing the falling limb. A successful simulation needs to incorporate the variation of the incoming hydrograph and reservoir operation during the simulation time.

Turbidity currents are the most difficult phenomena to simulate in reservoir sediment management. Vertical gradients in sediment concentration and temperature lead to stratified conditions with interactions between layers (entrainment). This process can be simulated by multi-layered codes, possibly including equations (like Rouse equation) such for the suspended sediment concentration profile to represent better interaction between layers. For even more detail, a particle dynamics algorithm can be employed to increase the efficiency of turbidity current simulation.

Simulation of sediment transport in a bypass tunnel considers supercritical flow and the impact of bedload transport on the erosion of lining materials. A controlling parameter is the sediment input at the intake. Some codes use a “flow weighted” assumption to divert the same percentage of water and sediment at the intake [140]. Users can limit the sediment diversion through a threshold grain class. Grain classes smaller than the threshold value divert according to the flow-weighted assumption, whereas coarser grain classes may not be diverted [81]. This can be accomplished using one-dimensional models. Multi-dimensional models are not necessary unless detailed information at special points such as the intake is required.
2.5.2 Remove or Redistribute Sediment Deposits model selection

Mechanical removal or excavation is the most common form of dredging. This alternative is useful for some areas, but mechanical equipment and heavy vehicles play an important role in the success of this management practice. One simulation mechanism is to take sediment at the upstream end of the reservoir and move it to below the dam. Modeling this scenario includes computing the quantities of sediment and grain size distribution at the point of extraction and then taking those quantities as inputs to the system at a point below the dam [78]. As far as the dam owner can afford the mechanical removal expenses, they can extend reservoir lifetime and reduce reservoir sedimentation. The few simulations found for mechanical removal are limited to case studies simulating the deposition pattern within the reservoir after dredging.

The most frequent simulated sediment management alternative is reservoir flushing. One-dimensional codes have successfully simulated flushing hydrodynamics and reservoir topographic adjustment. These codes averaged values in a cross-section and are therefore not suitable for answering questions about local variations around the outlet gate or scour cone variation during flushing. Multi-dimensional codes work better with the variation of sediment-laden flow and relocation of fine sediments at an area of interest but are currently practical for event-type simulations as opposed to seasonal or multi-year time frames.

There is no predetermined prescript that guarantees the success of a simulation. The interaction between water and sediment is a consistent phenomenon that can be simulated efficiently if available limitations for simulation will be known, and users or decision makers select a computer code more appropriate for predominant features.
2.6 Conclusion

Selecting the best sediment management alternative and evaluating its effectiveness using computer codes is important for operating the reservoir and extending its lifetime. Several computer codes with varying abilities and constraints have successfully been used to support these steps. We described the dominant physical processes associated with each sediment management alternative and reviewed the underlying equations of motion. The published simulations have been presented and important criteria for selecting a computer code to simulate each sediment management strategy were explained. To select the appropriate code with the required accuracy level, the model users in accordance with their research objectives and human, technical, and financial resources, should narrow their selection circle.

One-dimensional codes are generally adequate for the long-term simulation of downstream delta movement, defining the time for sediment to reach bottom outlets, the longitudinal sediment profile during sluicing and flushing, and the subsequent deposition pattern within the reservoir after dredging. These codes are suitable when field data are limited and averaged results at cross sections are satisfactory.

A vertically averaged two-dimensional code can simulate lateral variations better than vertical changes. These models can be used for successful turbidity current simulation if extra assumption and equations are applied to describe sediment entrainment between layers.

Two- and three-dimensional codes provide more details within an area-of-interest (such as scour hole in flushing or sediment around hydropower intakes) due to their gridding capabilities. Such codes can be used to simulate wide reservoirs that lack a clear, single flow direction or channel. Indeed, they are appropriate for detailed solutions for critical points—but require
excessive run times. Three-dimensional models are particularly useful for simulating the local scour and re-suspension of deposited sediment during pressurized flushing through bottom outlets.

Finally, these findings are based on current knowledge of computer codes; as more progress in computer codes are made, an updated study is required.
Large dams and reservoirs interrupt the continuity of sediment transport through river systems, causing sediments to accumulate. Sediment accumulation diminishes a reservoir’s capacity to store water over time, thereby limiting its service life [10]. Reservoir sedimentation also has significant impacts both up- and downstream of the reservoir pool. The more than 92,000 dams [141] in the United States national inventory were not designed to preserve water storage capacity indefinitely. Without sediment management, many reservoirs will see their function substantially impaired long before the reservoir has completely filled with sediment [43]. In the absence of sediment management, reservoir storage is an exhaustible resource with long-term consequences. For these reservoirs, dam decommissioning will be the unavoidable result [142], especially for high hazard dams [10]. Doing nothing and leaving the dam in place with a fully sedimented reservoir is not a realistic option for high hazard dams because of the effect of sediment abrasion on spillways. Furthermore, the cessation of reservoir-dependent economic benefits leaves no revenue stream to offset the costs of maintenance and repairs, or to address future dam safety deficiencies.

Reservoirs need to be evaluated for determination of either eventual decommissioning or sustainable sediment management. Dams may be decommissioned for several reasons, including problems with structural safety, economics, reservoir sedimentation, and river restoration. The dam decommissioning alternative leaves future generations with fewer, and increasingly more
expensive reservoir storage options to meet their water demands. However, there are some cases where dam removal might lead to significant benefits from ecosystem, and river restoration. The removal of two large dams on the Elwha River, Washington generated an estimated $3-$6 billion (USD) nationally [143].

The fairness between current and future generations is called intergenerational equity and is the core tenet of sustainable development [1]. The concept of intergenerational equity is derived from the Brundtland Commission’s definition of sustainability: the ability to meet the needs and aspirations of the present without compromising the ability of future generations to do so [38].

In the case of reservoirs, sustainability means balancing sediment inflows and outflows across a dam while maximizing its long-term benefits [4]. Sustainable management can be achieved by several well-established alternatives for removing reservoir sediments (described in chapter 1) to achieve sediment transport continuity. Sedimentation problems and specific management techniques vary widely from one site to another; nonetheless, these alternatives can mitigate many types of sediment-related problems both upstream and downstream of dams. Uncontrolled sedimentation may block dam outlet gates or reservoir water intakes, reduce recreation surface area, and shorten the useful reservoir life, while sediment management prolongs reservoir benefits, extending economic production and social well-being [144].

Sediment management strategies should extend the useful life of the reservoir and maximize net benefits. Evaluation of these strategies should include hydraulic and sedimentation analyses to model physical attributes and economic analysis to model benefits and costs [7, 77]. Reservoir planning and economic studies commonly employ exponential discounting and either a 50- or 100-year period of analysis (POA) [4]. Exponential discounting gives less weight to benefits and costs that occur farther into the future. The value of future benefits and costs can be
significantly diminished through exponential discounting, either with high discount rates or over a sufficiently long POA.

Furthermore, historical economic analyses never considered important costs, such as up-and downstream damages, and dam decommissioning; nor did they consider depleted benefits from decreased water supply, recreation area, and hydropower flexibility after depletion of dead storage\(^\text{1}\). Although engineers specializing in sedimentation conceptually understood that reservoirs were not sustainable, numerical modeling did not exist during the period of rapid dam construction in the mid-20th Century. If they had existed, numerical models could have simulated reservoir sedimentation impacts over time. In addition, methods to develop costs from sedimentation consequences, especially dam decommissioning, had not been developed. Because of exponential discounting and 50 or 100 years of analysis, planning studies for new dams did not acknowledge that reservoirs would eventually have to be decommissioned without sediment management nor did they consider future dam decommissioning methods or costs. The standard economic methodology did not provide decisionmakers with any incentive to consider sustainable sediment management. With 92,000 dams already in the national inventory, replacing all these dams at alternate locations likely is not possible and the consequences of lost reservoir benefits to future generations was not considered. Therefore, the call for comprehensive economic evaluations of reservoirs with and without sediment management represents a new paradigm compared to traditional and long-standing economic practices.

The purpose of this chapter is to introduce this new economic paradigm for new and existing water storage reservoirs. This new economic paradigm encourages policy makers to consider comprehensive economic evaluation and intergenerational equity to make water

\(^{1}\) “after depletion of dead storage” added posted publication.
resources projects truly sustainable. A comprehensive analysis would have a period of analysis and spatial area large enough to consider the following sediment-related effects:

- Diminishing benefits related to reduced storage capacity and recreation surface area over time,
- Costs associated with sedimentation of dam and reservoir facilities,
- Costs associated with the upstream sedimentation impacts to property, infrastructure, and habitat
- Costs associated with downstream channel degradation impacts to property, infrastructure, and habitat
- Costs and benefits associated with dam decommissioning

The remaining sections of this chapter discuss historical aspects of economic assessment of water resource projects and the proposed paradigm for future assessments. A case study illustrates application of the new paradigm and shows that sustainability is economically feasible by incorporating sediment management into dam design and reservoir operations.

3.1 How We Got Here

Formal applications of benefit-cost analysis (BCA) for federal water projects were first included in the Flood Control Act of 1936 [145]. This act permitted the U.S. Army Corps of Engineers to participate in projects “if the benefits to whomsoever they may accrue are in excess of the estimated costs, and if the lives and security of people are not otherwise adversely affected” [35]. This act pushed to apply a uniform set of principles and standards to monetize all benefits and costs for public investments. The first accepted guidelines for water resource projects emerged in 1950 with the publication of the “Proposed Practices for Economic Analysis of River Basin
Projects” known as the “Green Book” [34, 35]. According to the Green Book, water resource investments should be valued by 1) applying market prices whenever possible, 2) adjusting or estimating the value of benefits and costs that are ordinarily valued incompletely, and 3) efficiently describing intangible effects [146]. The benefit-cost ratio (BCR) would be the output of this evaluation. A detailed history of the development and application of BCA for the period 1933-1985 can be found in Hufschmidt (1985) [35]. Interest in the economic analysis of large dams peaked in the 1950s in North America and Europe [15]. BCA has also become the World Bank’s dominant decision support system for project appraisal since the 1970s [147].

In 1983, the President of the United States approved new economic and environmental principles and guidelines mostly based on national economic development and environmental quality [35, 148]. The Water Resource Development Act of 2007 called for revisions to the 1983 principles. This revision was released in 2013 and finalized in 2014. The new Principles, Requirements, and Guidelines [149] replaced the 1983 document and constitute the current comprehensive policy and guidance for federal investments in water resources. According to the PR&Gs, agencies are required to consider three key criteria in alternatives evaluation: 1) the interrelated environmental, economic, and social impacts, considered without hierarchy; 2) not all impacts can be monetized, and qualitative impacts should be given equal weight, and; 3) there could be more than one alternative that reasonably maximizes the public benefits relative to costs [149]. Furthermore, Federal agencies define Agency Specific Procedures [58] to implement PR&Gs in water resource projects that is an ongoing action [150]. The regulations since 1936 have been improved to consider different aspects of water resource projects. However, they have not explicitly required consideration of costs and diminishing benefits associated with sedimentation in the economic assessment of dams constructed at that time. For example, there are cases where
these conventional practice entails evaluating sedimentation volume to design the elevation of the
dam outlet but not economic consequences following that [151], considering benefits within the
project extents but not up-and downstream of the reservoir pool, or even considering constant
annualized benefits and cost without diminishing due to sedimentation in the period of analysis in
Tualatin Project in 1970\(^1\) [152].

Three elements of a BCA that significantly influence results include the period of analysis
(POA), the selection of costs and benefits to be evaluated, and discounting approach and rate (the
time value of money). Policy and decision-makers consider these elements differently depending
on how they perceive each and what they believe is most important. The following sections present
the historical evolution of these elements and investigate their deficiencies.

\subsection{3.1.1 Period of Analysis (POA)}

Reservoir planning and economic studies are evaluated over a specified future time period
that is called the period of analysis. In the planning phase of a new water storage project, a BCA
is conducted that evaluates a selection of benefits and costs over this POA. It typically covers
either 50 or 100 years [4, 153]. The concept that infrastructure will serve its purpose for a finite
period is called design life [19]. If well maintained, dam structures may last much longer than the
50 or 100 year design life, even centuries. However, sedimentation will impact the operations of
dam and reservoir facilities long before the reservoir completely fills with sediment. Dam
decommissioning of high hazard dams will often be necessary after reservoir operations become
significantly impaired [10].

\footnote{Added posted publication}
The reservoir storage reduction due to sedimentation is a relatively slow process [21] and produces a low rate of benefit loss [154]. Sedimentation impacts along the upstream channel, and degradation impacts along the downstream channel, tend to be experienced more rapidly, but the economics of those impacts have not been considered. Therefore, traditional applications of BCA in water project planning do not comprehensively account for the costs of sedimentation and consequently find that additional capital costs to manage sedimentation are not economically justified [26]. The design life approach analyzes reservoir benefits and costs over a certain time period and does not treat water storage as a resource in perpetuity [39]. The historical approach neglected the loss of water storage over time, the eventual cost of dam decommissioning, and damages from upstream sedimentation and downstream erosion. A reason for this historical approach might be that the present worth of annual costs is seldom significant beyond 50 years since they are heavily discounted. However, reservoir storage sites are an exhaustible resource, so the design life approach will likely leave future generations with few and expensive options to consider. At the end of reservoir life, and eventual dam decommissioning, a new replacement project would be expected to at least maintain historical benefits that were provided by the previous reservoir. New replacement dam and reservoir project will require a new and separate economic analysis and justification. However, new reservoir sites will not be as plentiful and will require greater engineering and permitting challenges. For example, in the 1970s, the Denver Board of Water Commissioners proposed building Two Forks Dam to help meet the water supply needs of the Denver metropolitan area. After 20 years of planning the permit to construct the dam was denied by the U.S. Environmental Protection Agency [155].
3.1.2 Considered Benefits and Costs

Dams have been built mainly to provide irrigation and municipal water supply, flood risk reduction, recreation, fish and wildlife benefits, hydropower, and river navigation. However, they entail huge investment costs such as planning and design, construction, land purchase, and resettlement and include other important factors such as social and environmental impacts. The latter can be estimated using different methods, such as found in [147, 156-158]. Knowing as much as possible about the costs and the benefits leads to better decisions [145]. Historically, economic analyses did not fully capture all the temporal, spatial, environmental, and social dimensions of dam construction projects. The negative externalities such as upstream and downstream environmental damages, infrastructure and land-use changes, water quality, and flood stage [44] have received much less attention. Given what is known today, economic assessment of water projects should be modified to consider all anticipated costs and benefits. Without such considerations, any future analysis is incomplete and therefore faulty [36].

3.1.3 Discounting Approach and Rate

Discounting is a mathematical procedure employed to make costs and benefits, which occur at different points in time, temporally equivalent. Discounting for temporal equivalence can be achieved using a variety of different approaches, referred to collectively throughout this thesis as discounting approach. The choice of discounting approach and discount rate have a high impact on the net present value (NPV) and the BCR of projects with a significant difference in the timing of costs and benefits. Projects like dams that require large initial capital outlay and benefits distributed across the project’s lifetime are highly affected by the discounting approach and rate [159, 160].
To reflect any serious responsibility to the next generations, the discount rate must be quite low [145, 161] but not zero. Zero discounting means current generations should reduce their incomes to benefit future generations [162] or sacrifice the current generation’s (the poorest generation) well-being [163] relative to future generations. A recently proposed solution to this problem is to use a discount rate which declines with time to raise the weight attached to the welfare and well-being of future generations [164]. In recent years new discounting approaches have attracted attention, but there is no agreement among economists for their use in water resource economic assessments [19, 162].

3.2 New Economic Paradigm

Ensuring that water storage is preserved to meet the demands of future generations, while reducing upstream and downstream impacts requires a focus on maintaining reservoir storage capacity over time. Sediment management can be applied at both new and existing reservoirs. The need for sediment management has become urgent because most reservoirs are approaching the end of the sediment design life [1]. Sediment design life is measured as the years from construction to exhaustion of the volume specifically allocated for sediment storage. At many lakes the sediment storage is dead storage, i.e. it is located below the lowest dam outlet. The reservoir may continue to operate for some years or decades after the sediment design life but will eventually have to be decommissioned. As opposed to the sediment design life, the total reservoir life is the years from construction to decommissioning.

Maintaining the remaining reservoir storage capacity may be possible but recovering storage capacity lost to decades of sedimentation may not be feasible for large reservoirs. This section describes how reservoir sediment management strategies can be objectively evaluated from an economic standpoint, and how with a comprehensive accounting of costs sustainability might be
the preferred economic alternative. To determine whether reservoir sediment management is economic, the sediment management cost should be compared to cost of continued sedimentation impacts and eventual dam decommissioning.

### 3.2.1 Life Cycle Approach

Developing and retaining enough reservoir storage space to satisfy water demand over the long term requires abandoning the conventional design life approach to dam design and adopting a life-cycle management approach. A major difference between the life-cycle management approach and the design life approach is the use of sediment management to preserve reservoir storage capacity over time [1, 19]. The life cycle approach offers a framework for sustainably maintaining project benefits across generations [41]. When sedimentation is controlled, dams can have useful lives exceeding any other type of engineered infrastructure [62] to meet current and future generations’ water demands. The author is not aware of a previous study that comprehensively compares these two approaches for new and existing reservoirs.

### 3.2.2 Economic Evaluation for New Projects

Johndrow et al. (2006) estimated that an annual investment of between $10–$20 billion (2006 USD) would be required for the construction of replacement dams and reservoirs to recover current worldwide reservoir storage loss due to sedimentation without additional storage creation [39]. Replacing lost reservoir storage capacity by constructing new dams would be challenging due to high land prices and a lack of favorable sites. Even when technically feasible sites exist for new dams, they may not be feasible from an economic, social, political, or environmental standpoint. Even before the major dam-building decades in the U.S., Brown (1946) recognized that major reservoirs are irreplaceable when he said [165]:

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If the contemplated public and private reservoir construction programs are carried out, we shall have utilized by the end of this generation a very substantial portion of all the major reservoir sites... we cannot discover new reserves, as we will of oil. Nor we can grow new resources, as we can of forests. To whatever degree we conserve the capacity of the reservoirs built on these sites, to just that degree shall we conserve this indispensable base of our national strength and prosperity.

Reservoir sediment management can be considered for new and some existing dams [71]. However, retrofitting, for example, low-level outlets for sediment management is more expensive than incorporating such outlets in the initial design and construction. The preserved benefits from sustainable sediment management can offset the additional costs as will be demonstrated in the case study portion of this chapter. In the absence of sediment management, economic benefits dependent on reservoir capacity are progressively reduced as sedimentation increases. These lost benefits should be accounted for in an objective economic analysis [166].

Unsustainable reservoir sedimentation not only causes storage capacity loss, but also leads to upstream and downstream environmental, social, cultural, and economic impacts. Upstream and within the reservoir, sediment accumulation will eventually bury dam and reservoir facilities, reduce recreation use, and impact upstream property through increased flood stage and groundwater levels [37]. The sediment deficit results in the downstream erosion of the stream channel beds and banks, disrupts natural ecosystems and channel substrate compositions, threatens riverine infrastructure, and leads to coastal delta and beach erosion [26]. Thus, the footprint defined for economic evaluation should include reaches far enough up-and downstream to capture all sedimentation or sediment-deficit impacts comprehensively.
For new reservoirs, implementing adequate spatial and temporal scales is essential. Objective economic analysis requires a long view of future effects as well as a broad assessment of impacts. Comprehensive accounting of benefits and costs over a sufficiently long POA will yield a BCR that fairly evaluates sustainable development. Such an analysis could indicate whether sustainable sediment management is economically justified versus the cost of sedimentation impacts and eventual dam decommissioning.

### 3.2.3 Economic Evaluation for Existing Projects

For an existing dam and reservoir, there are two categories of alternatives: sustainable sediment management that maintains the remaining storage capacity indefinitely, or non-sustainable sedimentation that requires eventual dam decommissioning. Objective economic comparison of these alternatives requires comprehensive accounting of all costs and benefits, which can be compared by net present value (NPV). NPV requires the same inputs as BCA but presents a metric useful for identifying maximum net benefits. In the absence of sediment management, economic benefits dependent on reservoir capacity are progressively reduced as sedimentation increases. These lost benefits should be accounted for in an objective economic analysis [166].

BCA is especially useful in determining the economic feasibility of an action alternative in comparison to a no action alternative. For example, determining the economic feasibility of a new dam construction project, where no action means not constructing the project. However, when considering sedimentation of existing reservoirs, no action eventually results in the decommissioning of the dam and lost project benefits. NPV provides a more intuitive and meaningful metric for comparing alternatives for existing projects, allowing decision makers to identify the alternative that maximizes net economic benefits.
3.2.4 Discounting Approaches

Exponential (classic) discounting is the approach traditionally used by economists and engineers. When exponential discounting is employed, costs and benefits occurring several decades into the future, even dam decommissioning cost, have practically no influence on the initial investment decision [10]. Projects can be economically justified without sediment management, but this can lead to integrational inequity. Several new discounting approaches have been described in recent years. Figure 3-1 illustrates the temporal differences across a selection of discounting approaches over 150 years. Arguably, these new discounting approaches may better represent future economic uncertainty, and sustainability considerations [162]. As a group, these new discounting techniques may be better suited for analyzing long-lived infrastructure and environmental investments. Many of these new discounting approaches result in declining discount rates (DDRs) over time. DDRs are more appropriate than constant discounting for reservoir economic assessment, climate change issues or other projects with intergenerational dimensions [159, 161]. DDRs have also been used by World bank group projects [19].

Among the nine discounting approaches depicted in Figure 3-1, three are investigated in the case study section of the chapter: exponential, hyperbolic, and inter-generational. The equations expressing these discounting approaches, as well as a brief description of each, are provided below.

Discounting future benefits or costs by a fixed rate, for each unit of time, is the basis of exponential discounting. However, as mentioned earlier it can be problematic and inappropriate for investments that are to be judged over longer periods of time since future generations will bear costs (or benefits) from actions of previous generations [167].
Figure 3-1: Different Types of Discounting Approaches Available in the Reservoir Sedimentation Economic Model (RSEM), Discount Rate=2.5% (Harpman and Piper 2014)

Exponential discounting:

\[ W_t = \left( \frac{1}{1+r} \right)^t \]  

(3-1)

where:  
\( W_t \) is the discount factor or weight at time (t)  
\( r \) is the (constant) discount rate  
\( t \) is a time period index

More generally, the rate at which people discount future benefits and costs decline as the length of the delay increases [168]. Hyperbolic discounting is an alternative discounting approach that decreases the rate of discounting as the delay occurs further in the future. Hyperbolic discounting will generally discount future benefits and costs more than exponential discounting for short delays, and less than exponential discounting for long delays [168].
Hyperbolic discounting:

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

where: $w_t$ is the discount factor or weight at time ($t$)

The parameter $h>0$ controls the effect of time perception, and $k>0$ influences the degree to which the hyperbolic discount factor differs from the exponential discounting [162].

In the future, some natural resources may not exist anymore or changes in their quantity/quality will affect their intrinsic value [167].

Preferences can change over time, and this characteristic makes it difficult for the analysts to assess whether current generations’ preferences reflect those of communities that are not born yet [167]. An alternate method of incorporating intergenerational impact is to consider the timespan of future generations. Intergenerational discounting accomplishes this by requiring two different discount rates and an assumed generation timespan [162, 169].

Intergenerational discounting:

$$W_t = \left(\frac{1}{1+r}\right)^t + \left[\frac{1}{1+r_{fg}}\right]^{\left(\frac{1}{1+r_{a}}\right)^{t-1}}$$

where:

- $W_t$ is the discount factor or weight at time ($t$)
- $r_a$ is the present generation annual discount rate
- $r_{fg}$ is the future generation annual discount rate
- $G$ is the assumed generation timespan
- $t$ is a time period index
- $\Delta$ is ($\frac{1}{1+r}$)/($\frac{1}{1+r_{fg}}$)

### 3.2.5 Decommissioning Fund

San Clemente Dam near Carmel, CA, filled with sediment and was decommissioned in 2015 due to dam safety and environmental concerns, and lack of project benefits. The dam was completed in 1921 and by 2008 was providing less than 5% of its original capacity. The California-
American Water Company (dam owner) had to ask the California Public Utilities Commission for a rate increase to pay their share of the dam removal cost ($49 million). The current generation (notably ratepayers) paid for the entire dam decommissioning cost but received little or none of the water storage benefits [170].

For existing reservoirs, some actions will have to be taken. In 2017, the Federal Advisory Committee on Water Information and its Subcommittee on Sedimentation approved a resolution on Reservoir Sustainability [171]. This resolution asked all Federal agencies to “…develop long-term reservoir sediment management plans for the reservoirs that they own or manage by 2030. These management plans should include either the implementation of sustainable sediment-management practices or eventual retirement of the reservoir.” In 2018, the U.S. Society on Dams adopted a similar resolution for owners of all dams and reservoirs [172].

One mechanism for financing eventual dam decommissioning is through a decommissioning fund. Such a fund would have a maturation date equal to the expected dam decommissioning year, based on the sedimentation rate and other assumptions. Annual contributions to the fund would be paid by project beneficiaries. It would be calculated as the cost of decommissioning (in present dollars) amortized over the remaining years of dam life. The decommissioning fund will approximate the cost of decommissioning in the year of dam removal. This fund could also serve to offset the cost of any emergency actions required as the dam and reservoir age.

For example, federal water projects are authorized for specific project beneficiaries who are responsible for a portion of project repayment through a cost allocation framework based on the “beneficiary pays” principle [173, 174]. Some portions of the project benefits (e.g., flood risk reduction, recreation, and fish and wildlife habitat) are often assigned to the American public. This framework could be extended to dam decommissioning annual fund contributions. Establishment
of a dam decommissioning fund could help achieve intergenerational equity to prevent future
generations from having to pay for dam decommissioning when they receive little or no project
benefits.

The concept of a dam decommissioning fund is similar to that used in other natural resources
extraction practices. The Surface Mining Control and Reclamation Act of 1977 (SMCRA)
provides that, as a prerequisite for obtaining a coal mining permit, an applicant must post a
reclamation bond to ensure that the regulatory authority has sufficient funds to reclaim the site in
the case the permittee fails to complete the approved reclamation plan [175].

An additional consideration is the comparison of the annualized cost of sustainable sediment
management to the annual contribution required to a decommissioning fund. If the comparison
indicates that the sustainable sediment management cost less than decommissioning fund
contributions, this bolsters the economic case for sediment management. This comparison also
presents an additional way to conceptually present objective economic analysis to key decision-
makers.

### 3.3 Case study

There are only a few widely available numerical models that can assist in the economic
analysis of reservoirs. These models simulate how different parameters affect reservoir operations
and forecast the consequences of different reservoir sediment management alternatives. The most
widely used is RESCON [176]; a more recent model was developed by Niu and Shah (2021) to
optimize for storage capacity while maximizing lifetime net benefits. A new model was developed
to support this thesis, the Reservoir Sedimentation Economics Model, RSEM, (Randle, T. J., T. L.
Gaston, and R. Anari. Reservoir sedimentation economics model (RSEM), U.S. Department of the
RSEM was applied to evaluate the economics of a new and existing reservoir for two general scenarios: without and with sediment management, while comprehensively accounting for all benefits and costs (upstream, downstream, and within the reservoir). The model computes net present value and a benefit-cost ratio for a range of discounting approaches. This chapter applied RSEM to evaluate and compare costs and benefits of sediment management alternatives for the case study reservoir.

A hypothetical western U.S. reservoir, called Muddy Reservoir, is considered for the case study. Muddy Reservoir is assumed to have the primary purpose of providing irrigation water to project lands. Other beneficial uses include flood control, municipal and industrial water supply, fish and wildlife, and recreation.

As emphasized earlier, a comprehensive treatment of benefits and costs is required for objective economic assessment of reservoir sediment management alternatives. All benefits and costs serving as inputs for the case study are estimated at a 2020 price level and reported in Table 3-1. The methods for determining detailed estimates of benefits and costs are beyond the scope of this study. The interested readers can apply these available references, [56, 149, 177-181].

The Exponential, Hyperbolic and Inter-generational discounting approaches were applied to compare economic results across the following reservoir management alternatives:

- Alternative 1: New dam and reservoir developed *without* sediment management; economic comparison metric is BCR.
  - Alternative 1a: Costs and lost benefits due to sedimentation are *not* accounted for as per the traditional approach.

---

1 The considered benefits and costs represent values for the 17 Western States. Depending on regions and reservoir sites, these values could be much higher or lower (Todd. L. Gaston, Bureau of Reclamation, personal communication 2022).
Alternative 1b: Costs and lost benefits due to sedimentation are accounted for as per new paradigm.

• Alternative 2: New dam and reservoir developed with sustainable sediment management; economic comparison metric is BCR.
  o Alternative 2a: Sluicing as sediment management technique.
  o Alternative 2b: Dredging as sediment management technique.

• Alternative 3: Existing dam and reservoir operated without sustainable sediment management; economic comparison metric is NPV.

• Alternative 4: Existing dam and reservoir operated with sustainable sediment management; economic comparison metric is NPV.
  o Alternative 4a: Sluicing as sediment management technique.
  o Alternative 4b: Dredging as sediment management technique.

Results for alternatives 1 and 2 are compared by BCR, as summarized in Table 3-2. For the case of existing Muddy Reservoir, cumulative NPV is compared for the alternative without sediment management (Alt 3) with the sediment sluicing alternative (Alt 4a) (Figure 3-2) and with the sediment dredging alternative (Alt 4b) (Figure 3-3). A summary comparison of results across all alternatives is presented in Table 3-3.

3.3.1 Discussion of Results

The results reported in Table 3-2 indicate that water projects achieve a higher BCR when the costs associated with sedimentation and dam decommissioning are unaccounted for. This is
## Table 3-1: The input data values used in the case study economic assessment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present reservoir age</td>
<td>0-year for new reservoir</td>
</tr>
<tr>
<td></td>
<td>30-year for existing reservoir</td>
</tr>
<tr>
<td>Reservoir elevation inputs</td>
<td></td>
</tr>
<tr>
<td>Top of live storage</td>
<td>1965.2 m (6447.5 ft)</td>
</tr>
<tr>
<td>Top limit of sedimentation</td>
<td>1962.9 m (6440.0 ft)</td>
</tr>
<tr>
<td>Recreation pool elevation</td>
<td>1959.8 m (6430 ft)</td>
</tr>
<tr>
<td>Normal W.S. elevation</td>
<td>1942.5 m (6373.0 ft)</td>
</tr>
<tr>
<td>Top of dead storage</td>
<td>1937.9 m (6358.0 ft)</td>
</tr>
<tr>
<td>Original streambed elevation</td>
<td>1916.3 m (6287.0 ft)</td>
</tr>
<tr>
<td>Reservoir elevation inputs</td>
<td></td>
</tr>
<tr>
<td>Total storage volume at top of live storage</td>
<td>25,768,500 m³ (20,950 acre-ft)</td>
</tr>
<tr>
<td>Dead pool volume</td>
<td>3,444,000 m³ (2,800 acre-ft)</td>
</tr>
<tr>
<td>Reservoir inflow characteristics</td>
<td></td>
</tr>
<tr>
<td>Mean Annual Reservoir Inflow</td>
<td>122,754,000 m³/year (99,800 acre-ft/year)</td>
</tr>
<tr>
<td>Standard deviation of mean annual inflow</td>
<td>6,308,670 m³/year (5129 acre-feet/year)</td>
</tr>
<tr>
<td>Original reservoir dimensions</td>
<td></td>
</tr>
<tr>
<td>Reservoir length at full pool</td>
<td>5.63 km (3.5 mi)</td>
</tr>
<tr>
<td>Reservoir surface area at full pool</td>
<td>120 ha (296 acre)</td>
</tr>
<tr>
<td>Reservoir average surface width at full pool</td>
<td>321.9 m (1,056 ft)</td>
</tr>
<tr>
<td>Boat ramp/marina #1 length from dam</td>
<td>4.5 km (2.8 mi)</td>
</tr>
<tr>
<td>Boat ramp/marina #2 length from dam</td>
<td>1.13 km (0.7 mi)</td>
</tr>
<tr>
<td>Dam characteristics</td>
<td></td>
</tr>
<tr>
<td>Dam type (drop down list)</td>
<td>Earth</td>
</tr>
<tr>
<td>Volume of dam material</td>
<td>995,450 m³ (807 acre-ft)</td>
</tr>
<tr>
<td>Hydraulic height</td>
<td>49.1 m (161 ft)</td>
</tr>
<tr>
<td>Dam crest length across river</td>
<td>234.7 m (770 ft)</td>
</tr>
<tr>
<td>Reservoir sedimentation characteristics</td>
<td></td>
</tr>
<tr>
<td>Annual storage percent loss</td>
<td>0.51 per year</td>
</tr>
<tr>
<td>Fine sediment portion (clay and silt)</td>
<td>70%</td>
</tr>
<tr>
<td>Reservoir sedimentation profile slope parameters</td>
<td></td>
</tr>
<tr>
<td>Delta topset slope factor</td>
<td>0.75</td>
</tr>
<tr>
<td>Delta foreset slope factor</td>
<td>6.0</td>
</tr>
<tr>
<td>Bottomset slope factor</td>
<td>0.1</td>
</tr>
<tr>
<td>Reservoir profile plotting interval</td>
<td>10</td>
</tr>
<tr>
<td>Predam river channel and degradation parameters</td>
<td></td>
</tr>
<tr>
<td>Channel sinuosity</td>
<td>1</td>
</tr>
<tr>
<td>Average bank full channel width</td>
<td>38 m (125 ft)</td>
</tr>
<tr>
<td>Average channel roughness (Manning's n coefficient)</td>
<td>0.022</td>
</tr>
</tbody>
</table>
### Table 3-1 Continued

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portion of bed material is armor size or coarser</td>
<td>15%</td>
</tr>
<tr>
<td>Armor layer thickness</td>
<td>0.15 m (0.5 ft)</td>
</tr>
<tr>
<td>Original channel slope reduced by a percentage to achieve a stable channel</td>
<td>95%</td>
</tr>
<tr>
<td>Reservoir benefits</td>
<td></td>
</tr>
<tr>
<td>Water storage capacity to yield</td>
<td>100%</td>
</tr>
<tr>
<td>Proportion of Consumptive Uses</td>
<td></td>
</tr>
<tr>
<td>Agricultural irrigation use</td>
<td>60%</td>
</tr>
<tr>
<td>M&amp;I water use</td>
<td>30%</td>
</tr>
<tr>
<td>Fish &amp; wildlife and other</td>
<td>10%</td>
</tr>
<tr>
<td>Benefits of consumptive uses</td>
<td></td>
</tr>
<tr>
<td>Agricultural irrigation use</td>
<td>$202,678/ Million m³</td>
</tr>
<tr>
<td>M&amp;I water use</td>
<td>$364,821 Million m³</td>
</tr>
<tr>
<td>Fish &amp; wildlife and other</td>
<td>$81,071 Million m³</td>
</tr>
<tr>
<td>Flood risk reduction</td>
<td>$32,429 Million m³</td>
</tr>
<tr>
<td>Hydropower production</td>
<td></td>
</tr>
<tr>
<td>Average annual energy production</td>
<td>0 MWh/yr</td>
</tr>
<tr>
<td>Average energy benefit rate</td>
<td>$0/ MWh</td>
</tr>
<tr>
<td>Annual hydropower benefit</td>
<td>$0/year</td>
</tr>
<tr>
<td>Recreation use benefits in present year</td>
<td></td>
</tr>
<tr>
<td>Present average, annual visitor days</td>
<td>26000 visitor days/year</td>
</tr>
<tr>
<td>Benefit per visitor day (NCS)</td>
<td>$45.06/day</td>
</tr>
<tr>
<td>Benefit dependent on all boat ramps/marinas</td>
<td>50%</td>
</tr>
<tr>
<td>Benefit reduction from loss of 1 boat ramp/marina</td>
<td>20%</td>
</tr>
<tr>
<td>Dam &amp; reservoir planning, design, and construction costs</td>
<td></td>
</tr>
<tr>
<td>Total construction cost</td>
<td>$108,000,000</td>
</tr>
<tr>
<td>O&amp;M costs</td>
<td></td>
</tr>
<tr>
<td>Annual OM&amp;R cost</td>
<td>$450,000</td>
</tr>
<tr>
<td>5-year recurring costs</td>
<td>$100,000</td>
</tr>
<tr>
<td>Design, construction, and contract cost additives</td>
<td></td>
</tr>
<tr>
<td>Increase for unlisted items</td>
<td>10%</td>
</tr>
<tr>
<td>Increase for mobilization and demobilization</td>
<td>5%</td>
</tr>
<tr>
<td>Increase for design contingencies</td>
<td>20%</td>
</tr>
<tr>
<td>Increase for procurement strategy</td>
<td>5%</td>
</tr>
<tr>
<td>Increase for overhead and profit</td>
<td>15%</td>
</tr>
<tr>
<td>Increase for construction contingencies</td>
<td>20%</td>
</tr>
<tr>
<td>Dam decommissioning costs and benefits</td>
<td></td>
</tr>
<tr>
<td>Dam removal unit cost</td>
<td>$3.9/ m³</td>
</tr>
<tr>
<td>Sediment management unit cost</td>
<td>$10.46/ m³</td>
</tr>
<tr>
<td>River diversion cost</td>
<td>$6,000,000</td>
</tr>
<tr>
<td>Coffers dam cost</td>
<td>$600,000</td>
</tr>
<tr>
<td>Salvage benefits</td>
<td>0</td>
</tr>
<tr>
<td>Other river restoration costs</td>
<td>0</td>
</tr>
<tr>
<td>Dam decommissioning cost</td>
<td>$221,611,905</td>
</tr>
<tr>
<td>Upstream sedimentation costs*</td>
<td></td>
</tr>
<tr>
<td>Deposition threshold for land impacts</td>
<td>0.91 m (3 ft)</td>
</tr>
</tbody>
</table>
Table 3-1 Continued

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit land devaluation cost</td>
<td>12,355 $/ha</td>
</tr>
<tr>
<td>Unit highway/railroad relocation cost</td>
<td>0 $/km</td>
</tr>
<tr>
<td>Unit fish &amp; boat passage cost</td>
<td>0 $/km/year</td>
</tr>
<tr>
<td>Downstream channel degradation costs</td>
<td></td>
</tr>
<tr>
<td>Minimum degradation threshold</td>
<td>0.61 m</td>
</tr>
<tr>
<td>Streambank protection factor</td>
<td>3</td>
</tr>
<tr>
<td>Unit cost of streambank protection</td>
<td>98.10 $/m³</td>
</tr>
<tr>
<td>Planned sediment design life</td>
<td>50 years</td>
</tr>
<tr>
<td>Project decommissioning age</td>
<td>91 years</td>
</tr>
<tr>
<td>Forced sediment management parameters:</td>
<td></td>
</tr>
<tr>
<td>Begin forced sediment removal (years after end of sediment design life)</td>
<td>10 years</td>
</tr>
<tr>
<td>Maximum portion of sediment inflow that will be removed in the year prior to dam decommissioning</td>
<td>50%</td>
</tr>
<tr>
<td>Forced fine/coarse sediment removal cost</td>
<td>10.46 $/m³</td>
</tr>
<tr>
<td>Sediment management alternative</td>
<td></td>
</tr>
<tr>
<td>Annual fine sediment removal</td>
<td>90%</td>
</tr>
<tr>
<td>Annual coarse sediment removal</td>
<td>75%</td>
</tr>
<tr>
<td>Sediment management capital cost before additives</td>
<td>$6,000,000 for sluicing</td>
</tr>
<tr>
<td>Equipment life</td>
<td>100 years for sluicing</td>
</tr>
<tr>
<td>Sediment management begins at dam age</td>
<td>2-year for sluicing</td>
</tr>
<tr>
<td>Fine sediment removal cost</td>
<td>0.65 (sluicing) $/m³</td>
</tr>
<tr>
<td>Coarse sediment removal cost</td>
<td>0.65 (sluicing) $/m³</td>
</tr>
<tr>
<td>water used for sediment management as % of capacity</td>
<td>0%</td>
</tr>
</tbody>
</table>

* Note: Here all listed upstream impacts are not discernible, but that may not be true for all reservoirs.

demonstrated by Alt 1a resulting in a higher BCR than Alt 1b across all periods of analysis and all discounting approaches. One implication of this result is that some existing projects that were economically justified by analyses omitting sedimentation and dam decommissioning costs might not in fact be economically viable. For example, when considering only exponential discounting, BCR for Alt 1a is 5% higher than that for Alt 1b over a 50-year POA, and 33% higher over a 100-year POA. If a project were marginally economically justified by an analysis that ignored the costs of sedimentation and dam decommissioning (i.e., the Alt 1a framework), then that project would
most likely not have attained economic justification by a comprehensive economic analysis (i.e.,
the Alt 1b framework).

Both sediment management alternatives for a new Muddy Reservoir (Alt 2a: sluicing, and
Alt 2b: dredging) have a lesser BCR than the comparable without sediment management
alternative (Alt 1b) over a 50-year POA, and a greater BCR than Alt 1b over a 100-year POA,
across all discounting approaches. This result is expected, as the sedimentation causes loss of
storage benefits and up- and downstream damages and costs due to sedimentation take decades to
become pronounced. Moreover, the dam decommissioning cost for Alt 1b is not captured until at
91-year age. The case study results indicate that long POA is important to consider a
comprehensive accrued benefits and incurred costs. Short POA means we ignore impacts that
happens after the analysis period like impacts from severe sedimentation and dam
decommissioning. However, some present decisions can have an irreversible nature [182] and
these impacts are meaningful in alternatives comparison. As BCRs in Table 3-2 indicate
accounting for the full life cycle of a reservoir without sediment management (i.e., Alt 1b over a
100-year POA), sustainable sediment management is economically justified even for exponential
discounting. Furthermore, when compared to exponential discounting, the applied hyperbolic and
intergenerational discounting approaches continue to significantly increase BCR beyond 100
years.

For the 30-year-old existing reservoir case study alternatives (Alt 4a and 4b) sediment
management begins well before the dead storage is exhausted. The benefits and costs are
discounted using Exponential, Hyperbolic and Intergenerational discounting approaches.
Table 3-2: Benefit cost ratios of without and with sediment management alternatives for the new Muddy Reservoir

| Alternative / POA (years) | Discounting approach |  |  |
|---------------------------|-----------------------|-----------------|-----------------|-----------------|
|                           | Exponential           | Hyperbolic      | Intergenerational |
| Alt 1a: Without sediment management (ignoring sedimentation and dam decommissioning costs) |  |  |  |
| 50                        | 1.55                  | 1.66            | 1.9             |
| 100                       | 1.94                  | 2.52            | 3.04            |
| 200                       |                       |  |  |
| 300                       |                       |  |  |
| Alt 1b: Without sediment management (considering sedimentation and dam decommissioning costs) |  |  |  |
| 50                        | 1.48                  | 1.58            | 1.81            |
| 100*                      | 1.46                  | 1.31            | 1.36            |
| 200                       |                       |  |  |
| 300                       |                       |  |  |
| BCR remains constant after dam Decommissioning, when dam age = 91 |
| Alt 2a: With sediment management (sluicing) |  |  |  |
| 50                        | 1.37                  | 1.47            | 1.68            |
| 100                       | 1.71                  | 2.2             | 2.64            |
| 200                       | 1.82                  | 3.03            | 3.66            |
| 300                       | 1.83                  | 3.55            | 4.18            |
| Alt 2b: With sediment management (dredging) |  |  |  |
| 50                        | 1.26                  | 1.34            | 1.49            |
| 100                       | 1.51                  | 1.84            | 2.1             |
| 200                       | 1.59                  | 2.34            | 2.66            |
| 300                       | 1.6                   | 2.61            | 2.91            |

* Dam decommissioned at dam age of 91; year

As illustrated by Figure 3-2, from analysis year 0 through 40 (dam age 30 through 70), without sediment (Alt 3) is only marginally more economic than with sediment management sluicing (Alt 4a). By the time of dam decommissioning at age 91, however, the NPV for Alt 4a significantly increases relative to Alt 3 across all discounting approaches. By analysis year 270, NPV for Alt 4a under hyperbolic and intergenerational discounting substantially increase (2 to 3 times higher) relative to exponential discounting. Regardless of discounting approach, comprehensive economic analysis for our case study reveals sediment management as the
preferred economic alternative to without sediment management. The POA needs to be long enough to account for dam decommissioning and lost project benefits.

Figure 3-2: Net present values of Alt 3 and Alt 4a using the selected discounting approaches for the existing Muddy Reservoir; the hatch mark on the x-axes after analysis year 100 indicates a gap of 150 years

Figure 3-3 shows that the sediment dredging alternative (Alt 4b) is less economic than without sediment management (Alt 3) across all discounting approaches, until dam decommissioning at age 91. However, NPV for Alt 4b significantly increases after dam decommissioning, relative to Alt 3. As in the case of sediment sluicing, the NPV associated with dredging substantially increases over the long-term using hyperbolic and intergenerational discounting.
For both new and existing reservoirs, case study results indicate that any additional costs associated with sustainable sediment management are more than offset by the preserved economic benefits, avoided up- and downstream sedimentation costs, and avoided dam decommissioning costs. In short, sediment management was found to have greater economic value for our case study than without sediment management regardless of reservoir age, sediment management technique, or discounting approach. This finding may also be true for other reservoirs, but site-specific analysis would be required.
For reservoirs without sediment management, a certain percentage of project benefits could be transferred each year into a dam decommissioning fund. With a constant transfer percentage, the amount of benefits transferred each year would decrease in proportion to declining water storage benefits. Thus, the first generation receiving water storage benefits would pay more than subsequent generations. The annual payment to the dam decommissioning fund was calculated based on Alt 1b (without sediment management while considering all costs and lost benefits due to sedimentation). The calculation indicates that an annual contribution to the decommissioning fund of 9% of annual project benefits would fully fund the dam decommissioning cost at the year of dam removal.

As illustrated theoretically in Figure 3-1, and empirically in Figures 3-2 and 3-3, modeling results are highly sensitive to the choice of discounting approach. Exponential discounting, even when employing a historically low discount rate of 2.5%, tends to produce economic results that favor the present generation over future generations. In contrast, intergenerational and hyperbolic discounting produce significantly greater BCR (Table 3-2) and NPV (Figures 3-2 and 3-3), especially beyond analysis year 100.

A comprehensive economic analysis of all costs and benefits is necessary to determine the economic viability of sediment management. Extending the life of a reservoir through sediment management increases the project benefits and helps to achieve intergenerational equity. The case study modeling results for alternatives without and with sediment management are compared in Table 3-3.
### Table 3-3: Comparison of without sediment management and with sediment management for new and existing (30-year-old) Muddy Reservoir

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reservoir status</th>
<th>Without sediment management</th>
<th>With sediment management (sluicing/dredging)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits and costs</td>
<td>New</td>
<td>Upstream and downstream sedimentation costs, dam decommissioning cost, sediment management cost, and reduced benefits are considered based on the case study project. These costs and benefits are modeled based on the inputs reported in Table 3-1.</td>
<td></td>
<td>Benefit-cost analysis to determine economic feasibility of constructing a new reservoir, indicated by BCR&gt;1</td>
</tr>
<tr>
<td></td>
<td>Existing</td>
<td></td>
<td></td>
<td>Economic analyses by comparison of net present value or least-cost to determine the most-economic way forward</td>
</tr>
<tr>
<td>Discounting approach</td>
<td>New/existing</td>
<td>The Exponential, Hyperbolic, Inter-generational discount approaches are considered. The base discount rate is 2.5%. All other required parameters are applied from (Harpman and Piper 2014).</td>
<td></td>
<td>The impact of discount rate is distinct for without and with sediment management alternatives. Declining discounting approaches advocate intergenerational equity.</td>
</tr>
<tr>
<td>Reservoir life</td>
<td>New</td>
<td>After 90 years, the reservoir's outlet becomes too difficult to maintain due to sedimentation, forcing the dam to be decommissioned. The cost of dam decommissioning is taken into account, as are the lost project benefits. A new, replacement project could be considered under a separate economic analysis (BCR&gt;1)</td>
<td>Sedimentation is controlled by including sediment management, allowing the reservoir to have a useful life of more than 300 years. The reservoir benefits are expected to last at least several generations.</td>
<td>Sediment management is effective way to extend the reservoir life. The reservoir can supply water and economic benefits not only for the present generation but also several generations in future.</td>
</tr>
<tr>
<td></td>
<td>Existing</td>
<td>At the dam age of 90 years (60 years-hence) the reservoir's outlet becomes too difficult to maintain due to sedimentation, forcing the dam to be decommissioned.</td>
<td>Sedimentation is controlled by including sediment management, allowing the reservoir to have a useful life of more than 300 years. The longer the delay in implementing sediment management, the greater reduction in benefits over long-term</td>
<td></td>
</tr>
</tbody>
</table>
3.4 Conclusion

Continuous sedimentation reduces a reservoir’s storage capacity over time, causes finite reservoir life, and negatively impacts both upstream and downstream river reaches. Sediment management extends the useful life of reservoirs, providing continued economic production and social well-being for future generations. Lack of sediment management results in dam decommissioning and a financial burden on future generations to meet their water demands. A need exists to develop policy, legislation, and regulation to advance sustainable sediment management. This chapter introduced a new economic paradigm in the evaluation of water resource projects, particularly reservoirs, to evaluate both new and existing reservoir construction and management plans. Historical analyses overlooked the near term and continuous economic impacts of sedimentation and relied on the effects of exponential discounting over insufficient periods of analysis to minimize or omit significant future costs. This new paradigm considers important sedimentation effects that were not previously considered by traditional approaches due to a lack of information and understanding. Key aspects of this new economic paradigm are summarized below.

– Reservoir sediment management operation can be included at new and existing reservoirs; the timing for sediment management implementation can be informed by an economic analysis.

– Reservoir sedimentation impacts are not limited to the reservoir itself. Both upstream and downstream impacts have environmental, social and economic consequences. Economic analyses should consider all benefits and costs. Moreover, any lost benefits should be accounted for.
The case study indicates that sediment management is economically preferred to the costs associated with sedimentation and the eventual dam decommissioning, regardless of discounting approach. We suspect this outcome would be true for many water storage reservoirs. If a dam is decommissioned, replacement reservoir storage (under a separate economic analysis and justification) would be necessary to maintain past project benefits. The environmental and economic analyses for a new replacement reservoir would have to account for sustainable sedimentation management or impacts and its associated costs and reduced benefits.

As reservoir storage space is displaced with sediment, the remaining storage space is necessarily an exhaustible resource. The value of an exhaustible resource is not constant. The value of reservoir storage capacity will increase over time as the capacity is diminished by sedimentation. This, however, will not be considered in this thesis.

For existing reservoirs, some actions will have to be taken. Present beneficiaries should pay for either sediment management or any emergency sediment management and eventual dam decommissioning through a decommissioning fund.

The choice of a discount rate has a significant impact on the BCR and NPV. The discount rate must be quite low to reflect any serious responsibility to intergenerational equity and sustainability. The alternative discounting approaches (e.g., declining discount rate) should be considered.
4 CASE STUDY HYDRAULIC MODELING

This thesis considers a case study to illustrate reservoir sedimentation impacts through a hydraulic simulation and economic assessment. The hydraulic simulation using SRH-1D is presented in the current chapter, and the economic assessment using RSEM will be presented in the next chapter. Figure 4-1 illustrates a flow chart consisting of the main parts of the hydraulic simulation.

4.1 Case Study Description

Paonia Dam and Reservoir are located 16 mi northeast of Paonia, Colorado, on Muddy Creek. Development of the Paonia Reservoir was authorized in 1956 as a participating project within the Colorado River Storage Project [183] and commissioned in 1962. The dam is an earthen fill structure with a total initial capacity of 20,950 acre-ft. It includes a primary vertical intake (about 70 ft high) on the right abutment to provide irrigation water, and an uncontrolled emergency spillway (90 ft higher). The Paonia reservoir provides irrigation water for 15,300 acres of land in the vicinity of Paonia and Hotchkiss [184]. Since 1962, nearly 25% of the reservoir’s original capacity has been lost to sediment deposition, leaving less room to capture water for storage or flood prevention [185, 186]. In 2010, the primary intake at Paonia Dam became partially blocked with sediment and debris, impairing water delivery [187].
Case study: Paonia Reservoir

1. Hydraulic Modeling

- Historical operation
- Flow and sediment input data
- Duration: 1962-2020
- Used Code: SRH-1D

Model Calibration

Adding low-level gate

New Operation

Without Sediment Management
With Sediment Management

Sensitivity Analyses

2. Economic Modeling

Figure 4-1: A Flow Chart Consists of Main Parts of Hydraulic Simulation of the Case Study (Paonia Reservoir)
Following the 2010 blockage, operations were changed to include drawing the reservoir to lower levels in the early spring and using high spring runoff flows to sluice and flush suspended sediment through the primary intake before closing the gates to refill the pool for the irrigation season [128]. In late-October 2014 the reservoir dead pool had completely filled with sediment [188]. Figure 4-2 shows the primary intake at Paonia Dam during construction in 1961 (a) and during operation in 2014 (b, c, d) that deposited sediment above the intake sill [189].

Figure 4-2: The Primary Intake at Paonia Dam: a) During Construction in 1961, b) During Operation in 2014, c) Cleaning Sediment and Woody Debris from the Intake Structure in 2014, d) the Primary Intake Surrounded by Deposited Sediment [189]
4.2 Previous Paonia Reservoir Modeling

Kimbrel and Greimann (2016) simulated two sets of one-year operational scenarios in the Paonia using SRH-1D [128]. The first set simulates a Spring sluicing through the primary intake, and the second set is for Fall flushing drawdown through the primary intake. Both Spring and Fall drawdowns are composed of different sub-scenarios. The Spring sluicing scenario captured different sluicing time durations, while the Fall flushing drawdown scenario examined different equilibrium water surface elevations, whether the reservoir is completely drawn down or kept 10 ft above the primary intake.

Results showed that keeping the reservoir drawn down in the Spring will allow higher inflows to pass higher concentrations of sediment through the reservoir, which is likely more efficient than flushing reservoir sediments in the Fall with lower flows. However, keeping the reservoir drawn down too long for reservoir sluicing increased the possibility of an incomplete fill. Fall draw down showed little relative effect on the amount of sediment released for all water surface elevations.

The SRH-1D model was updated to incorporate reservoir operations rules for simulation of Paonia Reservoir by Huang et al. (2019) [127]. They used SRH-1D to simulate the reservoir sediment sluicing process during 2016, a short-term drawdown simulation, as well as a 20 years simulation using the primary intake. The results indicated that Spring sediment flush or “sluicing” is a helpful method to pass and remove sediment from Paonia Reservoir. Most sediment erosion occurs during the spring flush when the reservoir water surface elevation is still low.

For the purpose of this thesis, a long-term Paonia operation is needed to investigate the impact of reservoir sediment management implementation that extends through potential dam commissioning. The following sections describe calibration and new operation simulations for the case study for the period 1962 to 2020.
4.3 Calibration

The calibration effort simulates discharge through the primary intake and emergency spillway (current Paonia condition). The updated SRH-1D model by Huang et al. (2019) that includes the reservoir operation rule was applied for this case.

The following are the reservoir operation rules:

1. For each Julian calendar day of a year, the minimum and maximum reservoir releases associated with reservoir water level are needed.
2. Reservoir releases are limited by the primary intake and emergency spillway capacities.
3. Changes in simulated releases are limited by a “ramping rate” to avoid numerical instability. The reservoir release was increased or decreased at a rate of no more than 100 cfs/hr.

The historical daily water surface elevations (WSE) that fulfill the reservoir operation rules are shown in Figure 4-3 and were obtained from the USGS, PAONIA RESERVOIR 09131495 station, with records available since 1991 [190]. The historic elevations show water levels almost above the primary intake elevation (5358 ft), the lowest possible drawdown elevation, and that sediment management was not a priority. The WSE drawdown happened only during irrigation season in July, August, September [127]. We used average daily WSE in the model.

Huang et al. (2019) derived suspended-sediment rating curves using sampled data from 2013 to 2015 [127]. Equation 4-1 is the rating curve relation, and Table 4-1 presents the coefficients.

\[ C_s = a Q^b \]  

Where \( C_s \) is the sediment concentration (mg/l), \( Q \) is the flow discharge (cfs), and \( a \) and \( b \) are sediment rating curve coefficients given in Table 4-1.
Figure 4-3: Historical Paonia Water Surface Elevation at USGS 009131495 Station; Primary Intake Elevation at 6358 ft (----), [190]

Table 4-1: Sediment Rating Curve Coefficients Estimated through Sampled Data from 2013 through 2015, [188]

<table>
<thead>
<tr>
<th>Time Period</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-Peak</td>
<td>0.7346</td>
<td>1.1477</td>
</tr>
<tr>
<td>Pre-Peak and post July 4th</td>
<td>If $Q \leq 30$ cfs</td>
<td>8.9 E-08</td>
</tr>
<tr>
<td></td>
<td>If $Q &gt; 30$ cfs</td>
<td>345</td>
</tr>
</tbody>
</table>

Figure 4-4 shows two sets of rating curves, the initial planned sediment rating curve in 1956 [191] and the sediment rating curve (sampled data from 2013 to 2015) utilized by Huang et al. (2019) [127]. The initial planning expected that incoming sediment would fill the dead storage within 100-year [191]; however, it took only 50 years to completely deplete total dead storage [188].
Since the sediment rating curve can be used for reconstructing long-term sediment transport records or compensating for missing data in existing sediment transport records [192], we gradually raised the amount of incoming sediment from the initial sediment rating curve to Huang et al. (2019) relation until the observed bed profiles and sediment deposition volume was in a reasonable match with what Collins and Kimbrel (2015) [186] and Gaston (2019) [184] reported.

Furthermore, according to field studies, fine-grained material (silt, clay, and fine sand) contributes nearly all the reservoir sediment [187, 191, 193]. In this study, two grain sizes were considered: medium silt (average diameter 0.31 mm) and fine sand (average diameter 1 mm).
Table 4-2 summarizes all other applied conditions for upstream and downstream boundaries to calibrate the current operation of Paonia Reservoir simulation using SRH-1D. The Paonia Reservoir's observed and calibration model results are compared in Table 4-3, Figures 4-5 and 4-6.

### Table 4-2: Input Data Applied to Calibrate Paonia Reservoir Model Using SRH-1D

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Upstream Boundary Condition</strong></td>
<td>Observed discharge time series (1985-2020) at USGS gage called Muddy Creek Above Paonia Reservoir (MUDAPRCO) available in Colorado Department of Natural Resources [194], <a href="https://www.dwr.state.co.us/Tools/Outlets/MUDAPRCO?params=DISCHRG">https://www.dwr.state.co.us/Tools/Outlets/MUDAPRCO?params=DISCHRG</a> We applied the period of record to the simulation period by simple repetition.</td>
</tr>
<tr>
<td><strong>Sediment Size Gradation</strong></td>
<td>Medium silt (average diameter 0.31 mm) and sand (average diameter 1 mm) were chosen as sediment grain sizes. - Sedimentation study Paonia reservoir, Grand junction Colorado, 1956, report number: D-757 [191] - Western Engineers INC. 2006. Evaluation of Bureau of Reclamation Paonia Sediment Surveys. North Fork Water Conservation District [193] - Erdogan, Z. 2013. Technical Memorandum: Results of physical properties tests, Paonia dam and reservoir, Paonia project, west-central Colorado. Bureau of Reclamation, Referral number: MERL-2013-9 [187]</td>
</tr>
</tbody>
</table>
Table 4-3 compares observed [184] and simulated Paonia Reservoir storage loss. The dead storage (2440 ac-ft) is about 12% of total storage (20950 ac-ft). The accumulated deposited sediment in 2016 indicates the live and dead storage are depleting near the same rate. The simulated storage loss is higher than observed data, about 1.5 %, which can be tracked visually in Figure 4-5. The reservoir storage loss is degrading rapidly at the initial years of water impounding. In 2010, when the outlet works at Paonia Dam became partially blocked due to deposited sediment elevation, this rate is flattening for either observed or simulated storage loss.

Table 4-3: Observed and Simulated Storage Loss of Paonia Reservoir Simulation Using SRH-1D

<table>
<thead>
<tr>
<th>Survey Date</th>
<th>Observed (% of Total Storage)</th>
<th>Simulated (% of Total Storage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1969</td>
<td>736 ac-ft (3.5 %)</td>
<td>752 ac-ft (3.6 %)</td>
</tr>
<tr>
<td>1988</td>
<td>3489 ac-ft (16.7 %)</td>
<td>3596 ac-ft (17.1 %)</td>
</tr>
<tr>
<td>2002</td>
<td>4973 ac-ft (23.7 %)</td>
<td>5380 ac-ft (25.7 %)</td>
</tr>
<tr>
<td>2013</td>
<td>5174 ac-ft (24.7 %)</td>
<td>5720 ac-ft (27.3 %)</td>
</tr>
<tr>
<td>2014</td>
<td>5260 ac-ft (25.1 %)</td>
<td>5728 ac-ft (27.3 %)</td>
</tr>
<tr>
<td>2015</td>
<td>5400 ac-ft (25.8 %)</td>
<td>5727 ac-ft (27.3 %)</td>
</tr>
<tr>
<td>2016</td>
<td>5429 ac-ft (25.9 %)</td>
<td>5729 ac-ft (27.4 %)</td>
</tr>
</tbody>
</table>

Plotting the timewise change in the reservoir’s longitudinal bottom profiles can provide insight into the sedimentation process and delta advance pattern [40]. Observed [186] and simulated Paonia Reservoir longitudinal (invert) profiles since dam commissioning in 1962 are shown in Figure 4-6. This Figure presents the steady loss of storage capacity and the consistent increase in reservoir bed elevation at the vicinity of primary intake. By shifting some of the fine sand to silt class, delta profile could have been improved where there is more deposition on the delta and not enough in the bottom lake near the dam.

Moreover, the simulated bed is lower than observed in the upstream part of the delta. The available record of reservoir lake water elevations (USGS stream gage) expands from 1991-2020,
not 1962-2020. That means for about the first 30 years, there is no lake elevation. On the other hand, the downstream boundary condition is a combination of rating curve and operational rules (reservoir elevation for each Julian day, which this elevation needed to be constant for each day throughout all simulation years). Comparing the 1988 simulated and observed bed elevation indicates the delta forest is in front of the observed 1988 forest, or it proceeded more toward the dam. Thus, the lake elevation was considered lower than what it was (since lack of data). The same was repeated for 2002 and 2013 (lower elevation than actual).

The yearly drawdown of the reservoir, while effective for passing sediment through the dam outlet, likely increased deposition rates in the dead pool and caused the delta front to migrate downstream towards the dam, overfilling the dead pool and partially burying the intake tower of the outlet. In the vicinity of the primary intake, the simulated delta eroded back between 2002 and 2013. However, the observed delta moved forward between 2002 and 2013. There are two potential reasons; in 2010, the intake became partially blocked due to deposited sediment and wood debris and causing a reduction in primary intake capacity. However, in simulation, the sedimentation reached the primary intake elevation, and as a result, more sediment could have been released downstream. The simulation does not consider any potential intake clogging. Moreover, since the simulated reservoir elevation is above the primary intake and lower than the observed elevation, it causes pressure flushing condition that scours deposited sediment along the invert. Furthermore, the lower simulated elevation than observed elevation helped to more erosion there. Regarding the purpose of the thesis, these discrepancies can be neglected.
Figure 4-5: Observed and Simulated Paonia Reservoir Storage Loss since Dam Commissioning in 1962

Figure 4-6: Observed and Simulated Paonia Reservoir Longitudinal Profiles since Dam Commissioning in 1962
The calibrated model was used to simulate a hypothetical Paonia Reservoir consisting of primary intake, a low-level gate that will sluice sediment, and an emergency spillway. This model was compared to the actual Paonia project. This assessment helps know how the low-level gate may potentially extend the reservoir lifetime and to route incoming sediment.

4.4 Paonia New Operation

The reservoir’s hydrologic capacity is an influential element in selecting sediment management techniques. Hydrologic capacity is expressed as the ratio of storage capacity to incoming mean annual flow (C: I) [24]. It is the same as the retention time expressed in years for the reservoir at full capacity [19]. Paonia hydrologic capacity is 0.2. That means that on average, this reservoir can be filled 5 times a year. Sluicing is an effective alternative to manage sedimentation in such reservoirs.

Moreover, incorporating a low-level gate in Paonia Reservoir was previously suggested as a viable option to mitigate sedimentation by sluicing sediments. Earlier, this alternative was described as re-opening a conduit in the bottom of the primary intake structure that was used for the diversion of the stream during the initial dam construction. Upon completion of the construction, this diversion opening was filled with concrete [195].

Fortunately, downstream sluiced sediment helps restore a sediment balance across the dam. During sluicing, sediment concentration mimics the natural increase and decrease of sediment in the stream. The amount of sediment discharging through the structure is comparable to the amount of material entering the reservoir from upstream [195]. Significantly, assuming regular sluicing as part of the intended regular reservoir operation means that approval from the U.S. Army Corps of Engineers is not required [196]. Such a system should be considered for all new and applicable dams.
SRH-1D was applied to simulate two alternatives:

1. A without-sediment management alternative for the actual Paonia project
2. A with-sediment management alternative that is hypothetical, including a low-level gate installed at dam commissioning along with the existing drainage facilities.

Figure 4-7 schematically shows the primary intake, emergency spillway, and hypothetical low-level gate.

Reservoir sedimentation varies with several factors such as sediment incoming load, sediment transportation rate, sediment type, reservoir operation, reservoir geometry, and streamflow variability [197]. For these two alternatives the reservoir was operated as follows:

1. For each Julian calendar day of a year, the minimum and maximum reservoir releases associated with reservoir water level are needed.

2. Reservoir releases are limited by the primary intake, emergency spillway, and low-level gate capacities.

3. Changes in simulated releases are limited by a “ramping rate”, to avoid numerical instability. The reservoir release was increased or decreased at a rate of no more than 100 cfs/hr.

Available Mean monthly flows in MUDAPRCO station above Paonia Reservoir [194] indicate two frequent times for peak flows, the first week of May and last week of April, respectively. In this section, we assumed the peak flow occurred in the last week of April.
Figure 4-7: Schematic Location of Paonia Reservoir Outlets; Primary Intake, Emergency Spillway, and Hypothetical Low-Level Gate

The low-level gate will be opened during the rising limb of the hydrograph and closed during the falling limb of the hydrograph to improve sluicing efficiency. The objective is to release sediment-laden flow and impound clear water [19]. The stored clear flow is used to irrigate downstream land in July, August, and September (irrigation season downstream of Paonia Reservoir). Figure 4-8 schematically shows how openings work during a typical year for the with- and without sediment management alternatives. The without sediment management alternative has no low-level gate. In this condition, the water surface is even lower than the historic water surface.
in Paonia Reservoir (Figure 4-3). Emergency spillway releases excessive water during refilling for either of alternatives. Figure B-2 (Appendix B) shows simulated water surface elevation.

Figure 4-8: The Time of a Year Low-Level Gate, Primary Intake and Emergency Spillway Work for the With-and Without-Sediment Management Alternatives. The Low-Level Gate is Closed Last Week of April

Sediment load discharging downstream in each month for the two alternatives are presented in Figure 4-9. In this figure the low-level gate closes in last week of April to refill the reservoir.
while the peak flows frequently occur in May. This is the reason why peak incoming flow happens later than peak in sediment load transported downstream.

Figure 4-9 (a) shows the downstream discharge of sediment of the two alternatives. Sediment volume released downstream in the without sediment management alternative is comparatively low and limited to that which is discharged through the primary intake. It takes about 50 years for the dead storage to fill up in the without sediment management operation. As shown in Figure 4-9 (b), the primary intake will pass more sediment downstream as the dead storage depletes. Nevertheless, this delay in passing sediments downstream or deposited sediments in the reservoir storage means shortening the reservoir lifetime. The useful life of Paonia is currently severely limited without sediment management, which will be further discussed in Chapter 5.

The opened low-level outlet at high spring flow while the reservoir is drawn down simulates a river, passing inflowing sediment through the dam outlets [198]. This is the case for Paonia with the low-level gate. The results of 58-year Paonia simulation (1962-2020) indicate the low-level gate is an effective way to pass incoming sediment from early years and the primary intake passes incoming sediments downstream mostly after depleting dead storage. The annual reservoir sedimentation in without-sediment management alternative is 45% more than with-sediment management alternative. The percentage of total storage remaining, and percentages of live and dead storage depletion have been added in Appendix B (Figure B-1).
Figure 4-9: Sediment Load Passing Downstream of With-and Without Sediment Management Alternatives in Different Time Interval a) 1-5 years and b) 46-50 years from Dam Commissioning
4.5 Sensitivity Analyses

4.5.1 Low-level Gate Size

As indicated in section 4.4, a conduit in the bottom of the primary intake structure used for diversion of the stream during the initial dam construction is considered as the low-level outlet in this thesis. The outlet diameter is 11ft that would be large enough to pass peak flows [195]. This is available size, but two other diameters are evaluated to examine impact of conduit size on the time needed to empty the reservoir and effectiveness on sediment removal. Figure 4-10 indicates how smaller or larger low-level gates compared to the original size (11 ft) impact on required time to empty the reservoir. The difference would be 17 hours sooner or 1.5 days longer to empty the reservoir for the smaller and the bigger outlets, respectively. Since the emptying time is so small, simulations of sediment management with other gate sizes were not performed. The existing gate, if not been plugged, could have been considered at the outset.

![Figure 4-10: Impact of Low-Level Gate Size on Required Time to Empty the Reservoir](image)

Figure 4-10: Impact of Low-Level Gate Size on Required Time to Empty the Reservoir
4.5.2 When the Low-Level Gate Closes

Available Mean monthly flows in MUDAPRCO station above Paonia Reservoir [194] indicate two frequent times for peak flows: the first week of May and last week of April, respectively. This section investigates the sensitivity of deposited sediment to the when low-level gate closes. The section 4.4 presents the results when the low-level gate is closed in last week of April. In this section the low-level gate is closed in first week of May.

Sediment load discharging downstream in each month for the different closing-time are presented in Figure 4-11 (Figure 4-11-b period scale is different from Figure 4-9-b to illustrate years that peak flow occurs in May). Since the highest flow frequently occurs later, the delay in closing low-level gate would be helpful to increase sluiced sediment volume in most years. Hence the deposited sediment volume would be less. Table 4-4 shows the difference in deposited sediment between considered operation alternatives.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Description</th>
<th>Annual Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Sediment Management</td>
<td>Low-level gate is closed in first week of May</td>
<td>48.2 ac-ft</td>
</tr>
<tr>
<td>With Sediment Management</td>
<td>Low-level gate is closed in last week of April</td>
<td>57.3 ac-ft</td>
</tr>
<tr>
<td>Without Sediment Management</td>
<td>No low-level gate</td>
<td>84.4 ac-ft</td>
</tr>
<tr>
<td>Historical Operation (last survey)</td>
<td>No low-level gate</td>
<td>101 ac-ft</td>
</tr>
</tbody>
</table>

(Alexander Funk 2019)
Figure 4-11: Sediment Load Passing Downstream of With Sediment Management Alternatives in Different Time Interval a) 1-5 Years and b) 35-39 Years from Dam Commissioning
4.6 Extended Reservoir Life

The Paonia operation, as discussed in section 4.5, has potential to affect sedimentation rates. This section assumes constant annual sedimentation rate for the rest of reservoir life in considered alternatives and presents the potential years that the sluicing may postpone the dead storage depletion (sedimentation reaches the primary intake elevation). Figure 4-12 compares the percentage of dead storage depletion within 100 years, since dam decommissioning is assumed 100 years. The Figure illustrates sluicing (through the hypothetical low-level gate) significantly reduces the sedimentation rate, either closing low-level gate in last week of April or in first week of May. The accumulated sediment takes maximum 50% of dead storage in 100 years which means can extend reservoir life at least twice. Furthermore, the sedimentation of existing Paonia can exceed the dead storage geometry, and reach elevation higher than the primary intake elevation, within 100 years which is 40 years away.

4.7 Discussion of Results

In this chapter, the Paonia Reservoir performance was evaluated in the context of sediment management. Historical operation shows that sediment management was not a priority for the Paonia Reservoir. In this thesis, a low-level gate was hypothetically added to the reservoir to sluice the Spring flood while not changing the reservoir operation during the irrigation season or other important reservoir beneficial functions.
Figure 4-12: Percentage of Dead Storage Depletion for the Considered Paonia Operations

The results indicate that the current Paonia Project with only a primary intake and emergency spillway delays sediment transport downstream until the dead storage is full. The deposited sediment was planned to reach the primary intake elevation in 100 years, when it actually filled dead storage in 50 years. Sediment accumulation around the reservoir’s primary intake structure is expected to adversely affect the reservoir in ways that may impede the ability to control the reservoir consistent with historic operations and supply downstream demands, and in a way which causes detrimental downstream environmental impacts due to loss of environmental flows [199].

Numerical results illustrate that incorporating the low-level gate is an effective way to pass incoming sediment downstream from the early days of dam impoundment. The passed sediment
downstream in the sluicing alternative is sometimes greater than the incoming load, meaning that some portions of deposited sediment are washed downstream.

Based on recent surveys, the observed average annual rate of sedimentation has been 101 acre-feet per year [185]. However, the sedimentation rate is lower in the current simulation for either without-and with sediment management alternatives. The difference between the historical reservoir operation and the simulated operation, which includes more frequent reservoir drawdown than historical and attention to peak flow time to minimize trapped sediment, can be assumed as main reasons of this difference. The annual sedimentation rate for without sediment management operation is 84.4 ac-ft compared to 57.3 ac-ft for the with sediment management alternative (closing the low-level gate in the last week of April). The deposited volume of sediment can be decreased by monitoring the possible peak flow time and keeping the low-level gate open to pass high incoming flow downstream. As in section 4.5.2, the result showed this could be a successful operation to reduce deposited volume (48.2 ac-ft annual sedimentations when low-level gate closed on the first week of May). However, it is crucial to notice the needed water for summer in selecting the appropriate time to close the gate. The current simulations meet required water for summer irrigation.

Furthermore, constant annual sedimentation rate assumption, in section 4.6, indicates sluicing sediment management could prolong the reservoir life at least twice by postponing dead storage depletion. In recent years, reaching sedimentation to the primary intake elevation has been interrupting the intake function and deserves another comprehensive study to determine the sensitivity of reservoir facilities to sedimentation.
The presented results are concluded under some assumptions such as:

- Repeated inflow hydrograph records due to lack of data: since this thesis is focusing on preserving water storage and not quantifying water supply and demand. This assumption would not impact the results of alternatives comparison.

- Downstream sediment management impact: the amount of sediment discharging through the sluicing structure mimics the natural increase and decrease of sediment in the stream and since nearly all sediment discharges are re-introduced into (i.e., discharged into) the river below the dam, the released sediments downstream may not make environmental issues. However, this thesis did not simulate downstream impacts.

Evaluation of a reservoir requires hydraulic and sedimentation analyses to model physical attributes and economic analysis to model benefits and costs. The available reservoir economic assessment models lack integration with a physically based model to evaluate a reservoir performance. We are not aware of any existing investigations that combined physically based computer modeling of sediment management with economic analyses. Hence, the next chapter will proceed economic analysis with the results from the hydraulic simulation to determine the feasibility of extending the useful life of the case study reservoir.
5 CASE STUDY ECONOMIC MODELING

5.1 Published Reservoir Economic Simulation

The economic assessment of reservoirs has gained attention in recent years. Morimoto and Hope (2004) applied a 100-year economic analysis to the Three Gorges project in China by incorporating environmental and social issues [200]. Kibler et al. (2012) presented a qualitative data visualization tool called Integrative Dam Assessment Model (IDAM) to evaluate dams or management options based on economic impacts [201]. Tabios (2018) implemented 50-year economic analysis to compare a single-high dam to nine low-dams construction scenarios in Philippines [202]. A 50-year ex-post analysis was applied for Samanalawewa hydroelectric reservoir plant in Sri Lanka in 2018. The project resulted in a negative net present value due to adverse environmental and socioeconomic issues [203]. Costs of sediment management in catchment-level due to land use and land cover changes versus flushing deposited sediment in a reservoir were compared by Shrestha (2021) in Mekong River Basin in Southern Laos [204]. Niu and Shah (2021) developed a model to determine the size of the initial reservoir capacity of the proposed Sambor dam in the lower Mekong River basin while maximizing lifetime net benefits, considering different sediment removal efficiencies and dam decommissioning costs [7].

There are only two available numerical models that can assist in the overall economic analysis of reservoirs. These feasibility-level models simulate how different parameters affect reservoir
operations and forecast the economic consequences of different reservoir sediment management alternatives. The most widely used is the Reservoir Conservation Model (RESCON) designed for pre-feasibility studies [176] to rank the economic performance of a selection of: no action, catchment management, flushing, hydro-suction (HSRS), dredging, trucking, by-pass, sluicing, density current venting, and options involving multiple techniques. A new model was developed that supports this work: the Reservoir Sedimentation Economics Model (RSEM) (Randle, T. J., T. L. Gaston, and R. Anari. Reservoir sedimentation economics model (RSEM), U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center, Denver, CO, Unpublished report).

RSEM can be applied to evaluate the economics of a new and existing reservoir for two general scenarios: without-and with sediment management, while comprehensively accounting for all benefits and costs (upstream, downstream, and within the reservoir). The model computes a net present value and a benefit-cost ratio for a range of discounting approaches (Exponential, Ramsey, Hyperbolic, quasi- Hyperbolic, Gamma, Weibull, Green Book, Intergenerational, Logistic). This thesis applied RSEM to evaluate and compare the costs and benefits of sediment management alternatives for the Paonia Reservoir. Furthermore, a comparison between RESCON and RSEM will be presented in section 5.3.2.

The drawback regarding available economic evaluation models is a discontinuity with the hydraulic simulation of reservoirs. The remaining storage due to sedimentation is a major outcome of hydraulic models and is a critical input to implement economic evaluation. While hydraulic simulation solves presented equations in section 2.2, these economic models may apply simplified empirical relations, assumptions, or user-based input data for reservoir sedimentation. That makes these analyses suitable for feasibility studies only, and require engineering judgment to interpret the results [205].
This thesis attempted to bridge this gap for the case study. This thesis uses simulated sedimentation results to drive the economic analysis models. The hydraulic simulation using SRH-1D from chapter 4 is combined with the economic assessment using RSEM in the current chapter. Figure 5-1 illustrates a flow chart consisting of the main parts of the economic assessment.

**Figure 5-1: Flow Chart the Economic Assessment of the Case Study (Paonia Reservoir)**
5.2 Model Description, Input, Assumptions

A complete list of parameters, values, and references used in the economic analysis is found in Table D-1 in Appendix D. Four assumptions were made:

1. For all alternatives presented here, the benefits and costs are converted to the base year ($2020) (personal communication with Todd. L. Gaston, Bureau of Reclamation) and discount rate 2.5% [206]
2. Storage loss due to sedimentation is imported from SRH-1D results.
3. Dam decommissioning for the Without sediment management alternative was set to 100 years. Section 5.2.1 evaluates this assumption.
4. The excess of mean annual runoff than initial storage (meaning water spilled through the emergency spillway) has zero benefit, as assumed by other researchers [142].

5.2.1 Dam Decommissioning Time Assumption

The decision to remove a dam is influenced by the costs of ongoing maintenance and repairs, particularly if the dam no longer serves its original purpose such as water supply, and recreation or provides few or no benefits.

Paonia Reservoir has operated for 60 years, and dead storage has completely filled to the elevation of the primary intake. To investigate decommissioning the dam after 100 years, eventual deposited sediment elevations and failure in the operation of the primary intake will be discussed here.

An SRH-1D run with 150 years duration was carried out. The deposited sediment elevations at the cross-section that includes the primary intake are presented in Figure 5-2 for different years (based on SRH-1D output interval). Figure 5-2 (a) shows the low channel (original river location).
The zoomed-in cross-section in Figure 5-2 (a) illustrates only the top 3 feet are open till the 90 years, and by 150 years, sediment has accumulated seven feet above the primary intake (the vertical opening of the primary intake is 7 feet).

However, the shape of the cross-section cannot be concluded using a one-dimensional model since parameters are averaged in a cross-section. Hence, we considered the average deposited sediment elevation at the cross-section as a criterion to determine how longer the primary intake may operate. In this thesis, the year that 50% of primary intake vertical opening is blocked due to sedimentation is considered the time for dam decommissioning, i.e., 100-year.

This decision can be justified by the observed condition of deposited sediment in Paonia. The North Fork River Improvement Association, in 2010 predicted the delta would reach the dam within the next ten to 20 years [199]. Furthermore, the reservoir drawdown in October 2014 revealed that the bottom lake elevation is 6 feet above the sill of the primary intake [186]. Because the dead storage was no longer available in the reservoir where sediment and debris could drop out, the sediment and debris stacked against the trash gates of the intake structure and adversely impacted operations [183]. Fire Mountain Canal Company and Northern Water Conservancy District crews began daily shifts removing the sediment and debris around the intake tower, as shown in Figure 5-3 [186]. Moreover, the concrete bulkhead is located internal to the frame of the intake structure, but periodic fall reservoir drawdown revealed that it is severely damaged. There is a substantial risk that a piece of concrete or the entire bulkhead could collapse, ruining the inside of the vertical shaft, causing further damage to the outlet works, potentially rendering it inoperable. Interruptions of service related to waterway failure is a potential source of substantial economic loss [207].
Figure 5-2: a) the Zoomed-in Area Around the Primary Intake, b) The Deposited Sediment Elevation at the Cross-Section Including the Primary Intake
If the primary intake becomes inoperable, the only other means of releasing water from the reservoir currently in place would be uncontrolled releases over the emergency spillway [183]. We did a separate SRH-1D run to find the reservoir condition if the primary intake is blocked. In this condition water surface remains at the elevation of the emergency spillway. The results indicated sediments settle down upstream end of the reservoir. The deposited sediment elevation in 2-year progresses toward boat ramp and causing the recreation benefit to vanish.
5.2.2 Considered Benefits and Costs

1. Upstream cost

Land devaluation, highway or railroad relocations, and fish and boat passage obstruction due to sedimentation are considered upstream costs in RSEM. The observed and numerical longitudinal bed profiles presented in Figure 4-6 indicate that in 2013, at least 2.5 ft sediment are deposited upstream from the reservoir. The economic model is calibrated with this data and assesses damage as upstream land devaluation cost.

2. Downstream cost

Clearer water released downstream is competent to carry sediment and causes downstream bed degradation until a new dynamic equilibrium is established. Dynamic equilibrium for a river channel can be defined as the condition where, over the long term, the river's sediment transport capacity is in balance with the upstream sediment supply. The river will continue to adjust its bed and banks in response to changing hydrologic and sediment supply conditions [77].

RSEM considers the Bureau of Reclamation’s reservoir degradation handbook [208], Computing Degradation and Local Scour handbook [209], and Bankhead and Simon (2015) [210] to compute annual downstream bed degradation depth and associated damage as presented in Appendix C.

3. Benefits/costs related to the without sediment management alternative

The existing primary intake’s gates have experienced problems and have not been upgraded since project construction, 60 years ago. The Paonia primary intake repair cost is estimated at $10,700,000 (2019 USD) [185], including repairing any damaged concrete, the trash rack, replacing damaged ladders and the air vent in the gate chamber and access shaft to keep the intake structure operable. This cost indicates one of the potential damages to the dam due to poor
managing sedimentation. Dam owners have not yet paid this cost; hence it is not taken into account in the current economic analysis. However, we will use it for further discussion.

4. Benefits/costs related to the with sediment management alternative

The capital cost to place a low-level gate consists of installing a low-level outlet to either route sediment through the reservoir basin or flush it out of the basin. Reopening the conduit in the bottom of the intake structure that was used for stream diversion during the initial construction would likely be the most cost-effective solution. This diversion opening was filled with concrete after the construction was completed. The reopening estimated cost would be $2,557,000 (2006 USD) [195]. Another option would be installing a new intake structure if reopening the previous construction diversion is deemed infeasible or inappropriate. This intake would be located adjacent to the existing one, placed at the elevation of the bottom of the existing intake drop structure. Total estimated cost is $4,950,000 (2006 USD) [195]. This thesis considers the higher cost as the capital cost of sediment management.

5. Reservoir operation benefits

**Irrigation:** Paonia Reservoir provides 14,000 ac-ft of water for irrigation downstream. Approximately 80 percent of Paonia irrigation water is applied to cropland and 20 percent to pastureland. The cropland consists of fruit orchards (apples, peaches, cherries, pears) and some smaller plots of vegetables [184, 211]. All Paonia Project irrigation water is diverted downstream through the Fire Mountain Canal.

The irrigation benefits are calculated as the difference in Net Farm Returns [199] 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). Dividing this irrigation benefit by the acre-feet of project irrigation water delivered yields the benefit per acre-feet of project irrigation water. Multiplying this value by total project irrigation deliveries yields the irrigation benefits provided
by the project. The computed irrigation benefits for Paonia Reservoir is $93.05 per acre-foot (2017 USD) [184].

**Recreation**: The annual economic benefits of recreation are estimated as the Net Consumer Surplus (NCS) of a recreation visit multiplied by total annual recreation visitation. A visit is equal to one day (12 hours). The 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 equals recreation consumer surplus of a visit under the With-Project condition minus recreation consumer surplus of a visit under the Without-Project condition. The With-Project condition assumes the presence of the dam, reservoir, and affiliated recreation facilities in their current condition, while the Without-Project condition assumes the absence of the dam and reservoir. 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 [184]. This thesis accounts for the effects of substitution.

The Paonia State Park offers hiking, camping, fishing, boating, and water sports. Boating is dominant recreation activity that is heavily dependent on water availability [199]. Paonia Reservoir has a water surface area of approximately 334 acres, and on average 26,000 annual recreation visits. Moreover, each recreation visit has a net consumer surplus of $42.42 (2017 USD) [184].

**Flood control**: The Paonia Reservoir has 2,280 ac-ft of capacity assigned to flood control and provides $9,841 (2017 USD) annual benefits [199].

The methods for determining detailed estimates of benefits and costs are beyond the scope of this study. The interested readers can apply these available references, [56, 149, 177-181].
Social impacts such as changes in income, employment, air and water pollution, health and satisfaction or any risk and life loss due to dam failure and flowing deposited sediment are not considered here.

5.2.3 Discounting

The considered benefits and costs must be discounted to make them temporally equivalent over different time periods. The employed discount rate depends on whether the benefits and costs are measured in real or nominal terms. Either real or nominal prices can be considered in making project assessments based on future time periods [156].

A real discount rate is adjusted to correct for the effect of anticipated inflation [212] and is approximately equivalent to subtracting the expected inflation from a nominal interest rate [156]. Under the real method of present value calculation, cash flows for all periods are expressed in constant dollars in time 0 or base year (in this case 2020) and discounted using the real discount rate (i.e., a discount rate which does not contain the effect of any expected inflation). The other alternative is forecasting the inflation rate for many years into the future over the long life of a water project and adjusting cash flows for the effect of inflation depending on the expected inflation. The net present value is consistent under both methods [213]. It is probably easiest to use real values, i.e., prices expressed in constant dollars. This would be what is applied for this thesis with 2.5% discounting rate.

In recent years new discounting approaches have attracted attention, but there is no agreement among economists for their use in water resource economic assessments [162]. Therefore, for this thesis besides exponential discounting, the Green Book, the hyperbolic and the inter-generational discounting approaches were employed for comparison. Additional detail about these approaches is presented in Table F-1 in Appendix F.
5.3 Alternatives Economic Assessment

5.3.1 New Paonia Reservoir Economic Assessment

Paonia Reservoir economic analysis includes the same alternatives described in section 4.4:

1. A without-sediment management alternative for the actual Paonia project
2. A with-sediment management alternative that is hypothetical including a low-level gate installed at dam commissioning along with the existing drainage facilities

Storage loss due to sedimentation associated with these alternatives are imported from SRH-1D results. The two alternatives are defined in RSEM using the indexed benefits and costs in Table D-1 in Appendix D. Table 5-1 compares Benefit Cost Ratios (BCRs) of alternatives discounted using selected discounting approaches. As presented in Table 5-1, BCRs for the majority of Period of Analysis (POA) are less than one, indicating that the new Paonia Project is not economically viable regardless of managing sedimentation either in 2020 or probably since 1962. It was mentioned in chapter 4 that the Paonia Project was a participating project within the Colorado River Storage Project [183] and not an independent water resource project. BCRs greater than one were possible only with sediment management and discount approaches that favor sustainability.

Moreover, BCRs of sediment management are greater than those without sediment management for all periods of analyses and discounting approaches. This demonstrates that with sediment management alternative can be more cost-effective than without sediment management alternative. This conclusion is under two assumptions; 1) additional cost due to primary intake maintenance (mentioned in section 5.2.2 – benefits/costs related to the without sediment management) is not incorporated into the without sediment management costs, and 2) the higher capital cost of incorporating the low-level gate (mentioned in section 5.2.2 – benefits/costs related
to the with sediment management) is taken into account. This assessment considers up-and downstream sedimentation damages and dam decommissioning costs. However, it is predictable that incorporating comprehensive incurred costs (such as increased maintenance cost) due to not managing sedimentation can worsen the economic viability for the without sediment management alternative.

Table 5-1: Benefit Cost Ratios of Without-and With Sediment Management Alternatives for the New Paonia Reservoir

<table>
<thead>
<tr>
<th>Alternative / POA (years)</th>
<th>Discounting Approach</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exponential</td>
<td>Green Book</td>
<td>Hyperbolic</td>
<td>Intergenerational</td>
</tr>
<tr>
<td>Without Sediment Management</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.62</td>
<td>0.57</td>
<td>0.67</td>
<td>0.88</td>
</tr>
<tr>
<td>100</td>
<td>0.64</td>
<td>0.6</td>
<td>0.6</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>BCR remains constant after dam decommissioning, when dam age = 100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>With Sediment Management (Sluicing)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.65</td>
<td>0.61</td>
<td>0.71</td>
<td>0.94</td>
</tr>
<tr>
<td>100</td>
<td>0.79</td>
<td>0.73</td>
<td>1.03</td>
<td>1.42</td>
</tr>
<tr>
<td>200</td>
<td>0.84</td>
<td>0.78</td>
<td>1.36</td>
<td>1.88</td>
</tr>
<tr>
<td>300</td>
<td>0.84</td>
<td>0.79</td>
<td>1.54</td>
<td>2.07</td>
</tr>
</tbody>
</table>

Although benefit cost analysis is expected to evaluate the economic performance of a new reservoir, the net present value (NPV) is also presented here to visually compare the differences between alternatives and discounting approaches. As Figure 5-4 (a) indicates, the NPV of without sediment management alternative is higher than with sediment management for about 30 years in exponential and 20 years for intergenerational approaches. This result is expected since the sedimentation causes storage benefit reduction, and up- and downstream damages that take time
to become pronounced while the sediment management capital cost incurred early at the time of construction. Eventually, increasing sedimentation and storage loss result in higher incurred costs and lower accruing benefits, resulting in greater NPV for the with sediment management alternative for the rest of the period of analysis. These results are independent of discount approaches. Figure 5-4 (b) shows the reservoir net present value can continue up to 300 years with a significant increase (even 4 to 5 times higher for inter-generational discounting) for with sediment management. In contrast, the cash flow stops after 100 years by dam decommissioning for without sediment management. Appendix E indicates contribution of each cost/benefit to net present value.

The case study results for the new Paonia Reservoirs indicate sustainable sediment management is economically viable compared to without sediment management. In other words, any additional costs associated with sediment management are more than offset by the preserved economic benefits, avoided up-and downstream sedimentation costs, and avoided dam decommissioning costs. The better performance of sediment management is independent of discount approaches. Nonetheless, the break-even point between discounted cost and benefit can be a function of the discount approach.

The break-even point indicates the year that the cumulative discounted benefits pay off the cumulative discounted costs (NPV=0) in payback period of the project. In other words, the year following the project payback period will see net profits or benefits to the project. The shorter a discounted payback period, the sooner a project or investment will generate cash flows to cover the initial cost [214]. For the Paonia Reservoir, this point is captured either with or without sediment management for Inter-generational approach and with sediment management for hyperbolic discount approach.
Figure 5-4: NPV Graphs of Without-and With Sediment Management (Sluicing) Alternatives for the New Paonia Reservoir; a) for 100 Years, b) for 300 Years. sed-mgt = Sediment Management. The Hatch Mark on the X-Axes After Year 110 Indicates a Gap of 90 Years.
5.3.2 Comparison With RESCON

As discussed in section 5.1, The RSEM and RESCON are two recent models for the economic assessment of reservoirs. The two models require data such as age, original and current live and dead storages, reservoir geometry, hydrology, sedimentation rate, and economic data related to reservoir operation and provide information about how the economic benefits and costs of a reservoir may change over time with sedimentation. The models can help identify the relative importance of these benefits and costs and where additional investigations would be useful. However, these models are different in major aspects that are summarized in Table 5-2.

This section compares without-and with sediment management (sluicing) alternatives using RESCON and RSEM applying exponential of 2.5% discount rate.

As presented in Table 5-2, there are discrepancies in RESCON and RSEM from considered benefits and costs in an economic analysis such as recreation benefits and up-and downstream costs. Figure 5-5 compares the NPV of RESCON and RSEM for the new Paonia Reservoir. The Figure includes three types of graph to improve comparability;

<table>
<thead>
<tr>
<th></th>
<th>Recreation</th>
<th>Up-and downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: RESCON- No recreation</td>
<td>Excluded</td>
<td>Excluded</td>
</tr>
<tr>
<td>B: RSEM- No up/downstream cost/ No recreation</td>
<td>Excluded</td>
<td>Excluded</td>
</tr>
<tr>
<td>C: RSEM</td>
<td>Included</td>
<td>Included</td>
</tr>
</tbody>
</table>
### Table 5-2: Major Differences Between RESCON and RSEM

<table>
<thead>
<tr>
<th></th>
<th>RESCON</th>
<th>RSEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sediment Management Alternatives</td>
<td>The user can have general comparison between without-and with sediment management. A particular sediment management alternative is simulated by specifying the annual removed sediment.</td>
</tr>
<tr>
<td></td>
<td>No action, catchment management, flushing, hydro-suction (HSRS), dredging, trucking, by-pass, sluicing, density current venting, and options involving multiple techniques</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Water Yield</td>
<td>RSEM applies a single user defined coefficient for ratio of yield to water storage capacity. This coefficient is constant in the period of analysis.</td>
</tr>
<tr>
<td></td>
<td>A relationship between water yield (water available for use) with a user defined reliability (probability of providing yield), reservoir capacity, hydrologic variability and distribution of annual flows is implemented in the model through the application of the Gould-Dincer method to determine the quantity of water that can be given economic value [176].</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Surface Area and Recreation Benefits</td>
<td>RSEM considers recreation benefits reduction over time as sedimentation continues to shrink the surface area. The user can define up to two boat ramp locations. RSEM assumes that reservoir boat ramps are no longer useable when the sedimentation level reaches the elevation of the recreation pool at the boat ramp. RSEM checks for this condition every decade.</td>
</tr>
<tr>
<td></td>
<td>Some benefits, such as recreation, do not degrade at the same rate as reservoir storage diminishes. The recreational benefit is function of reservoir surface area. RESCON does not consider degrading recreation benefit due to reservoir's surface area reduction.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Upstream sedimentation cost</td>
<td>The user can specify the reservoir sedimentation slopes of the delta topset and foreset to compute the reservoir longitudinal profile after each year of reservoir operation. Annual upstream aggradation is computed, and associated costs can be considered in economic analysis. Land devaluation, highway or railroad relocations, and fish and boat passage obstruction due to sedimentation are considered upstream costs in RSEM.</td>
</tr>
<tr>
<td></td>
<td>Coarse sediments settling upstream from the reservoir propagates the delta upstream and concludes decreasing in reservoir length. Such deposits upstream from the reservoir are not considered in RESCON (assumes the length of the reservoir is constant) [176].</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Downstream sedimentation cost</td>
<td>The model estimates the quantities and costs of rock rip rap required to prevent downstream bank erosion. The user can incorporate additional cost due to habitat degradation into the cost for streambank protection.</td>
</tr>
<tr>
<td></td>
<td>Downstream degradation cost due to sediment-hungry water is not incorporated in RESCON’s economic analysis.</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Discount Rate and Discount Approaches</td>
<td>RSEM allows discount rates between zero to 8.875% using discount approaches such as Exponential, Green Book, Ramsey, Quasi-hyperbolic, Hyperbolic, Intergenerational, Weibull, Gamma, and Logistic.</td>
</tr>
<tr>
<td></td>
<td>RESCON uses either a constant discount rate (Exponential discounting) or Green-Book declining discount rates over time [146]. The new version is intended to cover a variety of discount approaches.</td>
<td></td>
</tr>
</tbody>
</table>
The cost is relatively similar for the two economic scenarios A and B since additional cost such as upstream-and downstream costs are excluded. However, the scenarios A and B have different benefit. The calculated RESCON water yield for the case of sluicing is a function of available storage and annual volumetric water inflow in the reservoir which is reduced by the volume of water sluiced out of the reservoir [176]. The remaining water contributes to water storage benefit calculation in RESCON. However, during the non-irrigation season, no water is diverted into the Fire Mountain Canal downstream of Paonia resulting no irrigation related benefit.
to the reservoir managers [184]. This not diverted inflow does not contribute to RSEM benefit
calculation but does in RESCON. Hence, the impact of the water yield equation in RESCON
overestimates water storage benefit compared to RSEM benefit computation. This difference in
benefits causes a difference between NPVs as shown in Figure 5-5. However, defined RSEM
scenario C that includes the all costs and benefit causes the NPV be located in between scenarios
A and B.

For all scenarios, with sediment management outperforms without sediment management
except the early years. For the scenario B (blue line) that does not take advantage of water yield,
water storage benefits equal to the remaining storage, and not effected by incurred up-and
downstream cost, this point can go further in time, even up to 70 years. This can be a reason why
traditional economic analysis with limited period of analysis did not find sediment management
economically viable. Eventually, the NPVs of the with sediment management cross the without
sediment management alternative.

5.3.3 Existing Paonia Reservoir

The Paonia dam was closed in 1962 and has no remaining dead storage. Dredging
accumulated sediment around the primary intake is considered by consultants working on the
Paonia Reservoir as an immediate way to maintain the functionality of the dam [183]. This section
evaluates the viability of sediment dredging versus no action for the existing Paonia Reservoir.
Table D-1 in Appendix D presents dredging costs.

When considering sedimentation of existing reservoirs, no action eventually results in the
decommissioning of the dam and lost project benefits. NPV provides an intuitive and meaningful
metric for comparing alternatives for existing projects, allowing decision makers to identify the
alternative that maximizes net economic benefits. Figure 5-6 presents the cumulative NPV for the
dredging and no action alternatives. The NPVs for no action are greater than for dredging regardless of discounting approaches at the beginning of period of analysis. This outperformance is related to the capital cost of dredging and the annual cost of sediment removal. However, the economic benefits for which the dam was constructed are progressively lost if no action is taken and completely lost upon dam decommissioning. Eventually, the incurred dam decommissioning cost reduces NPVs dramatically. Because it occurs in the short future, this cost is not discounted as much as the discounted decommissioning cost for the new Paonia in the 5.3.1 section, particularly for declining discount rate approaches. The NPV associated with dredging substantially increases over the long-term using hyperbolic and intergenerational discounting.

For both new and existing case study results indicate sediment management was found to have greater economic value than without sediment management regardless of reservoir age, sediment management technique, or discounting approach. This finding may also be true for other reservoirs, but site-specific analysis would be required.

The historical choice to ignore the costs of dam decommissioning, because of discounting, meant there was no incentive for engineers to incorporate sediment management or plan for the eventual dam decommissioning. This approach also ignored the difficult predicament left to future generations. For many existing reservoirs, dam decommissioning due to reservoir sedimentation is only a few decades away and the discounted costs will be much more significant than for new reservoirs. Extending the life of a reservoir through sediment management increases the project benefits and helps to achieve intergenerational equity. Without sediment management, future generations will have to pay high dam decommissioning costs with previously diminishing benefits, plus pay high costs to develop a new water storage capacity probably at less desirable sites.
Figure 5-6: NPV of Dredging and No Action Alternatives for the Existing Paonia Reservoir; a) for 100 Years, and b) for 300 Years Dam Age. The Hatch Mark on the X-Axes Indicates a Gap of 90 Years.
5.4 Sensitivity Analysis

The NPV indicates the overall economic performance of a project or program. However, a considerable number of assumptions go into producing that single calculation. Sensitivity analysis examines the NPV results’ variability from the economic analysis to changes in critical assumptions. It identifies those input parameters (assumptions) that have the most significant influence on the outcome. In this thesis, parameters that were assumed or are influential on the reservoir’s economic assessment are examined to determine the sensitivity of the results and whether further inquiry is worthwhile to improve accuracy. All values are discounted at 2.5% using the exponential approach. Although sediment management can lengthen the reservoir life to centuries, only 100 years results are presented here due to limited space.

5.4.1 Dam Decommissioning

For any reservoir without sediment management, the dam will eventually require decommissioning. The decommissioning age for Paonia was determined to be 100 years in section 5.2.1. In this section, the impact of dam decommissioning cost incurring in 100-year is examined to find what value of dam decommissioning concludes without sediment management is better than with sediment management. Hence, three dam decommissioning costs are considered; a) base cost, presented in Table D-1 Appendix D, b) 50% decrease (0.5* base), and c) 100% increase (2*base).

Figure 5-7 indicates the sluicing sediment management for Paonia Reservoir may not be economical than having only primary intake at the beginning of reservoir construction due to the initial capital cost of low-level gate construction. Nonetheless, after 30 years, this additional cost is compensated with additional benefits due to managed sedimentation. Figure 5-7 shows the discounted dam decommissioning cost by exponential approach does not conclude without
sediment management works better than with sediment management. This can be true even if we assumed $zero cost or we discounted dam decommissioning cost with higher discount rate.

![Figure 5-7: Sensitivity Analyses of Dam Decommissioning Costs for Paonia Reservoir Without Sediment Management Compared to Sediment Management (Sluicing).](image)

We agree that exponential discounting will greatly reduce the discounted value of far-in-the future dam decommissioning for new reservoirs, especially when employing a high discount rate. However, the previous choices to ignore the costs of dam decommissioning, because of discounting, meant engineers and economists might have not previously acknowledged that reservoirs will eventually have to be decommissioned without sediment management, how they will be decommissioned, and the associated costs. Furthermore, in the case of dam decommissioning, the reservoir benefits are gone, and more challenges arise in terms of
substituting the water resource since there are many unknowns for future projects that are decades away.

5.4.2 Capital Cost of Sediment Management

As indicated in section 5.2.2 (costs/benefits related to the with sediment management), incorporating a low-level gate causes additional cost. It is worth knowing how expensive sediment management facilities, can reject sediment management compared to without sediment management for the Paonia dam. There are two estimated values for the cost of the low-level gate:

1. Reopening a conduit in the bottom of the intake structure that was used for diversion of the stream during the original construction; costs $2.6 million (2006 USD)

2. Constructing a new low-level outlet; costs $5 million (2006 USD) [195]

We considered the second option (as a base capital cost) and converted 2020 dollars. Figure 5-8 shows the results of changing the capital cost to; a) no capital cost (0* base), b) 50% decrease (0.5* base), and c) 100% increase (2*base). The analysis shows the increasing the capital cost of sediment management to twice higher than the base value can result in without sediment management is more profitable than sluicing. However, extending the period of analysis long enough can conclude that the expensive sediment management alternative can be economically viable after about 90 years with higher NVPs and continuing reservoir benefits. On the other hand, the dam decommissioning cost incurred in year 100 causes a reduction in NPVs of without sediment management.
The annual cost of sluicing sediment including gate operation and lining are assumed inherently in the reservoir’s annual maintenance and operation costs. However, different unit cost of sluicing sediment is examined in this section; a) base unit cost, presented in Table D-1 Appendix D, b) no unit cost (0* base), c) 100% increase (2* base), and d) 300% increase (4* base). Figure 5-9 illustrates that without sediment management crosses the with sediment management (sluicing) graphs at different point in time, as the unit sediment management cost increases this point moves further in time (up to 50 years), meaning without sediment management has higher NPVs for
longer time. However, by extending period of analysis and gradually diminishing storage benefits and accrued cost due to sedimentation, the sluicing outperforms without sediment management.

Since sluicing is relatively inexpensive in compared to other sediment management alternatives, this sensitivity should be investigated for other reservoirs and sediment management alternatives. But the results of sensitivity analyses of sediment management capital and unit costs indicate the importance of long period of analysis to capture positive impacts of sediment management and negative effects of ignoring sedimentation.

Figure 5-9: Sensitivity Analyses of Sluicing Sediment Management Unit Costs for Paonia Reservoir. sed-mgt = Sediment Management.
5.4.4 Unit Agriculture Benefit

As described in section 5.2.2, irrigation is the primary Paonia water storage benefit. The results of a unit agriculture benefit sensitivity analysis are shown in Figure 5-10 by considering these unit benefit; a) base, presented in Table D-1 Appendix D, b) no agriculture benefit (0* base), c) 50% decrease (0.5* base), and d) 100% increase (2* base). As Figure 5-10 illustrates the current agriculture benefit (base scenario, green line) with sediment management can perform better than without sediment management and can continue to deliver water downstream for longer time. By increasing the value of the agriculture benefit, the available water storage would be more critical and difference in NPVs of the two alternatives increases (2*base scenario, gray line). Increasing unit agriculture benefit to twice higher than base value can be practical by shifting from low-value to higher-value crops or even organic crops. By cultivating higher-value crops, maintaining reservoir storage by sediment management is economically justified. Moreover, by cultivating cheaper products or even losing agriculture benefit (moving towards the blue line), additional cost to manage sediment is not economically justified unless long-term reservoir operation be a priority.

Moreover, the difference between preserving current unit irrigation benefit by sediment management (solid or dashed green line) and losing irrigation benefit due to potential reservoir storage lack (dashed blue line) is considerable (about three times higher). Since there are no other irrigation options for the farms and ranches in Paonia area [215], losing the reservoir storage will be a devastating impact on existing agricultural water users. It continues with challenges of a replacement project.
5.4.5 Unit Recreation Benefit

As previously discussed, sedimentation degrades surface area and impacts on recreation activities of reservoirs. In the case of Paonia reservoir, these values are considered to analyze the sensitivity of the reservoir to unit recreation benefit; a) base, presented in Table D-1 Appendix D, b) no recreation benefit (0* base), c) 50% decrease (0.5* base), and d) 100% increase (2* base). The NPVs of these scenarios are presented in Figure 5-11. The Figure illustrates the relative outperformance of the sediment management alternative and how it improves by changing unit recreation benefit (moving towards the gray line).
Additionally, we mentioned in the section 5.2.1 that clogged primary intake due to sedimentation can cause losing available boat ramp in two years and vanishing recreation benefit. In this condition the difference between the without sediment management alternative with no recreation benefit (dashed blue line) and current recreation benefit (solid or dashed green line) is considerable.

**Figure 5-11: Sensitivity Analyses of Unit Recreation Benefit. sed-mgt = Sediment Management; Rec = Recreation.**

### 5.4.1 Downstream Degradation Unit Cost

Downstream degradation is due to clear water release. RSEM can consider reservoir downstream degradation limited by armoring layer and stable slope. The Paonia reservoir is located in a mountainous region that can limit degradation. However, we assumed due to trapped
coarse sediment in reservoir, and insufficient coarse material to form an armoring layer, degradation happens until the channel bed reaches to stable slope. The sensitivity analysis of unit degradation cost includes a) base, presented in Table D-1 Appendix D, b) no downstream degradation cost (0* base), c) 50% decrease (0.5 * base), and d) 100% increase (2* base) and is presented in Figure 5-12.

Figure 5-12: Sensitivity analyses of unit cost of downstream Degradation. sed-mgt = Sediment Management. Solid-lines are With Sediment Management Alternatives and Dash-lines are Without Sediment Management Alternatives
Figure 5-12 indicates all without sediment management scenarios are less economical than with sediment management (sluicing), and as degradation costs increases, the outperformance of with sediment management alternatives are becoming more obvious (moving toward the gray line).

It is worth noticing the point intersecting with and without sediment management alternatives. In the alternative assuming no degradation cost (blue line), without sediment management has higher NPVs than with sediment management for about first 50 years. However, by increasing this cost, moving from blue to gray line, the NPVs of without sediment management are higher for a shorter time, about 10 years for the gray line. Traditional ignoring the up-and downstream sedimentation costs in short period of analysis (50 to 100 years) is similar to the dashed blue line and can be a reason of not incorporating sediment management in traditional economic analysis of reservoirs. While the long period of analysis and comprehensive economic assessment can change the conclusion.

5.5 Discussion of Results

This chapter examined the economic performance of Paonia Reservoir. The two alternatives with sediment management incorporating a low-level gate and without sediment management are monetized and discounted using the exponential, Green-Book, hyperbolic and intergenerational approaches. Analyses were performed starting with the new reservoir and with the reservoir in its existing condition. The economic assessment includes up-and downstream sedimentation costs, dam decommissioning, and the loss of water storage benefits due to sedimentation.

The new Paonia Reservoir’s results indicate that comprehensive accounting of benefits and costs over a sufficiently long period of analysis will yield a BCR that fairly evaluates sustainable development applying sediment management for all periods of analyses and discounting
approaches. In other words, the sediment management plays a significant role in reducing the reservoir sedimentation while enhancing its net benefits. The net present value comparison shows the reservoir’s net benefits can continue up to 300 years with a significant increase (depending on discounting approach) while the economic benefits progressively decrease for without sediment management and completely lost upon dam decommissioning in 100 years. The case study results indicate that for the new Paonia Reservoir, any additional costs associated with sustainable sediment management are more than offset by the preserved economic benefits, avoided up- and downstream sedimentation costs, and avoided dam decommissioning costs.

The economic objective of addressing reservoir sedimentation for existing projects should be the identification of the alternative that maximizes net present value. For the existing Paonia Reservoir, the accumulated net present benefits illustrate that the cost of installing required facilities to dredge material is generally less expensive than decommissioning the reservoir filled with sediment. Even of the sediment management alternative can extend the reservoir’s life, the cumulated sediment in the existing reservoir has led to serious primary intake problems that threaten its long-term functionality.

Furthermore, two available economic models, RSEM and RESCON, were compared. These two models define benefits and costs differently. RSEM is strong in the economic consideration of different sedimentation impacts while RECON offers feasibility assessments of more sediment management alternatives. Hence, the results should be interpreted carefully.

Sensitivity analysis concerning several key economic parameters is also carried out. The results of the sensitivity study indicate:

- Dam decommissioning cost: although for about 30 years NPVs of the without sediment management are higher than the with sediment management (sluicing)
alternative, the gradual diminishing of reservoir storage and accumulated sediment reduce NPVs and incur inevitable dam decommission cost. Discounted value of far-in-the future dam decommissioning for the new Paonia reservoir does not conclude without sediment management works better than with sediment management. Traditional economic practice to ignore the costs of dam decommissioning, because of discounting, caused no incentive to incorporate sediment management or plan for the eventual dam decommissioning. However, a long period of analysis and comprehensive economic analysis can decline this premise.

- Capital cost of sediment management: the sensitivity analysis shows that increasing the capital cost of sediment management can result in higher NPVs of without sediment management. However, extending the period of analysis long enough can conclude that the expensive with sediment management alternative can be economically viable before incurring dam decommissioning cost for the without sediment management.

- Sediment management unit cost: for about 50 years, the without sediment management alternative outperforms the costliest considered with sediment management (sluicing). However, by extending period of analysis and gradually diminishing storage benefits and incurred cost due to sedimentation, the sluicing outperforms the without sediment management.

- Unit agriculture benefit: by increasing agriculture benefit, meaning shifting from low-value to higher-value crops, keeping water storage would be more critical and difference between with-and without sediment management in NPVs increases.
Moreover, the difference between preserving current irrigation benefit by sediment management and losing irrigation benefit due to potential reservoir storage losing is significant that confirms the importance of sustained water storage for the downstream farms and ranches.

- Unit recreation benefit: sediment management slows surface area reduction due to sedimentation. Hence, with sediment management (sluicing) provides higher NPVs than without sediment management. Additionally, misfunctioning the primary intake due to sedimentation can cause losing available boat ramp in a few years and vanishing recreation benefit. In this condition the reservoir recreation benefit degrades dramatically while preserving surface area by applying sediment management increases NPVs significantly.

- Downstream degradation unit cost: the without sediment management alternative remains economical than with sediment management (sluicing) alternative for short early year. By increasing degradation costs and extending the period of analysis, the outperformance of the with sediment management is becoming more obvious. The sensitivity analysis confirms the importance of a comprehensive economic analysis in long enough period of analysis to determine the economic viability of sediment management.

In short, our case study results do confirm the importance of comprehensively evaluating all costs and benefits and using a period of analysis long enough to consider these costs and benefits to determine the economic viability of sediment management. The case study showed sustainable sediment management is more economical than without sediment management, regardless of reservoir age (existing and new reservoir), sediment management technique (sluicing
and dredging), or discounting approach (Exponential, Green-Book, Hyperbolic and Intergenerational). The preserved benefits from sustainable sediment management offset any sediment management costs. Once the benefits of a reservoir have been lost to sedimentation, dam removal is often the eventual outcome and can be expensive for large sedimentation volumes. Even after dam removal, significant quantities of sediment may remain in the reservoir which will likely render the area unsuitable for future generations to use for water storage.
6 CONCLUSION AND RECOMMENDATION

Growing worldwide demands for fresh water due to population and climate change stresses mean that sustainable water supplies are increasingly important via reservoir storage. However, reservoir sedimentation is a serious problem that threatens the water storage capacities across the world. Also, all constructed dams are aging, and hence we are experiencing aging of water storage infrastructure.

Extending the dam’s life entails adopting a new design and operational paradigm that focuses on managing the reservoir and watershed system to bring sediment inflow and outflow into balance by including reservoir sediment management facilities. That can greatly extend operational life and restore downstream ecosystems. However, the cost of methods that remove the sediment from existing reservoirs can be prohibitive or technically infeasible and is a serious factor preventing sustainable sediment management.

Most of our presently functioning dams were approved based on a relatively short design life. This type of economic analysis heavily favors projects that avoid high initial costs while promising many short-term benefits. This effectively eliminates multi-generational reservoir projects that require the installation of sediment management facilities. This condition forces future generations who do not receive the water storage benefits to pay for maintenance, sedimentation costs and eventual dam decommissioning. Then they are left without water from the project.
Physical and computational models help select the best sediment management alternative and evaluate its effectiveness. With the rapid developments in numerical methods, computational modeling has become an attractive tool for studying flow and sediment transport. We described the dominant physical processes associated with each sediment management alternative and reviewed the underlying equations of motion. Published simulations have been presented, and important criteria for selecting a computer code to simulate each sediment management strategy were explained.

This thesis considered a case study to evaluate reservoir sedimentation. SRH – 1D was selected for the case study simulation. One-dimensional codes are generally adequate for the long-term simulation of delta movement, defining the time for sediment to reach bottom outlets, and the longitudinal deposited sediment profile.

The selected case study, Paonia Reservoir in Colorado, has lost 25% of the original capacity since the dam commissioning in 1962. The reservoir dead pool has completely filled with sediment and caused major problems in keeping the primary intake functional. This thesis investigated the effectiveness of low-level gate on reducing sedimentation in a hypothetical Paonia since the dam commissioning.

The result comparison of current Paonia operation with hypothetical Paonia (added low-level gate) proved sluicing incoming sediment-laden flow effectively reduces sedimentation without interrupting the reservoir targeted functions like downstream irrigation. In sluicing alternative, the passed sediment downstream is sometimes greater than incoming sediment volume, meaning some portions of deposited sediment are washed downstream. The deposited sediment volume could decrease more by monitoring the possible peak flow time and keeping the low-level gate open to pass high incoming flow downstream.
Evaluation of sediment management alternatives should include hydraulic and sedimentation analyses to model transport and deposition and economic analyses to model benefits and costs. As reservoir capacity diminishes with sedimentation, the importance of economic gains from sediment management considerably increases.

Traditionally, reservoirs are designed for a lifetime of 50 to 100 years. Economic analyses omitted critical costs associated with reservoir sedimentation, such as up-and downstream damages, degrading water supply benefits, and dam decommissioning, which produce non-sustainable projects.

Developing and retaining enough reservoir storage space to satisfy water demand over the long term requires abandoning the conventional design life approach and adopting a sustainable management approach. One of the fatal flaws in how the design life approach has been implemented historically is that no consideration was made for what would happen to the dam at the end of its design life.

The thesis introduced a new economic paradigm for new and existing water storage reservoirs. This new economic paradigm encourages policymakers to consider a comprehensive economic evaluation and intergenerational equity to make water resources projects truly sustainable. Three elements of a benefit cost analysis that significantly influence economic results include the period of analysis (POA), a comprehensive evaluation of costs and benefits, and the discounting approach and rate (the time value of money).

The sedimentation in Paonia Reservoir was also investigated from an economical point of view. This thesis applied RSEM to evaluate and compare the benefits and costs of continued sedimentation and eventual dam decommissioning (existing Paonia Reservoir condition) to sediment management costs and benefits (hypothetical Paonia Reservoir). The results illustrated
the sediment removal is advantageous because it contributed to a decrease rate of storage loss, and associated net benefits exceeded those in the without sediment management alternative. The preserved benefits from sustainable sediment management could offset the additional costs of incorporating sediment management.

Even with the high costs of modifying the existing Paonia dam, dredging deposited sediment was proved to be still less expensive than continuing sedimentation over the life span of the reservoir and future decommissioning.

The selected discounting approaches used to compare costs over time concluded a large difference in the computed present value of these two sediment management alternatives. Exponential and Green Book discounting heavily discounted future costs and favored present generations over future generations. However, declining discount approaches, like hyperbolic and intergenerational, gave more weight to sustaining benefits into the future.

In short, sustainable sediment management is more economical than without sediment management, regardless of reservoir age, sediment management technique, or discounting approach. The preserved benefits from sustainable sediment management can offset the additional costs of incorporating sediment management.
Recommendations:

– The findings presented in this study may be true for the selected reservoir, size, location and operation. The cost and effectiveness of any sediment management option may vary in different reservoirs. These results can be investigated for other reservoirs using the tools presented in this study.

– The hydraulic simulation did not model downstream degradation or bank erosion. A detailed simulation can investigate the bed and bank variation due to the reservoir’s operation.

– The considered sediment management did not interrupt the reservoir function, such as downstream irrigation. A new assessment can be done to compare the sensitivity of interruption in the reservoirs’ function due to sediment management.

– Considered sedimentation rate does not address potential future changes such as climate and watershed sediment yield changes. It may impact the selection of sediment management strategies and associated costs.

– It would be worthwhile to incorporate a runoff forecasting, and detailed downstream water demand in sediment management and economic evaluation.

– Economic assessment can extend to reusing dredged sediment in downstream farmlands and include environmental and social sedimentation costs.
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APPENDIX A. PARAMETERS OF EQUATIONS

A flow area
c volumetric sediment concentration
c\textsubscript{b} near-bed sediment concentration
c\textsubscript{be} equilibrium near-bed sediment concentration
\bar{c} depth averaged concentration
\bar{\bar{c}} cross sectional-averaged concentration
\bar{c}\textsubscript{*} new carrying capacity
D deposition rate of sediment onto the bed
E entrainment rate of sediment from the bed
g gravitational acceleration
h water depth
p pressure
q\textsubscript{b} vectorial bed load rate
q\textsubscript{s} suspended load transport rate
Q discharge
Q\textsubscript{b} bed load transport rate
Q\textsubscript{s} suspended load transport rate
S\textsubscript{0} bed slope
S\textsubscript{f} friction slope
t time
u flow velocity components in x direction
\bar{u} depth-averaged flow velocity components in x direction
\bar{\bar{u}} cross sectional-averaged flow velocity components in x direction
v flow velocity components in y direction
\bar{v} depth-averaged flow velocity components in y direction
w flow velocity components in z direction
w\textsubscript{f} sediment particle fall velocity
Z\textsubscript{b} bottom elevation
\alpha dimensionless coefficient that characterizes the rate at which the new carrying capacity is attained
\rho density of sediment water mixture
\epsilon\textsubscript{s} the eddy diffusivity of sediment-particle transport
\bar{\epsilon}\textsubscript{s} depth-averaged the eddy diffusivity of sediment-particle transport
\eta porosity of bed sediment
\tau\textsubscript{bi} shear stresses acting on the channel bottom (i = x, y)
\tau\textsubscript{si} shear stresses acting on the water surface (i = x, y)
u\textsubscript{t} eddy viscosity
APPENDIX B. MORE HYDRAULIC SIMULATION RESULTS

This section provides additional results for the hydraulic simulation of Paonia Reservoir.
Figure B-1: Simulated Total, Live and Dead Storage Reduction; With and without Sediment Management Alternatives
Figure B-2: Simulated Reservoir Water Surface Elevation, (the Target Reservoir Water Surface Elevation Is Shown by Figure 4-8)
Peak flow happens on April 29th.

Peak flow happens on April 15th.

Figure B-3: Comparison of the Incoming Sediment and Trapped Sediment for Without-and With Sediment Management Alternatives in First and Seventh Years
APPENDIX C. RSEM CHANNEL DEGRADATION MODELING

Here a part of RSEM manual associated with degradation is presented. This manual is in preparation.

RSEM channel Degradation Modeling

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

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

Channel Degradation

RSEM uses the methodology described by Pemberton and Lara (1984) to simulate the channel degradation profile after each year of reservoir operations. The model assumes that the downstream channel degrades each year as coarse sediment is trapped within the upstream reservoir. The degradation progresses both vertically and downstream over time. Channel degradation may be limited by the armoring of the streambed by gravel, cobbles, or boulders, if enough armoring size sediment is available, or until a stable longitudinal slope is achieved.
The maximum degradation depth that may be limited by armoring is computed by Equation C-1 as depicted in Figure C-1 [209]:

\[ y_d = y_a \left( \frac{1}{\Delta p} - 1 \right) \]  

(C-1)

where:
\( y_d \) = depth of degradation limited by armoring (depth from predam streambed to top of armoring layer)
\( y_a \) = armor layer thickness
\( \Delta p \) = portion of original streambed material larger than the armor gain size, \( D_c \)

![Figure C-1: Channel Degradation Limited by Armoring (Modified from Pemberton and Lara, 1984) [209].](image)

When there is insufficient armor size material in the streambed, channel degradation will continue until a stable longitudinal slop is reached. The longitudinal profile area of degradation is between the predam streambed and the degraded streambed, Figure C-2, and computed by Equation C-2:

\[ a_g = \frac{V_g}{B_d} \]  

(C-2)

where:
\( a_g \) = longitudinal area of channel degradation
\( V_g \) = volume of channel degradation, which is equal to the volume of coarse reservoir sedimentation \( (V_{c(h)}) \) (see Equation 3)
\( B_d \) = width of degraded channel
The cumulative volume of coarse sediment comprising the delta is computed from the average annual rate of coarse sediment inflowing to the reservoir times the age of the reservoir, minus the annual rate of any forced or planned sediment management times the coarse portion of sediment removed (Equation C-3).

\[
V_{c(n)} = R_c T - S_{MGT} P_c \tag{C-3}
\]

where:

- \( V_{c(n)} \) = Cumulative coarse sediment volume comprising the delta in year \( n \)
- \( T \) = time, in years since original filling of the reservoir
- \( R_c \) = annual rate of coarse sediment inflow
- \( S_{MGT} \) = annual rate of forced or planned sediment management removal
- \( P_c \) = coarse portion of reservoir sediment that is removed
The channel degradation depth just downstream from the dam is computed using Equation C-4:

\[ d_g = \left[ \frac{64}{39} a_g \Delta S_g \right]^{0.5} \leq y_d \quad (C-4) \]

where:
- \( d_g \) = channel degradation depth just below the dam
- \( \Delta S_g \) = longitudinal slope difference between the predam channel and stable slope channel

The stable slope of a degraded river channel can be computed using a sediment transport equation so that the bed-material load is zero for the hydraulics of a bankfull discharge and given grain size distribution [209]. RSEM uses a more simplified approach and computes the stable slope as a percentage of the predam slope. The difference in longitudinal slopes is computed from Equation C-5:

\[ \Delta S_g = S_o (1 - \beta) \quad (C-5) \]

where: \( \beta \) = the portion that the predam slope would be reduced by to achieve the stable slope
- \( S_o \) = predam longitudinal channel slope

For a given time, the channel degradation depth diminished with distance downstream. RSEM uses Equations C-6 through C-9 to estimate the distances where the degradation depth just below the dam has diminished to one-half, one-quarter, and near zero:

\[ L_1 = \frac{d_g}{2 \Delta S_g} \quad (C-6) \]
\[ L_2 = \frac{3}{8} \frac{d_g}{\Delta S_g} \quad (C-7) \]
\[ L_3 = \frac{3}{4} \frac{d_g}{\Delta S_g} \quad (C-8) \]
\[ L_g = \frac{13}{8} \frac{d_g}{\Delta S_g} \quad (C-9) \]
where:
\[ L_1 = \text{Length of channel degradation from the dam downstream to where the degradation has diminished to one-half the upstream amount} \]
\[ L_2 = \text{Length of channel degradation from where the degradation has diminished from one-half to one-quarter of the amount below the dam} \]
\[ L_3 = \text{Length of channel degradation from where the degradation has diminished from one-quarter the amount below the dam to near zero} \]

**Bank Stabilization Design and Cost**

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

A key part of the concept design for rip rap is estimating the median rock size based on the mean stream velocity for the bankfull discharge calculated in Equation C-10 and shown in Figure C-3.

\[ d_{50} = 2.510 \times 10^{-3} \ V_m^{2.620} \]  
(C-10)

where:
\[ d_{50} = \text{median rock rip rap size (feet)} \]
\[ V_m = \text{mean channel flow velocity (ft/s) at the bankfull discharge in Equation C-11:} \]

\[ V_m = \frac{1.486}{n} \times R_h^{2/3} \ S_0^{0.5} \]  
(C-11)

where:
\[ n = \text{Manning’s roughness coefficient} \]
\[ R_h = \text{hydraulic radius of the channel, which can be assumed equal to the bankfull depth or bank height (H_{Bank})} \]
The streambank protection concept design is presented in Figure C-4. The top elevation of the rock rip rap does not need to be as high as the top of the streambank, but the rip rap needs to extend below the streambed to protect against channel degradation and local toe scour.

Figure C-4: Streambank Protection Concept Design for Rip Rap (Modified from Baird et al. 2015) [216]
RSEM estimates the vertical height of streambank protection as 30% of the bankfull height, degradation depth and scour depth, (Baird and T. Randel, personnel communication, 2022) Equation C-12. The scour depth, Equation C-13, is estimated as 5% of the bankfull depth and degradation depth.

\[ H_{BP(m)} = 0.30(H_{Bank} + d_{g(m)} + d_{scour}) \quad \text{(C-12)} \]

\[ d_{scour} = 0.05(H_{Bank} + d_{g(m)}) \quad \text{(C-13)} \]

\[ H_{BP(m)} = 0.32(H_{Bank} + d_{g(m)}) \quad \text{(C-14)} \]

where:

- \( H_{BP(m)} \) = vertical height of streambank protection which extends below the streambed for reach \( m \)
- \( H_{Bank} \) = channel bankfull height
- \( d_{g(m)} \) = average degradation depth in reach \( m \) [the average degradation depth (see Figure C-2)]
- \( D_{scour} \) = depth of local scour caused by the rip rap

The cross-sectional length of streambank protection depends on the vertical height and the bank slope (Equation C-15).

\[ SL_{BP(m)} = \left[ \left( z H_{BP(m)} \right)^2 + \left( H_{BP(m)} \right)^2 \right]^{0.5} \quad \text{(C-15)} \]

where: \( SL_{BP(m)} \) = the slope length of rock rip rap for reach \( m \)

- \( z \) = bank slope (H:V)

The cross-sectional area of rock is computed from the slope length and thickness (Equation C-16).

\[ A_{BP(m)} = SL_{BP(m)}(2 d_{50}) \quad \text{(C-16)} \]

where: \( A_{BP(m)} \) = cross-sectional area of stream bank protection for reach \( m \)

The volume of rock is computed from the cross-sectional area and longitudinal length for each of three reaches (Equations 17 through 20). These equations account for the average degradation depth in each of three reaches (Figure C-2)
\[ V_{BP} = F_{BP} \left[ L_1 A_{BP1} + L_2 A_{BP2} + L_3 A_{BP3} \right] \] (C-17)

\[ A_{BP1} = 2 \, d_{50} \left\{ \left[ z \, 0.32 \left( H_{Bank} + \frac{3}{4} d_g \right) \right]^2 + \left[ 0.32 \left( H_{Bank} + \frac{3}{4} d_g \right) \right]^2 \right\}^{0.5} \] (C-18)

\[ A_{BP2} = 2 \, d_{50} \left\{ \left[ z \, 0.32 \left( H_{Bank} + \frac{3}{8} d_g \right) \right]^2 + \left[ 0.32 \left( H_{Bank} + \frac{3}{8} d_g \right) \right]^2 \right\}^{0.5} \] (C-19)

\[ A_{BP3} = 2 \, d_{50} \left\{ \left[ z \, 0.32 \left( H_{Bank} + \frac{1}{8} d_g \right) \right]^2 + \left[ 0.32 \left( H_{Bank} + \frac{1}{8} d_g \right) \right]^2 \right\}^{0.5} \] (C-20)

where:

- \( V_{BP} \) = volume of streambank protection along reaches 1, 2, and 3 (Figure C-2)
- \( F_{BP} \) = streambank protection factor to account for protection along the left and right channel banks and habitat degradation (1 \( \leq F_{BP} \leq 4 \))
- \( A_{BP1} \) = area of streambank protection for reach 1
- \( A_{BP2} \) = area of streambank protection for reach 2
- \( A_{BP3} \) = area of streambank protection for reach 3

The volume of rock rip rap is computed for each year. RSEM multiplies the increase in rock volume from the previous year by the unit cost for material, delivery, and installation.
APPENDIX D. PAONIA RESERVOIR ECONOMIC PARAMETERS

Table D-1 shows the input data values applied in the case study economic assessment. All benefits and costs are indexed at 2020 price level.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Description / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Age</td>
<td>year</td>
<td>zero</td>
<td>For the new hypothetical Paonia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
<td>For the existing Paonia, Commissioning year = 1962</td>
</tr>
<tr>
<td>Reservoir Elevation Inputs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top of live storage</td>
<td>feet</td>
<td>6447.5</td>
<td>Emergency spillway elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bureau of Reclamation, Paonia Dam [217]</td>
</tr>
<tr>
<td>Top limit of sedimentation</td>
<td>feet</td>
<td>6440.0</td>
<td>Assumption</td>
</tr>
<tr>
<td>Recreation pool elevation</td>
<td>feet</td>
<td>6430</td>
<td>Average elevation between cross-sections 35 and 36 (boat ramp location), and Todd L. Gaston (2019) [184], page 32</td>
</tr>
<tr>
<td>Normal W.S. Elevation</td>
<td>feet</td>
<td>6373.0</td>
<td>Top of Active Conservation Pool</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bureau of Reclamation, Paonia Dam [217]</td>
</tr>
<tr>
<td>Top of dead storage</td>
<td>feet</td>
<td>6358.0</td>
<td>For without sediment management; primary intake elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6300</td>
<td>For with sediment management; low-level gate elevation</td>
</tr>
<tr>
<td>Original streambed elevation</td>
<td>feet</td>
<td>6287.0</td>
<td>Streambed at dam axis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bureau of Reclamation, Paonia Dam [217]</td>
</tr>
<tr>
<td>Original Reservoir Storage Capacity Input</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total storage volume at top of live storage</td>
<td>acre-feet</td>
<td>20950</td>
<td>Bureau of Reclamation, Paonia Dam [217]</td>
</tr>
<tr>
<td>Dead pool volume</td>
<td>acre-feet</td>
<td>2440</td>
<td>Bureau of Reclamation, Paonia Dam [217]</td>
</tr>
<tr>
<td>Reservoir Inflow Characteristics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean Annual Reservoir Inflow</td>
<td>acre-feet/year</td>
<td>99,800</td>
<td>Paonia Reservoir data sheet</td>
</tr>
<tr>
<td>Standard deviation of mean annual inflow</td>
<td>acre-feet/year</td>
<td>5129</td>
<td>Paonia Reservoir data sheet</td>
</tr>
<tr>
<td>Reservoir Inflow Characteristics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir length at full pool</td>
<td>mile</td>
<td>3.54</td>
<td>Western Engineering Inc (2006) [193]- page 13, Paonia profiles</td>
</tr>
<tr>
<td>Reservoir surface area at recreation pool</td>
<td>acres</td>
<td>334</td>
<td>Bureau of Reclamation, Paonia Dam [217]</td>
</tr>
<tr>
<td>Reservoir average surface width at full pool</td>
<td>feet</td>
<td>1,056</td>
<td>Paonia Reservoir data sheet and V. Huang, B. Greimann, S. Kimbrel (2016) [188]</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Value</td>
<td>Description / Reference</td>
</tr>
<tr>
<td>-----------</td>
<td>---------------</td>
<td>-------</td>
<td>-----------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Boat ramp/marina #1 length from dam</td>
<td>mile</td>
<td>2.6</td>
<td>There is a boat ramp between cross-sections 35 and 36</td>
</tr>
</tbody>
</table>

**Dam Characteristics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Description / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dam type</td>
<td></td>
<td></td>
<td>Earthen fill</td>
</tr>
<tr>
<td>Volume of dam material</td>
<td>yr³</td>
<td>1,302,000</td>
<td>Bureau of Reclamation, Paonia Dam [217]</td>
</tr>
<tr>
<td>Hydraulic height</td>
<td>feet</td>
<td>167</td>
<td>Bureau of Reclamation, Paonia Dam [217]</td>
</tr>
<tr>
<td>Dam crest length across river</td>
<td>feet</td>
<td>770</td>
<td>Bureau of Reclamation, Paonia Dam [217]</td>
</tr>
</tbody>
</table>

**Reservoir Sedimentation Characteristics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Description / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual storage loss</td>
<td>ac-ft/year</td>
<td>101</td>
<td>Last reservoir survey</td>
</tr>
<tr>
<td></td>
<td></td>
<td>56</td>
<td>SRH-1D result for with sediment management:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>85.1</td>
<td>SRH-1D result for without sediment management:</td>
</tr>
<tr>
<td>Fine sediment portion (clay and silt)</td>
<td></td>
<td>80%</td>
<td>Sedimentation study Paonia reservoir (1956) [191], page 6</td>
</tr>
</tbody>
</table>

**Reservoir Sedimentation Profile Slope Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta topset slope factor</td>
<td>0.75</td>
<td>Assumption</td>
</tr>
<tr>
<td>Delta forest slope factor</td>
<td>6.0</td>
<td>Assumption</td>
</tr>
<tr>
<td>Bottomset slope factor</td>
<td>0.1</td>
<td>Assumption</td>
</tr>
</tbody>
</table>

**Predam River Channel and Degradation Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel sinuosity</td>
<td>1.1</td>
<td>Assumption</td>
</tr>
<tr>
<td>Average bank full channel width</td>
<td>feet</td>
<td>200.0</td>
</tr>
<tr>
<td>Average channel roughness (Manning's n coefficient)</td>
<td>0.022</td>
<td>V. Huang, B. Greimann, S. Kimbrel (2016) [188]</td>
</tr>
<tr>
<td>Portion of bed material is armor size or coarser</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>Armor layer thickness</td>
<td>0.5</td>
<td>Recommended by Pemberton and Lara. [209]</td>
</tr>
<tr>
<td>Original channel slope reduced by a percentage to achieve a stable channel</td>
<td>95%</td>
<td>Recommended by Pemberton and Lara. [209]</td>
</tr>
</tbody>
</table>

**Reservoir Benefits**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Storage Capacity to Yield</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Proportion of Consumptive Uses:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural irrigation use</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>M&amp;I water use</td>
<td>0%</td>
<td></td>
</tr>
<tr>
<td>Fish &amp; wildlife and other</td>
<td>0%</td>
<td></td>
</tr>
</tbody>
</table>

**Benefits of Consumptive Uses**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural irrigation use</td>
<td>$/acre-foot</td>
<td>98.85</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Value</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>------------</td>
<td>-------</td>
</tr>
<tr>
<td>M&amp;I water use</td>
<td>$/acre-foot</td>
<td>0.00</td>
</tr>
<tr>
<td>Fish &amp; wildlife and other</td>
<td>$/acre-foot</td>
<td>0.00</td>
</tr>
<tr>
<td>Flood risk reduction</td>
<td>$/acre-foot</td>
<td>0.58</td>
</tr>
<tr>
<td><strong>Recreation Use Benefits in Present Year</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Present average annual visitor days</td>
<td>visitor days/year</td>
<td>26000</td>
</tr>
<tr>
<td>Benefit per visitor day (Net Consumer Surplus)</td>
<td>visitor days/lake acre</td>
<td>$45.06</td>
</tr>
<tr>
<td>Benefit dependent on boat ramps</td>
<td>%</td>
<td>50</td>
</tr>
<tr>
<td>Benefit reduction from loss of 1 boat ramp</td>
<td>%</td>
<td>20</td>
</tr>
<tr>
<td><strong>Dam Construction, Operation, and Maintenance Costs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction cost</td>
<td>$</td>
<td>8,400,000</td>
</tr>
<tr>
<td>Annual OM&amp;R cost</td>
<td>$</td>
<td>450,000</td>
</tr>
<tr>
<td>5-year recurring costs</td>
<td>$</td>
<td>100,000</td>
</tr>
<tr>
<td><strong>Dam Decommissioning Costs and Benefits</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dam removal unit cost</td>
<td>$/yd$^{3}$</td>
<td>5</td>
</tr>
<tr>
<td>Sediment management unit cost</td>
<td>$/yd$^{3}$</td>
<td>14</td>
</tr>
<tr>
<td>River diversion cost</td>
<td>$</td>
<td>10,000,000</td>
</tr>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>Value</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>Cofferdam cost</td>
<td>$</td>
<td>1,000,000</td>
</tr>
<tr>
<td>Salvage benefits</td>
<td>$</td>
<td>0</td>
</tr>
<tr>
<td>Other river restoration costs</td>
<td>$</td>
<td>0</td>
</tr>
<tr>
<td>Dam decommissioning cost</td>
<td>$</td>
<td>188,716,933</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upstream Sedimentation Costs*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposition threshold for land impacts</td>
<td>ft</td>
<td>3</td>
</tr>
<tr>
<td>Unit land devaluation cost</td>
<td>$/acre</td>
<td>5,000</td>
</tr>
<tr>
<td>Unit highway/railroad relocation cost</td>
<td>$/mi</td>
<td>0</td>
</tr>
<tr>
<td>Unit fish &amp; boat passage cost</td>
<td>$/mi/year</td>
<td>0</td>
</tr>
<tr>
<td>Downstream Channel Degradation Costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum degradation threshold</td>
<td>ft</td>
<td>2</td>
</tr>
<tr>
<td>Streambank protection factor</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Unit cost of streambank protection</td>
<td>$/yd^3</td>
<td>75</td>
</tr>
<tr>
<td>Without Sediment Management Alternative</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planned sediment design life</td>
<td>years</td>
<td>50</td>
</tr>
<tr>
<td>Project decommissioning age</td>
<td>years</td>
<td>100</td>
</tr>
<tr>
<td>Forced sediment management parameters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forced fine sediment removal cost</td>
<td>$/yd^3</td>
<td>14.00</td>
</tr>
<tr>
<td>Forced coarse sediment removal cost</td>
<td>$/yd^3</td>
<td>14.00</td>
</tr>
<tr>
<td>Sediment Management Alternative</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual fine sediment removal</td>
<td>%</td>
<td>85</td>
</tr>
<tr>
<td>Annual coarse sediment removal</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Sediment management capital cost</td>
<td>$</td>
<td>7,300,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,000,000</td>
</tr>
<tr>
<td>Equipment life</td>
<td>year</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Sediment management begins at dam age</td>
<td>year</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60</td>
</tr>
</tbody>
</table>
Table D-1 Continued

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Description / Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine/coarse sediment removal cost</td>
<td>$/yd$^3</td>
<td>0.5</td>
<td>Sluicing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>Dredging</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$6.81 $/yd^3\text{ (2017 USD)} = $7$/yd^3\text{ (2020 USD)}$ = Todd L. Gaston (2019), [184], page 29</td>
</tr>
</tbody>
</table>

* Note: Here all listed upstream impacts are not discernible, but that may not be true for all reservoirs.
APPENDIX E. CONTRIBUTION OF CONSIDERED BENEFITS AND COSTS TO NET PRESENT VALUE

Table E-1: Contribution of Considered Benefits and Costs to Net Present Value of New Paonia Reservoir
Exponential Discounting Approach

<table>
<thead>
<tr>
<th>Water Storage Benefit</th>
<th>Recreation Benefit</th>
<th>Upstream cost</th>
<th>Downstream cost</th>
<th>Sediment Management Cost</th>
<th>Maintenance Cost</th>
<th>Construction</th>
<th>Dam Decommissioning</th>
<th>Benefit Sum</th>
<th>Cost Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Without Sediment Management</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>23.4%</td>
<td>15.0%</td>
<td>0.0%</td>
<td>6.1%</td>
<td>0.0%</td>
<td>5.9%</td>
<td>49.6%</td>
<td>0.0%</td>
<td>38.4%</td>
</tr>
<tr>
<td>100</td>
<td>24.2%</td>
<td>15.1%</td>
<td>0.0%</td>
<td>5.6%</td>
<td>0.0%</td>
<td>6.3%</td>
<td>41.4%</td>
<td>7.4%</td>
<td>39.3%</td>
</tr>
<tr>
<td><strong>With Sediment Management (Sluicing)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>24.9%</td>
<td>14.5%</td>
<td>0.0%</td>
<td>4.7%</td>
<td>0.3%</td>
<td>5.6%</td>
<td>50.0%</td>
<td>0.0%</td>
<td>39.4%</td>
</tr>
<tr>
<td>100</td>
<td>27.9%</td>
<td>16.2%</td>
<td>0.0%</td>
<td>4.6%</td>
<td>0.4%</td>
<td>6.4%</td>
<td>44.5%</td>
<td>0.0%</td>
<td>44.1%</td>
</tr>
<tr>
<td>200</td>
<td>28.7%</td>
<td>16.7%</td>
<td>0.0%</td>
<td>4.6%</td>
<td>0.4%</td>
<td>6.7%</td>
<td>42.9%</td>
<td>0.0%</td>
<td>45.4%</td>
</tr>
<tr>
<td>300</td>
<td>28.8%</td>
<td>16.8%</td>
<td>0.0%</td>
<td>4.6%</td>
<td>0.4%</td>
<td>6.7%</td>
<td>42.8%</td>
<td>0.0%</td>
<td>45.6%</td>
</tr>
</tbody>
</table>
Table E-2: Contribution of Considered Benefits and Costs to Net Present Value of New Paonia Reservoir
Intergenerational Discounting Approach

<table>
<thead>
<tr>
<th></th>
<th>Water Storage Benefit</th>
<th>Recreation Benefit</th>
<th>Upstream cost</th>
<th>Downstream cost</th>
<th>Sediment Management Cost</th>
<th>Maintenance Cost</th>
<th>Construction</th>
<th>Dam Decommissioning</th>
<th>Benefit Sum</th>
<th>Cost Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Sediment Management</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>28.7%</td>
<td>18.3%</td>
<td>0.0%</td>
<td>6.5%</td>
<td>0.0%</td>
<td>7.3%</td>
<td>39.2%</td>
<td>0.0%</td>
<td>47%</td>
<td>53%</td>
</tr>
<tr>
<td>100</td>
<td>24.9%</td>
<td>14.8%</td>
<td>0.1%</td>
<td>4.5%</td>
<td>0.0%</td>
<td>6.8%</td>
<td>20.5%</td>
<td>28.4%</td>
<td>39.7%</td>
<td>60.3%</td>
</tr>
<tr>
<td>With Sediment Management (Sluicing)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>30.5%</td>
<td>17.7%</td>
<td>0.0%</td>
<td>5.0%</td>
<td>0.4%</td>
<td>6.9%</td>
<td>39.5%</td>
<td>0.0%</td>
<td>48.2%</td>
<td>51.8%</td>
</tr>
<tr>
<td>100</td>
<td>36.9%</td>
<td>21.5%</td>
<td>0.0%</td>
<td>4.6%</td>
<td>0.5%</td>
<td>8.7%</td>
<td>27.8%</td>
<td>0.0%</td>
<td>58.4%</td>
<td>41.6%</td>
</tr>
<tr>
<td>200</td>
<td>40.5%</td>
<td>24.4%</td>
<td>0.1%</td>
<td>4.2%</td>
<td>0.6%</td>
<td>10.3%</td>
<td>19.9%</td>
<td>0.0%</td>
<td>64.9%</td>
<td>35.1%</td>
</tr>
<tr>
<td>300</td>
<td>41.3%</td>
<td>25.7%</td>
<td>0.1%</td>
<td>4.0%</td>
<td>0.7%</td>
<td>11.2%</td>
<td>17.0%</td>
<td>0.0%</td>
<td>67.0%</td>
<td>33.0%</td>
</tr>
</tbody>
</table>
APPENDIX F. CONSIDERED DISCOUNTING APPROACHES AND COEFFICIENTS
IN THE ECONOMIC ANALYSIS

Table F-1 presents the complementary information about all discount approaches included in RSEM and considered in Paonia Reservoir economic assessment. All discount approaches are quoted from Harpman and Piper (2014) [162] except the Green Book approach. The Green Book reported from UK Treasury Supplementary Green Book (2008) [220].

<table>
<thead>
<tr>
<th>Discounting Method</th>
<th>Variable</th>
<th>Variable description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exponential (Classic)</td>
<td>r</td>
<td>(constant) discount rate</td>
<td>0.025</td>
</tr>
<tr>
<td>Ramsey</td>
<td>ρ</td>
<td>pure rate of time preference</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>η</td>
<td>elasticity of marginal utility of consumption</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>ɡt</td>
<td>growth of consumption</td>
<td>0.025</td>
</tr>
<tr>
<td>Hyperbolic</td>
<td>h</td>
<td>effect of time perception</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>k</td>
<td>degree to which hyperbolic discount weight differs from exponential discount weight</td>
<td>0.08</td>
</tr>
<tr>
<td>Quasi-hyperbolic</td>
<td>β</td>
<td>Time-invariant constants. Future rewards are discounted by a factor of β<em>δt where 0&lt; β</em>δ ≤ 1.0.</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>δ</td>
<td></td>
<td>0.99</td>
</tr>
<tr>
<td>Gamma</td>
<td>rt</td>
<td>certainty equivalent discount rate at time (t)</td>
<td>μ/(1+tσ²/μ)</td>
</tr>
<tr>
<td></td>
<td>σ</td>
<td>standard deviation of the Gamma distribution</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>mean of the Gamma distribution</td>
<td>0.08</td>
</tr>
<tr>
<td>Weibull</td>
<td>r</td>
<td>constant annual discount rate</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>s</td>
<td>parameter affecting time perception</td>
<td>1.5</td>
</tr>
<tr>
<td>Green Book</td>
<td>r_t=0,1,2,…,30</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>r_t=31,…,75</td>
<td>31</td>
<td>0.0257</td>
</tr>
<tr>
<td></td>
<td>r_t=76,…,125</td>
<td>76</td>
<td>0.0214</td>
</tr>
<tr>
<td></td>
<td>r_t=126,…,200</td>
<td>126</td>
<td>0.0171</td>
</tr>
<tr>
<td></td>
<td>r_t=201,…,300</td>
<td>201</td>
<td>0.0129</td>
</tr>
</tbody>
</table>
Table F-1 Continued

<table>
<thead>
<tr>
<th>Discounting Method</th>
<th>Variable</th>
<th>Variable description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>rt = 301,...,T</td>
<td>301</td>
<td></td>
<td>0.0086</td>
</tr>
<tr>
<td>T</td>
<td></td>
<td>any year evaluated greater than 301</td>
<td></td>
</tr>
<tr>
<td>Intergenerational</td>
<td>r</td>
<td>the present generation annual discount rate</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>rfg</td>
<td>the future generation annual discount rate</td>
<td>0.00386</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td>the assumed length of a generation (in years)</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Δ</td>
<td>( \frac{1}{1/(1+rfg)/(1/(1+r))} )</td>
<td>1.076</td>
</tr>
<tr>
<td></td>
<td>rfg</td>
<td>the generational discount rate</td>
<td>0.08</td>
</tr>
</tbody>
</table>