Dam Removal Cost Databases and Drivers

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An excel-based Computation Guide for Cost Estimating is available with supporting documentation in appendix A.

14. ABSTRACT
We created planning-level cost estimating tools to assist with projects needing to consider the dam removal alternative: (1) new databases of case studies (Duda et al. 2023a; Tullos and Bountry 2023); (2) scoping questions to help determine if complexity cost drivers will be present; (3) machine learning based regression trees to estimate a potential cost range; and (4) a Computation Guide for Cost Estimating that can be used to inform discussions on potential dam removal cost items, quantities, and unit costs (Appendix A). Using the collected data and knowing some basic characteristics about the average annual flow and geographic location of the dam site, in addition to dam size, can improve the ability to use past case studies for planning-level cost estimating. By additionally incorporating scoping questions to assess likelihood of complexity cost drivers, the initial uncertainty of a cost estimate can be further reduced especially for small dams. Applying the Computation Guide for Cost Estimating requires more robust information but helps users reduce cost uncertainty. This step further refines the dam removal objective,

removal approach (partial or full; phased or instantaneous), engineering design, construction means and methods, quantities, and unit costs, and results in a quantitative cost estimate.

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Guidance provided in this document is for planning-level assessment of dam removal costs. This document includes a Planning-Level Dam Removal Computation Guide for Cost Estimating which must be configured with appropriate quantities and unit prices as noted in the instructions in appendix A.

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Cover Photo – National Park Service web camera photograph of Elwha Dam Removal on September 29, 2011, at 16:28.

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Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
ft	foot/feet
km^2	square kilometers
m	meter(s)
M	million(s)
m^3	cubic meter(s)
m^3/s	cubic meters per second
n	count, number of items in a dataset
NID	National Inventory of Dams
R^2	r-squared; coefficient of determination
Reclamation	Bureau of Reclamation
RSMeans	proprietary construction estimating cost databases
U.S.	United States
USACE	U.S. Army Corps of Engineers
USD	U.S. dollar(s)

Symbols

$	dollar(s)
=	equals
>	greater than
<	less than
-	minus
%	percent
+	plus

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1.0 Executive Summary

The United States (U.S.) has over 90,000 dams listed in the National Inventory of Dams that provide vital infrastructure to support water management for municipal and industrial uses including irrigation, hydropower, flood control, navigation, recreation, and habitat, among other uses (NID 2023). The Bureau of Reclamation (Reclamation) and U.S. Army Corps of Engineers (USACE) operate and maintain approximately 489 and 740 dams, respectively, as well as associated structures which provide flood risk management, navigation, water supply, hydropower, environmental stewardship, fish and wildlife conservation, and recreation benefits. As dams age, structural and operational maintenance investments increase until a time when decisions on whether to rehabilitate, replace, or decommission the dam need to be made. While most dams continue to provide important value even with maintenance requirements, at least 2,000 dams have been removed in the U.S. during the past 110 years, with an upward trend in the last few decades (American Rivers 2023). Decommissioning a dam may be considered when the purpose of the dam is no longer needed or other factors such as dam safety, fish passage, recreation safety, or river restoration goals take higher priority and are more economically feasible for the dam owner long-term.

Dam safety programs, river restoration programs, and asset class management programs need cost estimating methods to consider dam decommissioning when appropriate. Traditional cost estimating approaches in planning stages focus mainly on dam removal construction and may leave out or have uncertainty on important complexities that can have substantial effects on total costs and be critical for project success. As the numbers of dam removal case studies increase, a growing set of cost data has become available (Duda et al. 2023a; Tullos and Bountry 2023; American Rivers 2022). However, total costs vary over five orders of magnitude for similar size dams, and it was unclear why. We evaluated three sets of cost data that had varying level of details regarding elements contributing to dam removal costs reported by project managers working on the dam removal studies and construction means and methods.

We created planning-level cost estimating tools to assist with projects needing to consider the dam removal alternative: (1) new databases of case studies (Duda et al. 2023a; Tullos and Bountry 2023); (2) scoping questions to help determine if complexity cost drivers will be present; (3) machine learning based regression trees to estimate a potential cost range; and (4) a Computation Guide for Cost Estimating that can be used to inform discussions on potential dam removal cost items, quantities, and unit costs (appendix A). The collected data showed that dam height is important but is not a reliable predictor of the removal cost without considering other elements. However, knowing some basic characteristics about the average annual flow and geographic location of the dam site, in addition to dam size, can improve the ability to use past case studies for planning-level cost estimating. By additionally incorporating scoping questions related to sediment removal, mitigation, or other infrastructure, the likelihood of complexity cost drivers and the initial uncertainty of a cost estimate can be further reduced especially for small dams. Applying the Computation Guide for Cost Estimating requires more robust information but helps users reduce cost uncertainty. This step further refines the dam removal objective, removal approach (partial or full; phased or instantaneous), engineering design, construction means and methods, quantities, and unit costs, and results in a quantitative cost estimate.

2.0 Introduction

The United States (U.S.) has over 90,000 dams listed in the National Inventory of Dams (NID) that provide vital water management for municipal and industrial uses including irrigation, hydropower, flood control, navigation, recreation, and habitat among others (NID 2023). The average dam age in the NID is 61 years old, with 71 percent (%) regulated by states and 5% regulated by federal entities. Millions of additional small dams are in our Nation that are not listed in the NID. As dams age in the U.S., structural and operational maintenance investments increase until a time when decisions on whether to rehabilitate, replace, or remove the dam need to be made. While most dams continue to provide important value even with maintenance requirements, at least 2,000 dams have been removed in the U.S. during the past 110 years, with an upward trend in the last few decades (American Rivers 2023; figure 1).

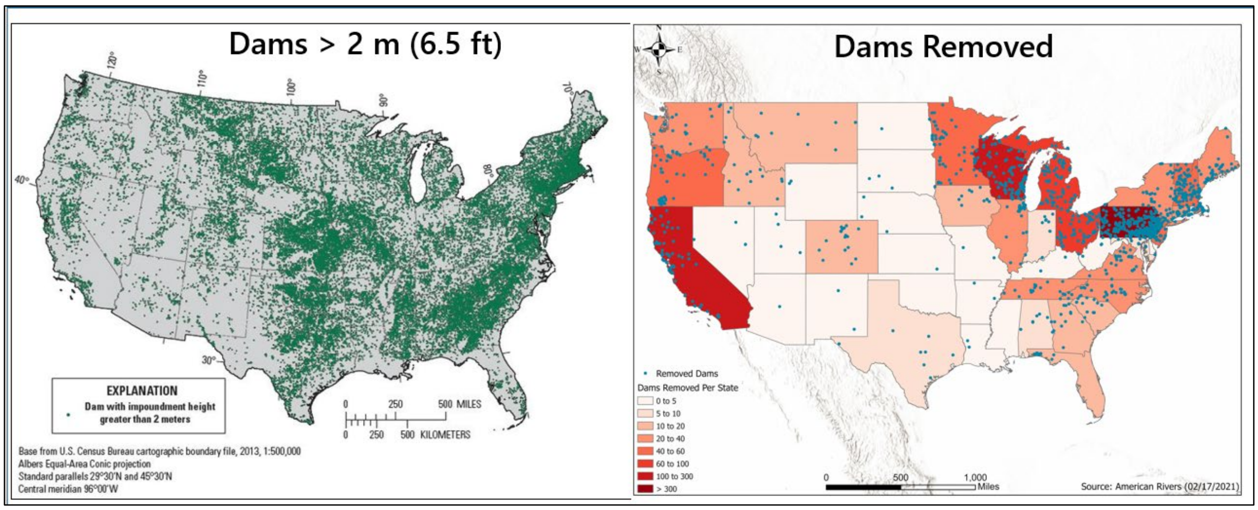

Figure 1.—Number and location of dams constructed (left image) versus removed (right image) in the U.S. (American Rivers 2021; National Inventory of Dams 2013).

In most dam removals, the remaining benefits of the dam no longer outweigh the costs to safely maintain the dam, the costs to mitigate environmental impacts, or both. Several factors can lead to the decision to remove a dam (Pohl 2002; U.S. Society of Dams 2015). Old dams that are structurally unsound pose risks of failure that can potentially result in negative economic, environmental, and human safety consequences. Obsolescence of dams, like mill dams in the northeastern U.S., has also been an important driver of dam removal. These dams may have been abandoned or are no longer serving their intended purpose.

Even when old or structurally deficient dams are still serving a purpose, economics can be a deciding factor, as the cost of removal can be substantially less than the cost for continued maintenance and repair (Bowman 2002; Magilligan et al. 2017). The role of the dam is important because dams that offer flood protection or water supply are generally maintained, whereas dams

providing other functions (e.g., hydropower that can be replaced with other resources, recreation) might be removed. As environmental and regulatory requirements have evolved or become legislative mandates, the economic calculus can change when large investments are required for compliance. In some cases, an insufficient return on investment might provide the deciding factor leading to dam removal. On the other hand, incentives for dam removal in the form of compensatory mitigation credits or similar vehicles can create opportunities for dam removal (Normand 2021). Some state dam safety programs have included provisions to fund dam removal where potential hazards of leaving the structure in place outweigh benefits of the dam (Gonzales and Walls 2020).

Reservoir sedimentation can also become an issue that affects both operation and maintenance costs as well as operational lifespan (Schleiss et al. 2016; Randle et al. 2021; Anari et al. 2023). Although some dams have stood for hundreds of years, most water storage dams were designed with an outlet structure that would be above the reservoir sedimentation level (at the dam) during the first 50 or 100 years of operation (Randle et al. 2021; Anari et al. 2023). The removal of dams often becomes the preferred option for dealing with dams at the end of their operational lifespan, both in the U.S. and abroad (O'Connor et al. 2015; Habel et al. 2020; American Rivers 2022).

Finally, the most common reason for dam removal has probably been river and ecosystem restoration. As the environmental consequences of dam construction on rivers became better understood (refer to reviews by Ligon et al. 1995; Petts and Gurnell 2005; and Poff et al. 2007), more dams were removed to restore the structure and function of the river (Duda and Bellmore 2021). Returning connectivity for aquatic organisms and restoring more natural flow, temperature, and sediment regimes to a river system can have rapid and lasting effects on the river ecosystem (Bellmore et al. 2019). Several examples exist of migratory fish moving past former dam locations into upstream habitats following dam removal (e.g., Hitt et al. 2012; Watson et al. 2018; Duda et al. 2021; and Wippelhauser 2021).

According to data maintained by American Rivers (2022), documented dam removals have occurred in every U.S. state except Mississippi. Yet, the distribution of dam removals across the U.S. is patchy. As of 2022, Pennsylvania (364), California (180), and Wisconsin (152) have the most dam removals, with several other states in the Midwest, Northeast, Pacific Coast, and Mid-Atlantic Coast removing more than 25 dams per state. Fewer dam removals have occurred in the mid-continent and southeastern regions, with most states removing less than 10 dams, with the exceptions of Georgia (32), Tennessee (33), North Carolina (57), and Florida (20). This unequal distribution by state is likely influenced by regional differences in the number of dams and their age distribution (e.g., increased older dams in the Northeastern states), in addition to state-by-state differences in dam safety policies and practices (Pohl 2002). Regional differences in efforts to remove dams for conservation also exist. For example, in the Northeast there is a desire to restore populations of coastal diadromous fishes like salmon, herring, and shad (Pess et al. 2014; Waldman and Quinn 2022). In the Northwest, there is a desire to restore salmon and steelhead populations, and one new study following the Elwha River dam removals in Washington shows near-term benefits for restoration (Munsch et al. 2023).

Despite a growing number of case studies, helpful decision-making guidance, and technical resources for dam removal, the process of estimating the cost of dam removal is not clear. Variability in cost can be high for similar dam sizes, which contributes to challenges in how to predict costs of future dam removals (Duda et al. 2023b). Of the dams removed with documented total costs, 94% are less than 10 meters (m) (32.8 feet [ft]) in height. Total costs for all documented dams varied over six orders of magnitude from a few thousand to hundreds of millions (M) of dollars (American Rivers 2022; Duda et al. 2023a). One potential explanation is that construction costs to remove the dam structure are often only a fraction of the total dam removal cost upon project completion. For example, the construction cost to remove the two large dams on the Elwha River between 2011 and 2014 was less than 10% of the total project cost (Bellas and Kosnik 2019). Pete Haug (written communication, Ayres & Associates 2020) proposed a complexity factor to explain variability in cost considering geographic influence and studies to address stakeholder concerns and litigation associated with variable regulatory processes. Gonzales and Walls (2020) found that dam height, length, type (earthen or concrete) and age were statistically significant in explaining cost variance if used together, but only explained 35% of the total cost. They proposed other factors such as sediment handling, mitigation, or other infrastructure may be responsible for additional project costs.

Building upon recent dam removal documentation, our Reclamation team set out to develop a planning-level cost estimating guideline for dam removals by drawing upon dam removal experience and cost data through a partnership with the U.S. Geological Survey, Oregon State University, and the U.S. Army Corps of Engineers. For this effort the team produced a paper (Duda et al. 2023b) in which the authors: "(1) describe the compilation of a dam removal cost database (Duda et al. 2023a) that includes cost drivers pertaining to sediment management, mitigation, and post-removal actions for completed projects in the U.S.; (2) contextualize the biogeographic trends and drivers of dam removal costs by creating common linkages with existing databases (i.e., the American Rivers Dam Removal Database, the Dam Removal Information Portal, and the National Hydrography Dataset Plus Version 2.1); (3) develop a predictive machine learning model to estimate the planning level cost of dam removal projects based on dam characteristics and prominent cost drivers, which is further packaged as an interactive and exploratory Shiny application for cost prediction (wrises.shinyapps.io/DamRemovalCostPredictiveModel/), and (4) conclude with a discussion of a detailed case study database (Tullos and Bountry, 2023) containing component-wise breakdowns of cost estimates to highlight the nuances and limitations entailed in cost estimation."

In addition to the new dam removal cost datasets and Shiny application documented in Duda et al. 2023b, scoping questions are provided for preliminary identification of potential cost drivers that may result in a higher dam removal project cost. The answers to the scoping questions along with readily available structure and geographic setting data can be used when applying the Shiny application which identifies ranges of expected project costs. Once engineering, construction means and methods for the dam removal, and reservoir or downstream river mitigation have been identified, a Planning-Level Dam Removal Computation Guide for Cost Estimating can be utilized with appropriate quantities and unit prices as noted in the instructions in appendix A.

The cost estimating guidance in Duda et al. 2023b and this report are intended for three resource management areas that need to consider the cost of dam removal. First, dam safety programs need cost estimates to inform planning efforts for aging infrastructure comparing the cost to decommission a dam with costs to maintaining and repairing dams, including the cost for mitigating lost water storage capacity due to sedimentation. Second, water conveyance programs with low-head diversion dams also require consideration of dam removal or replacement costs to modernize the infrastructure to improve fish passage, reduce operations and maintenance costs, or reduce safety hazards for recreation users. A third category of asset management involves technical support for dam removals where the decision has been made to decommission a structure and tools are needed to understand both construction and associated mitigation costs that may not be well defined at the beginning of the project. Uncertainty of cost estimates developed with these tools is dependent on project definition including engineering, construction means and methods, sediment management, and other mitigation plans associated with the dam removal.

3.0 Methods

To improve understanding of why dam removal cost varies substantially despite similar size structures, we generated and analyzed three sets of dam removal cost data: (1) Detailed Cost Database (Tullos and Bountry 2023); (2) Total Cost Database (Duda et al. 2023a); and (3) Construction Cost Database (table 1). Because cost estimating can be done at various project stages and improves as more engineering and construction means and methods become available, we created different levels of cost estimating guidance for planning stages. For preliminary resource planning efforts when limited information is available about the dam removal project, we created scoping questions to help resource managers explore if mitigation is likely to substantially increase project costs (referred to as cost drivers). The scoping questions are intended to help identify the likelihood and number of potential cost drivers. We created a decision tree that utilizes answers from the scoping questions to estimate what cost range the project might fall into using readily available data on the dam size and geographic setting. More information on the datasets and the analytical methods used to generate the decision tree are described further below. As the dam removal project progresses, engineering and construction means and methods are developed for the associated infrastructure and any potential mitigation. The Computation Guide for Cost Estimating can be utilized to further refine the project cost as described in more detail below and in appendix A.

Table 1.—Dam removal cost databases and drivers evaluated

	Total cost database (Duda et al. 2023a)	Detailed dost database (Tullos and Bountry 2023)	Construction cost database (internal sources)
Number of cases	667	15	26
Dam removal cost data	Total reported cost	Total cost and % cost by category	Cost items related to construction
Information source	455 bibliographic sources including reports, web-based information, practitioner reporting	Bid abstracts, practitioner surveys	Bid abstracts, schedule of values, estimates
Cost driver categories evaluated	Sediment management or contamination; coffer dam use; safety/access; river habitat features; flood protection, water supply, pumping plant, or water treatment mitigation; bridges, wells, roads, utilities, or fish hatchery mitigation; vegetation management; public facilities; geographic region	Construction, mitigation, design and planning, monitoring, litigation, stakeholder concerns	Structural dam demolition, river restoration, functional replacement, care and diversion of river, appurtenant structures demolition

3.1 Databases

The first dataset is referred to as the Detailed Cost Database and was created by Oregon State University (Tullos and Bountry 2023). This dataset focuses on detailed cost break downs for 15 dam removal projects. Information was gathered through oral interviews and/or written questionnaires with technical leads or resource managers involved in the dam removals and utilized construction cost estimates for the case studies where available. Respondents were asked to document what portion of the total dam removal cost was associated with construction, mitigation, design and planning, monitoring, litigation, and stakeholder concerns. Additionally, the respondents were asked detailed questions to characterize the design and management of removal. We fit regression lines with detailed costs as the dependent variable to dam height, dam crest length, dam age, drainage area upstream from dam, and sediment volume to evaluate the degree to which each variable could be a reliable indicator of cost. Some of the case studies in the Detailed Cost Database are represented as anonymous dam sites because the data were provided by private consultants who requested the name of the dam not be shared.

The second dataset is referred to as the Total Cost Database, which currently includes 667 dam removal projects and associated information for dams removed between 1965 and 2020 (Duda et al. 2023a). This represents about one-third of all recorded dams removed for which a “best available” total removal cost was found, with all but 21 sites having an associated dam height or dam height category (i.e., less than 5 m [16.4 ft], 5 to 10 m [32.8 ft], greater than 10 m) reported.

The Total Cost Database includes the total reported cost associated with each dam removal (adjusted to 2020 dollars with RSMeans[1]) and characteristics including year built, year removed, dam purpose, dam height, dam material, and geographic location. There were 517 single dams with reported costs, and 53 multi-dam removal projects where 2 to 18 dams were removed as one effort (150 dams, 22% of total). The majority (92%) of multi-dam removal projects had a total project cost without distinguishing what portion went with each dam in the project. Where height data were available, we adjusted multi-dam removal total cost to a single cost estimate assigned to each dam by using dam height to proportionally assign cost. For dams missing height information, 34 sites were assigned to the less than 5 m height category using project photos and scalable objects; missing heights were imputed based on the median height of dams within the less than 5 m height category (i.e., 2.1 m) (Duda et al. 2023b). There were 21 dams with no scaling option, and these were recorded as an unknown height category (Duda et al. 2023a) and excluded from analysis using dam heights. Average annual discharge, drainage area, and stream order based on the location of each removed dam were extracted from the National Hydrography Dataset Plus (Version 2.1). Additionally included were the presence or absence of 28 categorical cost drivers that were hypothesized by our team as potential contributors to higher costs. These drivers were related to reservoir sediment management (river erosion method, stabilization, mechanical removal, contaminants), downstream river habitat or water use mitigation (wells, municipal or industrial water supply, hatcheries), infrastructure mitigation (bridges, roads, flood protection, bank protection), reservoir landscape revegetation or shaping, mitigation for invasive vegetation or species, fish passage mitigation, or modifications at the dam site such as retaining walls, safety issues, or utility relocation. The presence or absence of drivers was determined based on first-hand knowledge of team members with the project or available citations including journal articles, white papers, technical reports, and online documentation.

The third dataset evaluated by the Reclamation team consists of 26 case studies referred to as the Construction Cost Database which contains proprietary schedule of values, bid abstracts, and government or private industry cost estimates for dam removal projects. The construction documentation contains cost items that are specific units of work for which a price is provided, and a contractor is expected to be paid (estimate) or is paid (actuals). Cost items that made up 80% of the total construction costs or estimates were categorized to evaluate which items contributed the most to the dam removal cost. The five categories of cost items are structural demolition, reservoir and river restoration, functional replacements and restoration, care and diversion of river or stream, and appurtenant structure demolition. Early analyses of the detailed and Total Cost Database case studies indicated more expensive dam removals may have unique cost drivers, and that 79% of total costs were less than $1M. The construction case studies were subdivided into dam removals with a total construction cost (or estimate) less than $1M dollars or greater than $1M dollars to determine if there were any unique differences for more expensive projects. Some of the case studies in the Construction Cost Database are represented as anonymous dam sites because the data are not publicly available.

[1] Additional cost data and indexing resources are provided in appendix A.

3.2 Computation Guide for Cost Estimating

Using the Construction Cost Database, the Reclamation team developed a Planning-Level Dam Removal Computation Guide for Cost Estimating that can be used for engineering analysis of potential cost items (see appendix A). The Computation Guide for Cost Estimating may be used to estimate the cost of dam removal when there is some level of project design, the construction means and methods are understood, quantities are defined, and unit prices have been developed for each cost item. The various cost items were generated based on one of the complex case studies noting that future dam removal projects may have additional unique cost items that would need to be added. Industry standards for cost estimating were evaluated to provide guidance to implement expected levels of uncertainty when planning dam removal costs based on the level of scope definition during major phases of a project design.

3.3 Empirical Methods

We assessed the relationship between dam removal costs and various cost drivers using regression trees, a simple analytical technique that recursively partitions data into binary sub-groups based on predictor variables that minimize sum of squares within the resultant subgroups (De'ath and Fabricius 2000). This technique provides a simple yet powerful tool to explore trends in complex data because they (1) are nonparametric or make no assumptions of linear relationships across the dataset, (2) can handle missing values, (3) are not very sensitive to outliers, (4) can capture non-additive behaviors, and (4) are easy to interpret and visualize (De'ath and Fabricius 2000).

Dam removal costs were computed in terms of thousands of 2020 U.S. dollars (USD); predictor variables included dam height and length (in m), Strahler stream order, drainage area (in km^2), average annual discharge at the dam site (in cubic meters per second [m^3/s]), region (categorized as Northeast, Northwest, Southeast, Southwest, or Midwest), and complexity drivers (i.e., the number of activities involved in dam removal that contributed to increased project complexity). Complexity drivers were further categorized into four potential predictor variables – sediment drivers, post-removal drivers, mitigation drivers, and total drivers. The data were split into training (80%, n=534 [n stands for count, number of items in database]) and testing (20%, n=133) data sets for model building and evaluation, respectively. There were 22 dams with no reported height; in these cases, the height was assumed to be less than 5 m based on additional information gathered about the project.

Regression trees built on the training data were pruned to drop lower-level decision nodes to create a more optimum and generalized tree. Pruning was conducted by selecting a tree size based on the one standard error rule, where the best tree is the smallest tree such that its cross-validated estimated error rate (obtained from a 10-fold cross-validation) is within one standard error of the minimum error obtained from the splits (Breiman et al. 2017). Pruned trees were then used to evaluate the response variable for the test dataset. Metrics such as root mean squared error and mean absolute error were used to evaluate model performance. Trees were built using the Rpart package (Therneau et al. 2015) in R, version 4.2.2 (R Core Team 2022), and were used to visualize the predominant drivers of removal costs and breakpoints in the data.

4.0 Results

Results are presented below for analyses of the Detailed Cost Database, Total Cost Database, regression tree (empirical methods), and the Construction Cost Database.

4.1 Exploring the Detailed Cost Data

Although the Detailed Cost Database (15 cases) is small relative to the Total Cost Database (667 cases), we explored if certain variables were uniquely influencing dam removal cost because the detailed cost data provided a greater depth of information (figure 2). Dam height (coefficient of determination R^2 = 96%) and sediment volume (R^2 = 97%) were both initially strongly correlated with total cost, but only if the three tallest dams (12, 32, and 64 m), two of which have the largest sediment volumes (4.9 and 16.1 M m^3), were included in the regression. When these three large dam sites were removed, the correlations between dam height (R^2 = 4.6%) and sediment volume (R^2 = 41%) with total cost were much reduced. This indicates a combination of large sediment volumes and very tall dams (tens of m) are likely to result in a high dam removal cost, although the detailed data set is quite small. The two tall dams in this dataset are Elwha and Glines Canyon Dams, where combined sediment volume was 21 M m^3 and required a phased dam removal over 3 years with 90% of project costs attributed to downstream mitigation (municipal and industrial water treatment plants, flood protection, fish hatchery improvements) required to allow the river time to transport the sediment and restore the downstream ecosystem. Sediment volume in the remaining 13 dams in this dataset is not a clear predictor of lower or higher dam removal costs by itself. Savage Rapids Dam (Oregon), which was removed in 2006 to improve fish passage, is the 12-m-high dam represented in the database with a large removal cost of $38.19M dollars. Sediment volume was only 0.15 M m^3 and was not a huge cost driver; the large cost resulted from the construction of a new pumping plant and pipeline crossing to maintain water diversion for irrigation. Dam crest length, age, and contributing drainage area were also individually tested against total cost but resulted in poor correlations, regardless of whether tall dams were included.

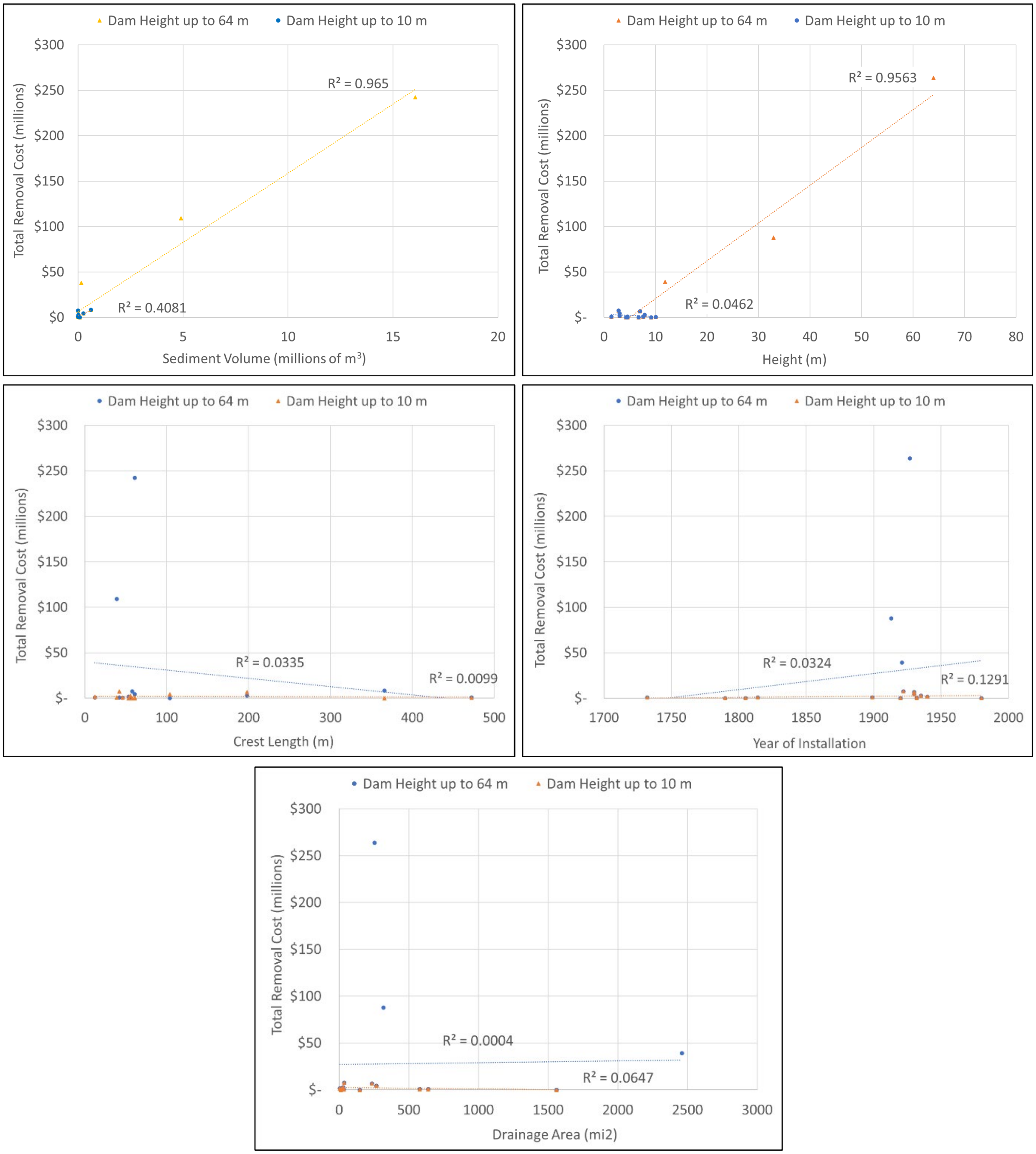

Figure 2.—Correlations with individual variables and total dam removal cost (in 2020 USD) from detailed cost database case studies.

The detailed case studies gave us another lens to look at what portion of the total dam removal cost resulted from construction, mitigation, design and permitting, monitoring, stakeholder concerns, or litigation, based on additional records and respondent knowledge of the project (figure 3, figure 4, and table 2). This revealed the three biggest contributors to reported total costs were construction related costs (6% to 82% of total, mean = 54%), mitigation (0% to 80% of total, mean = 22%), and design and permitting expenses (7% to 42% of total, mean = 20%), but each category had a wide range of costs, and additional complexities exist as to why some dams have more mitigation and design and permitting costs. We broke out less expensive dam removals (<$10M) versus higher cost removals (>$10M) to determine if the breakouts would change. The more expensive dam removals were the three tallest dams in the dataset (greater than 10 m) with a large percentage of total cost attributed to mitigation (53 to 86%); smaller (10 m or less) less costly dam removals had a range of no mitigation up to 45% of total cost.

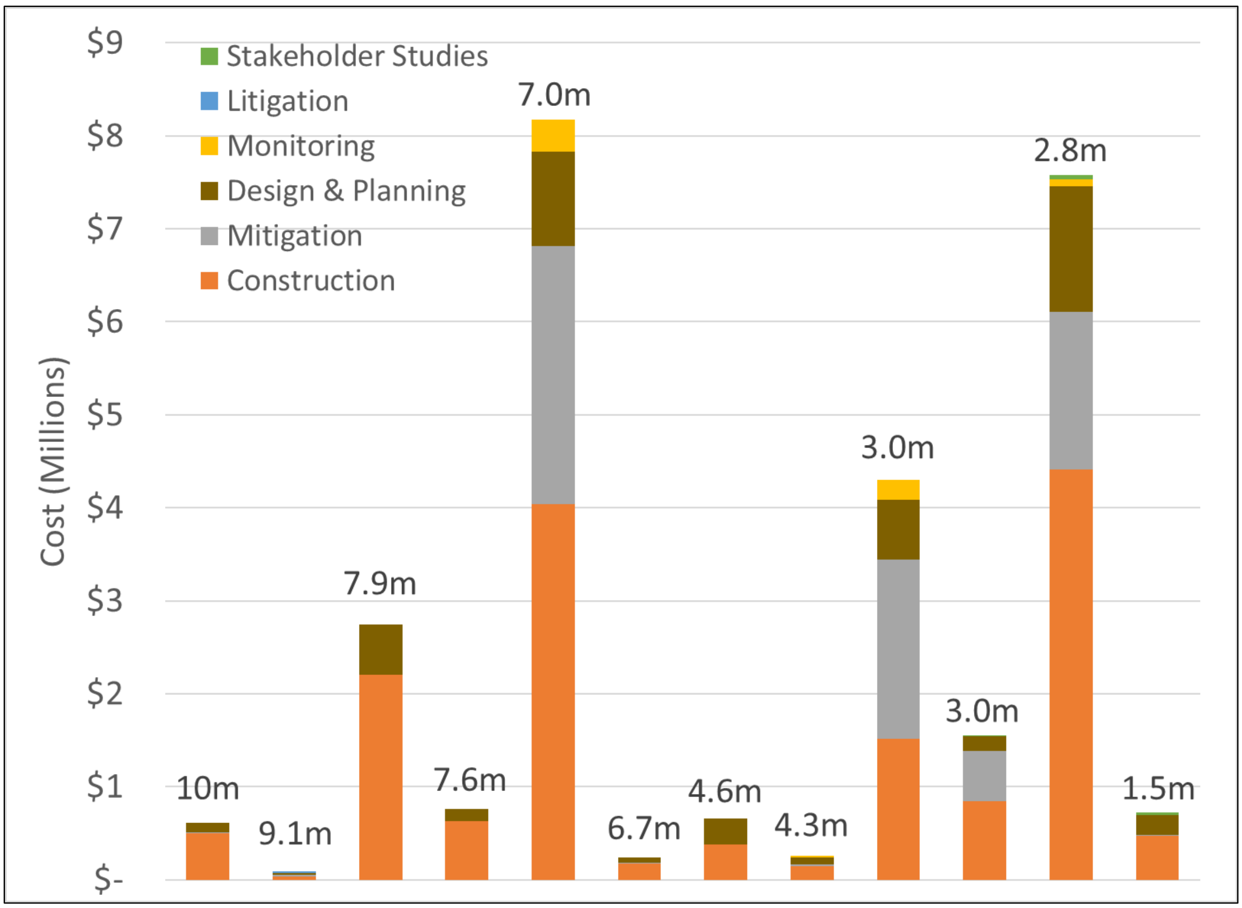

Figure 3.—Categorical breakouts for detailed cost database projects for less expensive dam removals ($8M of 2020 USD or less) with dam height of 10 m or less (dam height is labeled for each project).

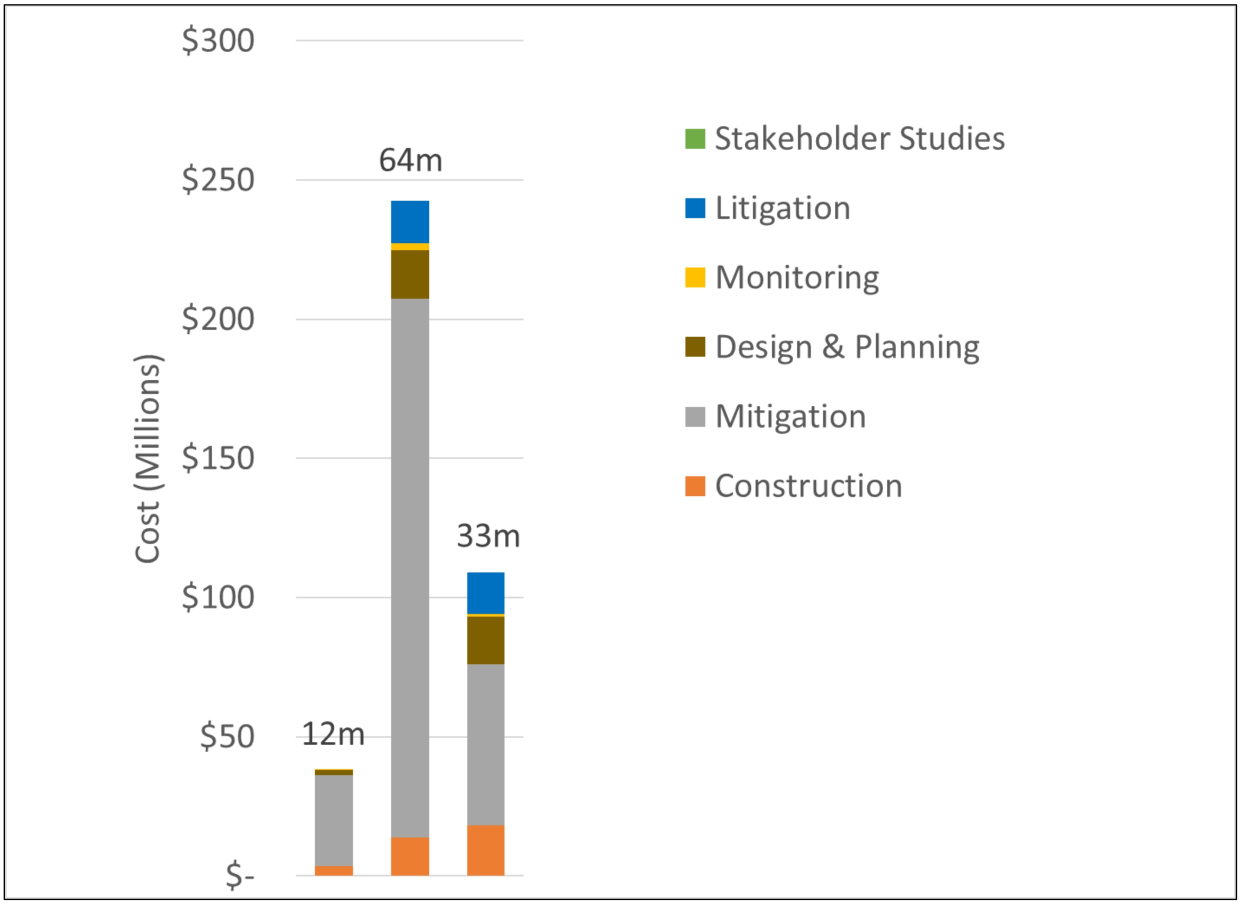

Figure 4.—Categorical breakouts for detailed cost database projects for more expensive dam removals ($10M in 2020 USD or more) and dam height 12 m or taller (dam height is labeled for each project).

Table 2.—Categorical breakouts by percent of total for detailed cost database case studies (in 2020 USD)

	Construction	Mitigation	Design and permitting	Litigation	Monitoring	Stakeholder concerns
Minimum (all cases)	6%	0%	7%	0%	0%	0%
Maximum (all cases)	82%	80%	42%	19%	6%	3%
Mean (all cases)	54%	22%	20%	3%	1%	0.3%
Mean (total cost <$10M)	61%	14%	21%	2%	1%	0.3%
Mean (total cost >$10M)	10%	73%	9%	7%	1%	0%

Monitoring costs contributed only a minor amount (0 to 6% of total), although it is unclear if all monitoring costs were reported because some may have been accomplished by research entities or regulatory agencies outside of the cost tracking provided. Stakeholder concern studies and litigation did not show up as large cost contributors (0 to 6% of total) except for one case study where 19% of total cost was associated with litigation. Stakeholder concern studies and litigation may occur prior to the decision to remove a dam and before the beginning of total cost tracking for the project as reported in the Detailed Cost Database. For example, Savage Rapids Dam had $1M spent by the local water district on litigation on whether to remove the dam (Barnard 2009), but this was not reported because the respondents were only aware of costs incurred after the dam removal decision was made.

4.2 Total Cost Database Highlights

The Total Cost Database offers less detail in cost breakdown (for example, sediment volumes are not reported - only presence/absence of sediment management is reported) but provides a much larger dataset to analyze. Most of the dams removed (309 or 46%) cost hundreds of thousands of 2020 USD (figure 5). The next largest number of dams removed (194 or 29%) cost tens of thousands of 2020 USD. Only three dams (0.4%) cost hundreds of millions (M) of 2020 USD. A wide range of dam heights are included in the Total Cost Database (646 with known height), but the majority are small dams with 83% less than 5 m, 12% between 5 to 10 m, and only 5% greater than 10 m. The sum cost of all 667 dam removals in the Total Cost Database is about $1.522 billion USD, with the mean dam removal cost at $2.282M USD; however, the median was only $0.232M USD indicating the mean is influenced by the less common, but very expensive dam removals. Because the Total Cost Database only represents one-third of all known dam removals, the total investment in dam removal in the U.S. is even higher.

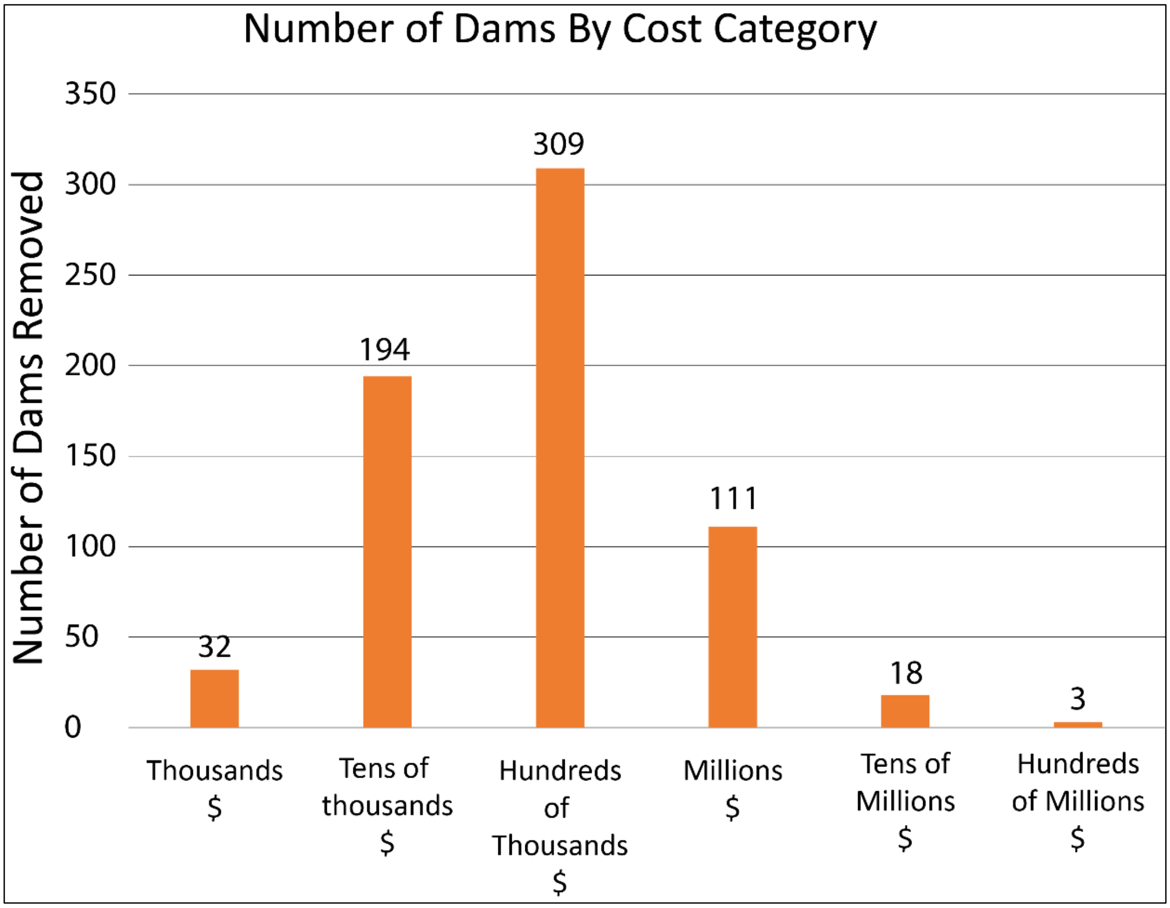

Figure 5.—Number of dams removed in six different cost categories (in 2020 USD).

Dam removal costs are represented in all regions of the U.S. in this database, of which 645 had dam height data that could be analyzed for trends by geographic region (figure 6). The U.S. Southeast had the fewest dam removals and was the only region that did not have any dams removed over 10 m. The largest number of dam removals occured in the Northeast and Midwest, accounting for 75% of all dams in the database of which 84% were less than 5 m in height (Duda et al. 2023b). The most expensive average dam removal cost occurred in the Northwest whereas the cheapest occurred in the Northeast (Duda et al. 2023b; table 3). The influence of geographic region on higher total dam removal costs in the Northwest portions of the continental U.S. can potentially be explained by their correlation with larger dams and permitting procedures, whereas less expensive costs in the Midwest and Northeast were typically small dams (less than 5 m) and may benefit from prior dam removal experience where numerous removals have taken place.

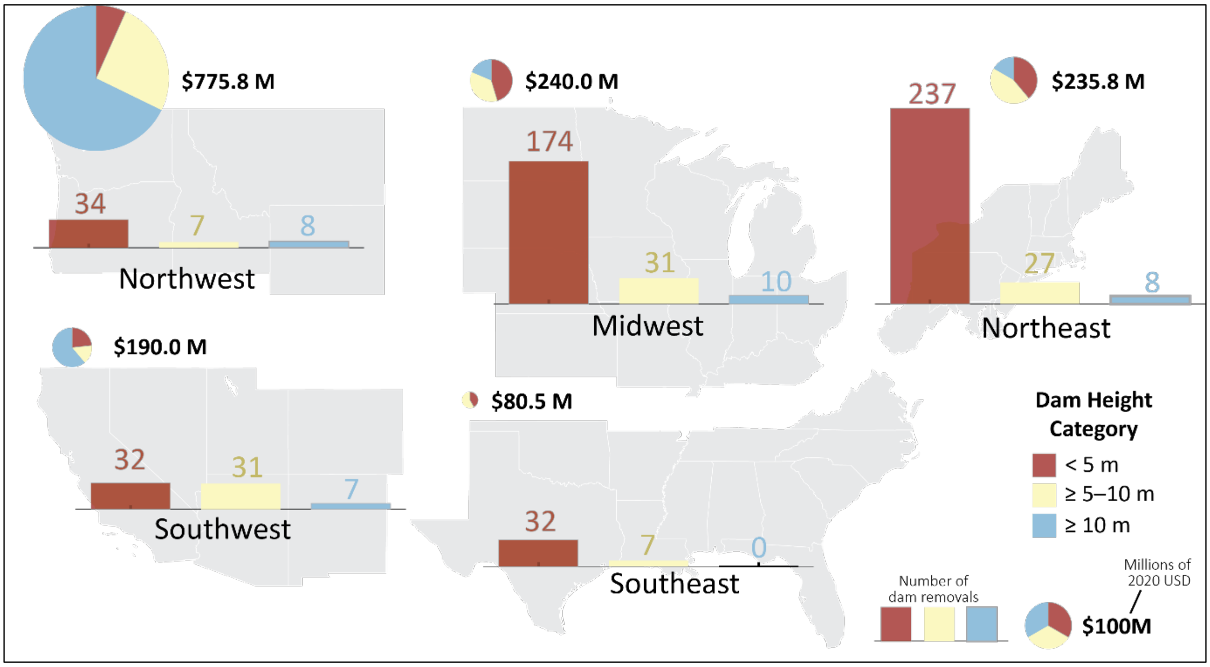

Figure 6.—Number of dam removals and sum cost by geographic region from Total Cost Database for 645 sites with both dam height and cost data available (compiled from data in Duda et al. 2023a and modified from Duda et al. 2023b).

Table 3.—Total and average cost (in 2020 USD) from Total Cost Database by geographic region in the U.S. as represented in figure 6 (645 sites with dam height data)

Geographic region	Cumulative total cost (M of 2020 USD)	Number dams removed	Average cost (M of 2020 USD)
Northwest	775.8	49	15.7
Southwest	190.0	70	2.6
Midwest	240.0	215	1.1
Southeast	80.5	39	2.1
Northeast	235.8	272	0.9

About one-third of the dam removals in the Total Cost Database included at least one of the 28 complexity cost drivers we identified. Based on experience, sediment management can result in larger dam removal costs due to either required mitigation for sediment impacts or removal of the sediment. To further explore the impact of sediment on dam removal cost, we evaluated 92 case studies in the Total Cost Database that had a sediment complexity driver noted (figure 7). Similar to the sediment volume correlation to total cost in the Detailed Cost Database, tall dams with large sediment volumes did result in more expensive dam removals in the M to hundreds of M of 2020 USD. However, for smaller dams less than 9 m, it was not easily discernable why certain dam sites with a sediment cost driver resulted in higher project costs than others. In fact, the total cost for smaller dam removals with a sediment complexity driver ranged over

five orders of magnitude. One hypothesis was that projects noting contaminated sediment presence may result in higher costs, but this was not valid as the costs still ranged over the five orders of magnitude for instances where contaminated sediments were not identified.

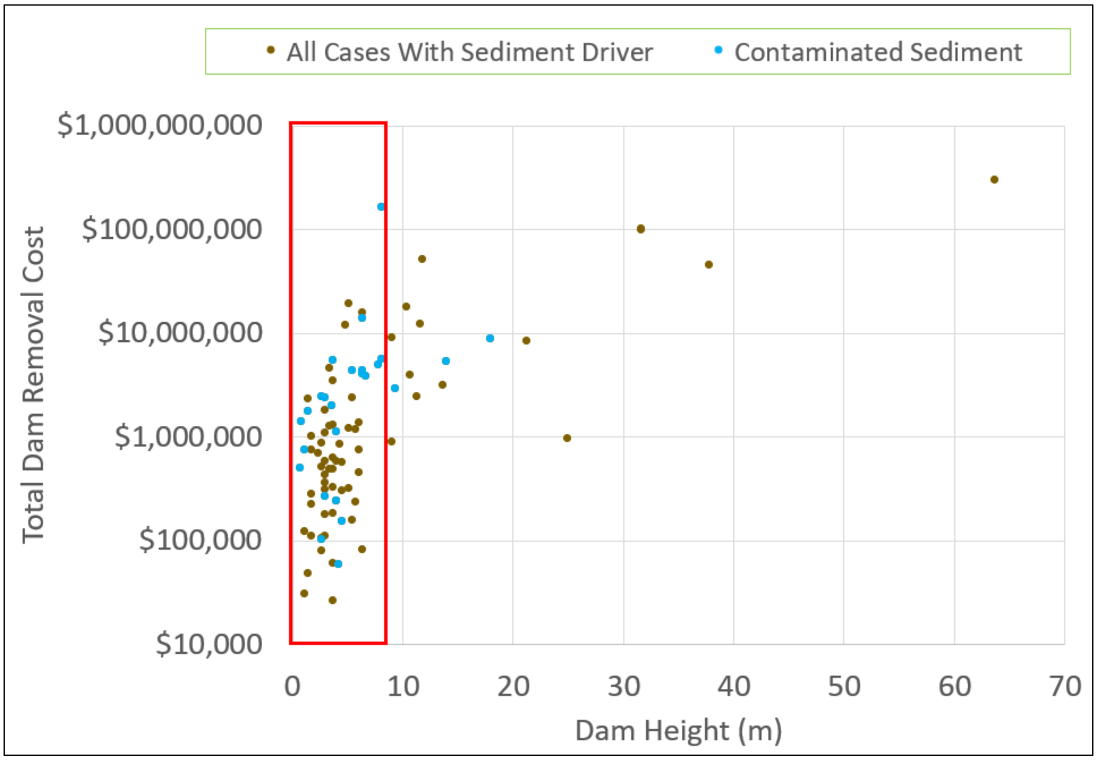

Figure 7.—Range of dam removal costs (in 2020 USD) for projects with sediment cost driver present and for projects with contaminated sediment noted in the Total Cost Database (Duda et al. 2023a).

4.3 Regression Tree Visualization

Results from looking at database variables independently as a predictor of total cost illuminated that to represent costs more accurately, a more complex approach was needed. The pruned regression trees provide a simple, yet powerful tool to explore and visualize the predominant drivers of dam removal costs and breakpoints in the data. Using the Total Cost Database, results from the regression tree showed that dam height, average annual discharge, geographic region, and the number of cost complexity drivers were influential in determining the general order of magnitude expected for total dam removal cost. Dam height and average annual discharge were responsible for the first three splits, indicating that they were the main drivers of dam removal costs. The pruned regression tree had eight nodes or categories of average dam removal costs and explained 30.3% of the variance in dam removal costs (figure 8). The least expensive dam removals had an average cost of $0.43M 2020 USD for dams less than 6.3 m in height on rivers with a small average annual discharge (less than 18 m^3/s). Dam removals costing M of dollars

ranged in height between 3.2 and 20 m with an average annual discharge between 18 and 99 m^3/s. For dams costing M of dollars, costs fell on the upper end of the range when dam height was greater than 6.3 m, more than two complexity cost drivers were present, and the project was located in the U.S. Northwest or Southwest. The most expensive dam removals cost tens to hundreds of M of dollars and occurred where dam height was greater than 20 m, on rivers with an average annual discharge greater than 99 m^3/s, and a dam height between 6.3 and 20 m. These case studies represented a small percentage of the total projects in the database and had a wider range of potential costs. When applied to the test dataset using the same regression tree parameters determined from the training dataset, the root mean squared error of the model was $8.47M 2020 USD and the mean absolute error was $2.56M 2020 USD. The concepts presented on figure 8 are further refined in the Shiny application (wrises.shinyapps.io/DamRemovalCostPredictiveModel/).

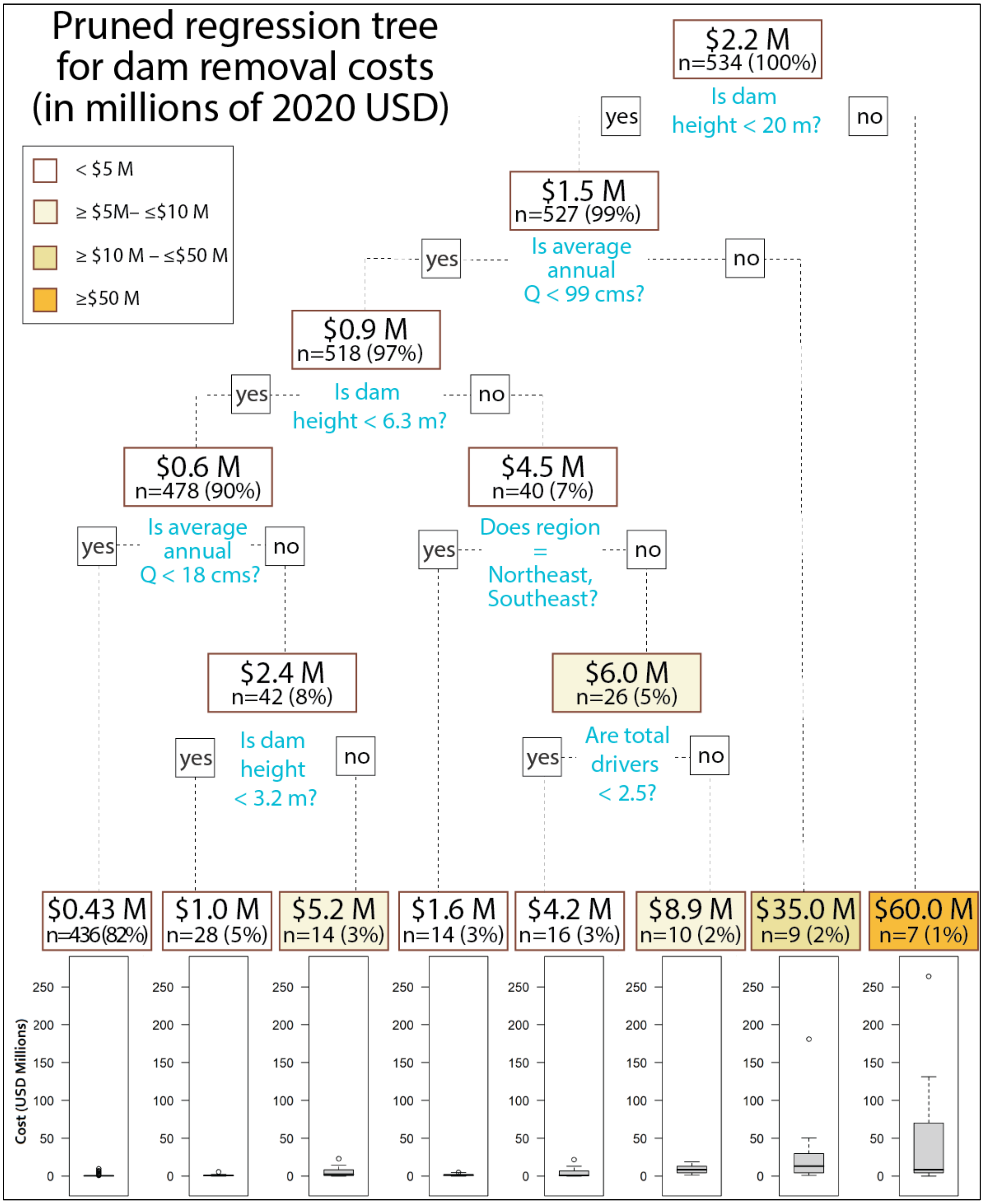

Figure 8.—Pruned regression tree results for Total Cost Database.[2]

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[2] Data in the boxes represent the average cost for that particular grouping of dam removals (number of cases = n and percentage of total cases evaluated). The questions represent the break points in the data based on the regression tree output of variable importance. Labels above the box and whisker plots (at the bottom of the graph) are color coded with white representing cheapest dam removals, yellow representing middle range, and dark yellow to orange representing the most expensive dam removals. The box and whisker plots show the average cost for that grouping (black line), 25 to 75% as lower and upper box extent, 5 to 95% confidence intervals as whiskers, and outliers shown as circles.

4.4 Construction Cost Database

Analysis of the Construction Cost Database case studies indicated that most of cost items contributing to total cost were in the category of structural demolition or river restoration and ranged between 35% and 47%. This was true for both lower cost dam removals (less than $1M in 2020 USD) and more expensive projects (greater than $1M in 2020 USD). Example structural dam demolition items with large costs include dam material removal (concrete, masonry, earth embankment), gate removal, and use of cranes for tall dams. River restoration cost items were diverse and some of the largest costs include mechanical sediment excavation, pilot channel excavation and vegetation removal, sediment stabilization, contaminated sediment management, hauling material, earth fill or backfill, erosion and sediment transport control, construction of habitat elements (large wood and fish passage), and reservoir vegetation planting and ground cover. For more detail of specific cost items identified from the case studies, refer to the full list in appendix B.

The other three categories of cost items varied in influencing total project cost but each contributed to less than 20% of the total cost. Functional replacement was only 1% for dam removals less than $1M 2020 USD and 12% of the total cost for projects over $1M 2020 USD. Functional replacement includes cost items to replace existing features at a dam with new infrastructure to allow the continued "function" of that project element. Examples in the case studies include a new pumping plant or new surface water diversion to maintain water withdrawal capabilities. The specific cost items to provide functional replacement include building of new structures using earth, concrete, or steel; installation of new pumps, piping systems, mechanical systems, electrical systems; and restoration of existing facilities.

Care and diversion of the flowing water was 16% of total cost for dam removals less than $1M in 2020 USD and 4% of the total cost for projects over $1M in 2020 USD. Cost items in the care and diversion category include access to the site, mobilization, coffer dams to control river flow, and dewatering activities. The last category, appurtenant structures, includes the removal of large features such as penstocks, turbines and generators, powerhouse and related structures, and bridges. In the case studies, cost items associated with appurtenant structures represent 1% of total cost for projects less than $1M in 2020 USD and 5% for dam removals costing more than $1M in 2020 USD.

Because dam removals have a wide range of cost with complexities not common to other construction sectors, we wanted to capture the uncertainty when developing planning level studies. Uncertainty occurs early in the dam removal design when knowledge is limited about the project scope and the means and methods to accomplish that scope. A preliminary early phase of cost estimation may have as much as -50 to +100% uncertainty when there is only 0 to 2% of the project scope defined, particularly for complex projects that are not routine (ASTM 2006). This preliminary phase is equivalent to considering the concept of dam removal, but without knowing details about the engineering and construction means and methods of the removal plan or what cost drivers will need to be addressed. To reach a Feasibility level (ASTM Class 3) cost estimate and reduce uncertainty, typically 10 to 40% scope definition is needed with an understanding of the project-specific engineering and construction means and methods. The amount of design work needed to improve scope definition is highly variable in dam removal projects. Scope

development ideally would consider which cost drivers are present, probable construction means and methods, and in some cases other categories like site restoration, replacement infrastructure, or mitigation activities.

We set out to determine which items represented the majority of costs in dam removal studies, as represented by which items made up 80% of total cost. Substantial costs in the construction case studies ranged anywhere from a few to most of the cost items. Eight percent of the cost items in one project represented 80% of the total project cost, whereas it took 92% of the cost items in another project to represent 80% of the total project cost. For all construction case studies, the average of cost items representing 80% of total project cost was 43%.

When separating projects into categories of less than or more than $1M 2020 USD in total cost, the cost data indicate that greater granularity of scope definition is needed for smaller projects. For projects costing less than $1M in 2020 USD, an average of 61% of the cost items represented 80% of the project cost. With projects costing more than $1M 2020 USD, an average of 23% of the cost items represented 80% of the project cost.

5.0 Developing Cost Estimates

A preliminary cost estimate is developed using Steps 1 to 2, then the cost estimate can be improved in Steps 3 and 4 with the Computation Guide for Cost Estimating once the engineering and construction means and methods have been developed for the dam removal and any mitigation projects. Additional work would be needed to finalize cost estimates during follow-up design phases of the project.

5.1 Step 1: Identify Potential Complexity Cost Drivers

We used the results from analyses of all three databases to develop scoping questions that identify potential cost drivers at a planning level (figure 9). Although qualitative in nature, the potential cost drivers optimally would be evaluated and discussed with the project team, partners, and stakeholders. As the major cost drivers are further scoped, this can reduce uncertainty in total cost and account for potential cost items that will increase overall cost of the project from design through implementation. The major cost driver scoping questions are associated with likelihood of complex construction, sediment management, stakeholder concern studies to better understand impacts and potential mitigation needed, or litigation for contentious sites where the decision to remove the dam is not mutually agreed upon.

This section qualitatively addresses a variety of factors that can increase cost of dam removal. These questions relate to factors that would drive cost above the average cost for a dam of a given height. Each question may be asked independently, but the topics may interact non-linearly such that costs may increase greatly as more factors are identified.

Will more advanced construction methods be required?
In some cases, the removal of a dam and its ancillary structures may mandate the use of complex engineering techniques, the construction of additional infrastructure, or the use of specialized machinery, all of which are cost drivers for dam removal. For example, the construction of coffer dams (for dewatering), new roads/bridges (for access to the site), or water treatment plants (to address elevated sediment loads) are all factors that inflate costs associated with dam removals. Complex engineering techniques may be needed in hard to access areas and for specific removal sequences, requiring large cranes or helicopters to bring in equipment and resources, which can increase costs. Very tall or old dams may also have complex engineering that varies in method depending on the dam material and volume being removed, and whether the river needs to be diverted around the dam or can be passed through or over the dam during construction.

Is sediment volume large relative to the river's sediment load?
Sediment management may be an important consideration in dam removal projects and become an important driver of dam removal costs. The ratio of reservoir sedimentation volume, relative to the mean annual sediment load, is a useful indicator of sediment management concerns, including the degree and rate of reservoir sediment erosion, channel incision through the reservoir delta, downstream sediment aggradation, and elevated turbidity (Tullos et al. 2016; Randle and Bountry 2017). High relative reservoir sedimentation volume (many years of stored average annual sediment load) or a reservoir that is much wider than the river channel is expected to have higher magnitudes of impact and risk (Major et al. 2017; Randle and Bountry 2017). In such cases, phased dam removal and active sediment management such as controlled downstream sediment release, sediment stabilization (including capping and isolation), and mechanical removal (including dredging) can substantially reduce environmental impacts but add to the cost of dam removals. If hauling of sediment is required, extended distance to disposal site and or special requirements for addressing sediment quality can be substantial cost drivers.

Will benefits from the reservoir or dam be "missed?"
In some cases, a dam to be removed may be valued by stakeholders. When dam removals cause a loss of function, supplanting infrastructure often must be built. For example, the removal of a dam to restore upstream fish passage and natural sediment loads to downstream reaches may prevent the diversion of water for agricultural, municipal, or industrial use or increase river stage during floods. In such cases, new construction may be required for water pumping plants, rock ramps and diversion weirs, water treatment plants, or construction of flood protection measures. Some dams may have historical or cultural value related to their roles in community. Similarly, the loss of intangible benefits as perceived by specific stakeholders (such as a loss of sense of place) may result in active opposition and litigation against a dam removal project, further prolonging the process and increasing costs. In addition to qualitative factors, some quantifiable metrics such as the number of lake-front property owners and the amount of recreation use may be useful indicators.

Will there be extensive remedial actions?
Most dam removal projects are accompanied by post-removal remediation of the reservoir and downstream riverine habitat. However, the extent of remediation required can greatly influence the cost of dam removal. Common remediation measures that can inflate costs include the reshaping of reservoir topography, revegetation of exposed surfaces within the former reservoir,

and streambank stabilization. For the Elwha River Restoration Project, water treatment plants, wells, levees, engineered log jams, and a fish hatchery were constructed to mitigate the impacts from reservoir sediments (accumulated over a century) passing downstream toward the sea (Bountry et al. 2018).

Is there "reason to believe" uncertainty will increase cost?

Engineers frequently act with imperfect information, and dam removal can involve unexpected factors related to unearthing materials or conditions not anticipated. Site-specific features such as the presence of contaminated reservoir sediment, invasive species, sites of cultural or historical significance, or buried infrastructure pose additional uncertainty and complexities that can elevate the costs associated with dam removals. For example, contaminated reservoir sediments might require additional impact assessment studies and sediment stabilization and containment or removal to prevent the spread of contaminants along the downstream river network; the presence of invasive species may warrant their eradication and ecological monitoring; and cultural or archeological sites may need additional mitigation or site preservation. These uncertainties are somewhat foreseeable at some sites (e.g., regions with a legacy of mining and contamination or cities with complex networks of infrastructure surrounding the dam).

Major Cost Drivers (surrogate indicators)	Yes	No
Will more advanced construction methods be required? (e.g., coffer dam for dewatering, cranes for tall dams, helicopters for remote access)		
Is sediment volume large relative to the river's sediment load? (e.g., many years average annual sediment load, reservoir width >> river width, phased removal)		
Will the reservoir or dam be missed? (e.g., infrastructure replacement, navigation use, lake recreation, expected litigation, stakeholder outreach, societal value, historical landmark)		
Will there be extensive remedial actions? (e.g., revegetation, restoration, grade control,…)		
Is there "reason to believe" complexities will increase cost? (e.g., sediment quality, archeological sites, buried infrastructure,…)		

Total number of "Yes" answers

Figure 9.—Scoping questions to identify potential cost drivers for a dam removal in the early planning stage.

5.2 Step 2: Utilize Shiny Application to Estimate Preliminary Cost

Based on the number of complexity drivers from the scoping questions in Step 1, dam height, average annual discharge, and geographic location of the project, use the Shiny application from Duda et al. (2023b; wrises.shinyapps.io/DamRemovalCostPredictiveModel/) to estimate a preliminary dam removal project cost range. The concept of the Shiny application is presented in the Regression Tree Visualization, although some updates were made in the online product as documented in Duda et al. 2023b (figure 8). Uncertainty is represented in the Shiny application based on the range of historical dam removal costs within each bin of similar project characteristics and can span multiple orders of magnitude in potential dam removal total costs. This range of cost uncertainty can be reduced by developing engineering means and methods along with identifying potential mitigation that can affect costs in the following Steps 3 and 4.

5.3 Step 3: Develop Engineering and Construction Means and Methods for the Dam Removal, and Any Needed Mitigation

A guideline by U.S. Society of Dams (2015) along with a series of questions can be asked to explore the engineering and construction means and methods for dam removal and mitigation. Reviewing past dam removal projects with cost estimators, design engineers, construction engineers, and practitioners can be good approach to developing answers to these questions and understanding if potential cost drivers can be identified and need to be addressed.

What extent of the dam would be removed, over what time period, and what method would be used to remove the dam?
In general, the greater the portion of the dam and related facilities that are removed, the greater the removal cost. However, long-term costs to secure and maintain any remaining facilities also are possible. The extent of dam removal depends on the project purpose (e.g., dam safety, fish passage, river restoration, cultural and historical considerations). For dam safety, enough of the dam is removed to leave the structure in a safe condition. For fish passage, enough of the dam is removed to enable upstream and downstream fish passage. For river restoration, enough of the dam is typically removed to restore natural streamflow processes and site aesthetics. For cultural and historical considerations, discussion with local stakeholders and regulatory teams can inform if portions of the structure and associated lands need to be left in place or restored.

In general, the longer the time required to remove a dam, the greater the cost. However, the magnitude of environmental impacts tends to be less with slower rates of dam removal. The time period of dam removal depends on the reservoir sedimentation volume, potential concerns for reservoir landslides, and downstream turbidity effects to the aquatic environment and water users.

The method of dam removal is important because some methods are more efficient and less expensive than other methods. For example, the construction of a coffer dam can be expensive and generally is only used when necessary for construction activities. The use of construction cranes for the removal of tall dams will increase costs. The drilling and blasting of concrete may be less expensive than use of pneumatic hammers.

Based on the dam removal plan, what is the expected fate of the reservoir sediment?
For this question, consider how much sediment might remain within the reservoir versus potentially erode and be released downstream (refer to Randle and Bountry 2017 for more guidance).

What reservoir sediment management and downstream mitigation may be needed?
Unless the reservoir sediments are contaminated, and at concentrations above background levels, it may be acceptable to allow river flows to erode the sediments from the reservoir and transport them along the downstream channel. If the reservoir is large enough to have captured many years of incoming sediment load or has recently experienced increased sedimentation due to extreme events like floods or wildfire (e.g., the reservoir sedimentation volume is many times the mean annual sediment load of the river), then mitigation may be required. If the sediment is allowed to be released downstream, reasons for mitigation include the need to alleviate the following effects: (1) streambank erosion and flood stage effects associated with sand or gravel deposition along the downstream channel; and (2) increased suspended sediment concentration and turbidity impacts to the aquatic environment and water users. To address these impacts, the construction of streambank protection, levees, road setbacks, bridge widening, modified water intakes, well relocations or modifications, or sediment settling basins could be necessary. River restoration features such as side channels or large wood structures are often added to dam removal projects to jump start ecosystem recovery, especially where dams have blocked off sediment and resulted in decreased habitat quality downstream.

If the reservoir sediment cannot be allowed to transport downstream, then stabilization within the reservoir area, relocation, or removal to an off-site disposal area may be necessary. The cost of sediment stabilization depends on whether the remaining sediments need to be protected from future erosion, and how robust and spatially extensive the remedy needs to be. Understanding future flood stage and potential lateral erosion risk is helpful for addressing stabilization or relocation plans. The cost of sediment removal depends on the volume, distance to be moved, and the creation and operation of the disposal area. Regardless of the sediment management approach, land areas formerly inundated by the reservoir would likely require vegetation management to establish native plants and prevent the growth of invasive species. Some regrading of reservoir sediment terraces may be necessary.

5.4 Step 4: Apply the Planning Level Computation Guide for Cost Estimating

Cost estimating for specific dam removal projects is based on the project objectives, scope, engineering design, construction means and methods, quantities, unit costs, contingencies, overhead, and profit. Using these principles, a computation guide was developed to help estimate the cost of dam removal project (appendix A, spreadsheet available at data.usbr.gov/catalog/7975/item/128528). The project scope determines the portion of dam removed, need for any replacement facilities, restoration of the former reservoir, and need for any downstream mitigation. The construction means and methods are determined by project requirements and constraints. Quantities are determined by the project scope and engineering design. Unit costs are a function of material types, construction means and methods, transportation, and local prices.

The Computation Guide for Cost Estimating was developed as a spreadsheet and organized into four worksheets:

- Total Cost Summary
- Dam Removal Cost (removal of the dam and associated structures)
- Reservoir Mitigation Cost (reservoir sediment management and mitigation)
- Downstream Mitigation Costs (reservoir sediment erosion and downstream transport mitigation)

The user can enter quantities and unit cost for each applicable cost item in each of the four worksheets. Not all listed cost items will be applicable for each project and some additional cost items may need to be inserted into the spreadsheet for a particular project.

6.0 Conclusions

Decommissioning a dam may be considered when the purpose of the dam is no longer needed, the benefits have been lost to reservoir sedimentation, or other factors such as dam safety, fish passage, recreation safety, or river restoration goals take higher priority and are more economically feasible for the dam over the long-term. Dam safety programs, river restoration programs, and asset class management programs all need to have cost estimating methods to consider dam decommissioning when appropriate. Traditional approaches in early planning design stages focus mainly on dam-removal construction related activities and may leave out important complexities that can have substantial influences on total costs and be important for project success. As the numbers of dam removal case studies increases, a growing set of cost data has become available (Duda et al. 2023a; Tullos and Bountry 2023; American Rivers 2022). However, reported total removal costs vary over five orders of magnitude for similar size dams. In addition, there is uncertainty as to what is included in the total reported cost of a given dam removal. We took multiple approaches to better understand the complexities and variability associated with estimating dam removal cost to provide guidance for engineers and resource management programs that can help inform dam decommissioning.

Typical federal planning-level cost estimating tools resulting from this study include (1) scoping questions to help resource managers determine if and what complexity cost drivers may be applicable; (2) new databases of case studies with cost information (Duda et al. 2023a; Tullos and Bountry 2023); (3) machine learning based regression trees to inform early planning level cost estimating; and (4) a Computation Guide for Cost Estimating that can be used to inform discussions on potential dam removal cost items, quantities, and unit costs (appendix A).

The data collected for this study indicated that dam height alone is not a reliable predictor of the removal cost. However, knowing some additional basic characteristics about dam material, project complexity, average annual streamflow discharge, drainage area, and geographic location of the dam site (in addition to dam height) can improve the ability to use case studies for planning-level cost estimating. By incorporating scoping questions to estimate whether complexity cost drivers are likely to be present, the initial uncertainty of a cost estimate can be further reduced especially for small dams. Once information is known about a dam removal objective, removal approach, engineering design, construction means and methods, quantities, and unit costs, then a quantitative cost estimate can be prepared with the Computation Guide for Cost Estimating.

Based on pruned tree regression analyses of the Total Cost Database, dam removal cost was found to be related to dam height, average annual discharge, and the degree of complexity (Duda et al. 2023b). Although the tallest dams and largest average annual discharges were the most expensive cases documented, once these outliers were removed from analysis, dam removal cost still varied widely and additional break outs based on these factors helped bin potential costs. Complexity cost drivers include managing sediment, reservoir dewatering mechanisms, replacing lost functions of the dam and reservoir, protecting cultural resources, constructing river habitat and infrastructure, regrading reservoir or downstream topography, managing vegetation, allowing fish passage, and protecting or relocating f utilities. In general, average dam removal cost tended to be substantially more expensive in the Northwest than in other regions of the continental U.S. The Northeast and Midwest had the lowest average dam removal costs, perhaps owing to the vast number of dam removal projects accomplished in these areas that may have helped with streamlining the planning and implementation process.

Cost savings may occur when there is there is stakeholder agreement on the decision to remove a dam, when there is a streamlined permit process (especially during emergencies), coffer dams are not needed, construction access is easy and already available, reservoir sedimentation volume is small, and the sediments are not contaminated so that extensive mitigation is not needed. Cost savings may be possible for multiple dams being removed in proximity when planning studies and construction equipment and labor can be shared.

Case studies in the construction cost database showed the most expensive cost items were associated with reservoir and river restoration actions including vegetation planting, sediment management, and channel habitat or fish passage features (appendix B). Construction case studies and professional experience with dam removal were used to generate a list of other complexities that can increase costs such as sediment quality (contaminants), cultural sites, or

old buried infrastructure in the former reservoir that require special handling and care beyond normal construction activities.

Case studies in the construction cost database indicated that dam removal with complex construction including coffer dams for care and diversion of the stream, requirements to dewater work areas, and use of helicopters can be important drivers of cost. The detailed database information revealed that case studies with large reservoir sediment volumes or a need for replacement infrastructure resulted in higher mitigation costs associated with dam removal.

Litigation and stakeholder outreach costs were not clearly identified in the available case study data, which largely relied on costs after the decision was made to remove a dam. However, these two categories may be cost drivers during the planning stage of a dam removal when stakeholders disagree on the fate of a dam.

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Appendix A

Planning-Level Dam Removal Computation Guide for Cost Estimating

Planning-Level Dam Removal Computation Guide for Cost Estimating

A new computation guide was developed to explore the planning-level construction cost for dam removal projects. This computation guide is not intended to replace agency-based cost estimating software or requirements. This computation guide was tested with construction quantities data from Boardman Dam, Michigan. The hypothesis tested was that the total dam removal cost can be predicted within uncertainty bounds if enough information is known, or can be inferred, about the construction means and methods, quantities, and unit costs. The term "construction means and methods" refers to the "labor, materials, temporary structures, tools, plant, and construction equipment, and the manner and time of their use, necessary to accomplish the result intended by this Contract" (Law Insider, 2022).

Dam removal costs are a function of the project scope, construction means and methods, quantities, unit costs, contingencies, overhead, and profit. The project scope determines the portion of dam removed, need for any replacement facilities, restoration of the former reservoir, and need for any downstream mitigation. The construction means and methods are determined by project requirements and constraints. Quantities are determined by the project scope and engineering design. Unit costs are a function of material types, construction means and methods, transportation, and local prices. Dam removal case studies can be used to help understand the potential total costs and major cost drivers.

The Computation Guide for Cost Estimating was developed as a spreadsheet and organized into four worksheets:

- Total Cost Summary
- Dam Removal Cost (removal of the dam and associated structures)
- Reservoir Mitigation Cost (reservoir sediment management and mitigation)
- Downstream Mitigation Costs (reservoir sediment erosion and downstream transport mitigation)

Values in the Total Cost Summary worksheet are linked to the other three worksheets. Each of these worksheets include a list of common cost items (one item for each worksheet row) based on the cost drivers previously identified (refer to Appendix B). Not all cost items will apply to each project, but the list serves as a reminder of cost items that could be considered when estimating total project costs.

For each applicable cost item, the user inputs the quantities and the unit price. This information requires an understanding of the likely construction means and methods based on the project requirements and constraints. Engineering construction knowledge and experience is needed to determine the lowest unit cost that will achieve project requirements. When the Computation Guide for Cost Estimating was tested against the completed Boardman Dam removal project, the results revealed challenges in trying to estimate the actual construction means and methods that

were used. By varying assumptions in haul distances and equipment used, the predicted cost varied substantially. The first test based solely on general pricing assumptions was three times the cost predicted in the second test when the plans, specifications and project conditions were more fully understood with unit prices revised to reflect a more comprehensive understanding of the project. The second test of the guide did result in a similar cost as the contract cost, well within industry standard of –50% to +100% of for preliminary level design. Therefore, unit prices ideally would be developed by cost estimators based on experience, knowledge of the specific project and other projects, and with supporting data from construction cost databases (reference list below) when using the guide.

Construction cost indexing is applied to data from previous projects to account for price changes over time. When preparing planning level cost estimates, information about the construction means and methods and quantities are provided by the engineering design and construction team. The spreadsheet provides default unit prices that can be easily overridden by the user. These default values are meant to help the user in deciding the appropriate unit prices for their project and can be used for rough order of magnitude estimates until more accurate price estimates become available.
To inform unit costs in the computation guide, the following sources provide information that may be useful:

- RS Means construction cost estimating data – www.rsmeans.com/
- Richardson Construction Estimating Standards – www.costdataonline.com/
- Craftsman Estimating Books – www.craftsman-book.com/
- Walker's Building Estimating Reference Books – www.frankrwalker.com/
- U.S. Army Corps of Engineers – www.nww.usace.army.mil/Missions/Cost-Engineering/
- Prevailing Wage Rates – www.sam.gov/content/wagedeterminations
- Fuel rates & trends – www.eia.gov/petroleum/gasdiesel/
- Engineering News Record – Quarterly Cost Reports – www.enr.com/
- Equipment Blue Book – www.equipmentwatch.com/resource-library/product-guides/
- Association of Builders and Contractors (ABC) – www.abc.org/
- Department of Transportation/ Highways – various states publish cost indexes/trends (CALTRANS, CDOT, TxDOT, UDOT, WSDOT)

The Dam Removal Cost worksheet (removal of the dam and associated structures) includes the following cost categories with one or more cost items per category:

- Construction access
- New permanent highway bridge to replace access provided by the dam
- Volume of dam materials to be removed
- Hazardous materials present? (yes or no)
- Powerhouse, buildings, and other structures to be removed
- Moving material from dam, powerhouse, and other buildings
- Diversion and care of stream flows
- Revegetation around dam site
- Demolition and possible relocation of utilities
- Site security fencing
- Other

The Reservoir Mitigation Cost worksheet (reservoir sediment management and mitigation) includes the following cost categories with one or more cost items per category:

- Reservoir sediment removal
- Reservoir sediment stabilization
- Reservoir draining mitigation
- Upstream bank protection
- Reservoir revegetation

The Downstream Mitigation Cost worksheet (reservoir sediment erosion and downstream transport mitigation) includes the following cost categories with one or more cost items per category:

- River aggradation and bank erosion mitigation
- Protection or upgrades to address increased sediment loads for existing water diversions for municipal, industrial, or environmental uses
    - New construction
    - Upgrades to existing infrastructure
    - Water diversion operation and maintenance costs
- Downstream river mitigation
- Monitoring and adaptive management

A subtotal cost is calculated for each worksheet (Dam Removal Cost, Reservoir Mitigation Cost, and Downstream Mitigation Cost). Additional cost items are added as percentages of the subtotal cost to account for uncertainty, overhead, and profit:

- ***Mobilization & Demobilization*** costs include contractor bonds and mobilizing (and de-mobilizing) contractor personnel and equipment to and from the project site, including initial project startup.

- ***Design Contingencies/Unlisted Items*** account for the cost of minor design and cost estimating refinements which are not practical to anticipate early in the project, but typically arise as the project advances through final design.

- ***Allowance for Procurement Strategy*** account for the additional cost when solicitations will be advertised and awarded under other than full and open competition. Examples of these practices include Hub-zone, 8(a) competitive and negotiated procurement, small business set aside, Public Law 93-638 Indian Self-Determination Act, or Request for Proposal where award may be based on technical considerations.

- ***Contractor Overhead and Profit*** account for the additional cost necessary to attract construction contractors for assuming the risk of performing the scope of work.

- ***Construction Contingencies*** cover minor differences in actual and estimated quantities, unforeseeable difficulties at the site, changed site conditions, possible minor changes in plans, and other uncertainties.

The Computation Guide for Cost Estimating calculates a planning level construction and mitigation cost estimate as the sum of anticipated costs. The tool assumes the probable low construction and mitigation cost estimate is 50% of the most probable cost. The probable high construction and mitigation cost estimate is assumed to be 200% of the most probable cost (ASTM 2006).

The total project cost is the sum of the costs from the other three worksheets plus the non-contract costs (design, permitting, and engineering oversight of construction) and the possible costs for litigation and stakeholder concern studies. These last two costs are estimated as percentages of the total cost. Litigation may occur in contentious projects and legal costs could be substantial. Stakeholders, including permitting agencies, may request or require additional studies to evaluate project impacts to the natural environment, people, property, or infrastructure. Together, litigation and stakeholder concern studies might increase the total project cost by up 25% (Pete Haug, Ayres and Associates, written communication, December 14, 2020). The project planning team may want to assess the potential for litigation and stakeholder concern studies. For planning level purposes, the Computation Guidance has a suggested range from 0 to 30% of total project cost to capture potential cost drivers associated with litigation or stakeholder concern studies.

For the application of the Computation Guide for Cost Estimating to Boardman Dam, data were obtained from Oregon State University. A list of cost items was provided with a short description, quantity, and total price for each cost item. The construction means and methods for each cost item were inferred based on quantity and price data, an interview with Michael Burke (Interfluve) on December 7, 2021, and a report by URS Corporation and inter-fluve (2015). Once the construction means and methods were estimated for each cost item, the unit prices were estimated based on experience, knowledge of other construction projects, and the RSMeans database. Three Boardman Dam cost items did not have enough information to independently evaluate and thus are included as lump sum costs in the case study test of the tool (table A-1). The three items represented 26% of the total project cost.

Table A-1. Lump sum cost items (in 2020 USD) for Boardman Dam removal

Cost description	Price
Traffic control and pavement	$100,000
Bridge and other structures	$375,000
Flow through or over structure during removal	$1,300,000
Total	**$1,775,000**

Appendix B

List of Construction Cost Drivers

List of Construction Cost Drivers

The following list documents construction cost drivers derived from analysis of the Construction Cost Database.

Structural Demolition

A. Concrete or masonry removal

- Saw cutting, concrete demolition, and loading on a truck
- Demolish concrete piers
- Blast spillway notch
- Remove dam to descending elevations
- Hydraulic hammering of concrete
- Remove concrete intake structure
- Remove open concrete flume
- Remove spillway concrete
- Remove forebay concrete
- Demolish spillway walls
- Dismantling of gabion vanes
- Removal of masonry blocks from dam
- Concrete transport and disposal (on-site or off-site)

B. Earth embankment removal

- Excavation of breach through dam
- Berm removal
- Dam excavation / miscellaneous excavation
- Riprap removal
- Export of unsuitable material (assume excavated material is not usable)

C. Gate removal

- Demolish gates
- Remove roller gate, stem, and operator (under water)

D. Other removal activities

- Build crane pads on rock shelf
- Core wall and sheet pile removal
- Soil cover over concrete rubble

Appurtenant Facilities Demolition

A. Penstocks

- Remove and dispose penstocks
- Remove steel transition manifolds
- Remove concrete items associated with penstocks
- Asbestos abatement (penstocks and saddles)

B. Turbines and generators

- Remove turbines
- Remove generator

C. Powerhouse and related structures

- Remove powerhouse concrete
- Remove structural steel
- Asbestos abatement
- Remove shop and warehouse
- Remove crane(s)
- Remove valves and mechanical equipment
- Remove stop logs and slots for intake steel
- Remove intake structure concrete and trash racks
- Demolish surge tank
- Pipe removal

D. Miscellaneous

- Remove current diversion tunnel plug
- Existing bridge and support structure demolition
- Existing mill race control structure removal

Reservoir and River Restoration

A. Excavation

- Excavation and stockpile for retaining wall placement
- Excavate and haul forebay material
- Sediment dredging
- Excavate streamflow diversion channel
- Excavation to achieve restored river channel and floodplain
- Stream channel relocation and site grading
- Channel bed construction
- Grading for rock ramp fishway
- Bench and stream grading

B. Fill or backfill

- Imported structural backfill
- Backfilling canal
- Compacted embankment
- Slope restoration
- Topsoil spoils and adjacent upland area
- Finish grading

C. Erosion and Sediment Control

- Fabric encapsulated soil (FES) bank construction
- Embankment, compacted-in-place (CIP)
- Large wood logs with and without root wads
- Large wood piles (restored channel)
- Streambank protection
- Articulated concrete block system
- Gabion bank stabilization
- Retaining walls
- Slope toe protection
- On-site placement of masonry from dam breach
- Import of stone lining for stream channel
- Imported riprap for tail race
- Imported stone for retaining walls and slope stabilization
- Large riprap for siphon stilling basin
- Rounded river rock for armoring
- Rock for accessway
- Boulders and cobbles for rock ramp fishway
- Stabilization stone
- Stockpile large stone for re-use in retaining walls and stabilization

D. Reservoir vegetation

- Containerized trees and shrubs
- Weed management
- Live cuttings
- Hydroseeding
- Riparian pole planting
- Ground seeding – hydroseeding
- Riparian irrigation
- Vegetation salvage and installation
- Planting

E. Ground cover

- Mulch
- Soil cover for disposal area

F. Miscellaneous

- Monitoring
- Maintenance paths
- Repair and stabilization of remaining dam concrete
- Fence (construction and tree protection) on very small projects
- Visitor improvements

Functional Replacements

A. Earthwork

- Compacted backfill and compacted embankment for structures
  Excavation of rock for structures

B. Concrete

- Structural concrete for pumping plant and intake structures
- Concrete reinforcement
- Backfill concrete for intake pipes
- Articulating concrete block revetment system

C. Steel

- Metal building system
- Miscellaneous metalwork
- Prefabricated steel truss pipe support
- Pedestrian access bridge
- Intake structure seats and guides
- Fish screens

D. Pumps and piping systems

- Vertical turbine & vertical mixed flow pumping units
- Vertical motors
- Steel piping manifold with valves
- Adjustable baffles
- 42-inch diameter PVC pressure pipe

E. Electrical

- Power transformer
- 5-kV motor control equipment
- 600-volt motor control center

F. Mechanical systems

- Air burst cleaning system
- Heating and ventilating system

G. Restoration of existing systems

- Slip lining 7-foot CMP (polymer coating), grouting, inlet modification
- Unit 501 restoration

Care and Diversion of River or Stream

A. Access
B. Site clearing
C. Temporary access and haul roads
D. Asphalt overlay and road repair
E. Rock excavation for haul road widening
F. Mobilization

- Construction management and oversight
- Construction hold period for in-water work window
- Mobilization and preparatory work

G. Coffer dams

- Coffer dams for structural removal
- Cofferdams for functional replacement (e.g., pumping plant)
- Vinyl sheet pile system installation

H. Unwatering and dewatering

- Water removal and control at Dam site
- Dewater reservoir
- Temporary siphon dewatering system installation and removal
- Temporary bypass pipes

Other Considerations

A. Contaminated sediments

Removal or stabilization of contaminated reservoir sediment could substantially add to the project cost. None of the case studies examined documented the handling of contaminated sediments. Refer to Randle and Bountry (2017) for more guidance on contaminated sediment requirements associated with dam removal projects.

B. Contingencies

Contingencies are often added to account for uncertainty in the cost estimate:

- Design contingencies (e.g., 20%)
- Construction contingencies (e.g., 20%)
- Allowance for procurement strategy (e.g., 5%)

C. Overhead and profit

- Mobilization and demobilization (e.g., 5%)
- Contractor overhead and profit (e.g., 15%)

D. Non-contract costs

- Additional assessment, permitting, Section 106, and engineering design (35% ± of construction)

- Engineering design and construction oversight