Dam Removal Cost Databases and Drivers

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Introduction

The United States has over 90,000 dams listed in the National Inventory of Dams (NID) 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 2022). There are also millions of additional small dams in our nation that are not listed in the NID. While most dams continue to provide important value, around 2,000 dams have been removed in the United States in the last century, with an increasing trend in the last few decades (American Rivers 2023). Further, many dams and associated infrastructure are aging and costs to safely operate and maintain them are increasing. In most dam removals, the dam purpose and benefit no longer outweigh the costs to safely maintain the dam, the costs to mitigate environmental impacts, or both.

Despite a growing number of helpful decision making and technical resources for dam removal, how to estimate the cost of dam removal is not clear. Often costs to remove the dam structure are only a fraction of the total dam removal cost upon project completion. For example, the construction cost to remove two large dams on the Elwha River between 2011 and 2014 was less than 10% of the total project cost (Bellas and Kosnik 2019). The range of dam removal costs also contributes to the confusion in how to predict costs of future dam removals. There can be huge variability in cost even with similar dam size classes. Of the dams removed, 94% are less than 10 m in height (American Rivers 2023) with costs varying over six orders of magnitude from a few thousand to hundreds of millions of dollars (Duda et al. 2022). Ayres & Associates (2020 unpublished Pete Haug) proposed a complexity factor to explain variability in cost considering geographic influence, stakeholder tension studies and litigation associated with variable regulatory processes, and stakeholder support or objections to dam removal. 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 total cost. They proposed other factors such as sediment handling, mitigation, or other infrastructure may be responsible for additional project costs.

Building upon existing efforts, our 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. Bureau of Reclamation, U.S. Geological Survey, Oregon State

University, and the U.S. Army Corps of Engineers Research Development Center. The effort was developed to support three asset management areas that need to consider the cost of dam removal. First, dam safety programs need cost estimates to inform planning efforts comparing the cost to maintain or repair dams with dam decommissioning for aging and unsafe dams. Second, water conveyance programs with low-head diversion dams also require consideration of dam removal or replacement to remove safety hazards or modernize the infrastructure to improve fish passage and recreation use. A third category of asset management involves river restoration grant programs that focus on opportunities for improvements to riparian and aquatic ecosystems, often for threatened and endangered species.

Methods

We utilized three sets of available data and professional knowledge of dam removal projects to identify cost drivers and created information to inform future dam removal cost planning efforts (Table 1). The first dataset is referred to as the Detailed Cost Database and was created by Oregon State University. This dataset focuses on more detailed cost break downs for 15 dam removal projects. Information was gathered through interviews 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 tension studies. Additionally, the practitioners were asked detailed questions to characterize the design and management of removal. We fit regression lines with cost as the dependent variable to dam height, dam crest length, dam age, drainage area upstream of dam, and sediment volume to evaluate the degree to which they co-varied as an indicator of their ability to predict cost.

The second dataset is referred to as the Total Cost Database which currently includes 668 dam removal projects and associated information (Duda et al. 2022). This represents about 1/3 of all recorded dams removed for which a “best available” total removal cost was found. The Total Cost Database includes the total reported cost associated with each dam removal (adjusted to 2020 dollars) and characteristics including year built, year removed, dam purpose, dam height, dam material, and geographic location. Average annual discharge, drainage area, and stream order based on the location of each removed dam were extracted from the National Hydrography Dataset Plus (NHDPlus Version 2.1). Additionally included were presence/absence of 28 categorical drivers that were hypothesized by our team as potential contributors to higher costs. These drivers were related to sediment, mitigation, and either construction, engineering, or removal outcome activities. The presence/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. To examine the influence of various drivers on dam removal costs, we constructed recursive partitioning regression trees using the rpart package (Therneau et al. 2015) in R version 4.2.2 (R. Core Team 2022). The root mean squared error (RMSE) and mean absolute error (MAE) of the pruned regression trees were used to evaluate model performance.

The third dataset evaluated by the Bureau of Reclamation consists of 26 case studies referred to as the Construction Cost Database that contains proprietary schedule of values, bid abstracts, and government or private industry cost estimates for dam removal projects. The construction documentation contains pay 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). Pay 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. Categories included structural dam demolition, river restoration, functional replacement, care and diversion of river, and appurtenant structure demolition. The case studies were subdivided into dam removals with a total construction cost (or estimate) less than one million dollars or greater than one million dollars to see if there were any unique differences for more expensive projects.

Table 1. Dam removal cost databases and drivers evaluated.

	Total Cost Database	**Detailed Cost Database**	**Construction Cost Database**
Number of cases	668	15	26
Dam removal cost data	Total cost	Total cost and percent cost by category	Pay 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 & planning, monitoring, litigation, stakeholder tension studies	Structural dam demolition, river restoration, functional replacement, care and diversion of river, appurtenant structures demolition

Using the Construction Cost Database, a spreadsheet cost-estimating tool was developed that can be used for engineering analysis of potential pay items. The spreadsheet tool 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 developed for each pay item. The various pay items were generated based on one of the complex case studies, and then checked against the remaining case studies to add any missing components. Best practices of cost estimating were evaluated to estimate expected levels of uncertainty when planning dam removal costs based on the level of scope definition during the project life cycle.

The final step in this effort was to create scoping questions for the planning stage of dam removal based on collective findings from the three datasets. Case studies in the construction cost database illustrated that dam removal with complex construction including coffer dams for care and diversion of the stream, requirements to dewater work areas, or helicopters can be a cost driver. 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 were not clearly identified in the case study data available from this study which largely relied on costs after the decision was made to remove a dam. However, these two categories are included to consider whether they may be major cost drivers for the planning stage of dam removal(s) that may be controversial and require more funding to navigate. Case studies in the construction cost database contained expensive pay items associated with site restoration actions including vegetation planting, sediment management, channel habitat or fish passage features. Construction case studies and professional experience with dam removal was 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.

Results

The Detailed Cost Database revealed the three biggest contributors to total cost were construction related costs (9% - 82% of total, mean = 54%), mitigation (0% to 70% of total, mean = 21%), and design and permitting expenses (10% to 42% of total, mean = 22%) for both small and large dams. Monitoring costs contribute (0 to 6% of total) but were overall a small percentage of the reported total and were likely underreported. Stakeholder tension studies and litigation did not show up as large cost contributors (0 to 3% of total) except for one case study where 19% of total cost was associated with litigation. However, it is possible that legal costs were under-represented in majority of case studies that we examined. Unaccounted costs associated with stakeholder tension and litigation studies may include costs incurred by parties other than agencies or firms conducting the design, construction, and implementation who provided information for this study. Stakeholder tension studies and litigation may also occur prior to the point where the decision is made to remove a dam when the "total cost" tracking begins.

Dam crest length, dam age, and drainage area upstream of dam were all poor predictors of total cost for regressions developed when using the Detailed Cost Database case studies. Dam height (R2 = 0.9563) and sediment volume (R2 = 0.9813) were strongly correlated with cost, but only if the two tallest dams with the largest sediment volume were included in the regression. When these two sites were removed, the correlations between dam height (R2 = 0.2385) and sediment volume (R2 = 0.4179) with total cost was lower.

A wide range of dam heights are included in the Total Cost Database: 1.3% are greater than 20 m, 3.1% are between 10 to 20 m, and 95.5% are less than 10 m, with the highest proportion between 0 to 4 m. The sum cost of all 668 dam removals in the Total Cost Database is $1.5 B USD (2020 dollars). We adjusted the multi-dam removal projects with a single cost estimate to a per dam estimate using a proportional height calculation. The minimum cost to remove a dam was around one thousand dollars for a location where multiple small dams were removed as part of one project, while the maximum cost was just $268.8M USD. The mean dam removal cost was $2.2M USD, while the median was only $229,000, indicating the mean is influenced by outliers of very expensive dam removals.

Dam removals are represented in all regions of the United States in this database. The Southeast portion of the U.S. had the fewest dam removals and was the only region that did not have any dams removed over 10 m in the Total Cost Database. The largest number of dam removals with cost data occur in the Northeast and Midwest, accounting for 75% of all dams in the database. The most expensive average dam removal cost occurred in the Northwest while the cheapest occurred in the Northeast. About 1/3 of the cases included at least one of the 28 identified cost drivers in the Total Cost Database, based on available information about each dam removal. To explore the impact of sediment management on cost, we evaluated the costs associated with 92 case studies in the Total Cost Database that had a sediment driver. There was still a wide range of costs, over five orders of magnitude, and it was not easily discernable why certain dam sites with a sediment driver resulted in higher project costs than others. Even separating out cases with and without contaminated sediment did not improve the correlation between sediment volume and cost. Collectively, the database highlights how dam height and sediment volume alone could not predict the cost of dam removals. Instead, complexity factors are also needed to predict dam removal cost.

The pruned regression trees provide a simple, yet powerful tool to explore and visualize the predominant drivers of removal costs and breakpoints in the data. Using the entire Total Cost Database, results from the regression tree showed that dam height, average annual discharge, region, and the number of cost complexity drivers were influential in determining dam removal costs. The pruned regression tree had eight nodes or categories of average dam removal costs (Figure 1). The least expensive dam removals had an average cost of \$0.43 M USD were less than 6.3 m in height on rivers with a small average annual discharge (less than 18 m^3/s). Dam removals costing millions of dollars ranged in height between 6.3 and 20 m, had an average annual discharge between 18 and 99 m^3/s, and fell on the upper end of the cost range when more than two cost drivers were present. The most expensive dam removals cost tens of millions of dollars and occurred on rivers with an average annual discharge greater than 99 m^3/s and a dam height between 6.3 and 20 m high or any dam with a height greater than 20 m regardless of average annual discharge. Because 90% of the dams were less than the identified threshold height of 6.3 m, we conducted a second pruned regression tree with only dam heights less than 6.3 m. This regression tree of smaller dams still identified average annual discharge as a key factor in separating out cost categories, but also identified that dam height within this group of smaller dams was a significant cost factor. Dam sites with average annual discharge greater than 66 m^3/s represented the most expensive dam removals for the small dams, with an average cost of \$9.6 M USD.

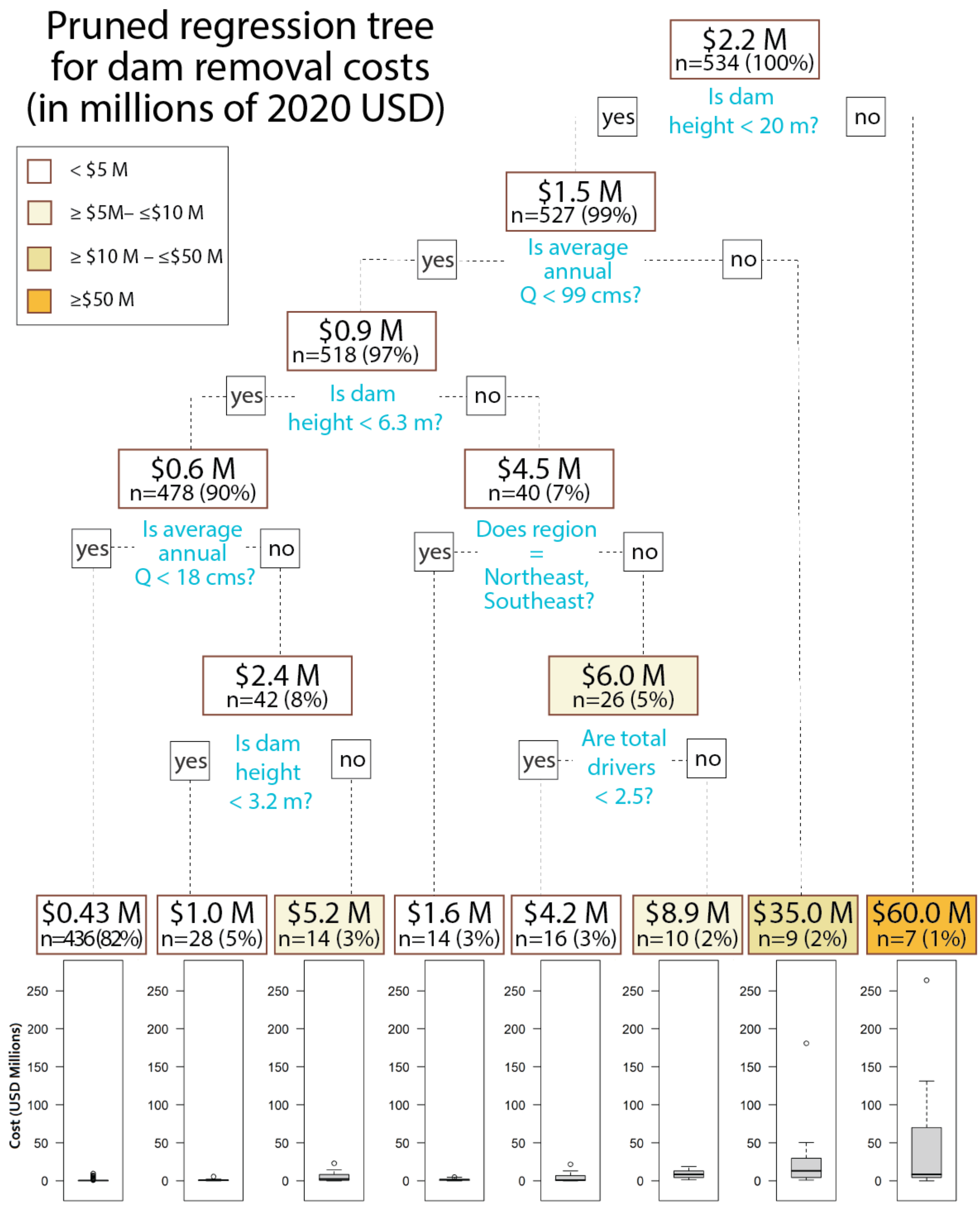

Figure 1. Pruned regression tree results for Total Cost Database.

The Construction Cost Database indicated that the majority of pay items contributing to total cost were associated with structural dam demolition and river restoration elements, ranging between 35% and 47%. This was true for both lower cost dam removals (less than $1M USD) and more expensive projects (greater than $1M USD). Example structural dam demolition items that had significant costs include dam material removal (concrete, masonry, earth embankment), gate removal, and use of cranes for tall dams. River restoration pay items were diverse and some of the significant 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.

The other categories varied in influencing total project cost but were all less than 20% of the total cost. Functional replacement was only 1% for dam removals less than $1M USD and 12% of the total cost for projects over $1M USD. Functional replacement includes pay 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 surface diversion water diversion to maintain water withdrawal capabilities. The specific pay 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 USD and 4% of the total cost for projects over $1M USD. Pay 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, pay items associated with appurtenant structures represent 1% of total cost for projects less than $1M USD and 5% for dam removals costing more than $1M USD.

Because dam removals have a wide range of costs with complexities not common to other construction sectors, we wanted to capture the uncertainty when doing planning level studies. Uncertainty occurs early in the dam removal design when there is limited knowledge 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 feasibility of dam removal, but without knowing details about the construction means and methods of the removal plan or what cost drivers will need to be addressed. To reach an appraisal level cost estimate and reduce uncertainty, typically 10 to 40% scope definition is needed with an understanding of construction means and methods. The amount of design work needed to improve scope definition is highly variable in dam removal projects. Scope development must 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.

From the case studies we found it took a wide range of pay items (8 to 92%) to determine 80% of the total dam removal cost (e.g., scope definition), with a mean of 43% of pay items required. Dam removals costing less than $1M had a slightly higher mean number of pay items required to explain the total cost (61%) than dam removals costing more than $1M (23%).

We used the results from analyses of all three databases to develop scoping questions that identify potential cost drivers at a planning level (Figure 2). While qualitative in nature, potential for major cost drivers identifies the need to analyze and discuss these items 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 pay 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 tension 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.

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,...)		

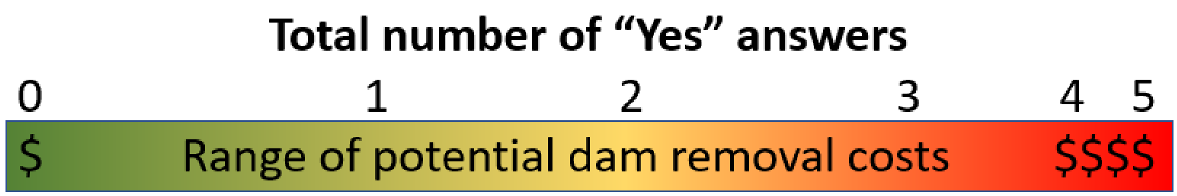

Figure 2. Scoping questions to identify potential cost drivers for a dam removal in the early planning stage.

Summary

Tools resulting from this study include: 1) scoping questions to help resource managers determine if complex cost drivers will be present; 2) new databases of case studies with cost information; 3) machine learning based regression trees to inform early planning level cost estimating; and 4) a cost-estimation spreadsheet tool that can be used to inform discussions on potential dam removal cost items, quantities, and unit costs. The collected data showed that dam size alone is not a reliable predictor of the removal cost, evidenced by the fact that small dams (less than 10 m) had costs ranging over six orders of magnitude. 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 case studies for planning-level cost estimating. By incorporating scoping questions to estimate whether complex cost drivers are likely to be present, the initial range of a cost estimate can be further reduced for small dams. Dam removals require unique management activities that involve mechanisms and considerations including the timing for draining the reservoir, condition of the dam, whether there is sediment that requires management to reduce downstream impacts on water quality and channel aggradation, access to the site, revegetation and restoration requirements, and environmental and cultural considerations. Complexity factors that can move total project cost into higher categories can include sediment management, replacement infrastructure if some functions of the dam need to be retained, and restoration of the reservoir area.

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