Sensitivity Analysis of Sediment Transport Analyses in Dam Removal Applications

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Abstract

Dam removal is a growing technique for river management and restoration in the United States with more than 1,200 dams removed nationwide (Bellmore et al, 2016; Foley et al, 2017). Dam removal may be considered as a viable alternative for common objectives such as removing aging infrastructure, reducing maintenance costs, and reestablishing upstream connectivity for aquatic habitat restoration (Major et al, 2017; Doyle et al. 2008; Heinz Center, 2002; Pohl, 2002). The ability to forecast the sediment impacts of dam removal is critical to evaluating different management alternatives that can minimize adverse consequences for ecosystems and human communities. Tullos et al. (2016) identified seven Common Management Concerns (CMCs) associated with dam removal. Four of these CMCs; degree and rate of reservoir sediment erosion, excessive channel incision upstream of reservoirs, downstream sediment aggradation, and elevated downstream turbidity are associated with stored sediment release and changing fluvial hydraulics. There are a range of existing qualitative and quantitative tools developed to infer or quantify geomorphic implications of disturbances like these in river environments (McKay et al., 2019). Sediment transport and geomorphic numerical modeling are critical tools for forecasting different management alternatives (e.g. full removal vs. staged removal vs. partial removal). However, these numerical tools require multiple sets of field data and selection of equations or methods within the tool to forecast the sediment impacts of dam removal. This study investigated how a 1D sediment transport model can inform the four CMCs associated with stored sediment release, develop an approach for assessing sediment transport model sensitivity in the context of the Simkins Dam removal, and use sensitivity analyses to identify key uncertainties, which can inform data collection and model building for other dam removal projects.

The Simkins Dam study site along the Patapsco River in Maryland was selected for this study. The Patapsco River, located southwest of Baltimore, MD is approximately 39 miles long with a drainage area of approximately 367 square miles (950 km2). The study reach (Figure 1) within the Patapsco River is approximately 8 miles (13 km) long. The study reach upstream boundary is located approximately 0.58 miles (0.93 km) southeast of Ellicott City, MD and its downstream boundary is located approximately 5.4 miles (8.7 km) upstream of the Patapsco River confluence with the Chesapeake Bay. The study reach falls within the Maryland Piedmont and the Atlantic Coastal Plain. The upper portion of the study reach lays within the Maryland Piedmont where gradients are steeper (~ 0.002) and the channel bed material is mostly gravel (MDNRWS,

2005). The lower portion of the study reach lays within the Atlantic Coastal Plain where the gradients are flatter (~ 0.0004) and the channel bed material is mostly sand, primarily formed in unconsolidated Quaternary sediments (Collins et al, 2017, McGreevy and Wheeler, 1985). Mean discharges vary throughout the year with high mean discharges during the late winter and early spring and low discharges during the late summer and early fall. The USGS gage at Hollofield (01589000), located approximately 3.73 miles (6 km) upstream of the upper boundary of the study reach, has an average annual discharge of 230 cfs (6.5 cms) and a mean annual flood of 13,240 cfs (375 cms) during the study time period. The USGS at Catonsville (01589025), located a few miles downstream of the Simkins Dam has an average annual discharge of 265 cfs (7.5 cms) and a mean annual flood of 14,125 cfs (400 cms) during the study time period.

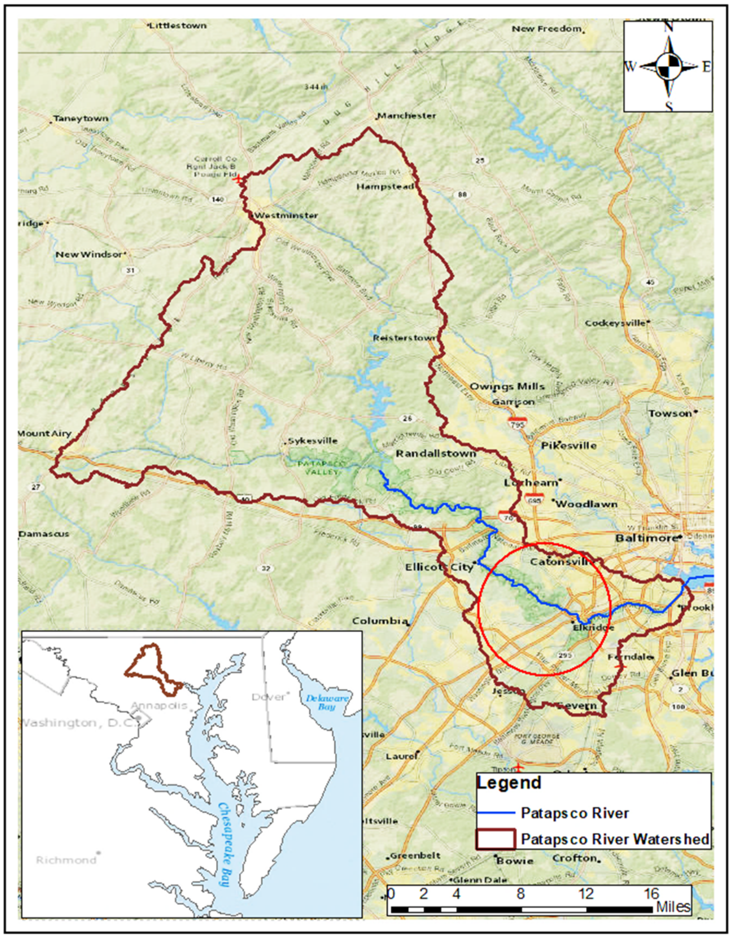

Figure 1. Patapsco River Watershed (study area located within the red circle).

The Simkins Dam was approximately 9.8 feet (3 m) tall and 217 feet (66 m) wide. The dam was built in the late 1800s and operated as run of river dam. The dam was located approximately 12 miles upstream of the Patapsco River confluence with the Chesapeake Bay (Cui et al, 2018). In the fall of 2010, the Simkins Dam was removed using a mechanical removal technique (hoe ram) to improve public safety, aquatic habitat, and migratory fish passage (Collins et al, 2017). A sediment volume of approximately 73,646 cubic yards (56,350 cubic meters) eroded from the dam reservoir from its removal to the November 2013 survey (Cui et al, 2018). The eroded sediment material was mostly sand and fine gravel. There are bedrock controls at some of the impounded areas downstream Simkins and Bloede dams with median grain sizes in the pebble range (4-64 mm) and cobble range (64-256 mm) based on the Wentworth classification (Collins et al, 2017). Extensive site data were collected before and after the Simkins Dam was removed. Data collection at the Simkins Dam site included surveys at 28 monitored cross sections and 5 monitored areas in 2010 (pre-removal), 2011, 2012, and 2013 (Figure 2).

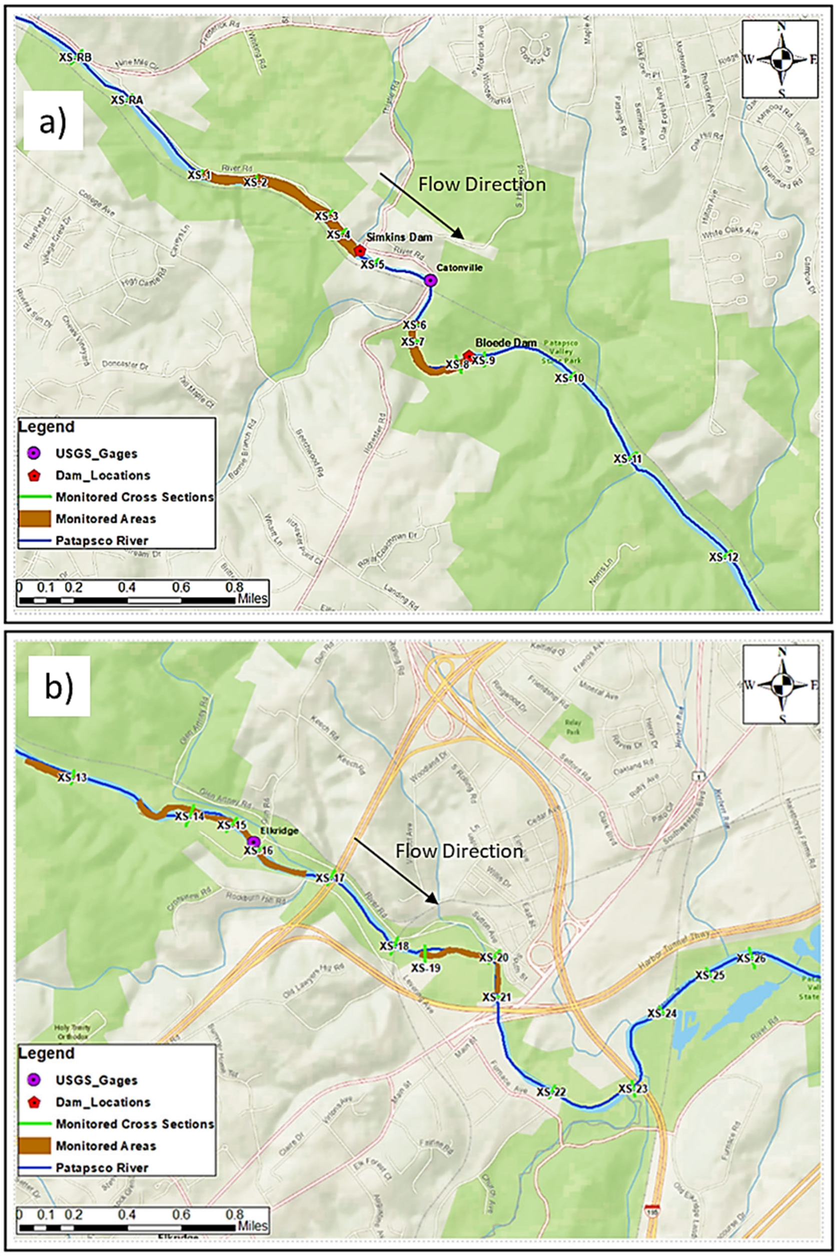

Figure 2. Monitored areas and cross sections along the study reach (a. monitored areas and cross sections in the upper portion of the study area; b. monitored areas and cross sections in the lower portion of the study area).

Bed material samples were also collected at monitored cross sections. The data were collected mainly to estimate changes in geometry and bed material along the study reach associated with the dam removal (Collins et al, 2017). Furthermore, the USGS gages near Hollofield (01589000), Catonsville (01589025), and Elkridge (01589035) have recorded multiple datasets including water discharge, stage, sediment discharge, suspended sediment concentrations, and water quality samples. Other studies with a wide range of objectives including, DeTemple and Wilcock (2014), Collins et al. (2017), Cui et al. (2018), and Cashman et. al (2021) also used data collected at the Simkins Dam site.

A 1D HEC-RAS version 5.0.7 quasi-unsteady sediment transport model of the study reach (Figure 1) was developed and calibrated to perform the sensitivity analysis. Site data including bathymetry, discharge, bed material gradations, and water temperature were used to develop the sediment transport model. Model outputs including Mean Effective Invert Change (MEIC), eroded sediment volume from reservoir, and sediment concentrations downstream of the dam were selected for calibration because they could inform CMCs associated with stored sediment release. For more detailed information about the development and calibration of the sediment transport model, please refer to Echevarria-Doyle et al (2023)[1].

Findings

After the removal of the Simkins Dam, degradation along the reservoir was observed and extended approximately 0.75 miles (1.2 kilometers) upstream of the dam as of the November 2013 survey. The model reasonably predicted the change in profile elevation for the February 2011 and November 2013 surveys when compared with the observed data (Figure 3). The initial profile elevation along the Simkins Dam reservoir had an almost flat slope. After the dam was removed, the slope along the reservoir increased to approximately 0.001 ft/ft. Also, aggradation immediately downstream of the Simkins Dam reservoir was observed during the February 2011 survey. The sediment deposited immediately downstream of the Simkins Dam reservoir continued to move further downstream based on additional surveys collected after the February 2011 survey.

The monitored cross sections XS-1 and XS-2 along the Simkins Dam reservoir maintained a similar channel width to the pre-removal (September 2010) monitored cross sections. The main change at these two locations between surveys was channel bed degradation. However, monitored cross sections XS-3 and XS-4 showed that an incision channel formed soon after the dam was removed. The channel then widened to a channel width similar to the pre-removal channel width. The volume of eroded sediments estimated by the model as of the November 2013 survey was compared with the volume documented in Cui et. al (2018) and had a percent of change below 10%. The model estimated an increase in sediment concentrations soon after the removal of the Simkins Dam from early December 2010 to early January 2011. Within this time period, the model distinctly overestimated sediment concentrations when compared with the observed concentrations recorded at the USGS gage near Catonsville, MD. Therefore, the sediment concentration simulation outputs were not used for the sensitivity analysis.

Sensitivity analysis is commonly used to examine how model outputs deviate from model calibration results because of the variation of input factors (Pianosi et al, 2016). A sensitivity

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[1] Echevarria-Doyle, W., S. K. McKay, and S. E. Bailey. 2023. Sensitivity Analysis of Sediment Transport Analyses in Dam Removal Applications. ERDC/EL TR-XX-X. Vicksburg, MS: U.S. Army Engineer Research and Development Center. (in review)

analysis was performed by evaluating the response of selected model outputs to changes in sediment input data and model algorithms.

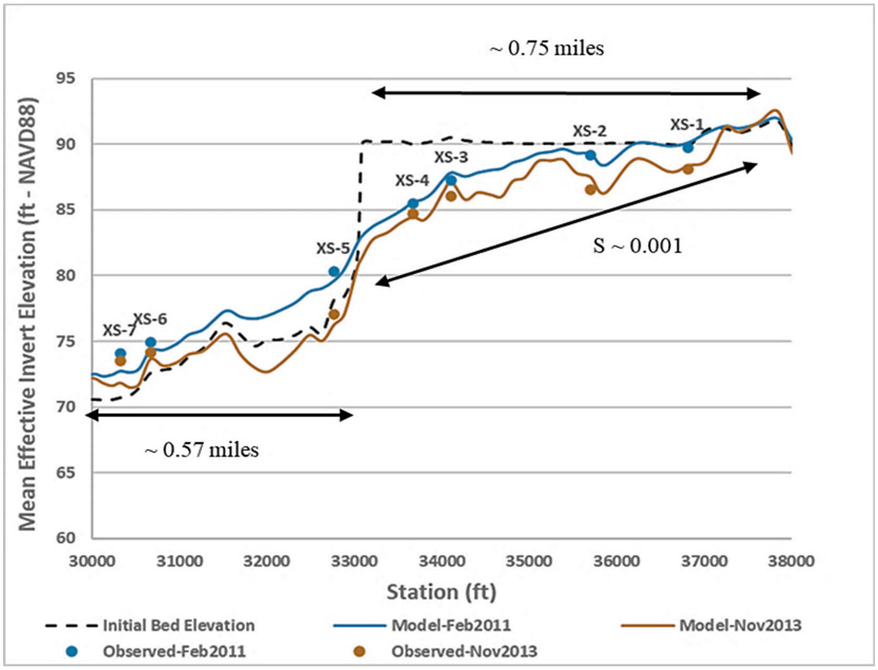

Figure 3. Mean Effective Invert Elevation along the Simkins Dam reservoir and immediately downstream of the dam for initial conditions, and the February 2011 and November 2013 Surveys.

An experimental design was developed by selecting the two model outputs that can potentially inform the four CMCs associated with sediment release: 1) MEIC, and 2) volume of eroded sediment from the Simkins reservoir (from removal to the November 2013 survey). Table 1 summarizes the sensitivity analysis of the 1D HEC-RAS sediment transport model for the Simkins Dam case study.

Figure 4 shows the MEIC for the model calibration, observed data, and sensitivity analysis along the study reach. Negative values indicate bed degradation and positive values indicate bed aggradation along the study reach. Figure 4a shows that the MEIC along the study reach estimated by Ackers-White and Meyer-Peter Müller changed slightly when compared with the calibration results and predicted similar aggradation and degradation trends for most of the study reach. Figure 4b shows that the channel evolution model – Cantelli algorithm predicted more degradation along the Simkins Dam reservoir than the Veneer method (calibration), likely because the incision channel that formed using the selected parameters is slightly narrower than the channel cross sections along the reservoir for the calibrated model. Therefore, the erosion method sensitivity using the channel evolution method will vary depending on side slope and channel parameter selection. Figure 4c shows that the Exner5 sorting method estimated more degradation along the Simkins reservoir (an average of 4 ft) and immediately downstream of the dam when compared with the Active Layer method (calibration). The MEIC particularly along the reservoir appears to be highly sensitive to the Exner5 sorting method for this case study. Figure 4d shows that the model estimated more channel degradation (an average of 3.6 ft) along the reservoir using a gradation approximately 20% finer than the gradation used for calibration along the Simkins Dam reservoir. Also, the model estimated less degradation within the Simkins

Dam reservoir using a gradation approximately 20% coarser than the gradation used for calibration and more degradation immediately downstream of the dam. Therefore, the MEIC along the reservoir seems to be highly sensitive to the bed material gradations particularly for the finer gradation along the reservoir.

Table 1. Summary of sensitivity analysis HEC-RAS simulations for the Simkins Dam case study.

Model Inputs	Rationale for examination	Baseline parameterization in HEC-RAS	Sensitivity Scenarios
Data Inputs			
Sediment gradations	Provide grain size distribution for the bed material	Develop a bed material gradation for the Simkins Dam reservoir using grain size distributions from collected bed material samples in the reservoir	Compare to a coarser and finer gradation for the Simkins Dam reservoir
Model Structure			
Sediment transport function	Predicts rates of sediment transport from given hydraulics parameters and sediment properties	Yang - used for calibration	Compare to Ackers-White and Meyer-Peter Müller transport functions
Sorting Method	Simulates bed sorting and armoring	Active Layer – used for calibration	Compare to Exner5
Erosion for reservoir deposits	"Veneer Method" is the default option to change cross sections in HEC-RAS. The area within the movable limits erodes or aggrades	Veneer Method – used for calibration	Compare to the channel evolution model (Cantelli algorithm): Modified approach to estimate erosion for reservoirs. The width and side slope of the incision channel are input parameters. A channel width = 80 ft and side slope = 0.5ft/ft were selected for the analysis

Figure 5 shows the percent of change of the volume of eroded sediments from the Simkins Dam reservoir (from removal to the November 2013 survey) estimated by the calibrated model with the sensitivity analysis results. Based on the results, volume estimation is highly sensitive to the bed material gradation and sorting method. The model estimated a volume of eroded sediments more than 80% higher than the calibration result when using a bed material gradation finer than the bed gradation used for calibration within the Simkins Dam reservoir. On the other hand, the model estimated a volume of eroded sediments approximately 48% lower than the calibration result when using a bed material gradation coarser than the bed gradation used for calibration within the Simkins Dam reservoir. The Exner5 sorting method estimated a volume of eroded sediments approximately 57% higher than the volume estimated using the Active Layer method. The Ackers-White transport function estimated a volume smaller than the volume estimated for calibration using Yang by approximately 35%. Also, Meyer-Peter Müller estimated a volume approximately 10% smaller than the volume estimated for calibration using Yang. However, the Veneer and channel evolution (Cantelli algorithm) erosion methods estimated very similar volumes, with slightly less (-0.57%) volume estimated using the channel evolution model. As mentioned earlier, the incision channel developed using the Cantelli algorithm had a slightly narrower area than the cross section along the reservoir in the calibrated model predicting a deeper invert elevation when compared with the Veneer method.

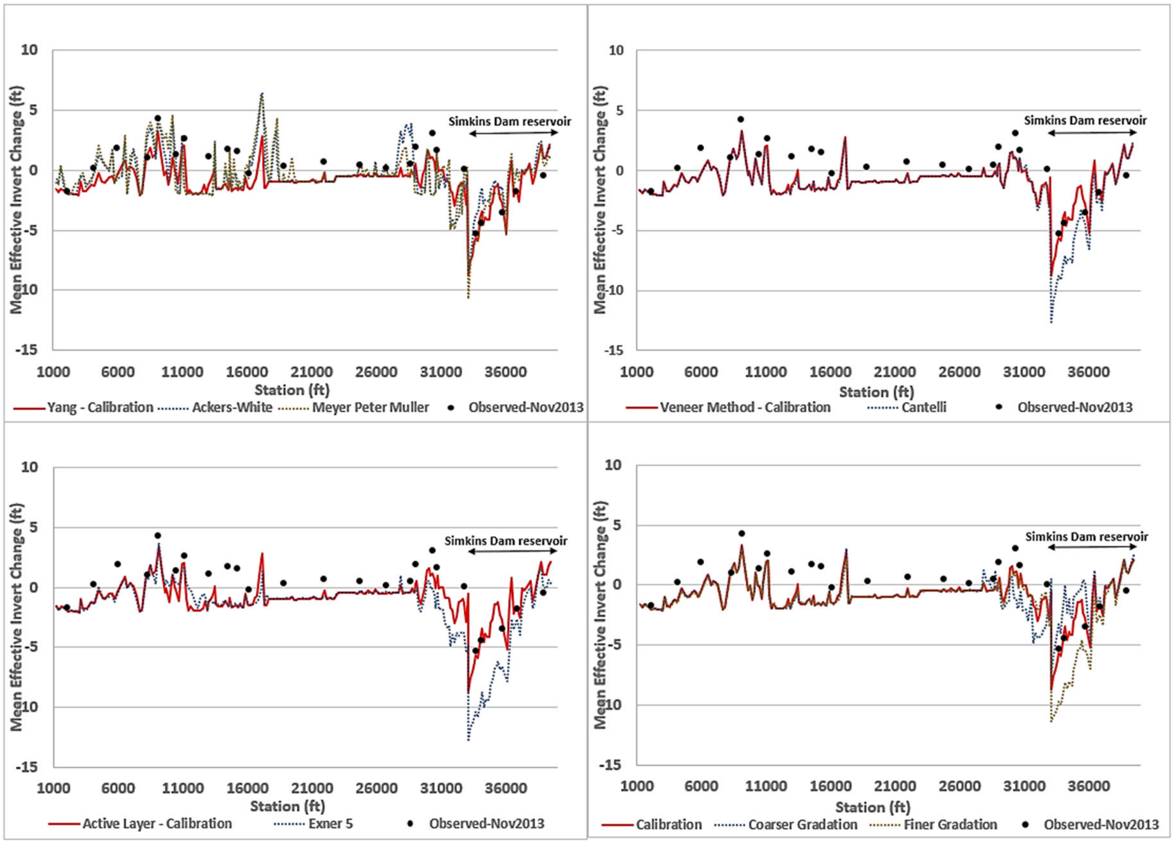

Figure 4. Mean Effective Invert Change for the November 2013 survey calibration and Sensitivity Analysis (a. transport functions, b. erosion methods, c. sorting methods, d. finer and coarser gradations).

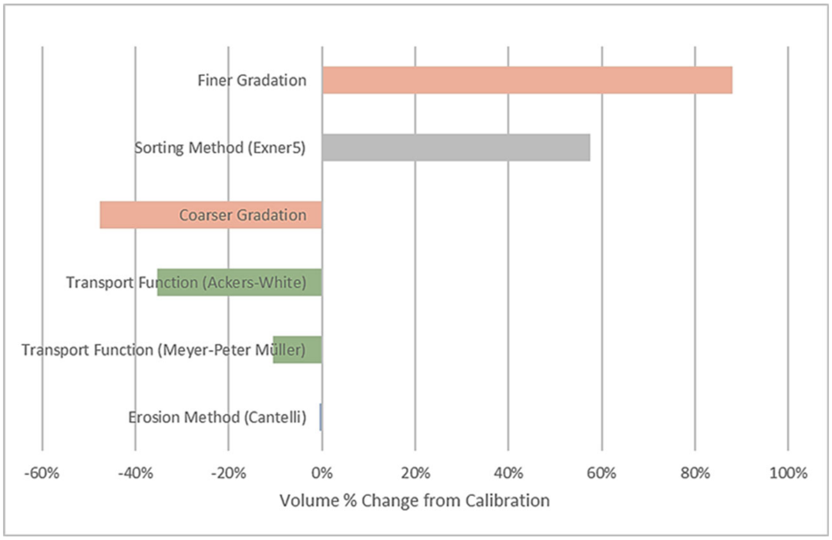

Figure 5. Percent of change of eroded sediment volume compared to calibration results.

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