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Sensitivity of Sediment Transport Analyses in Dam Removal Applications

Waleska Echevarria-Doyle, S. Kyle McKay,
and Susan E. Bailey

September 2023



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Sensitivity of Sediment Transport Analyses in Dam Removal Applications

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Abstract

Dam removal has become a widespread river management practice in the US for a variety of goals including ecosystem restoration, removing aging infrastructure, flood risk management, and recreation. 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). This study investigated how a one-dimensional (1D) sediment transport model can inform these four CMCs, 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. For the selected case study, model outputs including the mean effective invert change (MEIC) and eroded sediment volume from reservoir were highly sensitive to the variation of the reservoir sediment gradation and sorting method selection. These model outputs also showed some sensitivity to the selected transport functions. Erosion method sensitivity using the channel evolution method will vary depending on side slope and channel parameter selection.

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Preface

This study was performed for the Ecosystem Management and Restoration Research Program (EMRRP) under project number 2008-ER-37, “Ecological Effects of Sediment Erosion and Transport Associated with Dam Removal,” funding account code U4368938; AMSCO code 031342. EMRRP is managed by the US Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). The EMRRP technical monitor was Dr. Brook Herman.

Direct supervision of ERDC-EL aspects of this effort were provided by Mr. Warren P. Lorentz, chief of the Environmental Processes and Engineering Division, and Dr. Michael A. Rowland, chief of the Environmental Engineering Branch, as well as Mr. Mark D. Farr, chief of the Ecological Evaluation and Engineering Division, and Mr. Joseph Minter, chief of the Ecological Resources Branch. At the time of publication, the deputy director of EL was Dr. Brandon J. Lafferty, and the director was Dr. Edmund J. Russo.

Supervision of the ERDC, Coastal Hydraulics Laboratory (CHL) aspects were provided by Dr. David P. May, chief of the River and Estuarine Engineering Branch, and Dr. Cary Talbot, chief of the Flood and Storm Protection Division. The deputy director of ERDC-CHL was Mr. Keith Flowers, and the director was Dr. Ty V. Wamsley.

The authors deeply appreciate the contributions made by Mr. Mathias J. Collins from National Marine Fisheries Service, National Oceanic and Atmospheric Administration in Gloucester, Massachusetts, for providing extensive bathymetric and material data for the study site. Technical peer review comments were provided by Dr. Earl J. Hayter (ERDC-EL) and Dr. Travis A. Dahl (ERDC-CHL).

The commander of ERDC was COL Christian Patterson, and the director was Dr. David W. Pittman.

1 Introduction

1.1 Background

Dam removal is a growing technique for river management and restoration in the US with more than 1,200 dams removed nationwide (Bellmore et al. 2016; Foley et al. 2017a). 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 sediment accumulated behind dams is often a concern due to potential impacts the eroded sediments may have upstream and downstream of the dam (Tullos et al. 2016). Tullos et al. (2016) describe seven Common Management Concerns (CMCs) related to dam removal. Degree and rate of reservoir sediment erosion, excessive channel incision upstream of reservoirs, downstream sediment aggradation, and elevated downstream turbidity are four CMCs associated with stored sediment release and changing fluvial hydraulics. McKay et al. (2019) describe a series of potential tools ranging from qualitative geomorphic assessments to multi-dimensional numerical models that could potentially be applied to estimate the impact of eroded sediments following dam removal. Sediment transport and geomorphic numerical modeling are critical tools for forecasting different management alternatives (e.g., full removal versus staged removal versus 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.

The Simkins Dam study site along the Patapsco River in Maryland was selected for this study because of the extensive site data collected before and after the Simkins Dam was removed. The data collected at the site can be used to develop and calibrate sediment transport models to evaluate the model performance in predicting impacts associated with the sediment release following dam removal. A previous study conducted by DeTemple and Wilcock (2014) used data collected along the Patapsco River and the one-dimensional (1D) sediment transport model, HEC-RAS Beta version 4.2, to evaluate the model performance, estimate changes in sediment storage along the Patapsco River following the removal of Simkins Dam,

and make a forecast of sediment impacts from removal of Bloede Dam* (located approximately 0.62 miles downstream of the Simkins Dam).

The study presented herein used a more recent version of the 1D HEC-RAS (version 5.0.7) sediment transport model to identify 1D model capabilities and outputs that could inform the four CMCs related to sediment release included in Tullos et al. (2016). The purpose of this study was to assess model sensitivity in the context of the Simkins Dam case study by using selected input data and model algorithms to identify how model outputs deviate from calibration results. Moreover, this study used the November 2013 survey which was not included in the previous 1D HEC-RAS study.

Additional studies including Collins et al. (2017), Cui et al. (2018), and Cashman et al. (2021) also used data collected at the Simkins Dam site. Collins et al. (2017) conducted a study to test a proposed two-phase response model following dam removal using observed data from the Simkins and Merrimack dam removal sites. Cui et al. (2018) used observed data from the site to compare 1D DREAM-1 sediment transport model results using accurate and approximate channel geometry input data in the numerical model. Cashman et al. (2021) used data from the site to capture the channel response to a sediment pulse from a dam removal using routine gage data.

1.2 Objectives

The purpose of this study was to investigate how a 1D sediment transport model can inform the four CMCs associated with the release of sediment following dam removal and develop an approach to assess sediment transport model sensitivity in the context of the Simkins Dam removal case study. Model outputs including mean effective invert change (MEIC), eroded sediment volume from reservoir, and sediment concentrations could inform CMCs associated with stored sediment release. After developing a sensitivity analysis approach, sensitivity analyses were then performed to identify key uncertainties, which can inform data collection and model building for other dam removal projects.

* Bloede Dam was removed in the Winter of 2018. Source: Maryland Department of Natural Resources (<https://dnr.maryland.gov/fisheries/pages/fishpassage/bloede.aspx>).

1.3 Approach

The objectives of this study were completed by the following steps:

1. Site data gathering including the terrain digital elevation model (DEM), bathymetry, discharge, stage, suspended sediment concentration, and bed material gradations
2. Development and calibration of the 1D hydraulic and sediment transport models for the Simkins Dam case study
3. Development of the experimental design of sensitivity analysis
4. Comparison of the sensitivity analysis results with calibration results to assess the sensitivity of model results that could inform the four CMCs associated with sediment release to changes in selected input data and model algorithms

2 Methods

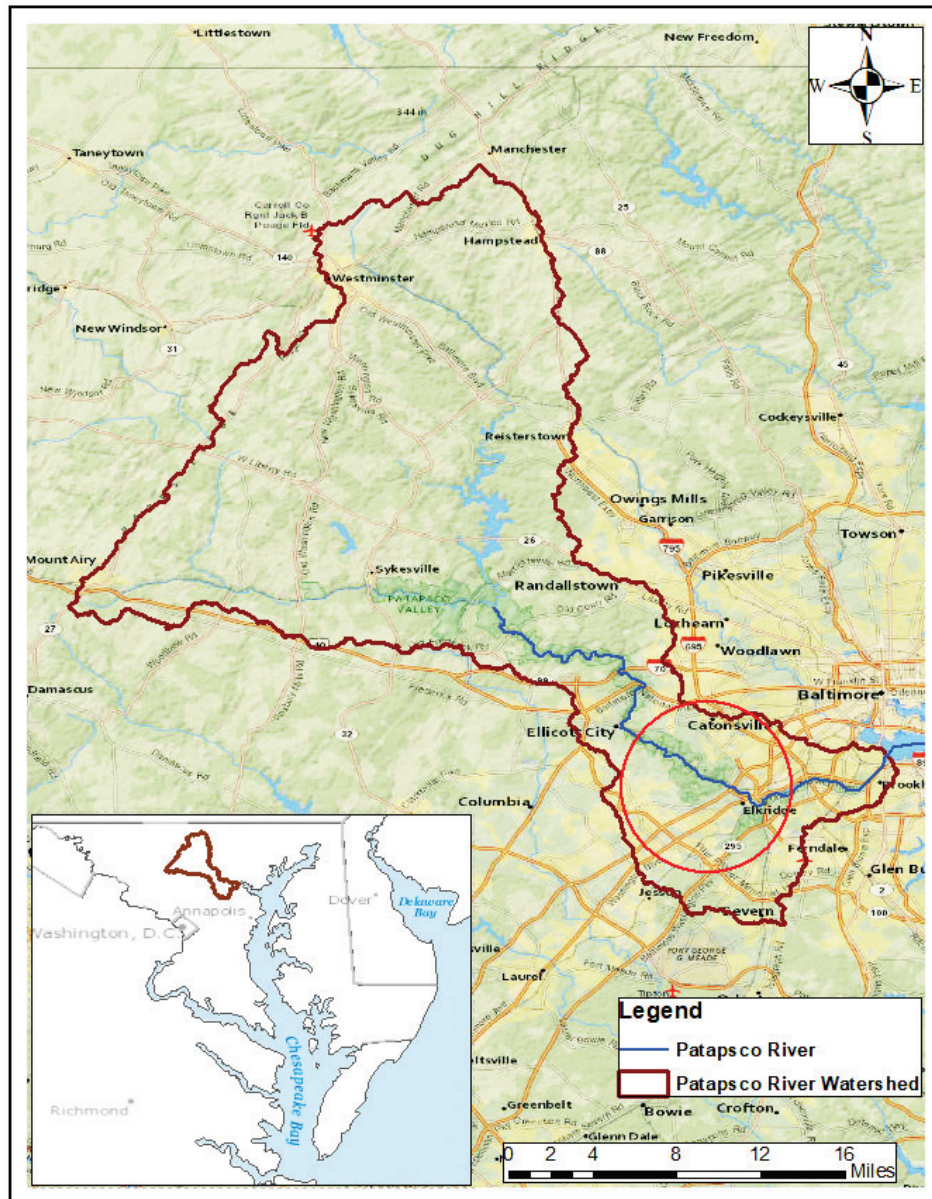
2.1 Study site

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 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 US Geological Survey (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 gage 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.

The Simkins Dam was approximately 9.8 ft (3 m) tall and 217 ft (66 m) wide. It was built in the late 1800s and operated as a run of river dam. The dam was located approximately 12 miles (19 km) 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 yd³ (56,350 m³) 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).

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



2.2 1D sediment transport model

This section describes the field survey data collection along the study reach, the development of the 1D HEC-RAS model version 5.0.7, and model inputs for the sediment transport model of the Patapsco River study reach.

2.2.1 Field Survey data collection before and after the Simkins Dam removal

A monitoring data collection effort was conducted prior and after the Simkins Dam removal to quantify the rate of morphodynamic response along the Patapsco River following the removal (Collins et al. 2017). The Simkins Dam was removed in the Fall of 2010. There are seven available field surveys: one pre-removal survey in September 2010 and six post-removal surveys in February 2011, April 2011, September 2011, April 2012, November 2012, and November 2013. Repeated topographic and bathymetric surveys were collected at 28 cross sections (Figures 2a and 2b) with Topcon GPT-3000, Trimble S3, or Trimble S6 total stations with vertical accuracy within 2 mm [0.08 in.] (Collins et al. 2017).

Additionally, five monitoring areas (Figures 2a and 2b) were surveyed at a higher resolution as part of the pre and post removal surveys to develop digital elevation models (DEMs). Figure 3 shows repeated cross sections located along the Simkins Dam reservoir during pre-dam removal and post-dam removal surveys. Bed material samples were also collected near the surveyed cross sections. Bathymetry and bed material gradations at monitored cross sections and areas from this data collection effort were provided by Mr. Mathias J. Collins from National Marine Fisheries Service, National Oceanic and Atmospheric Administration in Gloucester, Massachusetts.

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).

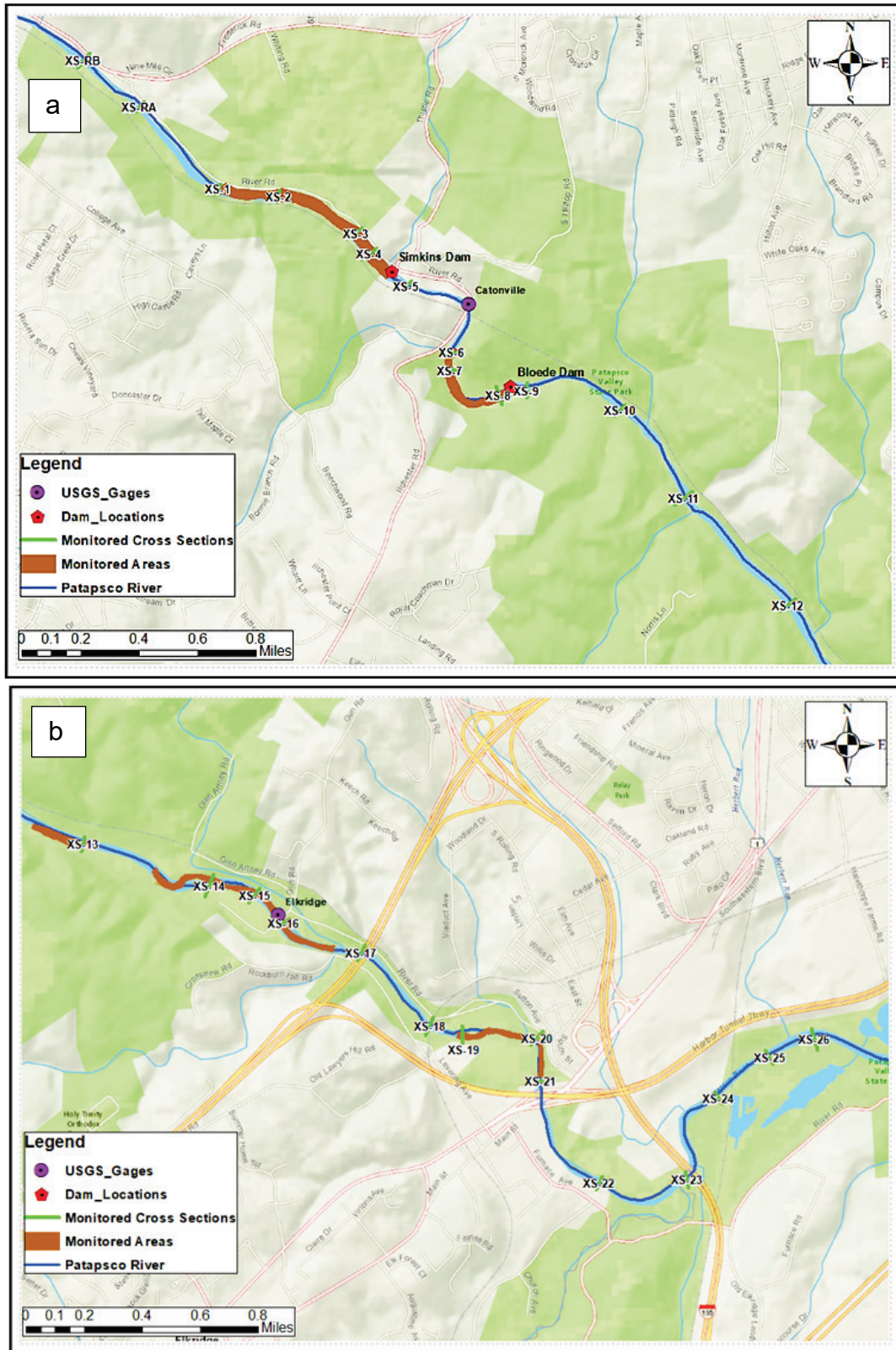
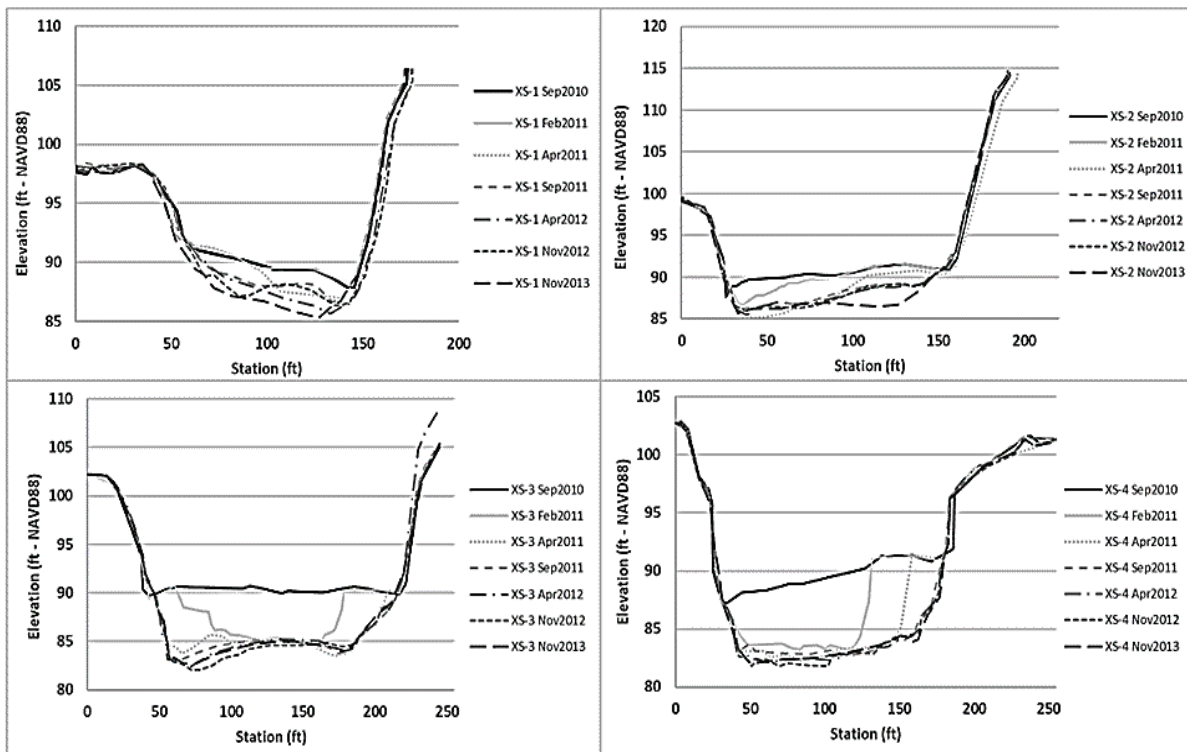


Figure 3. Monitored cross sections XS-1, XS-2, XS-3, and XS-4 for pre- and post-removal surveys along the Simkins Dam reservoir.



2.2.2 Terrain and HEC-RAS geometry

The Environmental Systems Research Institute (ESRI) ArcGIS 10.3 was used to start the development of the model terrain DEM for the study reach. Data layers used in ArcGIS included the Baltimore County 2005 LiDAR DEM (Baltimore County Government, GIS data download), aerial imagery from the early 2000s, and 2010 bathymetry from three monitored areas located downstream of the Simkins and Bloede Dams (Figure 2b). The coordinate system used for all datasets was “NAD_1983_StatePlane_Maryland_FIPS_1900_Feet.” Elevations are referenced to the North American Vertical Datum of 1988 (NAVD88). The 2010 bathymetry of the three monitored areas located downstream of the Simkins Dam were mosaicked into the Baltimore County 2005 LiDAR DEM to adjust the channel elevations at those locations.

The updated LiDAR DEM was then imported into RASMapper, a GIS tool within HEC-RAS. The 28 cross sections layers from the September 2010 survey were also imported into RASMapper. The location and bathymetry from these cross sections were used to create model cross sections at the same monitoring locations and adjust elevations from the LiDAR DEM to

represent the channel elevation at the monitored locations. Additional geo-referenced cross sections were added within the study reach using RASMapper. The DEM elevations for the additional geo-referenced cross sections were adjusted by estimating a cross section area under the DEM water reference similar to the average cross section area of the monitored locations. The underwater correction for the Simkins and Bloede Dams was calculated using bathymetry data from monitored cross sections. An average channel slope estimated based on the survey data was used to estimate the bathymetry for additional model geo-referenced cross sections along the Simkins and Bloede reservoirs. RASMapper was also used to create other geo-referenced geometry layers for the Patapsco River model including the river centerline, bank lines, and flow paths. Additional layers such as ineffective flow areas and inline structures were added using the HEC-RAS geometry window. HEC-RAS user and supplemental manuals were used as reference for model development (USACE, 2016 CPD 68 and CPD68d).

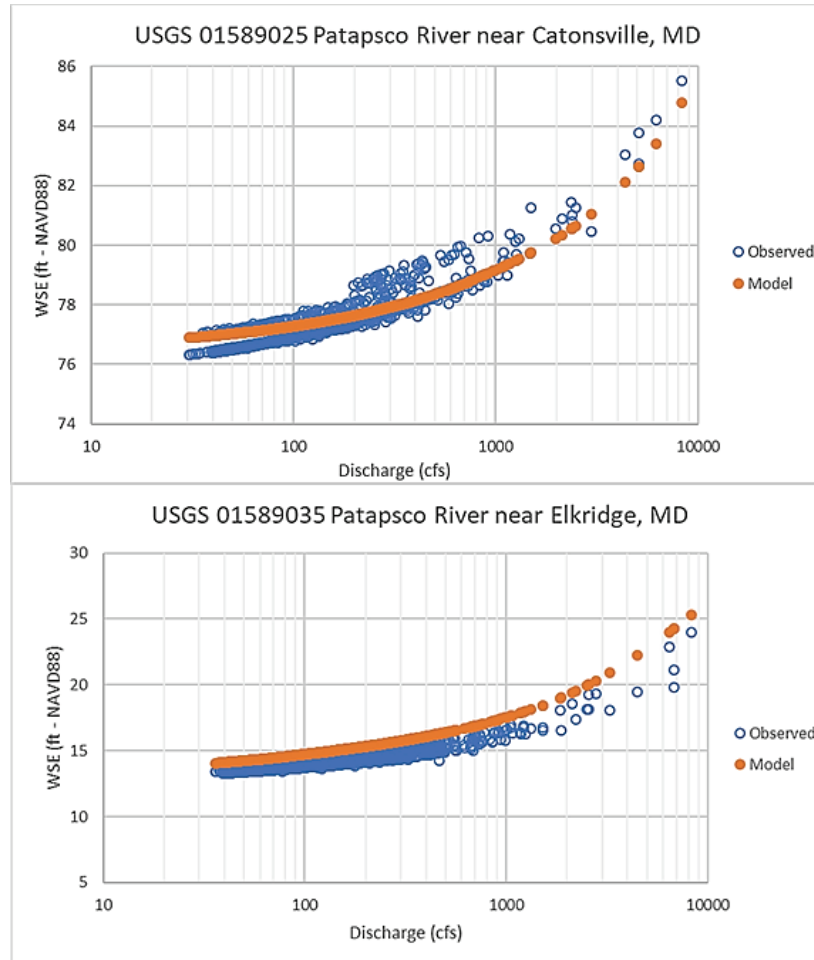
2.2.3 HEC-RAS model input data and parameters

The development of a numerical model requires input data from the study site and the selection of key parameters for the hydraulic and sediment simulations. As mentioned earlier, the 1D model HEC-RAS version 5.0.7 was used to perform sediment transport simulations for the selected study reach of the Patapsco River following the removal of the Simkins Dam. This section describes the input data and parameter selection for the hydraulic and sediment models of the study reach.

After completing the model geometry file, the steady-state hydraulic model of the study reach was calibrated by adjusting the roughness coefficients for the main channel and the overbanks in fixed bed mode using mean daily flows recorded at the USGS 01589025 Patapsco River near Catonsville, MD, and USGS 01589035 Patapsco River near Elkridge, MD, from October 2010 to November 2013. Observed water surface elevations were then compared to the model water surface elevation at those locations (Figure 4). A roughness coefficient of 0.039 was selected for the main channel and 0.10 along the overbanks for the calibrated model. The model downstream boundary is located approximately 6 miles (9.7 km) upstream of the Chesapeake Bay at Ferry Bar Channel. The normal depth option was selected to establish the downstream boundary conditions of the hydraulic model. A slope of approximately 0.00048 was estimated

from the 2005 DEM low water elevation and used for the model downstream boundary condition.

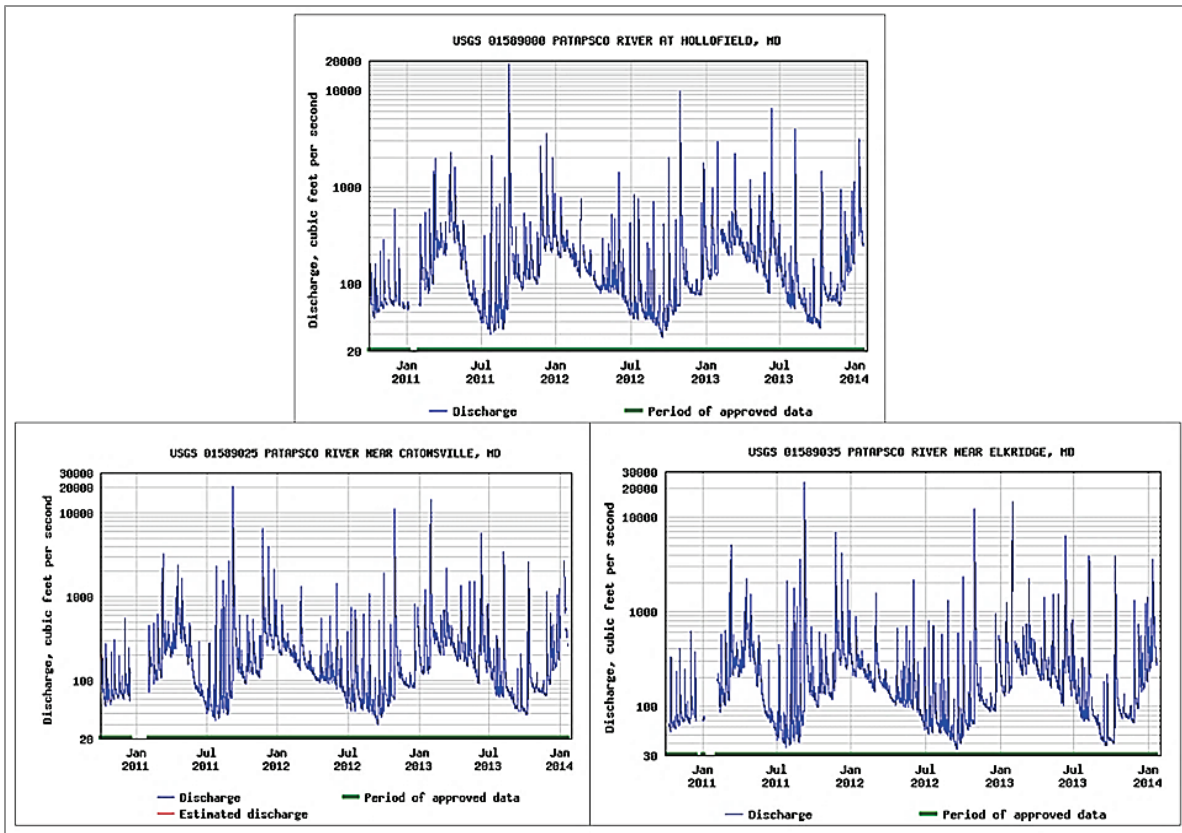
Figure 4. Observed and modeled water surface elevation at USGS gages near Catonsville, Maryland, and Elkridge, Maryland.



The development of the sediment transport model of the study reach requires additional data to develop the flow and sediment data files. As mentioned earlier, the USGS maintains three gages along the study reach, USGS 01589000 Patapsco River near Hollofield, MD, USGS 01589025 Patapsco River near Catonsville, MD, and USGS 01589035 Patapsco River near Elkridge, MD. All the gages have recorded daily mean discharge and fifteen minutes-incremented instantaneous discharge including the study period from November 2010 to November 2013 (Figure 5). Daily mean discharge values were used to develop a quasi-unsteady flow file for the sediment transport simulations. Flow change locations along the study reach were added at confluences of the Patapsco River with tributaries included in the USGS StreamStats maps. A method used in DeTemple and

Wilcock (2014) using interpolation and regression equations developed by Dillow (1996) was adopted to estimate water discharges at tributaries along the study reach. A limited record of temperature measurements at the USGS 01589000 gage near Hollofield, MD, from 1967 to 1989 was used to define temperatures in the quasi-unsteady flow file.

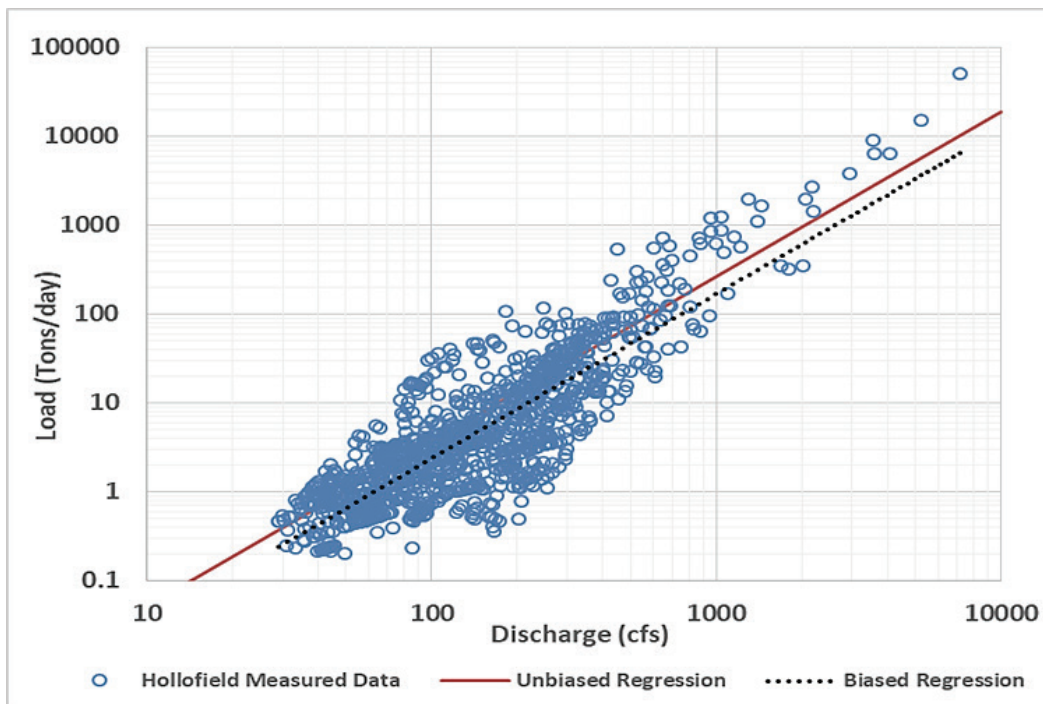
Figure 5. Discharge measurements at USGS gages near Hollofield, MD, Catonsville, MD, and Elkridge, Maryland, from October 2010 through January 2014 (Source: USGS website).



The sediment concentrations measured at the USGS 01589000 gage near Hollofield, MD, from 2010 to 2014 were converted to daily sediment load and plotted against flow. A power regression was used to estimate the sediment biased regression curve. The regression parameters were corrected using the Duan's 1983 unbiased correction factor. Duan (1983) unbiased correction estimated a "Smearing factor" of 1.44 raising the biased regression by 44%. The unbiased curve is plotted in Figure 6 using a standard log scale. Suspended sediment gradations data were not available for the study site. An initial sediment load gradation with a D_{50} of approximately 1 mm (coarse sand) was used for the selected discharges from the sediment rating curve. This parameter is highly uncertain and was slightly adjusted for calibration.

Sediment samples from the channel bed were collected at the 28 cross sections shown in Figures 2a and 2b during pre-dam and post-dam removal surveys. Pebble count and sieve grain analysis methods were used to develop bed material gradations. Figure 7 shows the bed material gradations used to develop gradations for the sediment transport model. Most of the bed material gradations in Figure 7 were developed using sediment samples collected during the September 2010 survey (pre-dam removal). Sediment gradations developed for the September 2011 survey were used only for monitored cross sections where samples were not collected during the September 2010 survey.

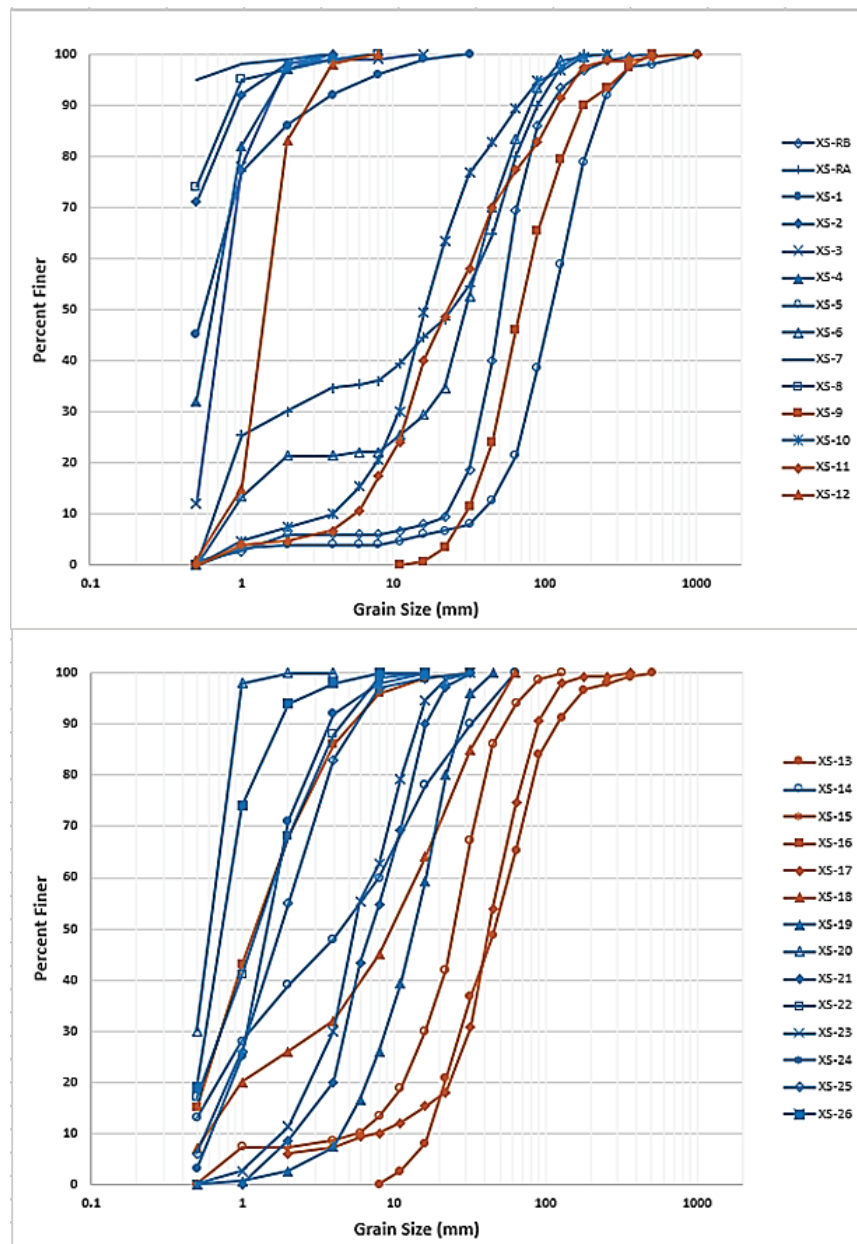
Figure 6. Flow-load data for the Patapsco River study reach sediment model.



The sediment data file in HEC-RAS also provides menus to select sorting methods, transport functions, bed change options, and fall velocity equations required to perform sediment transport simulations. HEC-RAS has three options for bed mixing algorithms including Exner 5, Exner 7, and the Active Layer method. The active layer sorting method was used as the sorting and armoring function for calibration after comparing the change in profile elevation along the study reach with observed data. HEC-RAS also includes multiple transport functions that could be applied for non-cohesive bed material including sand and gravel (of which this study reach is mainly composed). After testing multiple transport functions in HEC-RAS for sand and gravel systems, the Yang transport function was

selected for calibration. The bed change option allowing change to occur only within the movable bed limits was selected for calibration. The Ruby fall velocity method is the default option in HEC-RAS and was selected for calibration.

Figure 7. Bed material gradations at monitored cross sections: September 2010 survey (blue) and September 2011 survey (orange).



Cui et al. (2018) mentioned that approximately 73,703 yd³ (56,350 m³) of sediment eroded from the Simkins dam reservoir from the time the dam was removed to the November 2013 survey. This volume estimate was

compared to the volume of eroded sediments the model predicted during the same time period. The USGS 01589025 gage near Catonsville, MD, has a record of suspended sediment measurements from October 2010 to September 2020. Sediment concentrations recorded at this gage were also compared to the sediment concentrations predicted by the numerical model.

2.3 Experimental design of sensitivity analysis

This section describes the study approach for assessing sediment transport model sensitivity in the context of the Simkins Dam removal to identify key uncertainties associated with model outputs that could inform the four CMCs related to sediment release.

Sediment transport models usually include a broad set of parameters and uncertain input data making the calibration process more challenging than hydraulic models (Gibson et al. 2017). The selection of parameters, assumptions associated with input data, and equations within the numerical model could all introduce sources of assessment error and uncertainty to model outputs. 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).

For this study, a sensitivity analysis was performed by evaluating the response of selected model outputs to changes in sediment input data and model algorithms. An experimental design was developed by selecting the three model outputs that can potentially inform the four CMCs associated with sediment release; (1) MEIC, (2) volume of eroded sediment from the Simkins Dam reservoir (from removal to the November 2013 survey), and (3) suspended sediment concentrations downstream of the Simkins Dam after removal. The MEIC is an average change in bed elevation at cross sections along the study reach profile. Thus, the MEIC could estimate potential patterns of aggradation or degradation along the reach. The sediment input data selected for the sensitivity analysis include the sediment gradation used for the Simkins Dam reservoir. Model structure selected for the sensitivity analysis include transport functions, sorting methods, and erosion methods to identify potential sensitivities of the selected model outputs. For this study, model results from the sensitivity analysis simulations were compared to the results from the model

calibration. Table 1 provides a summary of sensitivity analysis for the Simkins Dam case study.

Table 1. Summary of sensitivity analysis HEC-RAS simulations for Simkins Dam removal 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 gradation 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 specifically for reservoirs. The width and side slope of the incision channel are input parameters. A channel width = 80 ft and side slope = 0.5 ft/ft were selected for the analysis. |

3 Results

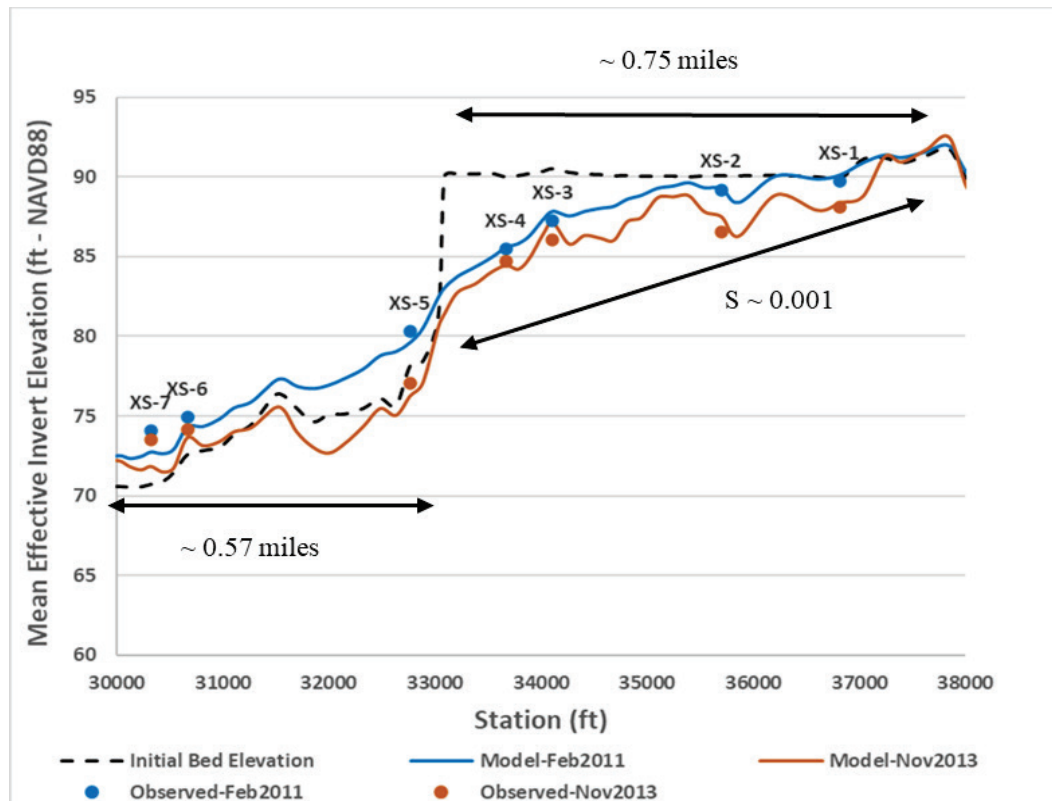
This section describes the results from the sediment transport model calibration and sensitivity analysis.

As discussed earlier, the 1D model HEC-RAS 5.0.7 was used to perform the sediment model calibration and sensitivity analysis for the Simkins Dam removal case study. Figure 8 compares the mean effective invert elevation estimated by the numerical model with observed mean invert elevations for the February 2011 and November 2013 surveys along the Simkins Dam reservoir and a portion of the study reach immediately downstream of the dam. The mean effective invert elevation represents the profile elevation along the study reach. After the removal of the Simkins Dam, degradation along the reservoir was observed and extended approximately 0.75 miles upstream of the dam as of the November 2013 survey. The model reasonably predicted the change in profile elevation for the two surveys when compared with the observed data. The initial profile elevation along the Simkins Dam reservoir had an almost flat slope (Figure 8). 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. Figure 9 shows the monitored cross section located immediately downstream of the Simkins Dam (XS-5) for the February 2011 and September 2011 surveys. An increase in channel elevation at this location was observed during the February 2011 survey. Then, the channel elevation at this location decreased to a channel elevation close to the elevation prior to the removal of the dam. The model was able to capture this process.

As previously shown in Figure 3, 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 removal. The channel then widened to a channel width similar to the pre-removal channel width. The "veneer" erosion method was used for calibration and the channel widths for the model cross sections were similar to the pre-removal cross

sections along the reservoir. The erosion and deposition of sediments occurred within the movable bed limits. The model estimated a volume of eroded sediments from the Simkins Dam reservoir approximately 6% higher than the volume published by Cui et al. (2018) as of the November 2013 survey.

Figure 8. 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.



The model estimated an increase in sediment concentrations soon after the removal of the Simkins Dam from early December 2010 to early January 2011 (Figure 10). 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. The model however was able to better predict lower sediment concentrations from late January 2011 to early March 2011.

Figure 9. Comparison of monitored cross section XS-5 located immediately downstream of the Simkins Dam with model cross section for the February 2011 and September 2011 surveys.

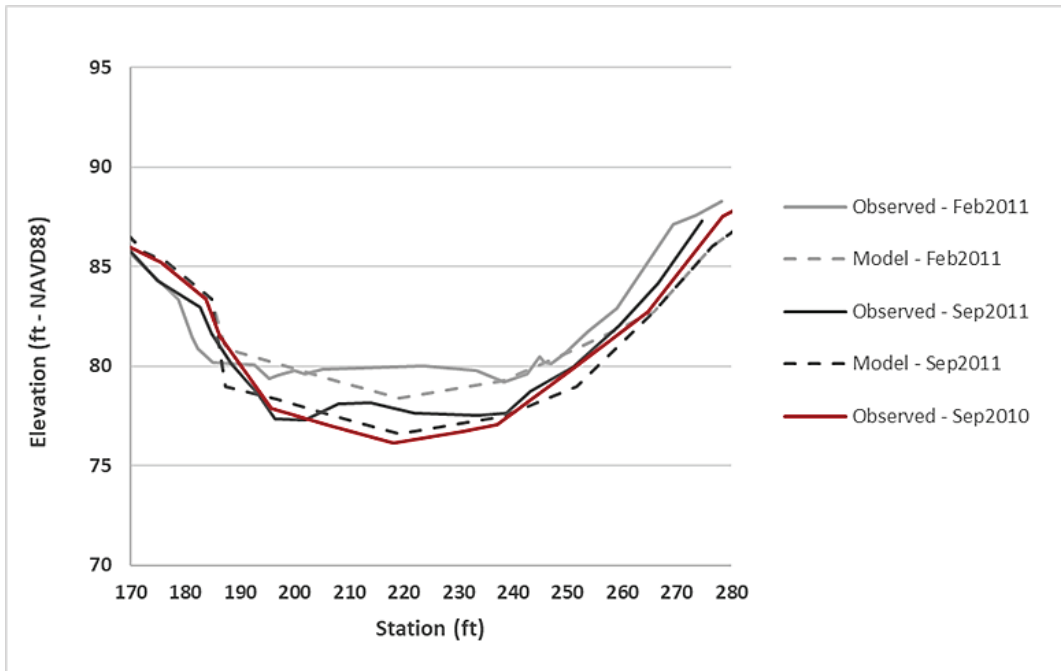


Figure 10. Observed and modeled sediment concentrations at the USGS gage near Catonsville, MD, from early December 2010 to early March 2011.

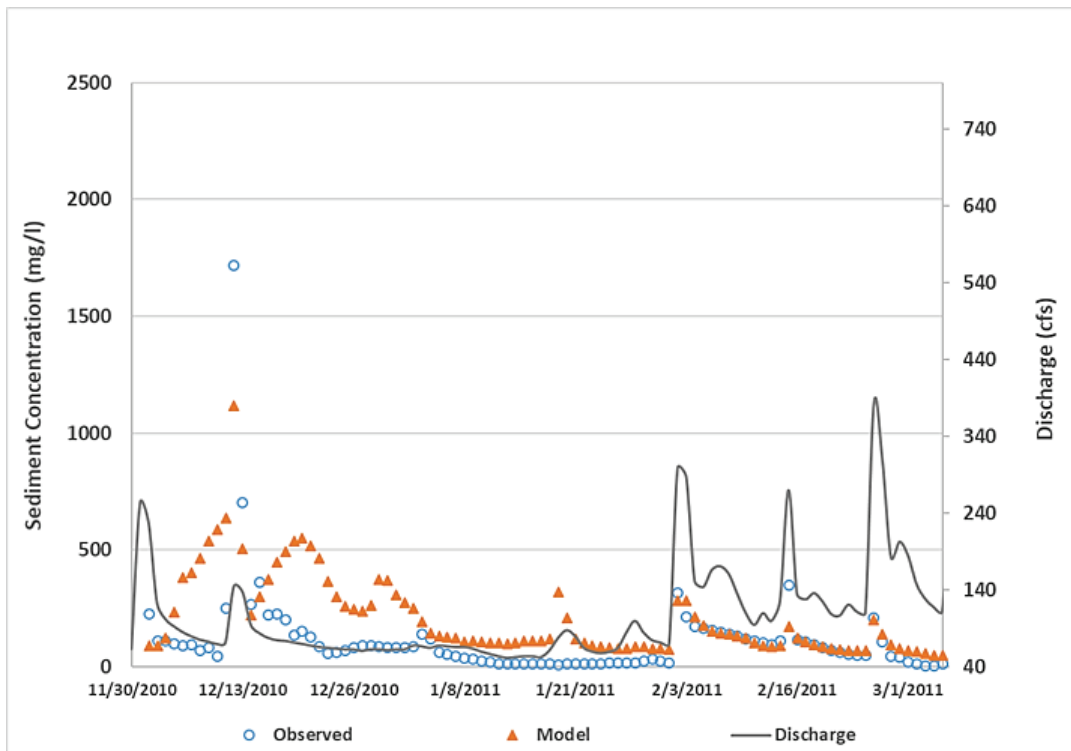


Figure 11 shows the MEIC for the model calibration, observed data, and sensitivity analysis along the study reach. Negative values indicate bed degradation and positive values indicate bed aggradation along the study reach. Figure 11a shows the MEIC for the Yang (calibration), Ackers-White, and Meyer-Peter Müller transport functions. The Ackers-White and Meyer-Peter Müller transport functions were developed for noncohesive sediment. The Ackers-White transport function is a total load function, and it is applicable only to non-cohesive sands greater than 0.04 mm. The Meyer-Peter Müller transport function has been typically applied in rivers with coarse bed material with particle sizes ranging from 0.4 to 29 mm (USACE 2020). Model results from these two transport functions were compared with calibration results using the Yang transport function which is applicable for sand and gravel. The results show that the MEIC along the study reach estimated by Ackers-White and Meyer Peter Müller changed slightly when compared with the calibration results. This finding may indicate that the MEIC has low sensitivity to the transport functions selected for the sensitivity analysis. All transport functions selected for the study (calibration and sensitivity analysis) were developed for noncohesive sediment bed material including sand and gravel.

Figure 11b shows the MEIC for two erosion methods: Veneer method (calibration) used for the entire study reach and channel evolution model – Cantelli algorithm used within the Simkins Dam reservoir. The Cantelli algorithm requires estimated incision channel parameters including the channel side slope and width. Also, the cross sections where this erosion method is going to be applied must be specified in the model. For the sensitivity analysis, a channel width of approximately 80 ft and a side slope on 0.5 ft/ft were used in the Cantelli algorithm for cross sections within the Simkins Dam reservoir. The model predicted more degradation along the reservoir with the channel evolution method – Cantelli algorithm when compared with the Veneer method. The incision channel that formed using the selected parameters is slightly narrower than the channel cross sections along the reservoir for the calibrated model. A reduction in channel area may have contributed to a lower invert elevation prediction.

Figure 11c shows the MEIC for the Active Layer (calibration) and Exner 5 sorting methods. Exner 5 estimated more degradation within the Simkins Dam reservoir (an average of 4 ft) and immediately downstream of the dam when compared with the Active Layer method. The MEIC seems to be

highly sensitive to the sorting method selection within the Simkins Dam reservoir and the channel section immediately downstream of the dam. However, further downstream of the dam, the MEIC shows low sensitivity to the sorting method selection. Figure 11d shows the MEIC for three bed material gradations within the Simkins Dam reservoir. These are gradation developed with observed bed material data within the Simkins Dam reservoir (calibration), a gradation approximately 20% finer than the gradation used for calibration, and a gradation approximately 20% coarser than the gradation used for calibration. The model estimated more channel degradation (an average of 3.6 ft) along the reservoir using a finer gradation within the Simkins Dam reservoir than the calibration results. Also, the model estimated less degradation along the reservoir using a coarser gradation within the Simkins Dam reservoir and more degradation immediately downstream of the dam than the calibration results. Therefore, the MEIC along the reservoir and immediately downstream of the dam seems to be highly sensitive to the bed material gradations.

Figure 11. 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.

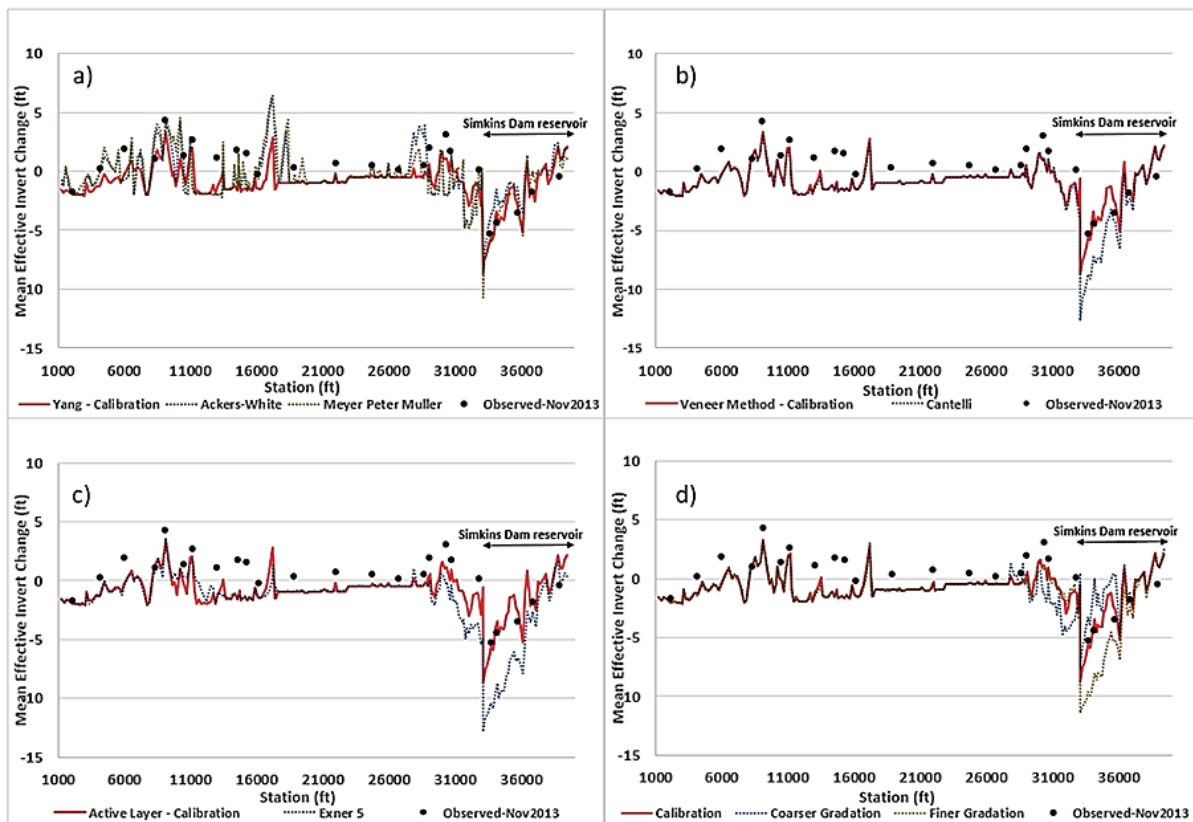
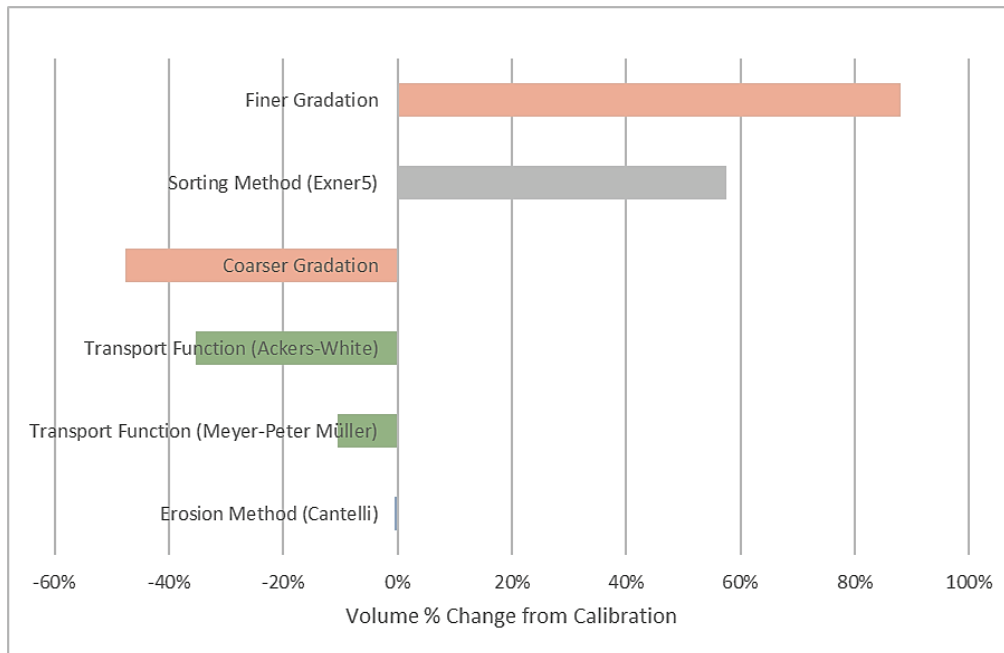


Figure 12 shows the percent of change of the volume of eroded sediments from the Simkins Dam reservoir (from removal to the November 2013 survey) estimated by the calibrated model with the sensitivity analysis results. Based on the results, volume estimation is highly sensitive to the bed material gradation 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 along 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 approximately 35% smaller than the volume estimated for calibration using Yang. 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 12. Percent of eroded sediment volume compared to calibration results.



The sensitivity analysis results show that the selected outputs for this study can be sensitive to certain input data and the selection of algorithms for the sediment transport simulations. This case study demonstrated that model outputs such as the MEIC and eroded sediment volume from the Simkins Dam reservoir can be highly sensitive to input data such as bed material gradations and model algorithms such as sorting methods. Also, only one set of parameters in the channel evolution model (Cantelli algorithm) was selected for the sensitivity analysis. The model sensitivity to this erosion method application along the reservoir can vary based on the selection of channel width and side slope parameters. The sensitivity analysis results also indicate that the selected model outputs show some sensitivity to the selected transport functions.

4 Discussion

The purpose of this study was to investigate how a 1D sediment transport model can inform the four CMCs related to sediment release following dam removal and develop an approach for assessing sediment transport model sensitivity in the context of the Simkins Dam removal. The purpose of the sensitivity analysis for the Simkins case study was to identify how selected model outputs deviate from calibrated results because of changes in input data and model algorithms. The model outputs selected for the sensitivity analysis included the MEIC and volume of eroded sediments from the Simkins Dam reservoir. These two model outputs could potentially inform CMCs associated with sediment release from the reservoir such as degree and rate of reservoir sediment erosion, excessive channel incision upstream of reservoirs, and downstream sediment aggradation. The calibrated sediment model was able to reasonably predict the profile elevation change along the study reach and eroded sediment volume from the reservoir when compared with observed data. However, the numerical model distinctly overestimated sediment concentrations soon after the dam removal (early December 2010 to early January 2011) when compared with the observed concentrations recorded at the USGS gage near Catonsville, MD. Therefore, the sediment concentrations simulation results were not used for the sensitivity analysis. The model however was able to better predict lower sediment concentrations from late January 2011 to early March 2011.

The sensitivity analysis results show that the selected outputs for this study can be sensitive to certain input data and the selection of algorithms for the sediment transport simulations. This case study demonstrated that model outputs such as the MEIC and eroded sediment volume from the Simkins Dam reservoir can be highly sensitive to input data such as bed material gradations and model algorithms such as sorting methods. The MEIC also showed some sensitivity to the channel evolution model – Cantelli algorithm for the selected width and side slope parameters. However, the volume of eroded sediments was less sensitive to this erosion method for the selected parameters used in the sensitivity analysis, likely because the incision channel developed using the Cantelli algorithm had a slightly narrower area than the cross section along the reservoir in the calibrated model. Only one set of parameters in the channel evolution model was selected for the sensitivity analysis. The model sensitivity to this erosion method application along the reservoir can vary based on the

selection of channel width and side slope parameters. The sensitivity analysis results also show that the MEIC is less sensitive to transport functions. However, the eroded sediment volume from the Simkins Dam reservoir seems to be more sensitive to transport functions than the MEIC.

As mentioned earlier, McKay et al. (2019) includes a list of conceptual and numerical tools that could be applied to inform CMCs associated with sediment release following dam removal. Some initial steps including the identification of potential CMCs that may need to be forecasted, site characteristics, data availability, and data needs can assist with the identification of potential tools that may be appropriate to predict impacts associated with sediment release following dam removal. The extensive data collected along the study reach before and after the Simkins Dam was removed was used to develop and calibrate the 1D numerical model and perform sensitivity analysis of selected model outputs. 1D sediment transport models such as HEC-RAS have many parameters and options that can be adjusted during the calibration process. This exercise provided insights about the sensitivity of selected model outputs that could inform CMCs associated with sediment release to certain data inputs and model algorithms, but the findings are limited to the data inputs and model structure selected for the study. Additional input data, model structure, and parameters could be tested in future sensitivity studies.

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| 14. ABSTRACT Dam removal has become a widespread river management practice in the US for a variety of goals including ecosystem restoration, removing aging infrastructure, flood risk management, and recreation. 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). This study investigated how a one-dimensional (1D) sediment transport model can inform these four CMCs, 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. For the selected case study, model outputs including the mean effective invert change (MEIC) and eroded sediment volume from reservoir were highly sensitive to the variation of the reservoir sediment gradation and sorting method selection. These model outputs also showed some sensitivity to the selected transport functions. Erosion method sensitivity using the channel evolution method will vary depending on side slope and channel parameter selection. | | | | | |
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