Tools for evaluating sediment impacts from dam removal – qualitative guidance

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Abstract

Dam removal has become a frequently applied river management technique, which is increasingly used to meet a variety of goals. Objectives for dam removal range from removing aging infrastructure and reducing flood risk to opening recreational pathways and restoring riverine ecosystems. The resulting release of sediment poses risks related to sediment erosion, deposition, and turbidity including the quantity, location, and timing of each as well as sediment quality. This study provides a brief overview of sediment transport due to dam removal and reviews the applicable tools, models, and associated capabilities. In particular, we review tools designed to answer two questions: (1) How much sediment is stored behind a dam? (2) What are the geomorphic implications of removal? The answer to each of these questions is dependent on site specific characterization and our ability to input sufficient information to these tools and utilize them to produce accurate results. A large range of tools are available which can be used to infer or quantify the geomorphic implications of dam removal prior to removal. We summarize predictive methods ranging in complexity from simple, conceptual models to complex, hydrodynamic and sediment transport models. Qualitative guidance is provided for selecting appropriate tools depending on issues such as focal questions, data availability, and analytical resources (e.g., time, funding, and expertise).

Introduction

The management, operations, maintenance, and long-term fate of dams has emerged as a central issue in both public infrastructure management and aquatic ecosystem restoration in the United States. FEMA (2011) estimated 85% of the 84,000 large dams in the US will have exceeded their design lifespan by 2020. ASCE's "Infrastructure Report Card[1]" gave dams a grade of D, noting that 15,500 dams are high hazard potential with 2,170 of those structures structurally deficient. ASCE estimates that $64 billion is needed to rehabilitate dams nationwide, and the USACE estimates its 694 dams will require $25 billion to address

[1] https://www.infrastructurereportcard.org/

deficiencies. While other management alternatives exist (e.g., repair, reconstruction), dam removal has emerged as a crucial tool for asset management and ecosystem restoration with more than 1,200 dam removals nationwide (Figure 1, Bellmore et al. 2016).

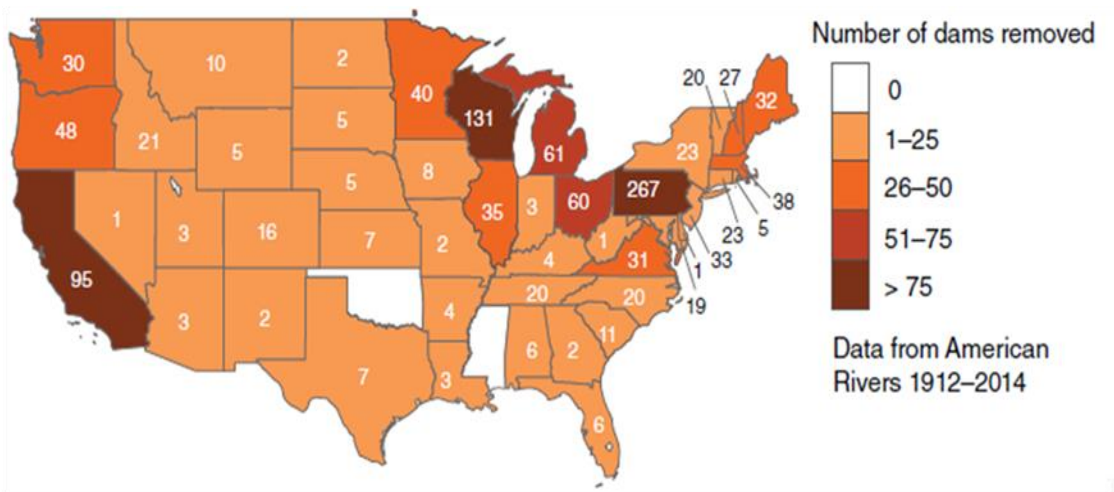

Figure 1. Dam Removal in the United States (Bellmore et al. 2016)

Dam removal represents a significant opportunity to restore geomorphic and ecological function in disturbed ecosystems. Restoration benefits associated with dam removal may not be evident for years, or even decades, and this will likely vary between components of the ecosystem (e.g., migratory pathways for fish vs. sediment storage) and as a function of various factors (e.g., dam size and type, impoundment volume, sediment quantity and grain size, sediment chemistry, removal method, etc.). In fact, decision makers must consider the potential for dam removal to cause temporary or even irreversible degradation to specific ecosystem attributes. The goal should be to minimize the negative impacts of a removal as well as to maximize the rate of recovery of the physical and ecological systems. Understanding sediment processes and geomorphic responses to various dam removal actions is central to achieving this goal.

One significant impediment to executing dam removal projects is prediction of morphological response and the consequent impacts and benefits of that response. Management of sediment stored in a reservoir is an important consideration in any dam removal project. Numerous management options exist and a number of factors contribute to the identification of the best approach(es). Tools are needed to better predict erosion, transport and deposition of sediments, geomorphic change associated with sediment release, short- and long-term ecological ramifications of sedimentation processes and potential contaminant release. A number of existing models and tools have been (or could be) applied to dam removal projects to assess the sediment storage, sediment processes (erosion, transport and deposition), and geomorphic response of a system to various decommissioning strategies. Within this paper, we qualitatively review models and tools designed to answer two important questions: (1) How much sediment is stored behind the dam? (2) What are the geomorphic implications of removal?

Models and tools associated with dam removal

Trade-offs in model selection

Generally speaking, all modeling efforts require balancing needed resolution and accuracy with available resources and time. To focus our discussion of tools associated with dam removal, we will compare modeling efficiency with the resolution of the information produced by modeling (Figure 2). In this case, modeling efficiency is defined as how quickly modeling results can be obtained and analyzed. Modeling resolution is defined as the degree of accurate information that can be obtained from the simulation (both spatially and temporally). Understanding these basic characteristics is essential when selecting an appropriate modeling strategy for a given dam removal project. For example, one-dimensional numerical models (e.g., HEC-RAS) are often the most practical tools available for understanding reach-averaged channel responses of non-cohesive reservoir sediment deposits following dam removal for planning purposes. However, even simpler models of geomorphic response (e.g., conceptual models, sediment budgets) might be appropriate in some cases such as extremely small dam removals with unconfined, uncontaminated sediment. Conversely, cases involving complex transport phenomena or cohesive sediments may require application of two- and three-dimensional sediment models (e.g., GSMB) containing dynamically linked hydrodynamic and sediment transport models. Unfortunately, such models may require additional site specific data, have much longer run time, and subsequently cost more to develop.

It is understood that all models require some level of site specific data, however the amount can vary widely. A simple box model may require information on sediment characteristics such a grainsize distribution or even general information that sediment is either fine or coarse material. However, when using a three-dimensional sediment model such as GSMB, the best case scenario is that data should be obtained from sediment cores which can be analyzed to determine the sediment grainsize distribution for the variation within the vertical layers of the bed. In addition, analysis of critical shear stress should be obtained from the cores to accurately depict erosion and deposition.

It should also be mentioned that the approach to model applications can also be varied based on the context of a particular study. Sensitivity analyses can systematically vary key input parameters to bracket outcomes, stochastic model runs could be executed across a range of potential inputs, or multiple simulations could be applied to understand a problem in its entirety. For example if site specific data for critical shear stress is unavailable for a Lagrangian particle tracking model, multiple simulations can be performed using a range of a given parameter (e.g., a reasonable minimum and maximum) to bracket potential results.

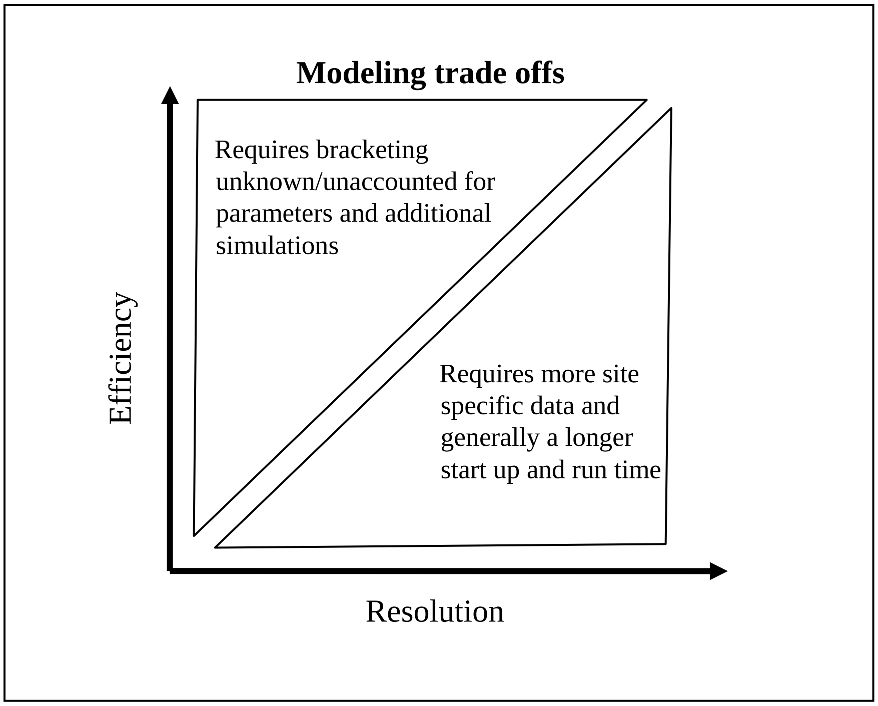

Figure 2. Model tradeoff diagram

Reservoir sediment storage

Reservoir sedimentation is a well-acknowledged technical challenge for both reservoir management and dam removal applications (Morris and Fan 2009). Sediment infill of reservoirs is a constraint on the life span and long-term viability of a structure (Juracek 2014), and stored sediment can also have beneficial or undesirable impacts upon release. The relative volume of stored reservoir sediment (i.e., the ratio of stored sediment volume to average annual volumetric sediment loading rate) has been identified as an important metric for predicting potential effects of sediment release from dam removal (Major et al. 2017) and serves as a key screening criteria for risk-based sediment analysis (Randle and Bountry 2017). It should be mentioned that in addition to volume storage, the character, quality, and gradation of sediment is also relevant. Although a key factor, volume alone is not enough to inform a model setup. Figure 3 shows an example of a reservoir sediment profile. A complex system with a variety of spatially varying sediment types can exist.

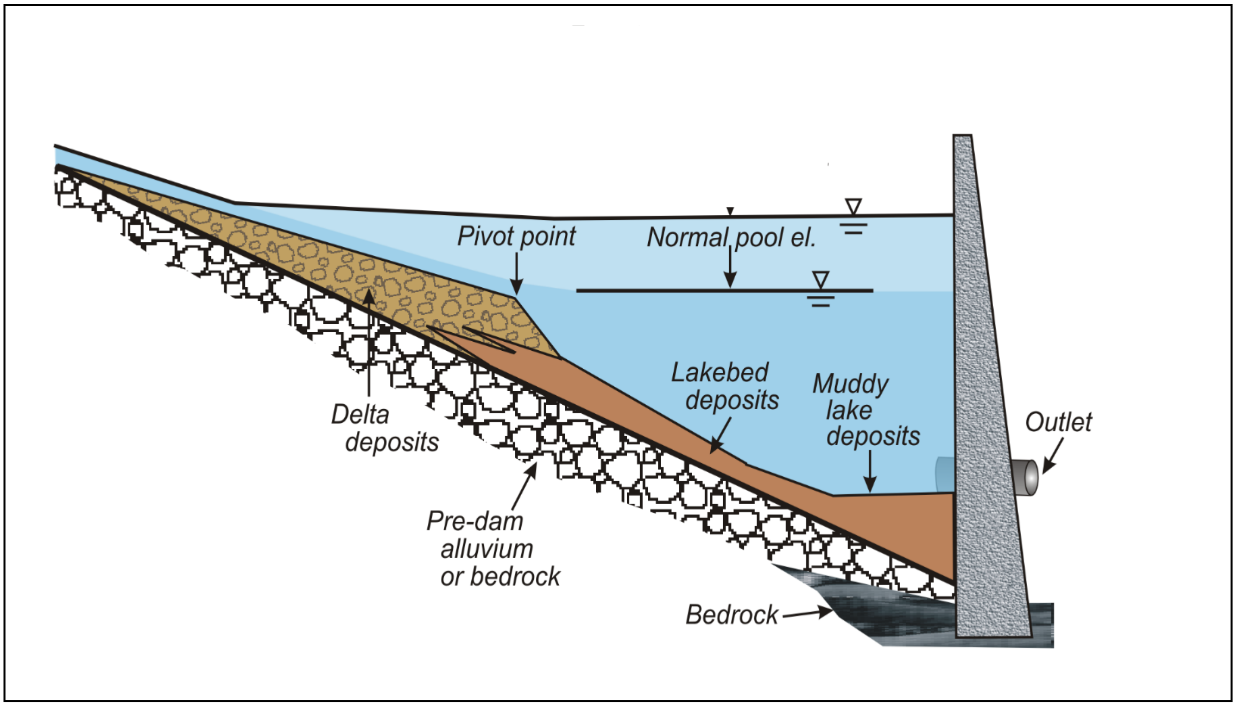

Figure 3. Example of reservoir sediment profile adapted from Randle and Bountry, 2017

Sediment volume may be estimated directly or indirectly through a variety of mechanisms (Strand and Pemberton 1982), which typically take one of four approaches based on Equation 1.

$$V_{s,t} = V_0 - V_t = Q_s tP \tag{1}$$

Where $V_{s,t}$ is reservoir sediment volume at time t, V_o is total initial reservoir volume, V_t is total reservoir volume at time t, Q_s is annual volumetric sediment loading rate, t is age of the reservoir (in years), and P is sediment trapping efficiency over the life of the reservoir.

First, sediment volume may be estimated directly using existing empirical databases such as the reservoir sedimentation database RESSED (Ackerman et al. 2009, Gray et al. 2010, Cooper 2015) and Reservoir Sedimentation Information (RSI) database (Pinson et al. 2016). The RESSED database is a large database with national coverage containing bathymetric and topographic surveys of reservoirs. Although powerful resources, databases tend to emphasize larger structures and only cover 2-3% of large dams (i.e., ~2,000 structures of the ~90,000 in the National Inventory of Dams, NID).

Second, site-specific surveys can be undertaken using techniques such as bathymetric mapping (Pinson et al. 2016), longitudinal profiling (Gartner et al. 2015), probing reservoir deposits, or ground penetrating radar surveys (Santaniello et al. 2013).

Third, estimates of the sediment loading rate (Alighalehbabakhani et al. 2017), structural age, and trapping efficiency (Brune 1953, Churchill 1948, Randle and Bountry 2017) can be combined into a sediment volume. Generally these methods are utilized by extracting a value for the estimate of sedimentation from an analytically developed curve. Both Brune's curve

(Figure 4) and Churchill's curve are extensively utilized, differing based on the specifics of the curve equation and added parameterization.

Fourth, total reservoir volume can be used as a proxy for the maximum volume of sediment stored in a reservoir. Notably, these methods result in varying levels of information about the levels of compaction or layering at a site, which can be important determinants of geomorphic change following removal.

Reservoir volumes, bathymetric surveys, and sedimentation rates all represent crucial data gaps at a national scale, and data compilation and standardization (e.g., Cooper 2015, Pinson et al. 2016) are important continuing needs. In particular, data are notably missing on small, non-Federal reservoirs, which are more typically the focus of dam removal (Bellmore et al. 2016).

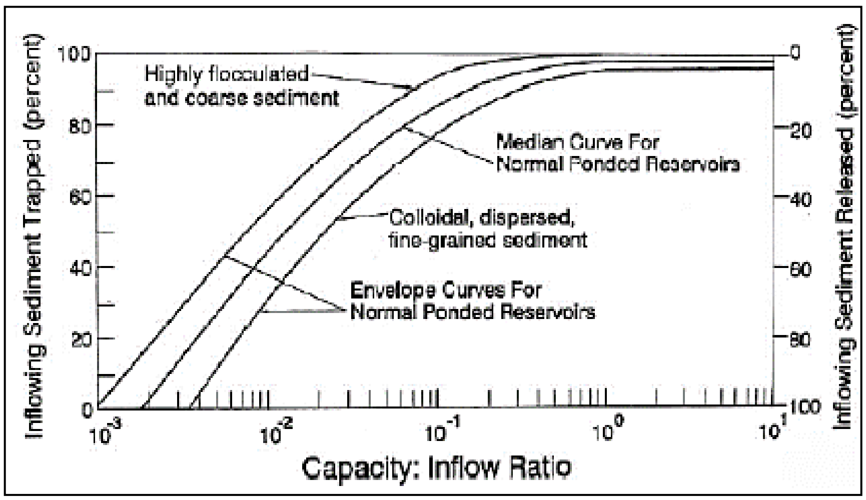

Figure 4. Brune's curve (1953)

Geomorphic implications of removal

The influence of dams on geomorphic processes has been a focus of river management for more than 65 years (Leopold et al. 1954), and the short- and long-term mobilization and fate of sediments is often a key uncertainty surrounding management decisions about dam removal. Using a database of published dam removal studies (Bellmore et al. 2015, Duda et al. 2018), Tullos et al. (2016) synthesized seven common management concerns (CMC) associated with dam removal, four of which are directly related to sediment management and geomorphic change (Table 1).

Table 1. Common management concerns for dam removal directly related to sediment. Framework adapted from Tullos et al. (2017) and supplemented with guiding questions and key driving variables from Foley et al. (2017a), Major et al. (2017), and Randle and Bountry (2017).

Management Concern	**Guiding Questions**	**Key Issues Affecting Biophysical Response**
CMC1: Degree and rate of reservoir sediment erosion	• How much of the sediment impounded within a reservoir will erode? • How quickly will the eroded sediment move through the downstream river corridor?	• High % fine grained sediment • Width (sediment deposit) / Width (channel) > ~2.5 • Phased removal • Degree of base level drop
CMC2: Excessive channel incision upstream of reservoirs	• Will a "knick point" form and propagate upstream? If so, how far? • Will upstream infrastructure be affected (e.g., bridge piers)?	• Reach-scale incision downstream • High % fine grained sediment • Phased removal • Coarse delta • Ephemeral flow • Channel slope (e.g., degree of base level drop, presence of grade control features)
CMC3: Downstream sediment aggradation	• Where will sediment deposit longitudinally (on average and specifically around infrastructure)? • Will bedforms be affected (e.g., pool filling)? Will sediment fill interstitial spaces (i.e., embeddedness)? Will channel complexity be reduced? • Will flood levels increase? • Will downstream water bodies be impacted?	• Proximity to dam • Low slope / unconfined channel • High relative sediment volume (ratio of stored sediment volume to average annual volumetric sediment loading rate) • Coarse grain size • Sediment pulse dispersion or translation (Pace et al. 2016)
CMC4: Elevated turbidity	• Will suspended sediment exceed ecological or regulatory thresholds? • Will turbidity influence human uses of the river (e.g., recreation, water intake)?	• High % fine grained sediment • High relative sediment volume • Rapid reservoir drawdown • Background turbidity levels

Table 1 emphasizes the complex interplay of geomorphic processes functioning across multiple time scales (short- vs. long-term), large and small spatial scales (e.g., long reaches vs. within a cross-section), and basin locations (e.g., upstream vs. downstream of a dam). Furthermore, each of these challenges is differentially affected by highly site-dependent variables such as removal strategy, topography, sediment properties, sediment volume, hydrologic conditions, valley morphology, and watershed characteristics (Major et al. 2017). Given these complexities, it is not surprising that a large range of tools may be used to infer or quantify the geomorphic implications of dam removal.

The following section summarizes some available techniques ranging in complexity from simple, conceptual models to complex, hydrodynamic tools. This list is not meant to be exhaustive but to describe some models/tools which have been or are in the process of being used for dam removal assessments. This list focuses on predictive, forecasting tools and families of modeling approaches (rather than monitoring tools and specific hydrodynamic codes, respectively). Notably, geomorphic tools should be selected in line with the project objectives, risks, data availability, and analysis time for a given dam removal; furthermore, multiple tools can be applied to a single site as an analysis proceeds from preliminary screening to permit application (Randle and Bountry 2017). Regardless of the project complexity, a site-specific conceptual model should be developed to document expected geomorphic change (Randle and Bountry 2017), which is consistent with guidelines for other types of ecosystem restoration projects (Fischenich 2008). Table 2 then summarizes a few specific hydrodynamic and geomorphic tools, which have particular relevance for dam removal applications.

Conceptual models: Generalized and site-specific conceptual models can inform short and long-term effects of sediment release, which can draw from response to other geomorphic phenomena (Doyle et al. 2002, Pizzuto 2002, Cannatelli and Curran 2012, Zunka et al. 2015).

Generalized rules: Empirical rules for system response to dams can indicate the sensitivity or vulnerability to sediment release (Schmidt and Wilcock 2008, Sawaske and Freyburg 2012, Major et al. 2017, Tullos et al. 2017).

Geomorphic analysis: Qualitative insight (e.g., pre-dam topography, sediment volume, grain size) may be gained from historical aerial photographs, soil maps, historical accounts, and field reconnaissance (Tonitto and Riha 2016, Randle and Bountry 2017).

Preliminary sediment analysis: A variety of simple, desktop analyses may be executed such as longitudinal analysis of stream power and transport capacity (Randle and Bountry 2017), sediment budgets (Warrick et al. 2015, Collins et al. 2017), sediment wave models (Doyle et al. 2002, Pace et al. 2016), and application of Exner equations (Gartner et al. 2015).

1-D sediment transport modeling: Reach-averaged hydraulic tools provide an important mechanism for assessing longitudinal change, but the data needs and outcomes can be widely variable (Downs et al. 2009, Gartner et al. 2015). Some tools are also incorporating higher order assumptions to account for channel dynamics (Boyd and Gibson 2014). Modeling of this type tends to be focused on total volume transported and reach-averaged response as opposed to spatially-explicit, cross-channel representation of deposition. Figure 5 shows layout for a HEC-RAS Dam Break simulation study (USACE 2014). Results for volumetric transport can be calculated at each cross section.

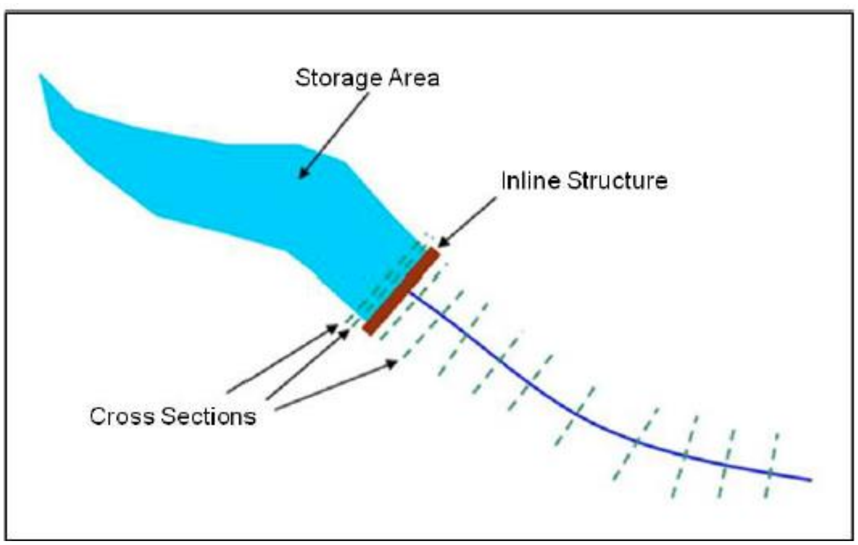

Figure 5. Example of Storage Area and Cross Section Layout for HEC-RAS Dam Break study (USACE 2014)

2-D Sediment transport modeling: Lateral movement of channels and cross-sectionally distributed outcomes require use of two-dimensional, depth-averaged tools (Wang and You 2016). Depth-averaged solutions are formulated with the assumption that there is no vertical stratification. This type of modeling works better when flow is not density stratified and when structures do not have a major impact on the model. Models of this type begin to allow for better assessment of sediment characterization addressing the issue of bed composition transition.

Lagrangian sediment transport modeling: Lagrangian sediment models can assess specific locations of sediment deposition, which could be extremely useful in dam removal applications (MacDonald et al. 2006, Gailani et al. 2016). This modeling style allows users to visualize sediment pathways and can be both qualitative and quantitative.

3-D sediment transport modeling: Three-dimensional models have not (to our knowledge) been applied in the context of dam removal, likely because of computation requirements. However, high risk or extremely sensitive applications could warrant their application. This method is best utilized when detailed knowledge of sediment characterization, bathymetry, sediment sources, and boundary conditions are known or can be obtained readily. Model start up and run time can be significantly longer than other methods but results should be more accurate and spatially resolved, allowing users to better understand detailed and site specific issues, such as water quality near habitat or bed morphology changes at specific locations of importance. GSMB has been applied by ERDC in several coastal, estuarine and riverine modeling studies (Hayter et al. 2012; Chapman et al. 2014; Chapman et al., 2015; Hayter et al. 2015; Hayter et al. 2016; and Bunch et al. 2018). The cohesive and noncohesive sediment transport and morphologic change models are dynamically linked to the hydrodynamic model.

Physical models: Flume studies have informed a number of dam removal assessments (Downs et al. 2009), and their use is likely to continue, particularly for enhancing understanding of key sediment processes and dynamics.

Table 2. Select hydrodynamic models with relevance to dam removal

Tool/Model	Description	Reference
CONCEPTS	Channel evolution model, simulates unsteady, one-dimensional flow, graded-sediment transport, and bank erosion processes in stream corridors	Langendoen (2000,2002)
Dream-1 & 2	1-D sediment transport models that simulate pulsed transport in rivers and address issues following dam removal. DREAM-1 simulates non-cohesive fine sediment. DREAM-2 simulates fine and coarse sediment transport. Spatial resolution output limited to 1-D.	Cui et al. (2006a,b)
HEC-RAS	1-D quasi-unsteady and unsteady sediment transport model that performs transport/movable boundary calculations in rivers and reservoirs. Simulates potential scour and deposition trends in rivers and reservoirs. Provides erosion bed change options for reservoir flushing drawdown or dam removal	Gartner et al (2015), Rumschlag and Peck (2007), Tullos et al (2010), Epstein (2009)
SEDMOD	1D steady state model. Simulates transport in networks of channels and computes resultant scour and fill. Uses hydrographs as stepwise steady state. Sediment size is limited.	Bennett (2001), Syed et al (2005)
FLUVIAL12	1D model simulates spatial and temporal variations in water-surface elevation, sediment transport, and channel geometry	Chang (1988, 2008)
River2D, River 2D-Morophology (R2DM)	2D Depth-averaged finite element two-dimensional hydrodynamic-morphological and gravel transport model	Kwan et al (2010)
MIKE -21C	2D comprehensive modeling system for the simulation of hydraulics and hydraulic-related phenomena. Applied to any two-dimensional free-surface flows where stratification can be neglected	DHI (1996)
SRH-2D	2D hydraulic and sediment transport model for river systems and Watersheds. Uses a layered hybrid approach	Lai (2005), Lai (2006),
PTM	Lagrangian Particle Tracking Model. Determines 3-D sediment fate and pathways in both large and small scale scenarios. Best used in dam removal if we just want to know where sediment is potentially going to go. Can run multiple scenarios easily, and can make up for lack of data.	MacDonald et al.(2006), Gailani et al. (2016)
GSMB (LTFATE)	Fully 3D unsteady multi-block sediment transport model. Determines bed morphology change, dynamically linked hydrodynamic and sediment transport modules, and easily depicts areas of deposition and erosion.	Hayter et al. (2012); Chapman et al. (2014); Chapman et al. (2015); Hayter et al. (2015); Hayter et al. (2016); and Bunch et al. (2018)

Conclusions

Dams often represent crucial pieces of water resources infrastructure critical to meeting societal needs for freshwater. However, dam removal has grown in prominence as a river management technique as the Nation's aging infrastructure portfolio intersects with a growing interest in ecosystem restoration. Sediment release associated with dam removal has the potential to impact both human and ecological outcomes. Here, we have qualitatively reviewed a variety of models and tools that could inform dam removal decisions, with a particular emphasis on two sediment related questions: (1) How much sediment is stored behind the dam? (2) What are the geomorphic implications of removal? In reviewing these tools, we emphasize that no single tool is required for all dam removal studies, but instead scientists and engineers must balance competing needs for model accuracy and resolution with efficiency, time, and resources. This paper provides a brief menu of analytical options for those tasked with selection of models and tools for assessing the potential effects of sediment release associated with dam removal.

References

Ackerman K.V., Mixon D.M., Sundquist E.T., Stallard R.F., Schwarz G.E., and Stewart D.W. 2009. RESIS–II—An updated version of the original Reservoir Sedimentation Survey Information System (RESIS) database: U.S. Geological Survey Data Series 434, available only online at http://pubs.usgs.gov/ds/ds434.

Alighalehbabakhani F., Miller C.J., Baskaran M., Selegan J.P., Barkach J.H., Dahl T., and Abkenar S.M.S. 2017. Forecasting the remaining reservoir capacity in the Laurentian Great Lakes watershed. Journal of Hydrology, 555, 926-937.

American Society of Civil Engineers (ASCE). 2017. Infrastructure report card: A comprehensive assessment of America's infrastructure. Accessed 30 August 2017. http://www.infrastructurereportcard.org/.

Bellmore J.R., Vittum K.M., Duda J.J., and Greene S. 2015. USGS Dam Removal Science Database (ver. 1.3, July 2015). U.S. Geological Survey, https://doi.org/10.5066/F7K935KT.

Bennett J.P., 2001, User's guide for mixed-sized sediment transport model for networks of one-dimensional open channels: U.S. Geological Survey Water-Resources Investigations Report 01-4054, 33 p.

Boyd P.M. and Gibson S.A. 2014. Regional Sediment Management (RSM) modeling tools: Integration of advanced sediment transport tools into HEC-RAS. ERDC/CHL CHETN-XIV-36. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Bunch, B., Hayter, E., Kim, S-C., Godsey, E., and Chapman, R. 2018. "Three Dimensional Hydrodynamic, Water Quality, and Sediment Transport Modeling of Mobile Bay," ERDC Letter Report to the USACE Mobile District.

Brune G.M. (1953) Trap Efficiency of Reservoirs. Trans. Am. Geophysical Union 34(3), 407-418.Cannatelli K. and Curran J. 2012. Importance of hydrology on channel evolution following dam removal: Case study and conceptual model. Journal of Hydraulic Engineering, 138 (5), 377-390.

Chapman, R.S., P.V. Luong, S.C. Kim, and E.J. Hayter. 2014. "Development of Three Dimensional Wetting and Drying Algorithm for the Geophysical Scale Transport Multi-Block Hydrodynamic, Sediment and Water Quality Transport Modeling System ," Technical Note, Dredging Operations and Environmental Research Program, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Chapman, R.S., Luong, P., Kim, S.C., and Hayter, E.J. 2015. "Development of a Three Dimensional Vegetative Loss Mechanism for the Geophysical Scale Transport Multi-Block Hydrodynamic Sediment and Water Quality Transport Modeling System (GSMB)," Technical Note, DOER.Churchill M.A. (1948) Discussion of "Analysis and Use of Reservoir Sedimentation Data", Proceedings of Federal Interagency sedimentation Conference, edited by L. C. Gottschalk, Denver, pp. 139-140, USA.

Chang, H. H. 1998. Generalized computer program: FLUVIAL-12 mathematical model for erodible channels, San Diego State Univ., San Diego

Chang HH. 2008. Case study of fluvial modeling of river responses to dam removal. J Hydraul Eng. 134:295–302. doi:10.1061/(ASCE)0733-9429(2008)134:3(295).

Collins M.J., Snyder N.P., Boardman G., Banks W.S.L., Andrews M., Baker M.E., Conlon M., Gellis A., McClain A., and Wilcock P. 2017. Channel response to sediment release: Insights from a paired analysis of dam removals. Earth Surface Processes and Landforms, doi: 10.1002/esp.4108.

Cooper D. 2015. USACE Reservoir Sedimentation Survey Database (RESSED) Oracle Conversion. Proceedings of the 10th Federal Interagency Sedimentation Conference, Reno, Nevada.

Cui, Y., Braudrick, C., Dietrich, W.E., Cluer, B., and Parker, G., Dam Removal Express Assessment Models (DREAM), Part 2: Sample runs/sensitivity tests, Journal of Hydraulic Research, 43(3), 308-323, 2006.

Cui, Y., Wooster, J., Baker, P., Dusterhoff, S., Sklar, L., and Dietrich, W.E., Theory of fine sediment infiltration into immobile gravel bed, submitted to Journal of Hydraulic Engineering

DHI. (1996). MIKE 21 hydrodynamic module users guide and reference manual. Danish Hydraulic Institute.

Downs P.W., Cui Y., Wooster J.K., Dusterhoff S.R., Booth D.B., Dietrich W.E., and Sklar L.S. 2009. Managing reservoir sediment release in dam removal projects: An approach informed by physical and numerical modelling of non-cohesive sediment. International Journal of River Basin Management, 7 (4), 433-452.

Doyle M.W., Stanley E.H., and Harbor J.M. 2002. Geomorphic analogies for assessing probable channel response to dam removal. Journal of the American Water Resources Association, 38 (6), 1567-1579.

Duda J.J., Johnson R.C., Wieferich D.J., and Bellmore J.R. 2018. USGS Dam Removal Science Database v2.0. U.S. Geological Survey. https://doi.org/10.5066/P9IGEC9G.

Environmental Advisory Board (EAB). 2006. Environmental benefits and performance measures: Defining National Ecosystem Restoration and how to measure its achievement. Chief of Engineers Environmental Advisory Board, U.S. Army Corps of Engineers. Access 30 August 2017. http://www.usace.army.mil/Portals/2/docs/Environmental/EAB/ebpm_mar07.pdf.

Epstein, JA 2009. Upstream geomorphic response to dam removal: The Blackfoot River, Montana. MS thesis, University of Montana.

Fischenich J.C. 2008. The application of conceptual models to ecosystem restoration. ERDC TN-EBA-TN-08-1. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Foley M.M., Bellmore J.R., O'Connor J.E., Duda J.J., East A.E., Grant G.E., Anderson C.W., Bountry J.A., Collins M.J., Connolly P.J., Craig L.S., Evans J.E., Greene S.L., Magilligan F.J., Magirl C.S., Major J.J., Pess G.R., Randle T.J., Shafroth P.B., Togersen C.E., Tullos D., and Wilcox A.C. 2017a. Dam removal: Listening in. Water Resources Research, 53, doi: 10.1002/2017WR020457.

Gailani, Joseph & C. Lackey, Tahirih & B. King, David & Bryant, Duncan & Kim, Sung-Chan & Shafer, Deborah. (2016). Predicting dredging-associated effects to coral reefs in Apra Harbor,

Guam - Part 1: Sediment exposure modeling. Journal of Environmental Management. 168. 16-26. 10.1016/j.jenvman.2015.10.027.
Gartner J.D., Magilligan F.J., and Renshaw C.E. 2015. Predicting the type, location and magnitude of geomorphic responses to dam removal: Role of hydrologic and geomorphic constraints. Geomorphology, 251, 20-30.
Gray J.R., Bernard J.M., Stewart D.W., McFaul E.J., Laurent K.W., Schwarts G.E., Stinson J.T., Jonas M.M., Randle T.J., and Webb J.W. 2010. Development of a National, dynamic reservoir sedimentation database. Proceedings of the 9th Federal Interagency Sedimentation Conference, Las Vegas, Nevada.
Hayter E.J., Chapman, R.S, Luong, P.V., Smith, S.J., and Bryant, D.B. 2012. "Demonstration of Predictive Capabilities for Fine-Scale Sedimentation Patterns within the Port of Anchorage, AK," Final Report prepared for USACE Alaska District, Anchorage, AK.
Hayter E.J., Chapman, R.S, Luong, P.V., Mausolf, G., and Lin, L. 2015. "Sediment Transport Modeling for the St. Louis River Estuary 40th Avenue Shoals and Island Design." Letter Report prepared for USACE Detroit District, Detroit, MI.
Hayter. E., R. Chapman, P. Luong, and G. Mausolf. 2016. "Modeling Sediment Transport using the Geophysical Scale Hydrodynamic and Sediment Transport Modeling System (GSMB)," *14th Estuarine and Coastal Modeling Conference*, Kingston, RI, June 13-15, 2016.
Juracek K.E. 2014. The aging of America's reservoirs: In-reservoir and downstream physical changes and habitat implications. Journal of the American Water Resources Association, doi: 10.1111/jawr.12238.
Kwan, S., Vasquez, J. Millar, R., and Steffler, P. (2010) "A two dimensional finite element hydrodynamic river morphology and gravel transport model" Proceedings Second Joint Federal Interagency Hydrologic Modeling Conference, June 27-July 1, 2010 Las Vegas, NV
Lai, Y.G. (2005). "River and watershed modeling: current effort and future direction," USCHINA Workshop on Advanced Computational Modeling in Hydroscience & Engineering, Sept. 19-21, 2005, Oxford, MS, USA.
Lai, Y.G, Holburn, E.R., and Bauer, T.R. (2006). "Analysis of sediment transport following removal of the Sandy River Delta Dam," Project Final Report, Technical Service Center, Bureau of Reclamation, Denver, CO.
Langendoen, E. J., and Simon, A. (2000). "Stream channel evolution of Little Salt Creek and North Branch West Papillion Creek, eastern Nebraska." Report, US Department of Agriculture, Agricultural Research Service, National Sedimentation Laboratory, Oxford, MS.
Langendoen, E.J., 2002. CONCEPTS: A process-based computer model of instream hydraulic and geomorphic processes. Hydrologic Modeling for the 21st Century, Proceedings Second Joint Federal Interagency Hydrologic Modeling Conference, June 27-July 1, 2010 Las Vegas, NV, on CDROM.
Leopold L.B., and Maddock T.M. 1954. The flood control controversy, big dams, little dams, and land management. Geomorphological Review, 45 (2), 301-303.
MacDonald N.J., Davies M.H., Zundel A.K., Howlett J.D., Demirbilek Z., Gailani J.Z., Lackey T.C., and Smith J. 2006. PTM: Particle Tracking Model Report 1: Model theory, implementation, and example applications. ERDC/CHL TR-06-20, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.
Major J.J., East A.E., O'Connor J.E., Grant G.E., Wilcox A.C., Magirl C.S., Collins M.J., and Tullos D.D. 2017. Geomorphic response to dam removal in the United States: A two decade perspective. Gravel-bed Rivers: Processes and Disasters (Ed. Tsutsumi and Laronnw), John Wiley & Sons Ltd.
Morris G.L. and Jiahua, F. 1997. Reservoir sedimentation handbook (Vol. 15). New York: McGraw-Hill.

Pace K.M., Tullos D., Walter C., Lancaster S., and Segura C. 2016. Sediment pulse behavior following dam removal in gravel-bed rivers. River Research and Applications, doi: 10.1002/rra.3064.

Pinson A., Baker B., Boyd P., Grandpre R., White K.D., and Jonas M. 2016. U.S. Army Corps of Engineers reservoir sedimentation in the context of climate change. Civil Works Technical Report, CWTS 2016-05, U.S. Army Corps of Engineers, Washington, D.C.

Pizzuto J.E. 2002. Effects of dam removal on river form and process. BioScience 52 (8), 683–691.

Randle T.J. and Bountry J. 2017. Dam removal analysis guidelines for sediment. Technical Service Center, Bureau of Reclamation, Denver, Colorado.

Revel, M T K, N & P G R Ranasiri, L & M C R K Rathnayake, R & Pathirana, Kariyawasam Pathiranage. (2013). Experimental Investigation of Sediment Trap Efficiency in Reservoirs. Engineer: Journal of the Institution of Engineers, Sri Lanka. 47. 10.4038/engineer.v47i2.6863.

Rumschlag, J.H. and Peck, J.A. 2007. Short-term sediment and morphologic response of the middle Cuyahoga River to the removal of the Munroe Falls Dam, Summit County, Ohio. J. Great Lakes Research, 33 (Special Issue 2): 142-153.

Santaniello D.J., Snyder N.P., and Gontz A.M. 2013. Using ground-penetrating radar to determine the quantity of sediment stored behind the Merrimack Village Dam, Souhegan River, New Hampshire. Reviews in Engineering Geology XXI, 45-57.

Sawaske S.R. and Freyberg D.I. 2012. A comparison of past small dam removals in highly sediment-impacted systems in the U.S. Geomorphology, 151, 50-58.

Schmidt J.C. and Wilcock P.R. 2008. Metrics for assessing the downstream effects of dams. Water Resources Research, 44 (W04404), doi:10.1029/2006WR005092.

Strand, R.I., and E.L. Pemberton, 1982. Reservoir Sedimentation, Technical Guideline for Bureau of Reclamation, Sedimentation and River Hydraulics Branch, Denver, CO.

Syed, A.U., Bennett, J.P., and Rachol, C.M., 2005, A pre-dam-removal assessment of sediment transport for four dams on the Kalamazoo River between Plainwell and Allegan, Michigan: U.S. Geological Survey Scientific Investigations Report 2004-5178, 41 p.

Tonitto C. and Riha S.J. 2016. Planning and implementing small dam removals: Lessons learned from dam removals across the eastern United States. Sustainable Water Resources Management, doi: 10.1007/s40899-016-0062-7.

Tullos D.D., Collins M.J., Bellmore J.R., Bountry J.A., Connolly P.J., Shafroth P.B., and wilcox A.C. 2016. Synthesis of common management concerns associated with dam removal. Journal of the American Water Resources Association, doi: 10.1111/1752-1688.12450.

Wang Y.H., You G.J.Y. 2016. Evaluation of fluvial geomorphic responses to the removal of dams with the consideration of hydrological uncertainty: A case study in Shihgang Dam. 12th International Conference on Hydroscience & Engineering, Tainan, Taiwan.

Warrick J.A., Bountry J.A., East A.E., Magirl C.S., Randle T.J., Gelfenbaum G., Ritchie A.C., Pess G.R., Leung V., and Duda J.J. 2015. Large-scale dam removal on the Elwha River, Washington, USA: Source-to-sink sediment budget and synthesis. Geomorphology, 246, 729-750.

Zunka J.P.P., Tullos D.D., and Lancaster S.T. 2015. Effects of sediment pulses on bed relief in bar-pool channels. Earth Surface Processes and Landforms, doi: 10.1002/esp.3697.