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Simulation of Sediment Transport Due to Dam Removal and Control of Morphological Changes

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ABSTRACT: This paper presents two case studies of post dam removal sedimentation in the United States. Two different one-dimensional channel evolution simulation models were used: CCHE1D and CONCEPTS, respectively. The first case is the application of CCHE1D to assess the long-term (up to 10 years) morphological response to the removal of Marmot Dam in the Sandy River, Oregon. Simulation results showed a persistent erosion of sediments from the reservoir over the 10-year period; the eroded sediments travel downstream as a wave. Further, it was found that the runoff will greatly affect the rate of morphologic adjustment. The second case is a CONCEPTS study of the sediment dynamics over a 37-year period after removal of the Plainwell and Otsego City dams along the Kalamazoo River, Michigan. Removing the dams would increase sediment loads twelve fold by rapidly eroding the fine-grained sediments stored behind the Otsego City Dam. Finally, to minimize morphological changes in the river reaches downstream of the dam site, this paper also showed the benefits of applying a simulation-based optimization tool with multiple objectives and constraints for finding the optimized sediment release and relocation during the process of dam-removal. Combining the presented optimization tool with models such as CCHE1D and CONCEPTS should be extended to manage sediment at the watershed scale.

Keywords: Sediment transport, Dam removal, Sediment control, Optimization

1 INTRODUCTION

When a dam is significantly deteriorated and is no longer able to serve the purpose for which it was constructed, or the costs of repair and maintenance exceed the expected benefits, the dam may need to be decommissioned (or removed). In the United States (US), dam removal in a river or stream is an effective engineering approach to restore river ecosystem. However, the downstream impact of sediments released from the reservoir post dam removal is a major concern. For reservoirs with large sediment deposits, released sediments may significantly change the river morphology in both the reservoir and the downstream channels. Before decommissioning a dam, it is important to study sediment transport and morphological changes upstream and downstream of the dam site that may result from dam removal.

The mechanics of sediment erosion and transport following dam removal is highly complicated due to the non-uniform spatial distribution of sediments in reservoirs and downstream river channels. In general, sediment transport processes are unsteady, nonlinear, and interacting with dynamic river flows. Quick release of reservoir sediments by a complete dam removal may result in a supercritical flow in the river reach near the dam location. Eroded sediments usually deposit immediately downstream. A headcut may form and migrate upstream through delta deposits if reservoir bed materials are cohesive. As a result, bank erosion and channel widening are important adjustment processes. Even if the dam removal process is gradual, river floodwaters during a storm may entrain a large portion of the deposits and pass it over the low-head dam. Thus, the assessment of potential impacts of dam removal on river hydrological and geomorphological environments requires integrated model capabilities to simulate multi-scale processes in river flow dynamics, morphodynamics, and ecosystem services.

This paper presents two examples of post dam removal sedimentation studies. Two different one-dimensional (1D) channel evolution simulation models were used: CCHE1D (Wu & Vieira, 2002) and

CONCEPTS (Langendoen, 2000), respectively. Both models are capable of simulating multiple flow regimes during the period of dam removal and multiple channel sedimentation processes. The first example is the application of CCHE1D to assess long-term (up to 10 years) morphological response to the removal of Marmot Dam in the Sandy River, Oregon (Figure 1a). The second one is a CONCEPTS study of the sediment dynamics due to removal of dams along the Kalamazoo River, Michigan (Figure 1b). To mitigate the downstream impact of eroded sediments, CONCEPTS was used to evaluate the erosion, transport, and deposition of sediments over a 37-year period for three different dam-removal scenarios.

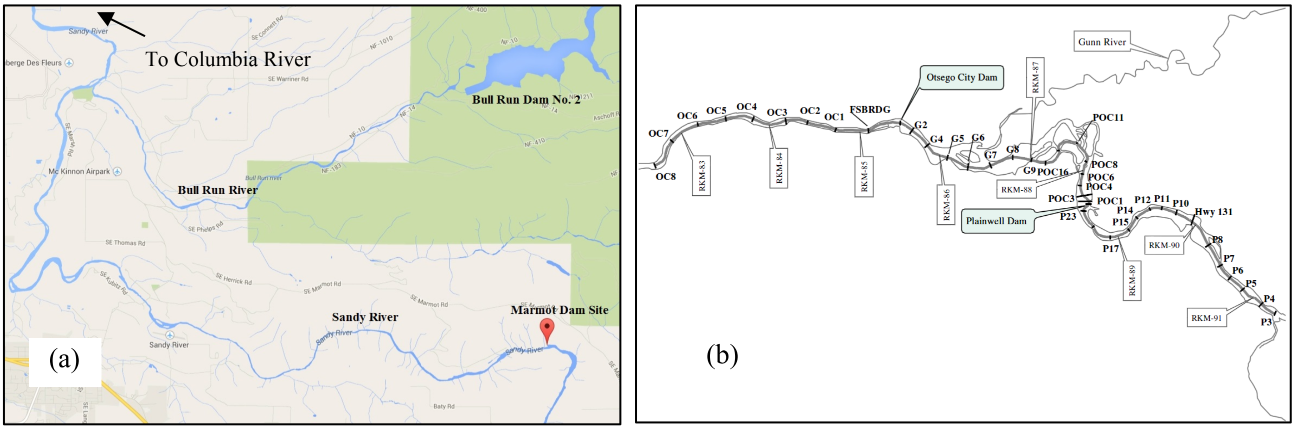

Figure 1. (a) Map of Sandy River basin; (b) Map of study reach on the Kalamazoo River, Michigan

To provide the most effective management plan to decommission the dam and release the reservoir deposits, it would be best if one could establish the optimal reservoir sediment release schedule (or the time-dependent controlled released process) to minimize the downstream impact of sedimentation. Thus, this paper discusses a simulation-based optimization tool (Ding et al., 2013) to search for optimal control of sediment releases for minimization of morphological changes in the Sandy River after the Marmot dam was removed. It is expected that this kind of integrated approach of simulation and optimization tools can provide the best management solution to reduce the impact of dam removal and to restore river ecosystem.

2 CASE 1: SEDIMENT TRANSPORT DUE TO MARMOT DAM REMOVAL

Marmot Dam was the only dam on the main-stem of the Sandy River, Oregon (Figure 1a). The Sandy River extends approximately 89 km from its headwater to its confluence with the Columbia River. The dam was located near the middle of the basin at river mile (RM) 30, downstream of the Salmon River confluence but upstream of the Bull Run River confluence and 2 km upstream of the entrance to the Sandy River gorge. Marmot Dam, a 47-foot-high, 345-foot-long roller-compacted concrete dam, was built in 1989 to replace an earlier timber structure, which was originally constructed in 1913. Portland General Electric (PGE), the owner and operator of the dam, decided to build a temporary cofferdam upstream of Marmot Dam to facilitate the removal of the dam body and prevent the disturbance of the deposited sediment behind the dam. After the dam was removed, the cofferdam was breached to allow the 80-km-long Sandy River to flow freely from Mount Hood, Oregon, to its confluence with the Columbia River. The breaching of the cofferdam was started on Oct. 19, 2007.

Due to long-term sediment accumulation in the reservoir, different sources and sizes of sediments deposited in the reservoir formed a layer structure (Squier Associates, 2000). The deposited sediments were mainly composed of a surface gravel layer (Unit 1), a sand layer underneath (Unit 2), and the pre-dam channel bed representing the third distinct unit. The uppermost unit (Unit 1) ranged from approximately 2-5.5 m in thickness and was composed of sandy gravel with a small amount of cobbles and boulders, becoming thicker toward the dam. Unit 2 was predominantly fine sediment (silty sand to sand with a small amount of gravel, ranging from 4 to 11 m in thickness). The pre-dam channel, below Unit 2, consisted primarily of coarse sediment and its thickness ranged from 0.8 to 3 m. At the time of decommissioning, the 3-km-long reservoir behind the dam was filled with nearly 750,000 m^3 sand and gravel, a volume equivalent to about 5 to 10 years of average annual sediment load. Most sediment transported by the river had been passing the dam for decades. The sediment transport rate was about 250,000 t yr^{-1} at the Marmot Dam, of which the majority was fine sediment (Stillwater Sciences 2000).

CCHE1D, a 1D river flow and sediment transport model, (Wu and Vieira, 2002), was used to assess morphological changes in the Sandy River due to the Marmot Dam removal. Several sediment transport formulations (e.g. SEDTRA formula, Ackers-White formula, Engelund and Hansen's formula, Wu-Wang-Jia's formula, etc.) are available in the model for simulations of sediment transport and morphological changes. The model simulates non-uniform sediment transport, bed aggradation and degradation, bed material composition (hydraulic sorting and armouring), and bank erosion. The flow model in CCHE1D simulates flows that must be primarily subcritical in all reaches of the channel network. However, it can handle local supercritical and transcritical flows without hydraulic jumps in few cross-sections through a hybrid dynamic/diffusive wave model. This hybrid dynamic-diffusive wave model can avoid numerical instability of the dynamic wave model in the transcritical flow regions.

The study reach (i.e. computational domain) extends from 2.5 km upstream of the dam site to 18.0 km of its downstream. The surveyed cross-section data provided by PGE (Stillwater Sciences, 2000) were used to generate cross-sections for the numerical simulation of hydrodynamic and morphodynamic processes. To improve the simulation results, a number of cross-sections have been linearly interpolated or extrapolated in several subreaches. The spacing between cross-sections varies from 12 m to 325 m and a total of 126 cross-sections are used in this model.

A discharge series spanning the period of model runs is required as input hydrograph to the model. The daily discharge data from the Sandy River is available at the US Geological Survey (USGS) Marmot gauge (station No. 14137000), which is located 0.5 km upstream of the Marmot Dam site. This station's hydrograph is used as a boundary condition at the inlet of the study reach. The maximum average daily discharge in the river in the first year after the dam removal from Oct. 19, 2007 to Sept. 30, 2008 reached 180 m^3/s. Another USGS hydrologic station (No. 14142500) is located 0.2 km downstream of the Bull Run River confluence. For specifying the water depth boundary condition at the downstream end for the numerical model, the water depths at the station are calculated by assuming a state of uniform flow at a cross-section.

For non-uniform sediment transport modelling, the sediment size distributions, Unit 1 and Unit 2 are used for creating sediment compositions in the reach behind the dam. Unit 1 is assumed to be the bed compositions (i.e. sandy gravel with some cobbles and boulders) in the downstream cross sections from the dam site. The graded sediments in the model are divided into 12 size classes. The representative sizes of the sediments vary from 0.09 mm to 188.34mm.

The calibration of those model parameters including the selection of sediment transport formulae in CCHE1D with the multiple size classes was carried out by simulating the flow and sediment transport starting at the moment of the dam removal, Oct. 19, 2007 to Sept. 30, 2008. To investigate the performance of the sediment transport capacity formulae, all the four available formulae in CCHE1D were examined by computing the first year morphodynamic processes. The intercomparisons of average bed elevation changes after the one year computed by the four formulae are presented in Figure 2. All the formulae give reasonable bed change patterns in comparison with the observed bed changes after the first year natural flush of reservoir sediments: the erosion before the knickpoint and the deposition downstream are well simulated. By evaluating the bed changes in both upstream and downstream, it is found that the Engelund and Hansen's formula produced a slower erosion rate in the reservoir, but an overestimated change in the downstream reaches; Wu-Wang-Jia's formula provided better morphological changes in the whole study reach. Therefore, Wu-Wang-Jia's formula was used for the further studies of modal validation and the long-term assessment of morphological changes in the Sandy River.

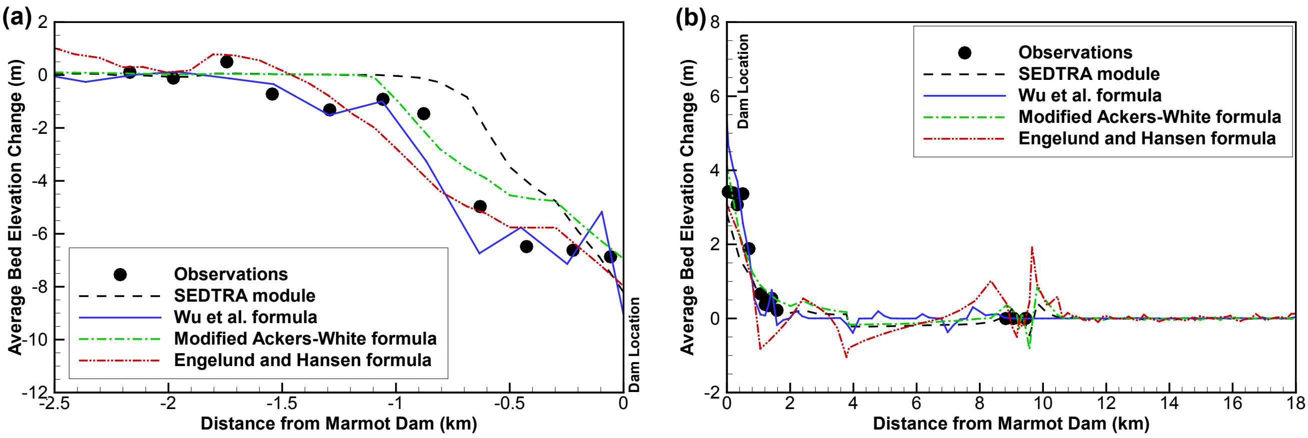

Figure 2. Comparisons of 1-year bed changes by using four sediment transport rate formulae

Then, the bed roughness coefficients along the river reach were also calibrated. It is found that the large roughness value (0.06) is appropriate to the downstream reach because the bed surface pre dam removal was armoured and consisted mainly of cobbles and boulders, and the morphology downstream is more complex; the best n value in the reservoir sections was close to 0.04.

By using the calibrated model parameters and Wu-Wang-Jia's sediment transport formula, a 10-year-long impact assessment of morphological changes in the Sandy River after the Marmot Dam Removal was performed. Similar to the approach implemented by Stillwater Sciences (2000) and Cui and Wilcox (2008), a 10-year long period containing ten yearly hydrographs was assumed to be the synthetic hydrological forcing in the river. The recorded first-year (i.e., 2008) hydrograph after the dam removal is used as the input for the first year of simulation. The other nine years were selected randomly from the historic yearly records in the Sandy River to represent the normal and extreme flow events. The peak discharge in the 10-year hydrograph varies from 180.4 m^3/s in the first year to 390.8 m^3/s in the 10^{th} year.

For the 10-year average bed changes, Figure 3 shows that there is an increasing erosion upstream (Figure 3a), and a continuing aggradation in the immediate downstream of the dam (Figure 3b). It is obvious that the travelling wave of the eroded sediments from the reservoir causes these morphological changes. The rate of upstream bed erosion seems slightly slower than that of deposition downstream; One of reasons is that the downstream cross-sections are narrower than those upstream inside the reservoir. Meanwhile, erosion is also highly related to the initial bed material size. It is expected that following dam removal, the slope of the riverbed would gradually return to the pre dam condition. The results show that the bed changes from year 5 to year 10 are much more than those from year 3 to year 5. This is because the peak discharges in the second five years are significantly greater than those in the first five years. And more river waters in the second five years create more bed changes at a few cross sections around 4 km and 7 km (not plotted in the figure). It is also found that there is an increasing erosion at a reach from 1.4 – 1.8 km, due to accelerated river flows by the narrow cross sections in the reach. The computed trend of the bed changes depends on the hydrological conditions of the selected water years. If more cycles of simulations of the ten water years can be repeated, an equilibrium state of morphology may be found, which remains as a future topic of this study.

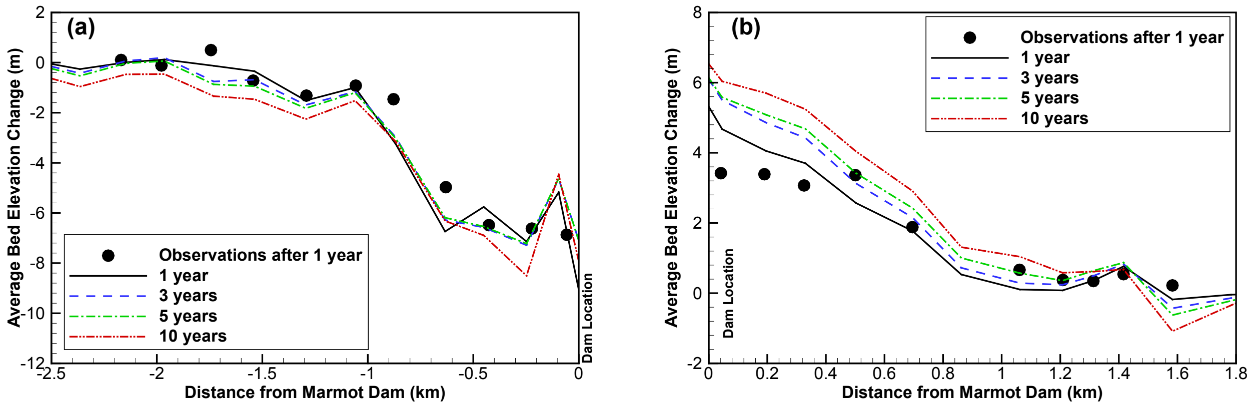

Figure 3. Long-term bed change evolutions computed by using calibrated model parameters

3 CASE 2: SIMULATION OF POST DAM REMOVAL SEDIMENT DYNAMICS ALONG THE KALAMAZOO RIVER

Between the mid-1800s and the early 1900s, four dams were constructed on the Kalamazoo River between Plainwell and Allegan, Michigan. The impoundments have been the depositories of upstream sediment and industrial waste materials containing polychlorinated biphenyl (PCB) and kaolinite clays. During the 1960s, water levels behind the decommissioned hydroelectric dams were lowered, exposing the previously inundated material. In response to the lowering of water levels, the river began to erode the sediments and transport them downstream, but much of this waste clay remains impounded behind the dams mainly as floodplain deposits. The state of Michigan is interested in removing the dams while minimizing impacts locally and to downstream reaches. CONCEPTS was used to simulate sediment loadings from PCB-contaminated stream banks and channel changes for a section between Plainwell and Otsego, which contains the Plainwell and Otsego City Dams, under three different scenarios: (1) dams in (DI) or baseline, (2) dams out (DO), and (3) design (D). The design scenario evaluates a redesigned stream-riparian corridor to minimize the adverse local and downstream impacts of the dam removal.

The CONCEPTS computer model has been developed to simulate the evolution of incised streams and to evaluate the long-term impact of rehabilitation measures to stabilize stream systems and reduce sediment yield (Langendoen, 2000). CONCEPTS simulates unsteady, 1D flow, graded sediment transport, and bank erosion processes in stream corridors. It can predict the dynamic response of flow and sediment transport to in-stream structures. Its features are similar to those of the CCHE1D model, which was used in the previous section.

The study reach of the Kalamazoo River is 8.8 km long, from river kilometer (rkm) 82.4 (cross-section OC8), to cross-section P3, at rkm 91.2 (Figure 1b). The model of the study reach is composed of 52 cross sections and contains both Plainwell and Otsego City Dams. The Plainwell Dam is 52.4 m wide and 4.3 m high. The Otsego City Dam is 46.0 m wide and 4.0 m high. The study reach can be separated into three distinct subreaches based on location relative to the Plainwell and Otsego City Dams. The Otsego (OC) reach extends from rkm 82.4 to the Otsego City Dam at rkm 85.3. The Plainwell-Otsego (POC) reach extends from the upstream end of the Otsego City Dam to the Plainwell Dam at rkm 88.3. The Plainwell reach extends from the Plainwell Dam to the upstream boundary of the study reach at rkm 91.2.

Flows for all three simulation scenarios are based on a 17.7-year discharge record (October 1984 to June 2002) from the USGS gage on the Kalamazoo River at Comstock, Michigan (#04106000). The Gunn River flows into the POC section of the study reach from the north between cross-sections G5 and G6 (Figure 1b). Because there is no flow data for this tributary, the flow from the Gunn River (296 km^2) was estimated using a drainage area comparison with the flow record from the Kalamazoo River at Comstock (2740 km^2). Given the respective drainage areas, the Gunn River discharge record was 17% of the Kalamazoo River at Comstock discharge record. A sediment rating curve for fines (clays, silts, and very fine sands) was derived from 51 suspended-sediment samples collected by the USGS at the Plainwell gauge. For coarse sediment particles transported as bed load, the sediment transport rates at the inlet are assumed to equal the local sediment-transport capacity of the flow.

The simulation period is August 2000 through November 2037. The start date coincides with the first cross-section surveys by the USGS. The inflow record of water and sediment consists of the observed flow through June 2002 followed by two sequences of the 17.7-year flow record discussed above. The simulation period is long enough for channel adjustments to reach equilibrium for the DO and D scenarios.

Bed material stratigraphy and composition were determined at 101 transects covering the study reach (Rheaume *et al.*, 2002, 2004) and were directly used in the model simulations. Data on bank material stratigraphy, composition, and properties were collected at 27 locations. Regions with similar bank material were identified, and data collected in these regions were aggregated. Critical shear stress of the bank material ranges from a minimum of 1.3 Pa along the POC reach to a maximum of 70 Pa along the left bank immediately upstream of the Plainwell Dam. Effective cohesion ranges from a minimum of 0 Pa for sandy bank material to a maximum of 6.8 kPa for the right bank of the most upstream cross sections.

The DI scenario assumes current channel geometries and boundary sediments as initial conditions. This simulation is used as a baseline by which to compare the two alternative scenarios in terms of gross amounts of channel change, the mass of material eroded from channel banks, and fine-grained sediment transport. The DO scenario also assumes current channel geometries as initial conditions but with the Plainwell and Otsego City Dams no longer in place, leaving 3-4 m high knickpoints. Finally, the design scenario also assumes that the two dams are no longer in place; however, design channel geometry is used instead of the current channel geometry for initial conditions (Rachol *et al.*, 2005). For the D scenario, channel geometry, channel location, floodplain area, and channel elevation were modified between the Otsego City Dam (rkm 85.3) and cross-section P15 (rkm 89.0) to minimize potential flooding, erosion, or sedimentation problems after removal of the dams. Cross sections in the impounded area upstream of the Plainwell Dam were mainly modified by lowering the channel to its pre-dam elevation and removing impounded sediment to increase floodplain area. The slope through this reach is similar to that for pre-dam conditions. In the POC reach, the slope of the designed channel is steeper than that for pre-dam conditions. In the anastomosing part of the reach, valley cross sections were modified by simplifying the multiple channel system into one or two main channels. Downstream of the multichannel reach, the channel elevation was lowered below its pre-dam elevation to provide a smooth transition to the incised reach downstream of the Otsego City Dam and impounded sediment removed to create a floodplain area. Streambeds of excavated cross sections were assigned material composition and properties found at the level of excavation.

The DI modeling scenario represents a baseline condition with existing channel geometries (including the low-head dams) and boundary characteristics. In general, the simulation predicted aggradation in the Plainwell reach with sediment deposited in the backwaters caused by U.S. Highway 131 bridge and the Plainwell Dam (Figure 4a). The main branch of the POC reach is slightly erosional, whereas the OC reach is mainly a transport reach. Results show that over the entire study reach, there is a net annual deposition of material (4100 t yr^{-1}). However, silts and clays are eroded primarily from the bed at an average annual rate of 1990 t yr^{-1}.

For the DO scenario, large-scale erosion of the deposits upstream of the dams occurred very quickly as the fine-grained particles were unable to resist the increased shear (Figure 4b). The channel incises down to its parent bed material (pre-dam elevations), limiting the extent of erosion to the depth of the reservoir deposits. In the Plainwell reach, bed deposition of 6400 t yr^{-1} for the baseline (DI) scenario turned to erosion of 289 t yr^{-1} for the DO scenario. Net bed erosion in the POC reach increased 1346% to 6580 t yr^{-1} for the DO scenario compared with the DI scenario (455 t yr^{-1}). Bank erosion also increased greatly (1645%) in the POC reach from about 157 to 2740 t yr^{-1} on average, due to higher shear stresses exerted by the flow caused by the initial steepening of the channel, especially upstream of the Otsego City Dam location.

Figure 4c shows the differences between the current thalweg profile and that of the design channel for the D scenario. Simulation shows the POC and OC reaches are fairly stable because of the coarse-grained bed material. Channel deposition (2570 t yr^{-1}) simulated under this scenario is 37% lower than the DI scenario (4100 t yr^{-1}). Erosion of stream bank materials <63 µm (112 t yr^{-1}) is 28% greater than that for the DI scenario (87.7 t yr^{-1}).

Over the simulation period, the DI/baseline scenario provides the smallest load passing the outlet (Table 1). The total load is the largest for the DO scenario; however, the silt and clay fraction is smallest for the DO and D scenario. The increase in sand-sized sediment transport appears to limit the amount of fines being transported. Sediments eroded from the channel boundary and downstream sediment load are similar and fairly low for the DI and D scenarios, indicating a stable stream system. Removal of the low-head dams induces severe channel bed and stream bank erosion upstream of the former dam locations, significantly increasing sediment load. However, most of these sediments are eroded in the first 3 years (Table 1). The quantities of fine-grained material (<63 µm) transported past the downstream boundary over the last 35 years of the simulation are similar to those of the DI and D scenarios. Therefore, most of the channel adjustment due to dam removal occurs in the first 3 years of the simulation.

Although the DI (baseline) case clearly provides the smallest loads for total sediment transport, in order to improve navigation and fisheries within this reach of the Kalamazoo River, the removal of the low-head dams and implementation of the design proposed by the USGS provides reduced loadings in materials less than 63 µm, and total loads passing OC8 are comparable with the existing DI loadings.

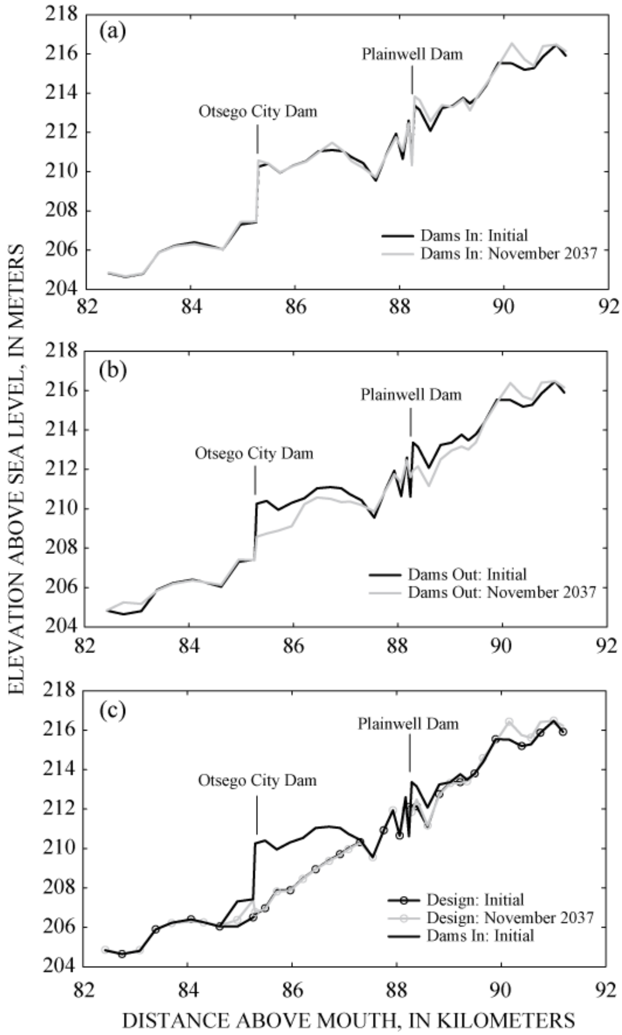

Figure 4. Initial and final thalweg profiles for the (a) dams in (DI), (b) dams out (DO), and (c) design (D) scenarios

Table 1. Simulated Average Annual Sediment Load Passing the Downstream Boundary of the Kalamazoo River Study Reach (Sediment yield in kilotons per year)

Scenario	< 63 µm	< 2 mm	Total
Dams in (DI)	10.4	10.5	10.5
Dams out (DO)	8.9	25.9	30.1
Dams out (DO, year 1–3)	43.7	114	127
Dams out (DO, year 4–38)	6.5	20.0	23.6
Design (D)	8.4	13.9	14.2

4 OPTIMIZATION OF SEDIMENT RELEASE

Most dam removal practices result in a natural (freely) downstream flush of reservoir sediments. A concern for the natural flush is the significant downstream impact of sedimentation in a relative short period after dam removal. For better sedimentation management, it should be best to find the optimal release operation, that is the controlled sediment routing at the dam site, to minimize this kind of geomorphic impact. Ding *et al*. (2013) have applied a simulation-based optimization model to find the optimal sediment release schedule to minimize the morphological changes in the downstream reaches. The simulation model is based on CCHE1D. The optimization technique was developed based on the variational adjoint sensitivity approach which is an efficient and effective nonlinear optimization method to seek the optimal control action such as the time-varying sediment release rate.

To apply this innovative optimization model to control the downstream deposition due to natural flush of reservoir sediments, it is assumed that by employing certain engineering methods (e.g. dredging or pumping) the sediment release can be regulated by diverting extra sediments at the dam site out of the river system (i.e. sediment relocation). The optimal control duration for the Marmot Dam removal was started immediately after the dam removal and lasted one year. Figure 5 presents the optimal sediment control results and comparisons with the bed changes by natural flush (no control). The left plot shows two release sediment rate curves from reservoir based on natural flush and the optimal control. The controlled release peaks of the sediments in the blue curve correspond roughly to the storm peaks of the river flows. The right plot shows the morphological changes due to the natural flush and the control sediment routing. The optimization results provide the best performance of the controlled sediment release which can reduce significantly the downstream sedimentation, if a certain amount of reservoir sediments can be diverted out of the river. However, a question on how to control the sediment release so precisely still remains for further discussions.

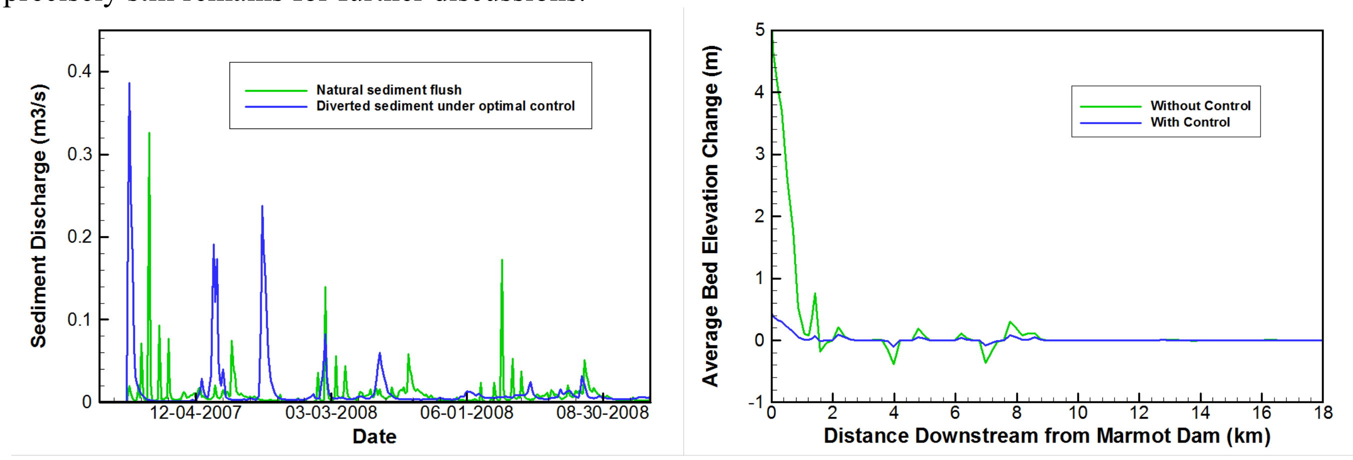

Figure 5. Left: Release rate from reservoir through natural flush (green line) and the optimal control (blue line); Right: Bed changes due to natural flush and the controlled sediment routing (blue line)

5 CONCLUSIONS

This paper presented two examples of post dam removal sedimentation studies in the US. Two different 1D channel evolution simulation models, CCHE1D and CONCEPTS were used respectively. The first example is the application of CCHE1D to assess the long-term morphological response of the Sandy River, Oregon to the removal of the Marmot Dam. The model simulated non-uniform and nonequilibrium sediment transport, which accounted for graded sediment compositions of the reservoir deposits and the downstream sand bed. Using the observed morphological changes after the dam removal, sediment transport capacity formulas and model parameters such as bed roughness were calibrated. The calibrated parameter values and selected formula were used for the long-term impact assessment of the dam removal. The results showed that over a 10-year period, sediment deposition would reach 10-km downstream of the dam site. Simulation results showed a persistent erosion of sediments from the reservoir over the 10-year period; the eroded sediments travel downstream as a wave. Further, it was found that the runoff will greatly affect the rate of morphologic adjustment.

The second example is a CONCEPTS study of the sediment dynamics after removal of the Plainwell and Otsego City dams along the Kalamazoo River, Michigan. To mitigate the downstream impact of eroded sediments, CONCEPTS was used to evaluate the erosion, transport, and deposition of sediments over a 37-year period for three different dam-removal scenarios: (1) dams in (DI) or baseline, (2) dams out (DO), and (3) design (D). The design scenario evaluated a redesigned stream-riparian corridor to minimize the adverse local and downstream impacts of the dam removal. For the DO case, the average-annual sediment load increased 12 times, the erosion of material finer than 63 μm increased 2.2 times, and the mass of fine-grained sediments increased 1.6 times compared to the DI case. For the D case, the average-annual sediment load was one-third of the DO case but still 4 times greater than the DI case. The relative contribution of fines to total load was larger for the DI case compared to the DO and D case, and the relative contribution of fines to total load in the D case was twice the DO case. The DI (baseline) case clearly provides the smallest loads for both total and fine-grained sediment transport.

Prediction results by the models can be used for managing and planning river sedimentation after the dam removal. The optimal sediment transport rate found by the simulation-based model can minimize the deposition at the downstream. It can be used as an engineering management guidance to plan a better scheduled dam decommissioning if releasing reservoir deposits can be operated.

The presented applications confirmed that the latest computational simulation technology is capable of making predictions of the outcomes of alternative dam removal plans and sediment movement designs. Therefore, it is recommended that during the design phase of control measures and sediment management plans, modeling studies and optimization analyses are conducted to select the optimal (compromised) decisions in sediment movement and relocation control. Then, the dam removal project shall be cost-effective in the short- and long-term from watershed management and regional point of view.

ACKNOWLEDGEMENTS

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