

MODELING PRE- AND POST-DAM REMOVAL SEDIMENT DYNAMICS: THE KALAMAZOO RIVER, MICHIGAN¹

Robert R. Wells, Eddy J. Langendoen, and Andrew Simon²

ABSTRACT: The state of Michigan is interested in removing two low-head dams in an 8.8 km reach of the Kalamazoo River between Plainwell and Otsego, Michigan, while minimizing impacts locally and to downstream reaches. The study was designed to evaluate the erosion, transport, and deposition of sediments over a 37.3-year period using the channel evolution model CONCEPTS for three simulation scenarios: Dams In (DI), Dams Out (DO), and Design (D). The total mass of sediment emanating from the channel boundary, for the DI case, shows net deposition of 4,100 T/y for the study reach, with net transport (suspended and bed load) of 10,500 T/y passing the downstream boundary. For the DO case, net erosion is 19,200 T/y with net transport of 30,100 T/y (187% increase) passing the downstream boundary. For the D case, net deposition is 2,570 T/y (37% decrease) with transport of 14,200 T/y (35% increase) passing the downstream boundary. The most significant findings were: (1) removal of the low-head dams will cause significant erosion of sediments stored behind the dams and increased sediment loads passing the downstream boundary and (2) sediment loads for the proposed channel design are similar to existing conditions and offer reduced fine-sediment loadings.

(KEY TERMS: dams; fluvial processes; hydrodynamics; numerical simulation; rivers/streams; sediment transport.)

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INTRODUCTION

Between the mid-1800s and the early 1900s, four dams were constructed on the Kalamazoo River between Plainwell and Allegan, Michigan. Three hydroelectric dams (Trowbridge, Otsego, and Plainwell) were decommissioned as power generators in the mid-1960s, and by 1970, the Michigan Department of Natural Resources had assumed responsibility for the structures. The Otsego City Dam, which

remains in operation, was originally built to support freight business on the river and has been providing a continuous industrial water supply for a paper mill built in the 1880s. The impoundments have been the depositories of upstream sediment and industrial waste materials. According to Camp Dresser & McKee (1999c), the primary industrial activity associated with polychlorinated biphenyl (PCB) releases to the Kalamazoo River was the recycling activities at various area paper mills. Between 1957 and 1971, Kalamazoo area paper mills recycled carbonless copy

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²Respectively (Wells, Langendoen, Simon), Research Hydrologist, Research Hydraulic Engineer, and Research Geologist, USDA-ARS, National Sedimentation Laboratory, Oxford, Mississippi (E-mail/Wells: rrwells@ars.usda.gov).

paper containing PCBs as ink solvent and incorporated these PCBs in their waste discharge. The paper wastes also included kaolinite clays, which were found in the impounded sediments to contain concentrations of PCBs as high as 94 mg/kg (Blasland *et al.*, 1994). During the 1960s, water levels behind the decommissioned hydroelectric dams were lowered, exposing the previously inundated material (Camp Dresser & McKee, 1999a,b, 2000). 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 (Rheaume *et al.*, 2002, 2004).

Because of the PCB contamination, U.S. Environmental Protection Agency (USEPA) has designated the Kalamazoo River from the City of Kalamazoo to its outlet into Lake Michigan as a Federal Superfund site. The State of Michigan is interested in removing the dams while minimizing impacts locally and to downstream reaches, and to provide for improved fisheries. Concerns over the fate of PCB-laden channel sediments in the Kalamazoo River between Plainwell and Otsego, especially its release by bank erosion, resulted in the U.S. Geological Survey (USGS) supporting a study by the USDA-ARS National Sedimentation Laboratory to simulate sediment loads and channel changes in the reach under three different scenarios: (1) Dams in (DI) or baseline, (2) Dams out (DO), and (3) Design (D).

Study Reach

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 1). The study reach can be separated into three distinct sub-reaches 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 (P) reach extends from the Plainwell Dam to the upstream boundary of the study reach at rkm 91.2.

Modeling Scenarios

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. This simulation does not model a dam breach, only the resulting hydraulic and sediment-transport processes associated with the “instantaneous” change resulting from removal of the non-erodible structures. 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).

Numerical Approach

Polychlorinated biphenyls tend to be adsorbed on to fine-grained sediments comprising streambeds, banks, and floodplains. Prediction of the erosion, transport, and deposition of these materials requires a model that can simulate streambank erosion processes, be they due to hydraulic shear stresses at the bank toe or to gravity-induced mass failure, as well as the conventional hydraulic and entrainment processes typical of non-cohesive sediments. The CONCEPTS (CONservational Channel Evolution and Pollutant Transport System) channel-evolution model, developed by the USDA-ARS National Sedimentation Laboratory (Langendoen, 2000, 2002), provides deterministic simulation of these processes and allows for identification of sediment sources by particle-size class. In this way, river managers and action agencies involved with the Kalamazoo River can make informed decisions regarding stream-rehabilitation measures.

CONCEPTS has been specifically developed to simulate the evolution of adjusting stream systems (Langendoen, 2002). The agreement between channel adjustments observed following dam removal and available conceptual channel-evolution models of incised stream systems suggest that current understanding of incised channel processes can be adapted to manage dam removal (Doyle *et al.*, 2003). Upstream channel adjustment is characterized by channel incision and channel widening through mass wasting if incision continues past a critical bank height. Width adjustment may comprise a significant mode of adjustment (Simon, 1992; Doyle *et al.*, 2003). Downstream channel morphology is governed by the rate and magnitude of erosion of the reservoir deposit and parent bed and bank material. CONCEPTS has been successfully used in similar morphological studies of: (1) the advancement of knickpoints in James Creek and Yalobusha River, Mississippi (Langendoen *et al.*, 2002; Simon *et al.*, 2002) and (2) the effects of

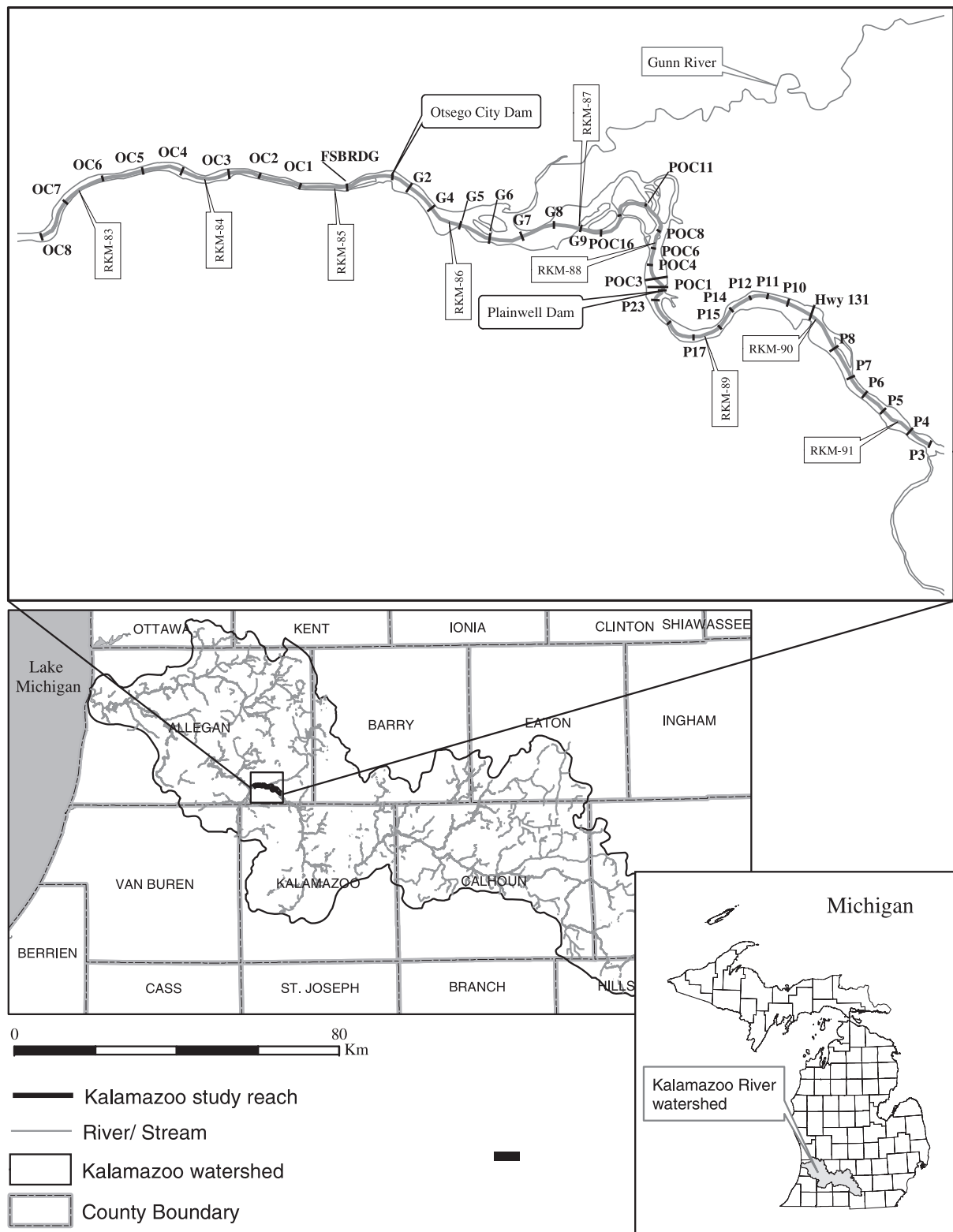


FIGURE 1. Map of Study Reach Showing Modeled Cross Sections and Locations of the Plainwell and Otsego City Dams.

instream grade-control structures in Mississippi and Nebraska (Bingner and Langendoen, 1997; Langendoen *et al.*, 2000).

The one-dimensional model, CONCEPTS, simulates unsteady flow, graded-sediment transport, and bank-erosion processes in stream corridors (Langendoen,

2000). Channel evolution is computed by tracking bed changes and channel widening. Bank erosion is simulated using flow-induced basal scour and geotechnical analysis of mass wasting processes (slab, planar, or cantilever-type bank failures). Streambanks may be composed of soil layers with different material properties. Transport of cohesive and cohesionless sediments, both in suspension and on the bed, are simulated selectively by size class. CONCEPTS is limited to straight channels or channels of low sinuosity, 14 pre-determined sediment particle-size classes, homogeneous bed-material across the channel, and steady pore-water pressure in the streambank.

Flow over the Plainwell and Otsego City Dams is assumed to be a free overfall and, therefore, critical. The dynamic equation then simply states that the Froude number equals one. Sediment particles transported in suspension will pass the dams, whereas sediment particles transported as part of the bed load will deposit immediately upstream of the dam as long as the upstream invert of the dam is above the elevation of the streambed. Once the streambed elevation reaches the elevation of the dam, all sediment particles will pass the structure.

Boundary Conditions

Flow. 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). This period was selected because it provides the most recent continuous period of flow record. The gage was not operational for a number of years prior to October 1984. On average, mean-daily flows at the Comstock gage for the modeling period are 30% higher than for the discontinuous period stretching back to 1934. Rather than adjust flows to better represent the longer period of record, we decided to use the higher, more recent flows to provide conservative estimates of current sediment loads and potential channel changes. This recent period contains a peak flow in 1985 (181 m³/s) that is similar in magnitude to the 1947 (196 m³/s) peak of record.

A 17.7-year flow record was created using daily data from 1984 to 1989 and hourly data from 1989 to June 2002 to account for changing hydraulic conditions and instantaneous peaks. Comparison with 3 years of mean-daily flow data at a recently installed gage at Plainwell (04106906; upstream of Plainwell Dam) showed flows entering the study reach were approximately 20% greater than those at the Comstock gage due to discharges from Portage and West Portage Creeks. Time-series analysis of the

differences in 15-min flow data for the two gages resulted in the following adjustment of discharge at the upstream boundary of the modeling reach:

$$Q_P = 1.82Q_C^{0.94} \quad (1)$$

where Q_P is discharge at the Plainwell gage in m³/s, and Q_C is the discharge at the Comstock gage 10 h earlier in m³/s. A 37.3-year flow record (August 2000 to November 2037) was created by looping the 17.7-year record.

The Gunn River flows into the POC section of the study reach from the north between cross-sections G5 and G6 (Figure 1). Because there is no flow data for this tributary, the authors estimated the flow from the Gunn River (296 km²) using a drainage area comparison with the flow record from the Kalamazoo River at Comstock (04106000; 2,740 km²). Given the respective drainage areas, the Gunn River discharge record was 17% of the Kalamazoo River at Comstock discharge record.

Sediment. Between February 2001 and September 2003, the USGS collected 51 suspended-sediment samples at the Plainwell gage. From these data, the following rating curve has been derived:

$$L = \begin{cases} 0.019Q^{0.97} & D \leq 0.063 \text{ mm} \\ 3.6E^{-6}Q^{2.81} & D > 0.063 \text{ mm} \end{cases} \quad (2)$$

where L is suspended sediment load in kg/s and D is sediment particle size. The r^2 value for the clay and silt-sized suspended load is 0.84, whereas that for the sand-sized suspended load is 0.77. The clay and silt-sized suspended load is equally distributed over the three clay and silt size classes in CONCEPTS. The sand-sized suspended load is assigned to the smallest sand size class in CONCEPTS. 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 USGS collected one suspended-sediment sample on the Gunn River in February 2002. The suspended-sediment load computed using this data value falls close to the derived rating curve at the Plainwell gage. Hence, the rating curve (2) is used to compute suspended-sediment load contributions from the Gunn River. The sediment transport rates for coarse sediment particles transported as bed load are assumed to equal the local sediment-transport capacity of the flow.

Channel Cross Sections and Planform. The 8.8 km modeling reach is composed of 52 cross sections and contains two low-head dams, Plainwell and

Otsego City (Figure 1). A third dam, "Otsego" is about 3 km downstream of the downstream-most cross section. The upstream end of the backwater of this dam is downstream of the outlet of the modeling reach (Rheaume *et al.*, 2004). Of the 52 cross sections used in the modeling reach, 20 were surveyed in the early to mid-1990s by the consulting firm Blasland, Bauck, and Lee (with floodplain extensions in 2001 by the USGS), 19 were surveyed in 2001 by the USGS, and 13 were synthesized based on adjacent channel geometries. The synthetic cross sections were generated from surveyed cross-section data to provide upstream and downstream transitions and boundaries for the structures, as well as to extend the OC reach to provide for improved water-surface elevations below the Otsego City Dam.

The Kalamazoo River is anastomosing along the upper half of the POC reach. Because CONCEPTS simulates flow as a single-thread channel, for this part of the Kalamazoo River the authors simulated the flow in the largest thread that conveys the majority of the water and sediment. The dominant thread conveys about 70-95% of the flow and allowed realistic boundary characteristics and conveyances to be used. Combining the various threads into a single channel would have entailed synthesizing an entirely new channel with different wetted perimeters and boundary characteristics.

The distribution of discharge in the anastomosing section was determined using velocity data collected by the USGS in 2001 and 2002 (Rheaume *et al.*, 2004). Branches of the Kalamazoo River downstream of the Plainwell Dam were simulated by withdrawing water and sediment at two locations: (1) cross-section POC6 (rkm 88.2) and (2) cross-section G9 (rkm 87.3; see Figure 1 for cross-section locations). The withdrawal rate of water is imposed, whereas that of sediment is a function of the transport capacity upstream and downstream of the point of withdrawal. The withdrawn water is returned to the modeling reach a distance downstream, whereas all withdrawn sediment is assumed to deposit in the side channels. The rate of flow withdrawal at cross-section POC6 is 30% and the flow is returned at cross-section POC16 (rkm 87.5). The rate of flow withdrawal at cross-section G9 is 20% and the flow is returned at cross-section G6 (rkm 86.7).

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 (Rachol *et al.*, 2005). 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 multi-channel reach, the channel elevation was lowered and impounded sediment removed to create a floodplain area.

The simulation period is August 2000 through November 2037. The start date coincides with the first cross-section surveys by the USGS (Rheaume *et al.*, 2002). 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.

FIELD DATA COLLECTION

Physical properties of each channel section are defined in terms of those variables that describe the forces and resistance acting on each surface of that cross-section. Sampling and testing of bed- and bank-material for textural composition and geotechnical properties were conducted. Geotechnical testing and sampling of banks was conducted by the ARS. Textural and bulk unit weight analysis was conducted by the USGS and from historical data.

Borehole Shear Testing and Bulk Unit Weights

To properly determine the resistance of cohesive materials to erosion by mass movement, data must be acquired on those characteristics that control shear strength; that is cohesion, angle of internal friction, pore-water pressure, and bulk unit weight. Cohesion and friction angle data can be obtained from standard laboratory testing (triaxial shear or unconfined compression tests) or by *in-situ* testing with a borehole shear-test (BST) device (Lohnes and Handy, 1968; Lutenege and Hallberg, 1981; Thorne *et al.*, 1981; Little *et al.*, 1982). The BST provides direct, drained shear-strength tests on the walls of a borehole. Advantages of the instrument include:

1. The test is performed *in situ* and testing is, therefore, performed on undisturbed material.
2. Cohesion and friction angle are evaluated separately with the cohesion value representing apparent cohesion (c_a). Effective cohesion (c') is

then obtained by adjusting c_a according to measured pore-water pressure and ϕ^b (the rate of increase in shear strength with increasing matric suction) (Fredlund *et al.*, 1978).

3. A number of separate trials with different applied stresses are run at the same sample depth to produce single values of cohesion and friction angle based on a standard Mohr-Coulomb failure envelope.
4. Data and results obtained from the instrument are plotted and calculated on site, allowing for repetition if results are unreasonable.
5. Tests can be carried out at various depths in the bank to locate weak strata (Thorne *et al.*, 1981).

Submerged Hydraulic Jet Testing: Erodibility of Fine-Grained Materials

The submerged jet-test device is used to estimate erosion rates due to hydraulic forces in fine-grained *in situ* materials (Hanson, 1990, 1991; Hanson and Simon, 2001). The device shoots a jet of water at a known head (stress) onto the streambed causing it to erode at a given rate. As the bed erodes, the distance between the jet and the bed increases, resulting in a decrease in the applied shear stress; theoretically, the rate of erosion beneath the jet decreases asymptotically with time to zero. A critical shear stress for the material can then be calculated from the field data as that shear stress where there is no erosion.

The rate of erosion ε (m/s) is assumed to be proportional to the shear stress in excess of a critical shear stress and is expressed as:

$$\varepsilon = k(\tau_0 - \tau_c)^a \quad (3)$$

where k is erodibility coefficient ($\text{m}^3/\text{N s}$), τ_0 is average boundary shear stress (Pa), τ_c is critical shear stress, and a is exponent assumed to equal 1.0. An inverse relation between τ_c and k occurs when soils exhibiting a low τ_c have a high k or when soils having a high τ_c have a low k . The measure of material resistance to hydraulic shear stresses is a function of both τ_c and k .

Two jet tests were conducted at each site where cohesive bed or bank-toe material was present. In general, the average value of the two tests were used to represent the cross section and for input into CONCEPTS. CONCEPTS computes k given τ_c to reduce variability (especially in k) in field measurements. A plot of the Kalamazoo River bank-toe measurements is shown in Figure 2. The relation used for the Kalamazoo River study reach is

$$k = 2.52\tau_c^{-0.52} \quad (4)$$

For coarse-grained materials, bulk samples were obtained for particle-size analysis that was performed by the USGS. Critical shear stress of these types of materials can then be calculated using conventional techniques as a function of particle size and weight (Shields, 1936).

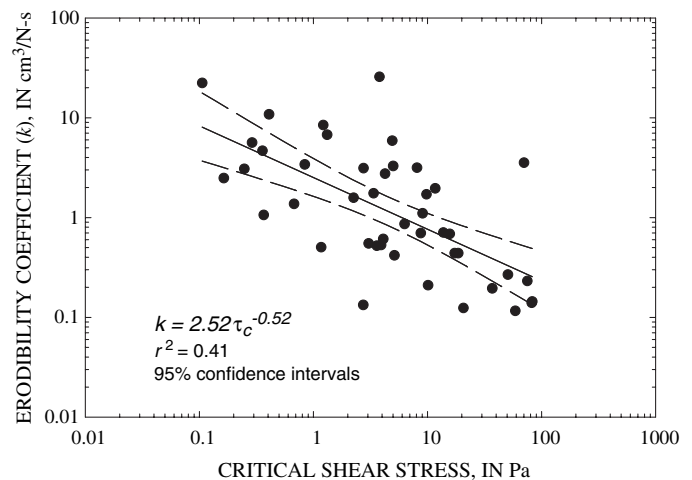


FIGURE 2. Relation Between Erodibility Coefficient (k) and Critical Shear Stress (τ_c) for Fine-Grained Materials Based on Jet Tests from the Kalamazoo River.

Hydraulic Roughness

Roughness values (Manning's n) were assigned to bed, bank, and floodplain sections of each cross section based on visual inspection of the channel and using guidelines set forth by Chow (1959). Calibration of n values was carried out to match observed water-surface elevations between US HWY 131 (rkm 89.9) and cross-section OC8 (rkm 82.4). The observed water-surface elevations were measured by the USGS over the period 2000-2002 (Rheaume *et al.*, 2002, 2004). Figure 3 shows the comparison between observed and simulated water surface elevations. In general, roughness values for the channel bed and banks ranged from 0.025 to 0.04 and from 0.05 to 0.10 for the floodplain.

Physical-Property Values Used by CONCEPTS

This section presents a brief overview of the physical properties assigned to streambeds and streambanks for cross sections comprising the study reach. Bed material stratigraphy and composition were determined at 101 transects covering the study reach

(Rheume *et al.*, 2002, 2004), and were directly used in the model simulations. Data on bank-material stratigraphy, composition, and properties were collected at the 27 BST and jet-test 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. A comprehensive report of the measured values and those assigned to each model cross section is provided in Wells *et al.* (2004).

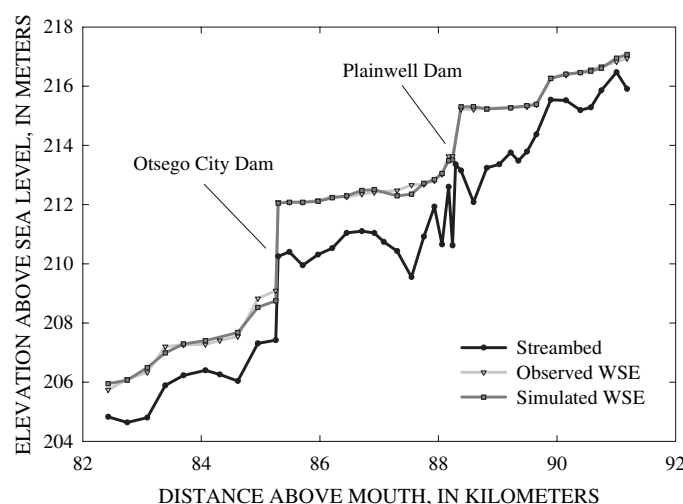


FIGURE 3. Comparison of Simulated and Observed Water Surface Elevations (WSE).

Modeling Assumptions. Past use of CONCEPTS has shown that it can accurately predict channel evolution and sediment loads, when upstream channel loadings are known and physical properties of the boundary are adequately determined *in situ* (e.g., Langendoen *et al.*, 2002; Simon *et al.*, 2002). To evaluate the three modeling scenarios, however, assumptions had to be made about the data assigned to cross sections within the POC reach. These assumptions concern sediment loadings from the Gunn River, the amount of water, and sediments withdrawn from the main channel and deposited in the side channels, and critical shear stress of streambank material.

To examine the effects of uncertainty in the sediment loadings from the Gunn River on the evolution of the modeling reach, two additional simulation runs with different sediment loadings from the Gunn River were carried out for the DI (baseline) scenario: (1) no sediment loadings and (2) a 100% increase in sediment

loadings. Reduction in sediment loadings from the Gunn River further exacerbated the sediment-starved system. Combined bed and bank erosion within the POC reach increased 16%, although erosion of material $<10\ \mu\text{m}$ decreased 28%. The OC reach also had a 28% increase in bed erosion. An increase in sediment loadings from the Gunn River reduced the amount of erosion within the POC reach by 88%, primarily due to bed deposition of coarse silt-sized material. Bed erosion within the OC reach dropped 69%, although there was a 39% increase in bed erosion of material $<10\ \mu\text{m}$ (the OC reach is primarily composed of coarse gravel and cobble-sized material). Hence, the uncertainty in the magnitude of sediment loadings from the Gunn River does have a minor impact in the study reach; however, there was only a single sediment concentration measurement from the Gunn River and this measurement plots on the rating curve derived for the station upstream of the Plainwell Dam. Evaluation of the three scenarios was therefore carried out with loadings based on Eq. (2).

The complex planform of the upper part of the POC reach is represented by a single channel with two withdrawal points. Although, this representation is fairly accurate for flow discharge, it is difficult to determine how much sediment is withdrawn with the water. Therefore, additional simulations were carried out for the DI (baseline) scenario in which the amount of sediment that is withdrawn was varied from 0% to 100% of the local carrying capacity of the flow. Minor differences in evolution and sediment loads were observed only for the larger withdrawal rates. Whereas, the lower part of the POC reach is slightly aggrading for the smaller and moderate withdrawal rates, it incises slightly for large withdrawal rates. The amount of sediment withdrawn has negligible impact on bank erosion. Sediment loads at the downstream boundary of the study reach reduce from an average of 11,500 T/y for small and moderate withdrawal rates to 7,000 T/y for large withdrawal rates. Evaluations of the three modeling scenarios were performed with a moderate withdrawal rate.

The largest input uncertainty concerns the critical shear stress of streambank material in the POC reach. The number of jet tests carried out along the main channel in this reach was limited because of access problems. The critical shear stress assigned to each cross section in the POC reach is an average of all measured values within the reach (1.3 Pa). The critical shear stress used in the POC reach was varied as 1.0, 1.3, and 2.6 Pa in each of the three modeling scenarios. The following section on simulation outcomes will report the effects of bank-toe critical shear stress on the evolution of the study reach and sediment loads.

RESULTS AND DISCUSSION

Dams In-Baseline

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 US Highway 131 bridge and the Plainwell Dam. The main branch of the POC reach is slightly erosional, whereas the OC reach is mainly a transport reach (Figure 4a). Results show that over the entire study reach there is a net annual

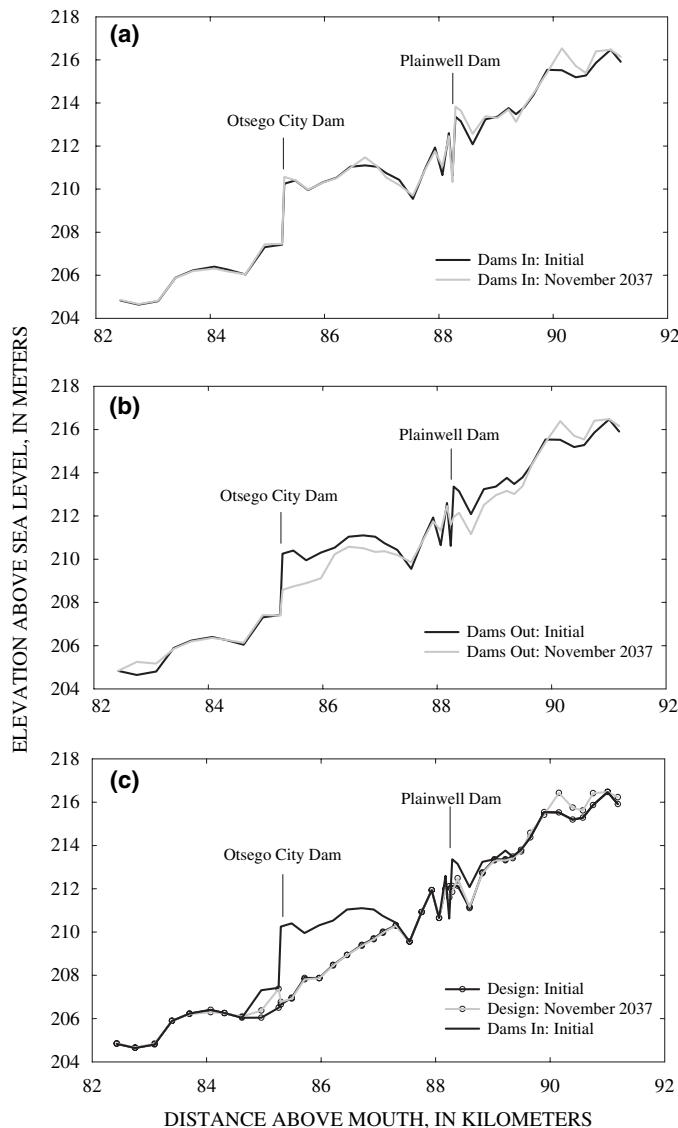


FIGURE 4. Initial and Final Thalweg Profiles for the (a) Dams In, (b) Dams Out, and (c) Design Scenarios.

deposition of material (4,100 T/y). However, silts and clays are eroded primarily from the bed at an average-annual rate of 1,990 T/y. Table 1 summarizes the mass of material eroded (negative) or deposited (positive) along the channel boundary for each reach. Results shown in Table 1 are broken down by location (bed or banks) and by general particle-size class. The finer fractions (<63 and $<10 \mu\text{m}$) are of particular interest, as PCBs tend to be absorbed on these fine materials. The last row "Total" represents the average-annual sediment load transported past OC8 in T/y (Figure 5a).

The deposition immediately upstream of U.S. Highway 131 (rkm 89.9) is unrealistic. The higher roughness assigned to the bridge crossing reduces the stream power available to transport the sediment. Similar deposition occurred for the DO and D modeling scenarios.

Simulated annual loads of total sediment at the downstream boundary of the study reach (OC8) are shown in Figure 5a. As one might expect, years with high runoff correspond to years with high annual sediment loads. Years of peak sediment for peak-flow years after 2001 do not show the great increases from low and moderate flow years as occurred in 2001. This is probably due to a simulated 2001 flushing of fine-grained sediment stored in the reach. For the DI case, the simulated average-annual sediment load (suspended and bed load) at the downstream boundary of the study reach (OC8) was 10,500 T/y with almost 98% of this material (10,300 T/y) finer than $63 \mu\text{m}$.

Dams Out

The DO scenario was simulated using existing channel morphologies except for the removal of the non-erodible sections representing the Plainwell and Otsego City Dams. 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 6,400 T/y for the baseline (DI) scenario turned to erosion of 289 T/y for the DO scenario. Net bed erosion in the POC reach increased 1346% to 6,580 T/y for the DO scenario compared with the DI scenario (455 T/y) (Table 2). Bank erosion also increased greatly (1,645%) in the POC reach from about 157–2,740 T/y 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. The OC reach is erosional providing

TABLE 1. Mass of Sediment Eroded (–) or Deposited (+) in T/y for the Dams in Modeling Scenario.

Reach	Total			Total	Bank		Total	Bed	
	<63 μm	<10 μm			<63 μm	<10 μm		<63 μm	<10 μm
P	6,410	684	–341	0	0	0	6,400	682	–341
POC	–587	–669	–286	–157	–87.7	–60.1	–455	–605	–226
OC	–1,720	–2,000	–631	–0.05	–0.03	0	–1,730	–2,010	–631
Total	4,100	–1,990	–1,260	–157	–87.7	–60.1	4,220	–1,930	–1,200

Note: P = Plainwell, OC = Otsego, POC = Plainwell-Otsego.

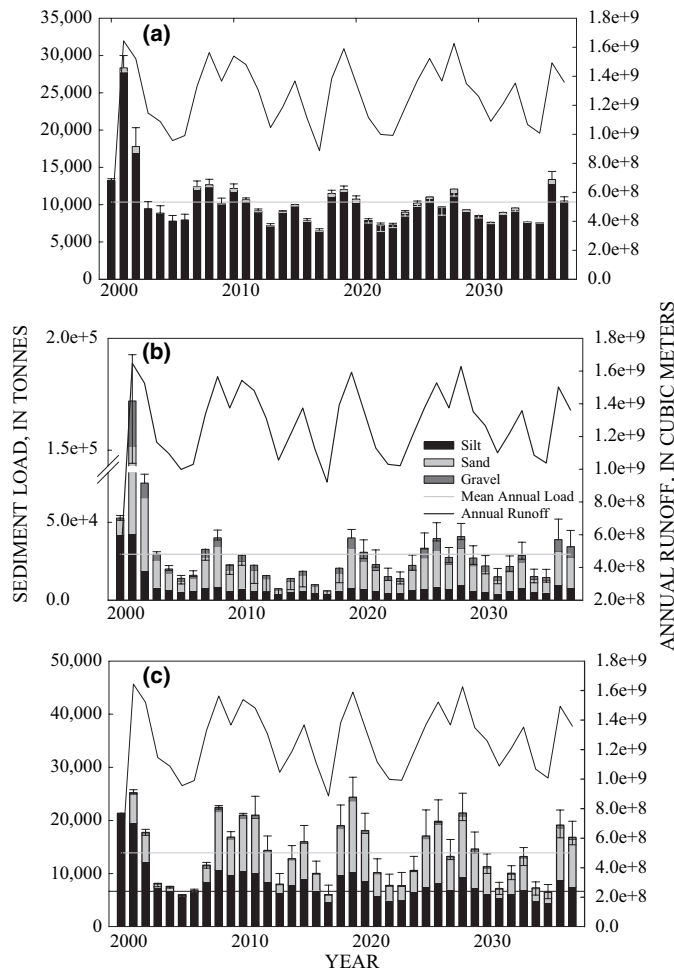


FIGURE 5. Sediment Loadings at the Outlet of the Study Reach for the (a) Dams In, (b) Dams Out, and (c) Design Scenarios. Note ordinate scale differences.

9,390 T/y to the total sediment load of the study reach.

Simulated average-annual sediment load for the DO case was 30,100 T/y, 187% greater than the DI/baseline case (Figure 5b). The mass of fine-grained materials (finer than 63 μm) transported annually beyond the downstream boundary at OC8 is 8,860 T/y. This is a 14% decrease in the amount transported under the baseline (DI) condition.

Removal of fine-grained sediment has coarsened the bed, thereby greatly reducing fine-grained sediment transport in later years. Table 2 provides details regarding the mass of sediment eroded and deposited during the DO scenario for each of the simulated sub-reaches.

The evolution of the lower part of the POC reach agrees well with the conceptual model (CM) of Doyle *et al.* (2003). Figure 6 shows that the central portion of the bed of cross-section G1 incises, concentrating flow in a narrow channel with steep banks, which corresponds to stage C of the CM. The ensuing channel widening is a combination of fluvial entrainment of bank-toe material and bank mass-wasting (stage D of the CM). Channel widening is halted when the more resistant, parent bank material becomes exposed. Channel width adjustment is rapid, almost 100 m in 6 months. Further upstream, the lowering of the water surface elevation does not concentrate flow and the bed incises over its entire width (Figure 6, cross-section G5). Figure 6 shows that heightening and toe erosion leads to retreat of the left bank of cross-section G5. Bank erosion is significantly reduced after about 15 m of bank retreat.

Design Channel

The USGS designed a channel to minimize erosion of PCB-laden channel sediments after the removal of the Plainwell and Otsego City Dams (Rachol *et al.*, 2005). Figure 4c shows the differences between the current thalweg profile and that of the design channel. Multi-thread sections designed for the POC reach were handled identically to those sections in the DI and DO modeling scenarios. That is flow and sediment are withdrawn at sections POC6 and G9 and returned to the channel at sections POC16 and G6 (Figure 1). Streambeds of excavated cross sections were assigned material composition and properties found at the level of excavation (Rheume *et al.*, 2002, 2004).

Simulation shows the POC and OC reaches are fairly stable because of the coarse-grained bed material.

TABLE 2. Mass of Sediment Eroded or Deposited (T/y) for the Dams Out Modeling Scenario.

Reach	Total			Bank			Bed		
	Total	<63 μm	<10 μm	Total	<63 μm	<10 μm	Total	<63 μm	<10 μm
P	-512	1,410	-340	-232	-98.1	-51.7	-289	1,510	-287
POC	-9,320	-627	-986	-2,740	-1,180	-817	-6,580	547	-170
OC	-9,390	-637	-30	-22.6	-5.13	-3.29	-9,380	-638	-27.1
Total	-19,200	148	-1,360	-3,000	-1,280	-872	-16,200	1,420	-485

Note: P = Plainwell, OC = Otsego, POC = Plainwell-Otsego.

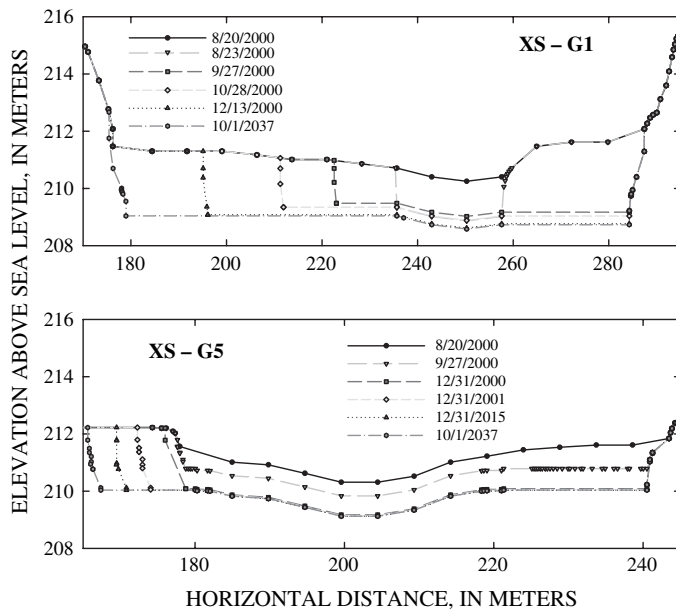


FIGURE 6. Simulated Changes in Geometry of Cross-Section G1 (top, rkm 85.4) and Cross-Section G5 (bottom, rkm 86.0).

Channel deposition (2,570 T/y) simulated under this scenario is 37% lower than the DI scenario (4,100 T/y) (Table 3). The simulated average-annual total sediment load passing OC8 for the D Case was 14,200 T/y, 35% larger than the DI scenario (Figure 5c). This is not surprising given that both the DO and D scenarios include the removal of the dams. On average, however, fine-grained sediment loads at the downstream boundary (8,410 T/y) are 18% smaller

than fine-grained sediment loads for the DI scenario (Figure 7).

Sensitivity to Critical Shear Stress of Bank-Toe Material

The above results were obtained using the measured values of bank and bed material properties. However, the number of measurements used to quantify the erodibility of bank-toe material within the POC reach was limited. The rate of streambank erosion can be significantly affected by the erodibility of the bank-toe material. Therefore, for each scenario two additional simulations were carried out to determine the effect of the critical shear stress of bank-toe material on the evolution of the study reach and sediment loads. Critical shear stress values for bank materials within the POC reach were reduced by 25% (1.0 Pa) and increased by 200% (2.6 Pa). These limiting values of critical shear stress represent the range of measured values within the POC reach.

For all three scenarios, varying critical shear stress of bank-toe material greatly affected the amount of sediments eroded from the streambanks within the POC reach. It had a small effect on the amount of material deposited on or eroded from the streambed. Increasing the critical shear stress reduced the amount of bank erosion, whereas reducing critical shear stress increased the amount of bank erosion. This was especially noticeable for the DI and D scenarios where in the simulations discussed above streambank erosion was limited to only

TABLE 3. Mass of Sediment Eroded or Deposited (T/y) for the Design Modeling Scenario.

Reach	Total			Bank			Bed		
	Total	<63 μm	<10 μm	Total	<63 μm	<10 μm	Total	<63 μm	<10 μm
P	4,580	349	-519	-112	-51.7	-37	4,680	397	-482
POC	-448	1,340	-40.2	-273	-59.8	-36.7	-176	1,400	-3.59
OC	-1,570	-199	-139	0	0	0	-1,570	-201	-139
Total	2,570	1,490	-698	-385	-111	-73.7	2,940	1,600	-624

Note: P = Plainwell, OC = Otsego, POC = Plainwell-Otsego.

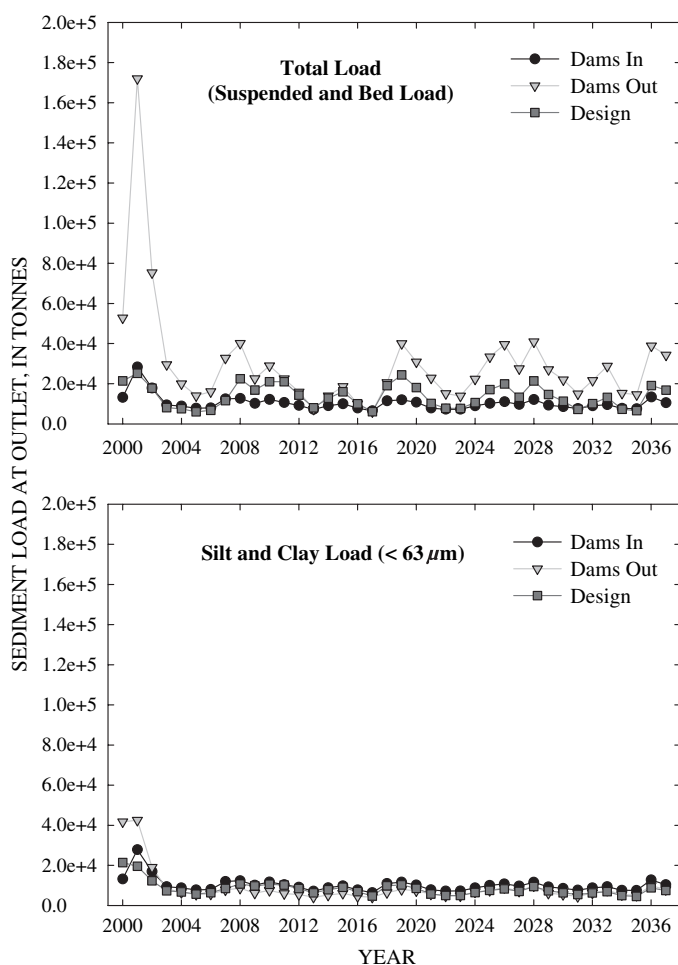


FIGURE 7. Sediment Loads Broken Out by Size Class at the Downstream Boundary (OC8) for the Three Modeling Scenarios.

a few sections. Increasing critical shear stress reduced bank erosion by 98%. Reducing critical shear stress led to an 800% increase in bank erosion in case of the DI scenario and a 250% increase in case of the D scenario. Increased streambank erosion is limited to the upper portion of the POC reach where more cross sections are experiencing streambank erosion. Because bank erosion is already significant in case of the DO scenario, the relative impact of varying critical shear stress is smaller than that for the DI and D scenarios. Increasing critical shear stress reduces bank erosion by 75%, decreasing critical shear stress increases bank erosion by 80%. However, the doubling of the critical shear stress yielded a much narrower channel upstream of the location of the former Otsego City Dam (between cross-sections G1 and G2).

The impact of varying bank-toe erodibility in the POC reach on the amount of material eroded from the streambed in the POC reach is small for the DI and D scenarios, especially for fine-grained particles (<5%). The impact of critical shear stress was greatest

for the DO scenario. For the DO scenario, banks in the POC reach were the main source of fine-grained sediments for critical shear stresses of 1.0 and 1.3 Pa; however, the streambed was the main source of fine-grained sediment for a critical shear stress of 2.6 Pa. For each scenario differences in simulated thalweg profiles for the three values of critical shear stress were negligible.

Error bars in Figure 5 denote the range in simulated annual loads at the outlet of the study reach for the increased and reduced critical shear stresses of bank-toe material in the POC reach. The average annual sediment load varies between 10,200 and 10,600 T/y for the DI scenario, 26,800 and 34,200 T/y for the DO scenario, and 12,300 and 14,200 T/y for the D scenario.

To summarize the impact of erodibility of bank-toe material in the POC reach on the evolution of the study reach is: (1) the number of cross sections experiencing bank erosion in the upper part of the POC reach and (2) the equilibrium width of the channel upstream of the Otsego City Dam for the DO scenario. This sensitivity analysis shows that the uncertainty in the measured critical shear stress within the POC reach is important, and affects the amount of fine-grained material stored between the Otsego City and Plainwell Dams that will be eroded when the dams are removed. The comparison of modeling scenarios, hereafter, will be based on the results from modeling runs using the observed, aggregated values of critical shear stress.

Comparison of the Three Modeling Scenarios: General

Over the simulation period, the DI/baseline scenario provides the smallest load passing the outlet (Figure 8). 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 (Figure 5b).

Comparison of the final thalweg profiles (Figure 8) shows significant differences in downcutting between the DI/baseline scenario and the DO modeling scenario. Responses in the P and OC reaches are almost identical for the DO and D scenarios.

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 streambank erosion upstream of the former dam locations, significantly increasing sediment load. However, most of these sediments are eroded in the first 3 years (Table 4). 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.

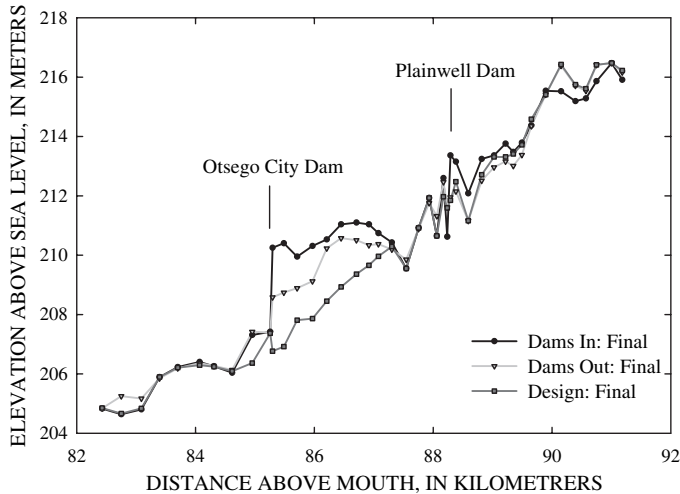


FIGURE 8. Final Thalweg Profiles for the Three Modeling Scenarios.

TABLE 4. Average Annual Sediment Load at the Downstream Boundary of the Modeling Reach.

Scenario	Sediment Load in T/y		
	<63 μm	<2 mm	Total
DI	10,300	10,500	10,500
DO	8,900	25,900	30,100
DO (year 1-3)	34,400	89,700	100,000
DO (year 4-38)	6,500	20,000	23,500
D	8,400	13,900	14,200

Note: DI = Dams In, DO = Dams Out, D = Design.

SUMMARY AND CONCLUSIONS

Three numerical simulations were carried out over a 37.3-year period of record to evaluate the response of the Kalamazoo River between Plainwell (rkm 91.2) and Otsego (rkm 82.4), Michigan to current channel conditions (DI), instantaneous removal of two low-head dams (DO), and a design channel without the low-head dams (D). A field data collection campaign was conducted to determine the resistance of the boundary sediments to erosion. The measured values were used “as-is” in the model simulations. Boundary roughness was calibrated through agreement of measured and simulated water-surface elevations.

Total change in boundary sediments for the DI case show net deposition of 4,100 T/y in the study reach (primarily due to deposition above US HWY 131 bridge). The Plainwell reach contributed 6,410 T/y (deposition), the POC reach contributed 587 T/y (erosion), and the OC reach contributed 1,720 T/y (erosion). The average-annual sediment load (suspended and bed load) at the downstream boundary is 10,500 T/y. Total change in boundary sediments for the DO case show a net erosion of 19,200 T/y at the downstream boundary. The Plainwell reach contributed 512 T/y (erosion), the POC reach contributed 9,320 T/y (erosion), and the OC reach contributed 9,390 T/y (erosion). The average-annual sediment load (suspended and bed load) at the downstream boundary is 30,000 T/y. Total change in boundary sediments for the D case show a net deposition of 2,570 T/y at the downstream boundary. The Plainwell reach contributed 4,580 T/y (deposition), the POC reach contributed 448 T/y (erosion), and the OC reach contributed 1,570 T/y (erosion). The average-annual sediment load (suspended and bed load) at the downstream boundary is 14,200 T/y.

Fine-grained erosion (sediment particle diameters <63 μm , clay and silt and <10 μm , clay and very fine silt) shows a similar pattern of deposition in comparing the different modeling scenarios: DI case, contributing 1,990 (<63 μm) and 1,260 (<10 μm) T/y; DO case, contributing deposition of 148 T/y (<63 μm) and erosion of 1,360 T/y (<10 μm); and D case, contributing deposition of 1,490 T/y (<63 μm) and erosion of 698 T/y (<10 μm). For the DI case, the banks contributed 157 T/y with 56% of the total in the 63 μm class and 38% of the total in the 10 μm class. For the DO case, the banks contributed 3,000 T/y with 43% of the total in the 63 μm class and 29% of the total in the 10 μm class. For the D case, the banks contributed 385 T/y with 29% of the total in the 63 μm class and 19% of the total in the 10 μm class.

Bank erosion and bed erosion increased with the DO case. Bed erosion in the Plainwell reach increased from 6,400 T/y deposition to 289 T/y erosion. Bank erosion in the Plainwell reach increased from 0 T/y (DI) to 232 T/y due to greater hydraulic shear stresses on the bank toe caused by initial steepening of the channel. For the DO case, the average-annual sediment load increased 187%. For the D case, the average-annual sediment load increased 35% compared with the DI case but still 112% smaller than the DO case. The relative contribution of fines to total load was larger for the DI case compared with the DO and D case, and the relative contribution of fines to total load in the D case was similar to the DO case.

The DI (baseline) case clearly provides the smallest loads for total sediment transport. However, 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.

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