NUMERICAL SIMULATION OF CHANNEL ADJUSTMENT OF THE KALAMAZOO RIVER FOLLOWING THE REMOVAL OF TWO LOW-HEAD DAMS BETWEEN OTSEGO AND PLAINWELL, MICHIGAN

Eddy J. Langendoen, Research Hydraulic Engineer, USDA-ARS-NSL, Oxford, MS, elangendoen@msa-oxford.ars.usda.gov; Robert R. Wells, Research Hydrologist, USDA-ARS-NSL, Oxford, MS, rrwells@msa-oxford.ars.usda.gov

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 to the study reach and downstream reaches. The study was designed to evaluate the erosion, transport, and deposition of sediments over a 38-year period using the channel evolution model CONCEPTS for three simulation scenarios: Dams In, Dams Out, and Design. The total mass of sediment emanating from the channel boundary for the Dams In case shows net deposition of 8,760 T/y for the study reach, with net transport (suspended and bed load) of 10,500 T/y passing the downstream boundary. For the Dams Out case, there is net erosion of 9,180 T/y with net transport of 30,100 T/y passing the downstream boundary. For the Design case, net deposition was 9,070 T/y with transport of 14,200 T/y passing the downstream boundary. The most significant finding is that removal of the low-head dams will cause significant erosion of PCB-contaminated bed and bank material upstream of the dams.

INTRODUCTION

Between the mid 1800s and the early 1900s, four dams were constructed on the Kalamazoo River between Plainwell and Allegan, Michigan (see Fig. 1). 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 still remains in operation, was originally built to create freight business on the river but has since been providing a continuous industrial water supply for a papermill built in the 1880s. The impoundments have been the depositories of upstream sediment and industrial waste materials. Between 1957 and 1971, Kalamazoo area paper mills recycled carbonless copy paper containing polychlorinated biphenyls (PCBs) as ink solvent and incorporated these PCBs in their waste discharge. The paper wastes also included kaolinite clays, which were found in the impoundment sediments to contain concentrations of PCBs as high as 94 mg per kg (Blasland, Bouck & Lee 1994). 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 (Rheaume et al. 2002; 2004).

The state of Michigan is interested in removing the dams while minimizing impacts to the study reach and 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.

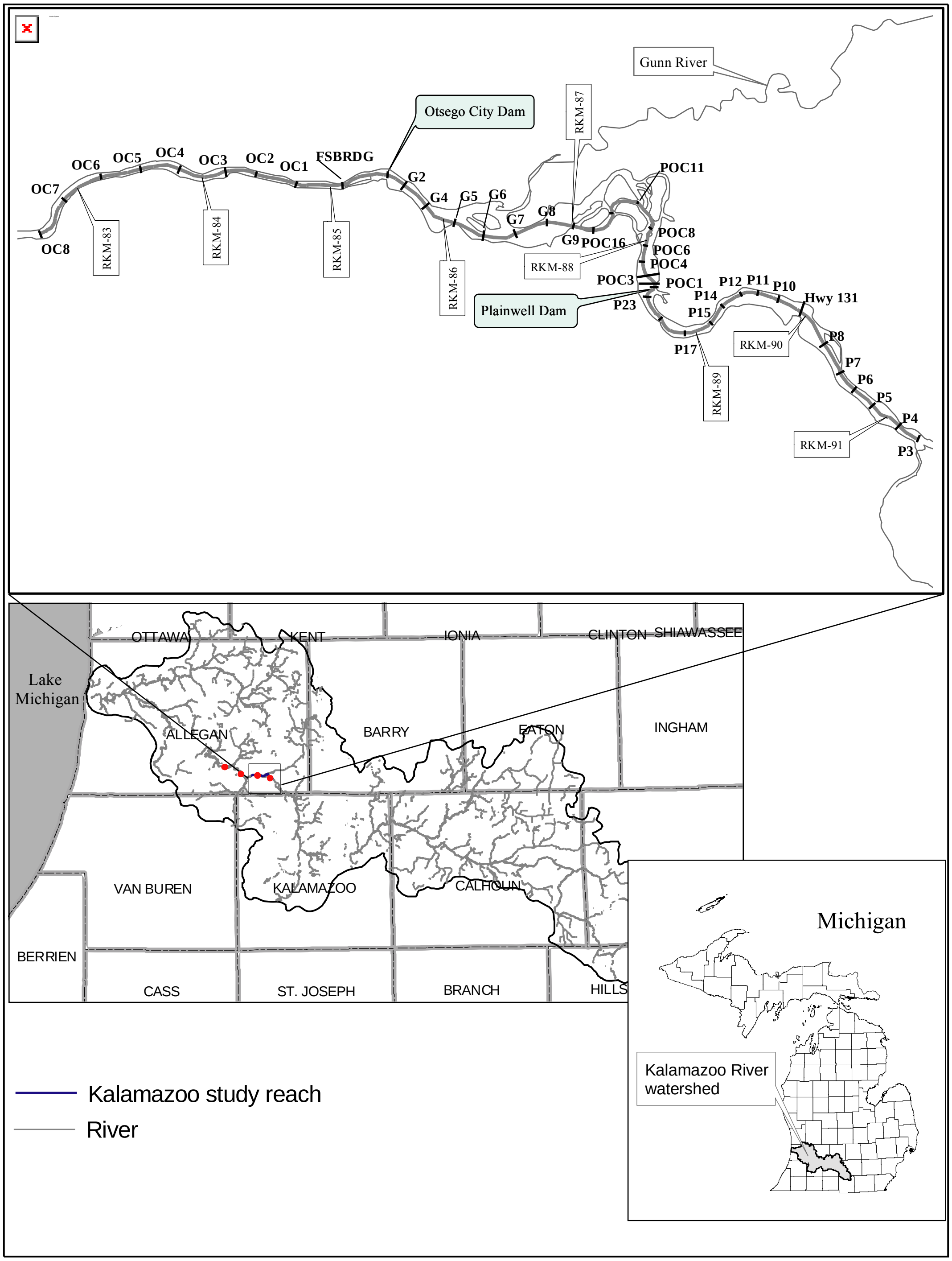

Figure 1 Map of study reach showing modeled cross sections and locations of the Plainwell and Otsego City Dams.

MODELING APPROACH

The PCBs between Plainwell and Otsego are mainly adsorbed onto fine-grained sediments comprising parts of the streambed, and most of the banks and floodplains. Prediction of the erosion, transport and deposition of these materials after dam removal requires a model that can simulate streambank erosion processes 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 for a 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 successfully used in similar morphological studies of incised stream systems (Bingner and Langendoen 1997; Langendoen et al. 2000; Langendoen et al. 2002; Simon et al. 2002).

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 a combination of flow-induced basal scour and mass wasting (slab or planar and 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.

To estimate volumes and rates of sediment transport within the study reach and to address specific objectives of the study, three modeling scenarios were identified, one representing current channel conditions and two others representing alternative schemes. The three scenarios are termed: (1) “Dams In” (DI) or baseline, (2) “Dams Out” (DO), and (3) “Design” (D). 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 to 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-erodable structures. Finally, the Design scenario also assumes that the two dams are no longer in place; however, a design channel geometry is used instead of the current channel geometry for initial conditions.

STUDY AREA

The modeling reach of the Kalamazoo River extends 8.8 km from approximately 82.4 km above the confluence with Lake Michigan (cross-section OC8), to cross-section P3, approximately 91.2 km above the confluence with Lake Michigan (Fig. 1). The study area 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 km 82.4 to the Otsego City Dam at km 85.3. The Plainwell-Otsego (POC) reach extends from the upstream end of the Otsego City Dam to the Plainwell Dam at km 88.3. The Plainwell (P) reach extends from the Plainwell Dam to the upstream boundary of the study reach at km 91.2.

Flows for all three simulation scenarios are based on a modified 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 discharge record was used to construct a time series of flow covering the simulation period from August 2000 through November 2037. The start of the simulation period coincides with dates the modeling reach was surveyed.

The Kalamazoo River is anastomosing along the upper half of the POC reach. CONCEPTS simulates flow in a single-thread channel. Velocity measurements by Rheaume et al. (2004) show the existence of a main thread carrying about 75 to 90% of the flow. The anastomosing segment is therefore simulated as a single thread, withdrawing: (1) 30% of the flow at section POC6 and returning it at section POC16; and (2) 20% of the flow at section G9 and returning it at section G6 (Fig. 1). The water is returned to the channel, whereas the sediment is deposited. This is supported by the study of Rheaume et al. (2004), which shows that the side channels are filling in.

Bed- and bank-material composition and geotechnical properties at each cross section were provided by testing and sampling conducted by the ARS, laboratory analysis by the USGS, and from historical data. Wells et al. (2004) tabulate the bank- and bed-material properties used in the simulations.

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 was carried out to match observed water surface elevations along the modeling reach. In general, roughness values for the channel bed and banks ranged from 0.025 to 0.04; for the floodplain, values ranged from 0.05 to 0.1.

RESULTS AND DISCUSSION

Dams In Scenario: The DI modeling scenario represents a baseline condition with existing channel geometries (including the low-head dams) and boundary characteristics. Within the P reach, deposition upstream of the HWY 131 bridge crossing (rkm 90) is predicted. This deposition is predicted for all three scenarios; however, it is not supported by observations. As a result, simulated sediment loads at the downstream end of the P reach may be underpredicted. Fig. 2 further shows progressing simulated deposition upstream of the Plainwell Dam (rkm 88-89), but minor channel changes along the POC and OC reaches. Table 1 summarizes the mass of material eroded from (positive) or deposited on (negative) the channel boundary for the three reaches. Results shown in Table 1 are broken down by location (bed or banks) and by general particle-size class. The finer fractions (<63 μm and <10 μm) onto which the PCBs may be adsorbed are of particular interest. The simulated average-annual sediment load (suspended and bed load) at the downstream boundary of the study reach (OC8) is 10,500 T/y with 98% of this material (10,300 T/y) finer than 63 μm.

Dams Out Scenario: The Dams Out scenario has been evaluated using existing channel morphologies except for the removal of the non-erodable sections representing the Plainwell and Otsego City Dams. During the simulation, large-scale erosion of the channel bed in the

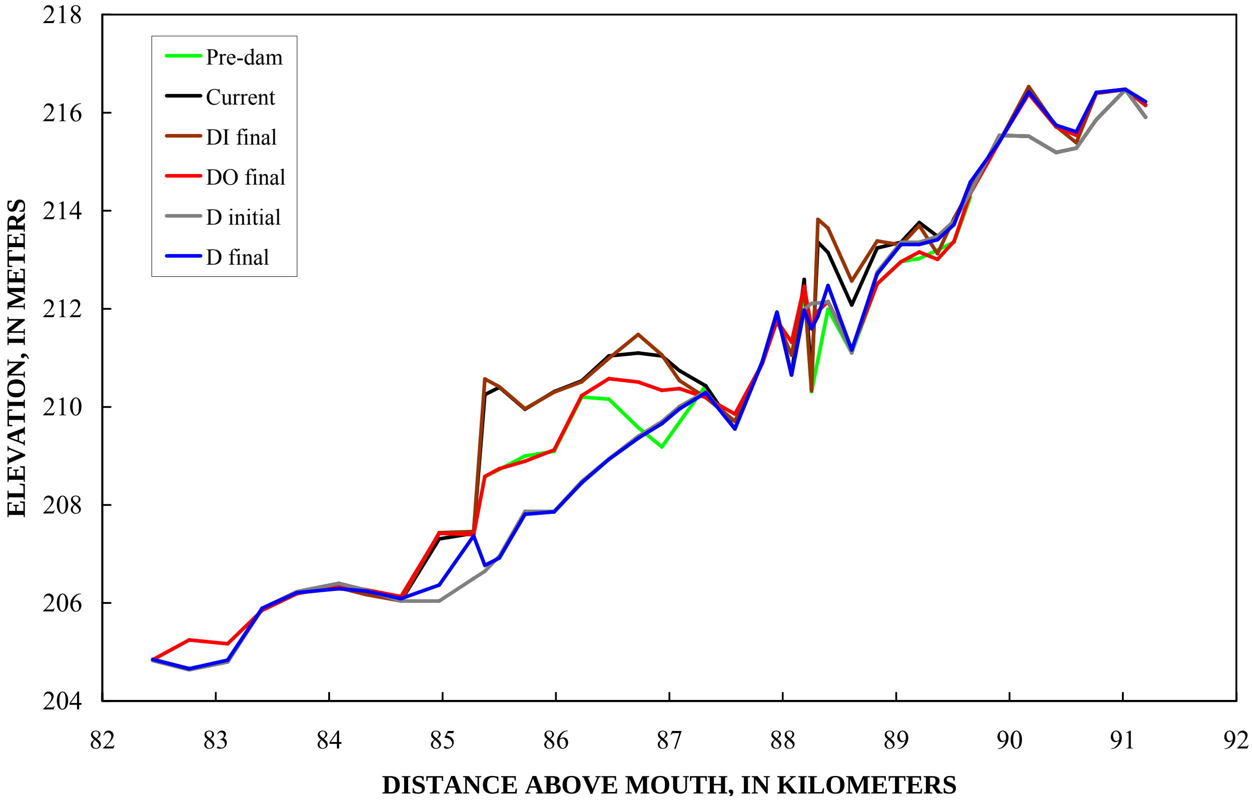

Figure 2 Initial and final thalweg profiles for the Dams In (DI), Dams Out (DO), and Design (D) modeling scenarios.

Table 1 Mass of sediment eroded (+) or deposited (-) in T/y for the Dams In modeling scenario.

	Total			Bank			Bed		
Reach	Total	<63 µm	<10 µm	Total	<63 µm	<10 µm	Total	<63 µm	<10 µm
P	(6,410)	(684)	341	0	0	0	(6,400)	(682)	341
POC	(4,070)	(2,910)	(311)	157	87.6	60.0	455	605	226
OC	1,720	2,000	631	0.061	0.014	0.009	1,730	2,000	631
Total	(8,760)	(1,590)	661	157	87.6	60.0	(4,220)	1,930	1,200

Plainwell and POC sub-reaches occurred as knickpoints migrated headward through these sub-reaches as a direct result of simulated dam removal (Fig. 2). Fig. 3 shows that the channel upstream of the Otsego City Dam rapidly incises to the coarse pre-dam bed-material and widens ensuingly. Table 2 shows bank erosion increased from 157 T/y for the DI scenario to 3,000 T/y, with an increase in eroded bed material of 20,500 T/y. Simulated average-annual sediment load at the outlet for the Dams Out case is 30,100 T/y, three times greater than the baseline case. However, the mass of fine-grained materials (finer than 63 µm) transported beyond the downstream boundary reduced to 8,860 T/y, which is caused by a coarsening of the bed-material resulting in an increase of the fraction of sand in transport.

Design Channel Scenario: The USGS designed a channel to minimize the scour of PCB-laden channel sediments after the removal of the Plainwell and Otsego City Dams. Fig. 2 shows that

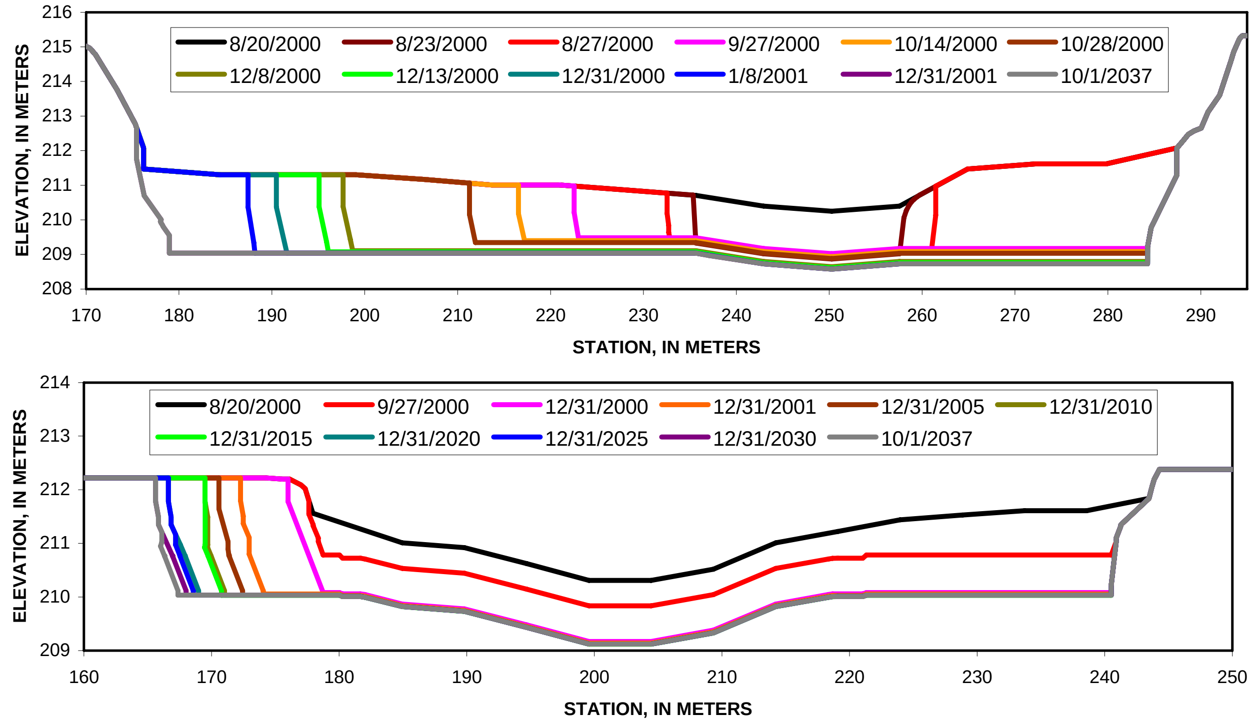

Figure 3 Simulated changes in geometry of cross section G1 (top, rkm 85.4) and cross section G5 (bottom, rkm 86.0)

Table 2 Mass of sediment eroded (+) or deposited (-) in T/y for the Dams Out modeling scenario.

	Total			Bank			Bed		
Reach	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)	288
POC	(719)	(3,950)	470	2,743	1,180	817	6,580	(547)	170
OC	9,390	637	30.1	22.6	5.13	3.29	9,380	638	27.1
Total	9,180	(4,720)	839	3,000	1,280	872	16,200	(1,420)	485

the thalweg profile of the design channel matches the pre-dam profile, except upstream of the Otsego City Dam where the design streambed is located within the pre-dam bed material. Multi-thread sections designed for the POC reach are handled identically to those sections in the DI and DO modeling scenarios. Streambeds of excavated cross sections are assigned material composition and properties found at the level of excavation.

Minor changes in streambed elevation are simulated (Fig. 2). Table 3 shows that the amount of bed and bank-material eroded along the modeling reach is similar to that of the DI scenario. The simulated average-annual total sediment load at the outlet (14,200 T/y) is slightly larger than that of the DI scenario. Similar to the DO scenario, fine-grained sediment loads at the downstream boundary (8,410 T/y) are slightly smaller than for the DI scenario.

Table 3 Mass of sediment eroded (+) or deposited (-) in T/y for the Design modeling scenario.

	Total			Bank			Bed		
Reach	Total	<63 μm	<10 μm	Total	<63 μm	<10 μm	Total	<63 μm	<10 μm
P	(4,580)	(349)	519	112	51.7	37.0	(4,680)	(397)	482
POC	(6,060)	(5,530)	(241)	272	59.6	36.6	176	(1,400)	3.58
OC	1,560	199	139	0	0	0	1,570	200	139
Total	(9,070)	(5,680)	417	385	111	73.5	(2,940)	(1,600)	624

Table 4 Average annual sediment load at the downstream boundary of the modeling reach.

	Sediment load in kilotonnes/year		
Scenario	< 63 μm	< 2 mm	Total
DI	10.4	10.5	10.5
DO	8.9	25.9	30.1
DO (year 1-3)	43.7	114.0	127.0
DO (year 4-38)	6.5	20.0	23.6
D	8.4	13.9	14.2

SUMMARY AND CONCLUSIONS

Three numerical simulations are carried out over a 38-year period 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).

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 three 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 three years of the simulation.

If the dams have to be removed, mitigation measures should be considered to prevent PCB-contaminated sediment from being eroded. One mitigation measure is channel reconstruction based on the designed channel (D scenario). The designed channel appears to be stable. Some minor streambank erosion may occur between rkm 88.0 and 88.8 near the current location of the Plainwell Dam.

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