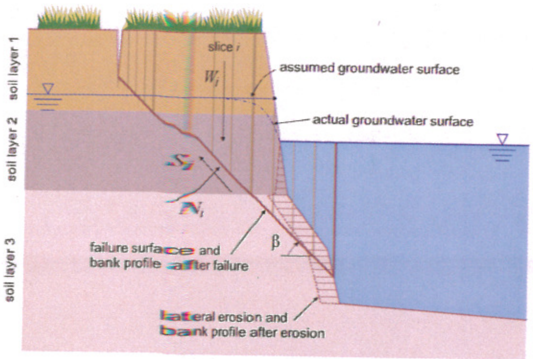
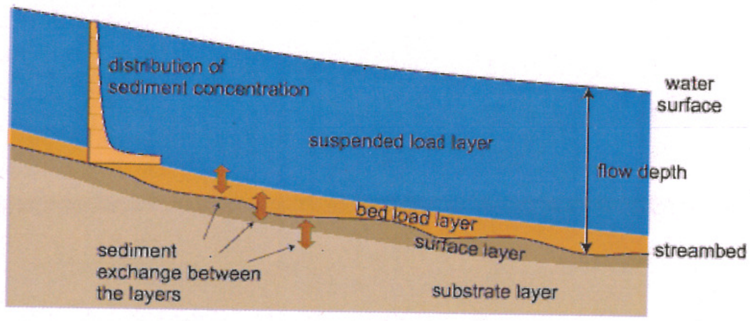
Numerical Simulation of Sediment Loads and Channel Changes along the Kalamazoo River between Plainwell and Otsego, Michigan





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EXECUTIVE SUMMARY

Concerns over the fate of PCB-laden channel sediments in the Kalamazoo River between Plainwell and Otsego, Michigan 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. The 8.8 km reach of the Kalamazoo River contains two low-head dams. The state of Michigan is interested in removing these dams while minimizing impacts to the study reach and downstream reaches, and to provide for improved fisheries. This study was designed to evaluate the erosion, transport, and deposition of sediments in the Kalamazoo River between Plainwell and Otsego, Michigan. Numerical modeling of channel-erosion processes over a 17.7-year period was conducted using CONCEPTS for three specific scenarios, Dams In or baseline, Dams Out, and Design. The USGS conducted channel surveys, collected and analyzed bed-sediment cores, and performed particle-size analysis for all channel material samples collected by the USDA-ARS. USDA-ARS conducted *in-situ* measurements on the erodability of channel materials. Flows for all three scenarios are based on a modified discharge record from the USGS gage on the Kalamazoo River at Comstock, Michigan (04106000).

The total change in the mass of sediment emanating from the channel boundary (17.7 year simulation), for the Dams In (baseline) case, shows net erosion of 3670 T/y for the study reach. The Plainwell reach contributed 9660 T/y (erosion), the Plainwell-Otsego reach was a net sink of 8480 T/y (deposition), and the Otsego reach contributed 2490 T/y (erosion). Passing the downstream boundary there is net transport of 5010 T/y (suspended and bed load). For the Dams Out case (17.7 year simulation), net erosion jumps to 41,600 T/y for the entire study reach with net transport (suspended and bed load) of 59,200 T/y passing the downstream boundary. This is primarily due to channel incision and headward migration of knickpoints, particularly in the Plainwell reach where erosion of about 29,600 T/y was simulated. The Plainwell-Otsego reach contributed 27,700 T/y (erosion). The Otsego reach became a sink for sediment (15,600 T/y) due to relatively flat channel gradients and the greatly heightened loads emanating from the eroding reaches upstream. The total mass of sediment derived from the channel boundary for the Design case (17.7 year simulation)showed net erosion of 3870 T/y. The Plainwell reach contributed 24,800 T/y (erosion), the Plainwell-Otsego reach contributed 4790 T/y (deposition), and the Otsego reach was again a sink for sediment eroded from upstream (16,100 T/y). Sediment loads passing (suspended and bed load) the downstream boundary were about one-third of the Dams Out case (20,100 T/y) but still 4 times greater than the Dams In baseline case.

Fine-grained erosion (sediment particle diameters <65μm, clay and silt, and <10μm, clay and very fine silt) shows a similar pattern as total erosion in comparing the different modeling scenarios(17.7 year simulation): Dams In case, contributing 3570 (<65μm) and 993 (<10μm) T/y; Dams Out case, contributing 5790 and 2220 T/y, respectively; and Design case, contributing 5100 and 1500 T/y, respectively. For the Dams In case, the banks contributed 42% of the total in the 65μm class and 99% of the total in the 10μm class. For the Dams Out case, the banks contributed 56% of the total in

the 65μm class and 98% of the total in the 10μm class. For the Design case, the banks contributed 40% of the total in the 65μm class and 95% of the total in the 10μm class.

The most significant findings of this research are that:

- Removal of the low-head dams will cause erosion in the study reach and sediment loads passing the downstream boundary to increase significantly,
- Bed erosion is the major source of eroded sediment, and
- The Plainwell reach is the greatest contributor of total sediment and fine-grained sediment.

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1.0 INTRODUCTION and PURPOSE of STUDY

Concerns over the fate of PCB-laden channel sediments in the Kalamazoo River between Plainwell and Otsego, Michigan 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. The 8.8 km reach of the Kalamazoo River contains two low-head dams. The state of Michigan is interested in removing these dams while minimizing impacts to the study reach and downstream reaches, and to provide for improved fisheries.

PCBs tend to be adsorbed on to the 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 channel-evolution model, developed by the USDA-ARS National Sedimentation Laboratory (Langendoen, 2000) 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. To evaluate the impacts of removing the Plainwell and Otsego City Dams on erosion in this 8.8 km reach of the Kalamazoo River, the CONCEPTS model was run for three different scenarios as outlined by the U.S. Geological Survey.

1.1 Modeling Scenarios

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. These 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 scenario simulates channel-adjustment processes such as headward-progressing streambed erosion resulting from their removal. 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 channel geometry designed by the U.S. Geological Survey is used instead of the current channel geometry for initial conditions.

1.1.1 Modeling Reach

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 (Figure 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 reach extends from the Plainwell Dam to the upstream boundary of the study reach at km 91.2.

CONCEPTS assumes gradually varying flow and therefore cannot simulate the rapidly varying flow on hydraulic structures. Plainwell and Otsego City Dams are represented as internal boundaries. At internal boundaries flow is calculated using a continuity and a dynamic equation (Langendoen, 2000). The continuity equation states that the discharges immediately upstream and downstream of the dam are equal. The dynamic equation relates discharge to water surface elevations immediately upstream and downstream of the dam. The flow on 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.

1.1.2 Flows Entering the Modeling Reach

Flows for all three modeling 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) (Figure 2). 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 (Figure 2). 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 that is similar in magnitude to the 1947 peak of record.

CONCEPTS uses 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 two years of mean-daily-flow data at a recently installed gage at Plainwell (04106906) 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-minute flow data for the two gages resulted in the following adjustment for the upstream boundary of the modeling reach:

$$Q_P = 1.87\,(Q_C)^{0.93897} \tag{1}$$

where Q_P is discharge at the Plainwell gage, in m^3/s, and
Q_C is the discharge at the Comstock gage 10 hours earlier, in m^3/s.

This regression was used to modify the discharge record at the Comstock gage for the modeling period. Sediment discharge at the upstream boundary was set to local transport capacity computed by CONCEPTS.

The Gunn River flows into the POC section of the study reach from the north between cross-sections G5 and G6 (Figure 1). There was no flow and sediment data for this tributary available; therefore, we estimated the flow from the Gunn River using a drainage area comparison. Using the flow record from the Kalamazoo River at Comstock (04106000) (Figure 2), the drainage area at Comstock (2740 km^2), and the drainage area at the mouth of the Gunn River (296 km^2), we created a 17.7-yr flow record for the Gunn River and used this record in all simulation scenarios. Given the respective drainage areas, the Gunn River discharge record was 17% of the Kalamazoo River at Comstock discharge record. Sediment transport capacity at the outlet of the Gunn River could not be computed because no data was available on reach geometry, or bed and bank materials for the Gunn River; hence, sediment discharge was set to zero. The timing of the flow was the same as the Plainwell (upstream boundary) record.

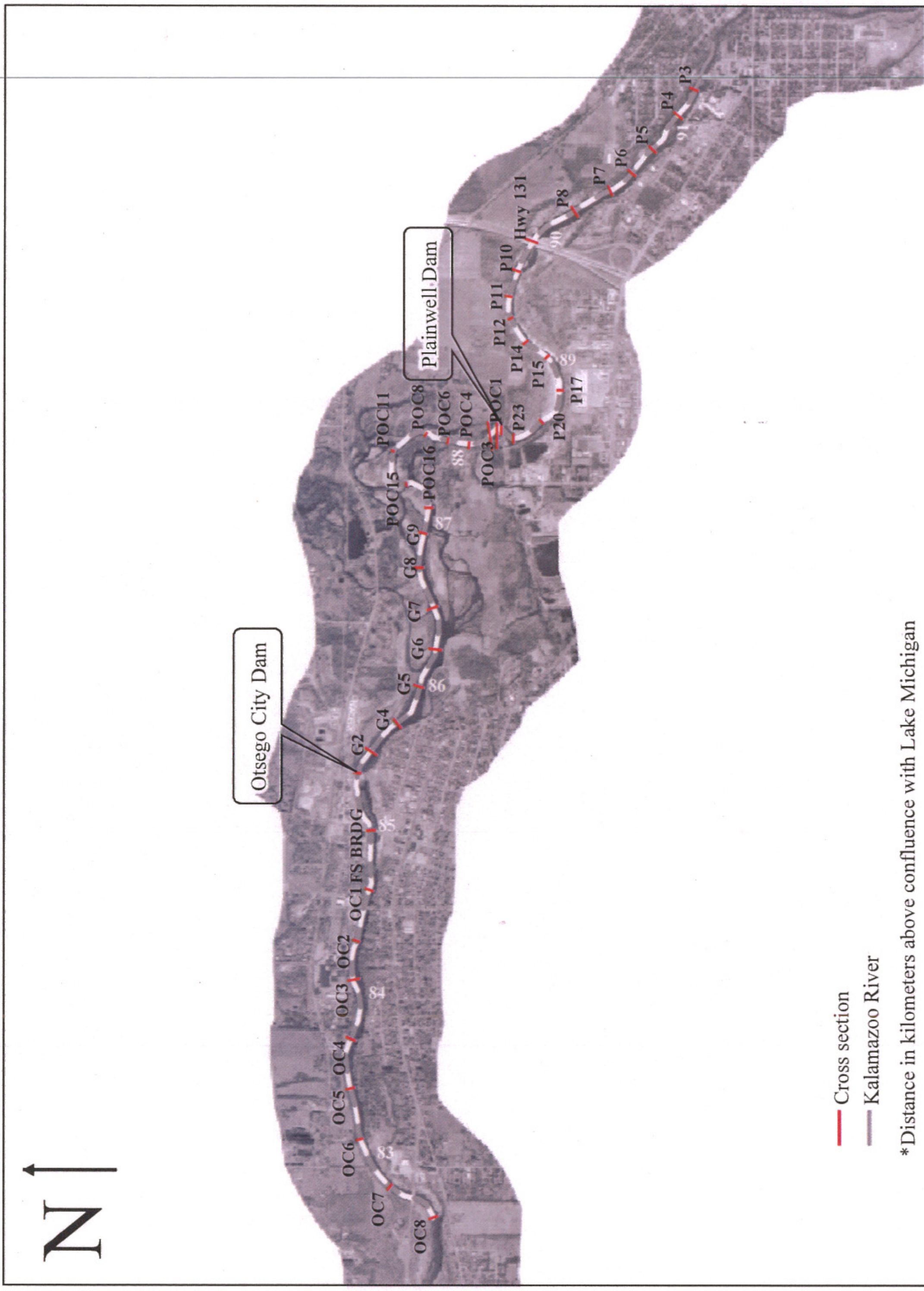

Figure 1 – Map of study reach showing modeled cross sections and locations of the Plainwell and Otsego City Dams.

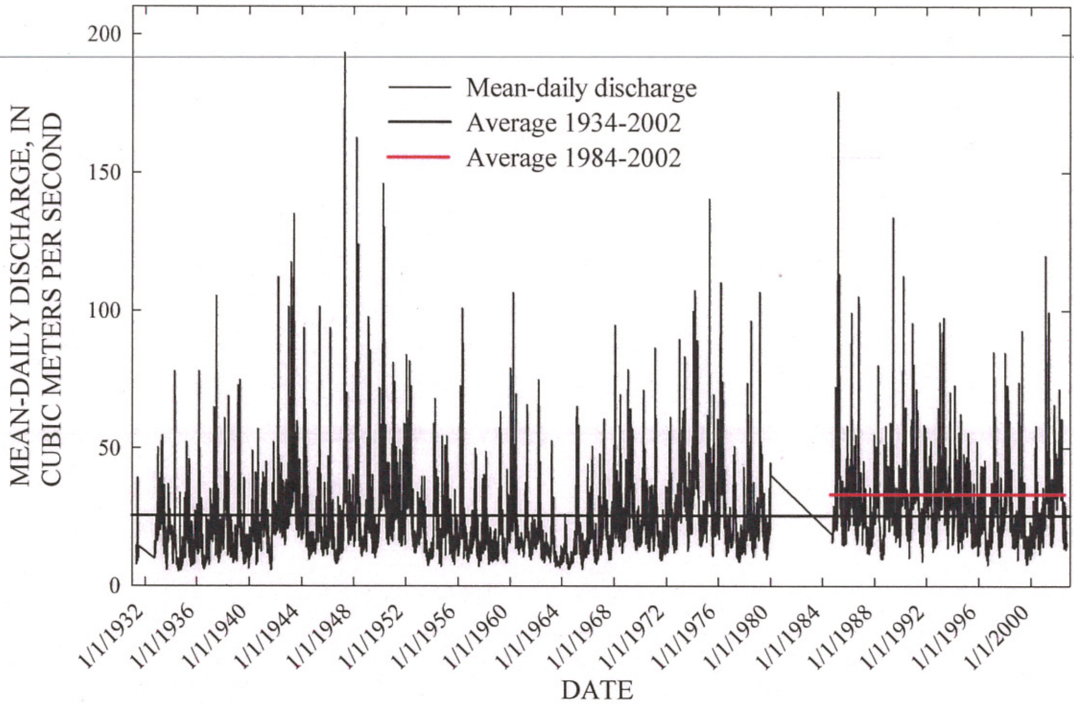

Figure 2 – Mean-daily discharge at Kalamazoo River at Comstock (04106000) showing mean for period of record and for modeling period.

1.1.3 Cross-Section Schematization

The modeling reach is composed of 52 cross sections and contains 2 low-head dams, Plainwell and Otsego City (Figure 1). A third dam, "Otsego", is about 3 km downstream of the downstream-most cross section. Although the third dam has an effect on the streambed and water-surface profiles upstream, the dam itself is beyond the scope of this study. Of the 52 cross sections used in the modeling reach, 20 were surveyed in the early to mid 1990's 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 stream corridor is schematized as reaches connecting cross sections. A reach is defined as a stream segment that transfers information between two adjacent cross sections. Each cross section is a node that holds unique hydraulic and channel-boundary information. Cross sections specify the boundary geometry, material properties, and characterize the flow-carrying capability of the stream and adjacent floodplain. Each cross section is associated with a river kilometer and stationing and elevation to describe the channel profile at any time step during simulation. Cross sections are comprised of left and right floodplains, banks, and the streambed. Each of these channel surfaces is associated with material properties and flow-resistance characteristics.

2.0 PHYSICAL PROPERTIES of the CHANNEL BOUNDARY

Physical properties of each cross section are defined in terms of those variables that describe the forces and resistance acting on each surface of that cross section. 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.

2.1 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; Lutenegger 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 (Figure 3). 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; and
5. Tests can be carried out at various depths in the bank to locate weak strata (Thorne *et al.* 1981).

BST results for the Kalamazoo River are shown in Table 1. The test location is given in columns 1-4, a description of the material is given in column 5, (where USCS is the Universal Soil Classification System), and physical properties of the material are given in columns 6-9. An asterisk next to a value denotes that the value was estimated.

Samples of a known volume were obtained at each BST testing location/depth to provide data on bulk unit weight, moisture content, and saturated density. Samples were analyzed by the USGS. Results from several batches of samples were deemed unreliable because of exceedingly low reported gross weights and bulk unit weights. In these cases, default values for given material types were used.

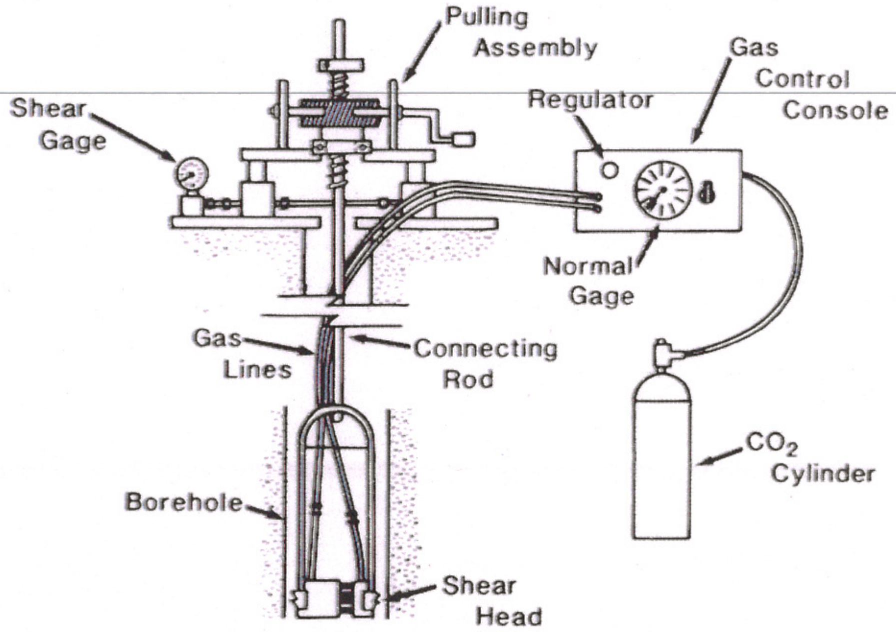

Figure 3 - Schematic representation of borehole shear tester (BST) used to determine cohesive and frictional strengths of *in situ* streambank materials. Modified from Thorne *et al.*, 1981.

Table 1. Borehole shear tests (BST) conducted at sites along the Kalamazoo River.

Location of Test		**Bank Layer Properties**						
Cross Section Label	**Bank**	**Layer from top bank**	**Depth of layer from top (m)**	**USCS**	**c_a (kPa)**	**c' (kPa)**	**ϕ' °**	**γ_{sat}, kN/m^3**
P3	R	1	0-5.0	SP-GP	5.0	0.0	24.2	16.0
P3	R	2	5.1-6.6	ML	4.6	4.3	21.9	10.6
P4	R	1	0-4.7	SP-GP	5.0	0.0	24.2	13.1
P4	R	2	4.8-6.0	ML	11.0	10.6	15.9	10.6
P6	L	1	0-1.53	ML-SP	2.2	0.8	40.6	9.1
P6	L	2	1.54-4.6	SP-CL	3.9	1.4	27.9	16.0
P8	R	1	0 - 5.5	SP-GP	1.9	0.0	25.7	15.6
P8	R	2	5.5-7.0	ML-CL	9.8	8.2	21.2	18.0
Trans11	R	1	0-3.0	SP-GP	1.9	0.0	25.7	18.0
Trans11	R	2	3.1-5.1	ML-CL	9.8	8.2	21.2	12.7
P10	R	1	0-5.6	SP-GP	2.7	0.0	27.5	16.4
P10	R	2	5.61-8.6	ML-CL	4.9	4.0	23.8	10.1
P11	R	1	0-5.2	SP-GP	6.2	2.1	23.2	16.7
P11	R	2	4.51-8.5	ML-SP	6.1	4.0	18.7	11.3
P13	R	1	0-3.7	ML-SP-GP	3.7	1.9	23.5	15.0
P16	L	1	0-2.2	Pavement on top of concrete, cobbles, sand	0.0	0.0	30.0	*15.9
P16	L	2	2.3-5.8	CL	6.7	6.1	20.4	11.6

P17	L	1	0 - 1.7	ML-SP	3.7	1.9	23.5	15.7
P17	L	2	1.71 - 2.7	SP	0.0	0.0	35.0	*15.9
P17	L	3	2.71 -6.2	CL	10.2	10.7	14.6	16.9
P19	L	1	0-4.93	ML-SP-GP	10.2	4.5	16.7	14.9
P19	L	2	4.94-7.5	CL	8.8	7.8	12.5	12.9
P21	L	1	0-4.1	SP-GP	5.5	3.3	11.2	15.2
P21	L	2	4.2-6.6	CL	16.0	13.7	26.6	12.5
P23 & 24	L	1	0-6.1	SP-GP	0.0	0.0	30.3	14.5
P23 & 24	L	2	6.2-8.9	CL	2.6	1.9	21.1	12.6
POC 2&3	R	1	0-2.25	ML-SP	2.6	1.5	24.6	15.6
POC5	L	1	0-0.42	ML-SP	0.4	0.1	29.1	12.9
POC5	L	2	0.43-2.2	Cobbles	0.0	0.0	30.0	*15.9
POC7	L	1	0-1.9	ML	8.9	7.6	19.8	15.0
POC9/9a	R	1	0-2.6	ML-SP	0.3	0.0	19.1	12.5
POC10	R	1	0-2.4	ML-CL	5.2	4.4	24.0	12.5
POC16	L	1	0-3.9	ML-CL	6.3	6.2	16.9	9.7
POC18	R	1	0-1.7	ML-SP	3.6	3.2	19.4	16.2
POC22	L	1	0-4.0	ML-SP	2.3	0.0	10.9	7.4
POC27	R	1	0-0.50	SP	2.2	2.1	31.4	12.7
POC27	R	2	0.51-1.20	SP-CL	6.8	5.7	35.0	11.5
POC28	R	1	0-0.87	CL-SP	0.0	0.2	29.3	18.2
POC30	R	1	0-0.82	SP	2.3	2.1	10.9	13.8
OC0	L	1	0-2.8	ML-SP	5.6	0.0	19.0	15.9
OC1	L	1	0-5.2	ML-SP	3.7	3.4	29.3	14.8
OC3	R	1	0 - 4.1	SP-GP	0.2	0.0	11.2	15.8
OC5	R	1	0 - 9.8	SP-GP	3.6	1.6	21.3	17.2
OC7	R	1	0-5.5	SP-GP	3.6	1.6	21.3	17.2
OC7	R	2	5.6-8.3	ML-CL	4.7	0.0	30.0	9.3
OC8	L	1	0-11.58	SP	0.0	0.0	29.7	14.6

2.2 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) (Figure 4). 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:

$$\varepsilon = k\,(\tau_o - \tau_c)^{a} = k\,(\tau_e)^{a} \qquad (2)$$

where k = erodibility coefficient (m^3/N-s); τ_o = average boundary shear stress (Pa); τ_c = critical shear stress; a = exponent assumed to equal 1.0 and τ_e = excess shear stress (Pa). 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. Based on observations from across the United States, k can be estimated as a function of τ_c (Figure 5). This is generalized to:

$$k = 0.1\,\tau_c^{-0.5} \tag{3}$$

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. Values are shown in Table 2. CONCEPTS uses Equation 3 to compute k given τ_c to remove variability (especially in k) in field measurements; however, a plot of the Kalamazoo River bank-toe measurements (Figure 6) showed that significant error would result from the use of Equation 3. The relationship used for the Kalamazoo River study reach is provided in Figure 6.

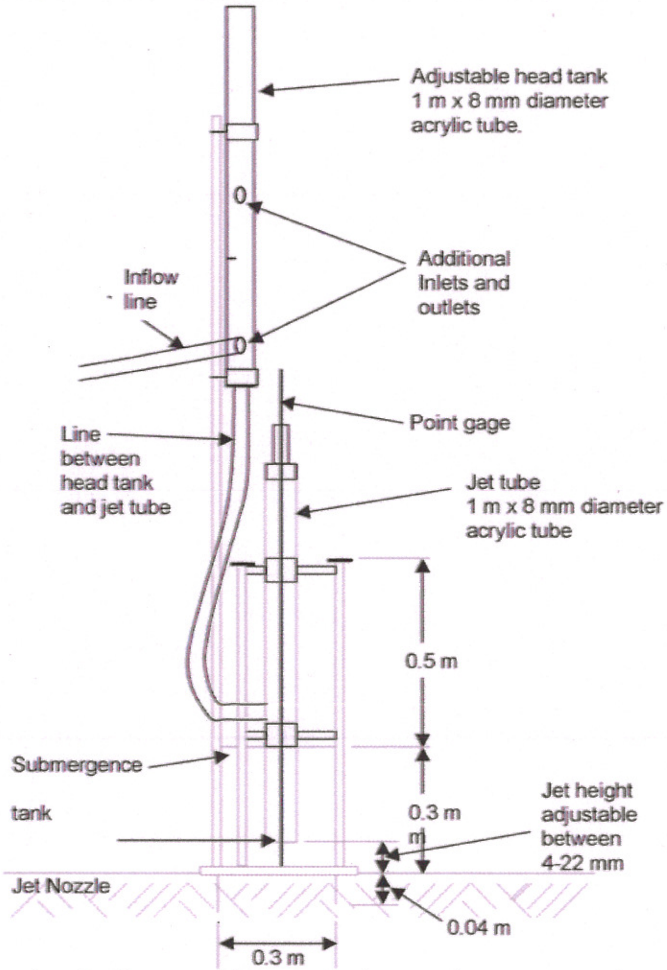

Figure 4 - Schematic of submerged jet-test device used to measure the erodibility coefficient (k), and the critical shear stress (τc), of fine-grained materials.

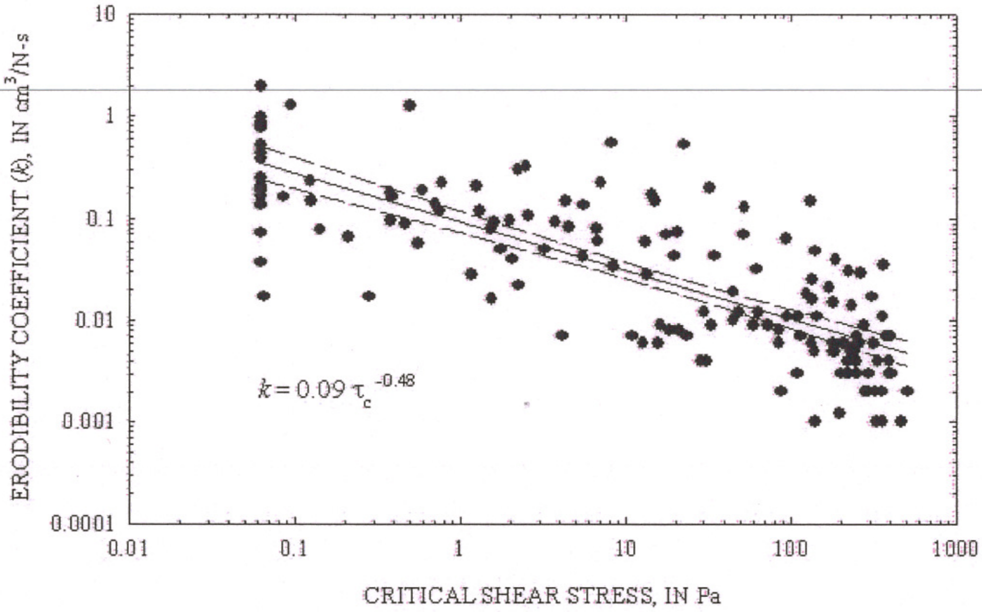

Figure 5 - General relation between the erodibility coefficient *k*, and critical shear stress τ_c for fine-grained materials based on jet tests from across the United States (Hanson and Simon, 2001).

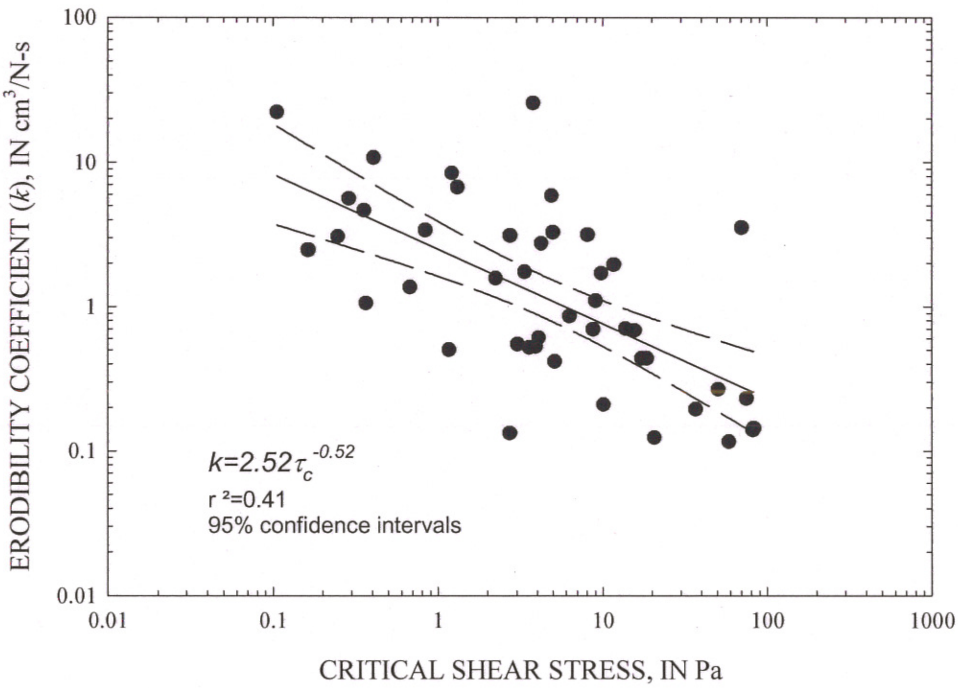

Figure 6 – Relation between erodibility coefficient (k) and critical shear stress (τ_c) for fine-grained materials based on jet tests from the Kalamazoo River.

Table 2. Submerged jet-test values obtained for the Kalamazoo River.

Site	Date	Test #	Material Description	τ_c (Pa)	*k* (cm3/N-s)
P4 Right Bank	10/30/2002	1	Black silty clay	8.74	0.699
P4 Right Bank	10/30/2002	2	Black silty clay	15.7	0.685
P6 Left Bank	6/24/2002	1	Toe: Firm Gray clay	20.7	0.124
P6 Left Bank	6/24/2002	2	Toe: Firm Gray clay	2.74	0.133
P8 Right Bank	11/6/2002	2	Soft gray clay	0.677	1.37
Trans11 Right Bank	10/29/2002	1	Dark gray silt	9.80	1.71
P10 Right Bank	10/29/2002	1	Gray clay	18.6	0.439
P10 Right Bank	10/29/2002	2	Gray clay	17.3	0.439
P11 Right Bank	10/28/2002	1	Gray silty clay	2.25	1.58
P11 Right Bank	10/28/2002	2	Gray silty clay	13.8	0.708
P13 Left Bank	4/1/2002	1	Toe: Soft clay with sand on top	0.106	22.3
P13 Left Bank	4/1/2002	2	Toe: Soft clay with sand on top	3.8	25.7
P13 Left Bank	4/1/2002	3	Bank face: Firm grey clay with crack	37.0	0.195
P13 Left Bank	4/1/2002	4	Bank face: Firm grey clay with crack	4.1	0.609
P16 Left Bank	4/3/2002	1	Toe: Firm Gray clay	50.7	0.268
P16 Left Bank	4/3/2002	2	Toe: Firm Gray clay	82.8	0.144
P16 Right Bank	3/27/2002	2	Bed: Soft Grey to black clay	0.164	2.48
P16 Right Bank	3/27/2002	3	Toe: Soft clay	6.3	0.861
P16 Right Bank	3/27/2002	4	Toe: Soft clay	4.25	2.75
P17 Left Bank	4/3/2002	1	Toe: Firm Gray clay	75	0.231
P17 Left Bank	4/3/2002	2	Toe: Firm Gray clay	70.3	3.54
P17 Left Bank	4/3/2002	3	Toe: Firm Gray clay	58.9	0.116
P17 Left Bank	4/3/2002	4	Toe: Firm Gray clay	82.2	0.140
P17 Right Bank	3/27/2002	1	Toe: Soft gray to black clay	0.409	10.8
P17 Right Bank	3/27/2002	3	Toe: Soft gray to black clay	5.01	3.28
P19 Right Bank	3/28/2002	1	Toe: Soft Dark gray to black clay	8.10	3.15
P19 Right Bank	3/28/2002	2	Toe: Soft Dark gray to black clay	1.22	8.43
P21 Right Bank	3/28/2002	1	Toe: Soft Dark gray to black clay	11.7	1.96
P21 Right Bank	3/28/2002	2	Toe: Soft Dark gray to black clay	3.92	0.529
P23/24 Right Bank	3/29/2002	1	Toe: Soft Dark gray to black clay	9.07	1.10
P23/24 Right Bank	3/29/2002	2	Toe: Soft sandy muck	2.75	3.12
P23/24 Right Bank	3/29/2002	3	Bank face: Silty sand	3.37	1.75
P23/24 Right Bank	3/29/2002	4	Bank face: Silty sand	0.290	5.63
POC16 Left bank main	6/27/2002	1	Dark Brown Clay	0.367	1.06
POC16 Light bank main	6/27/2002	2	Dark Brown Clay	3.05	0.55
POC16 Light bank main	6/27/2002	3	Dark Brown Clay	0.84	3.40
POC16 Right Bank	10/31/2002	1	Dark brown clay	1.17	0.504
POC16 Right bank main	6/27/2002	1	Dark Brown Clay	1.32	6.75
POC22 Left bank main	7/9/2002	1	Dark Brown Silt	4.91	5.88
POC22 Left bank main	7/9/2002	2	Dark Brown Silt	0.358	4.67
POC27 Left bank	6/25/2002	1	Gray to black clay	0.248	3.07
POC28 Right bank	6/26/2002	2	Dark gray-brown clay	10.13	0.21
OC7 Left Bank	7/8/2002	1	Toe: Firm Gray clay	5.14	0.418
OC7 Left Bank	7/8/2002	2	Toe: Firm Gray clay	3.60	0.521

2.3 Bank-Toe Erodibility

In situ bank-toe materials are composed of a wide range of materials ranging from silts and clays to gravel and concrete. In cases where bank-toe material is fine-grained alluvium a submerged jet-test device (modified to operate on inclined surfaces) was used to determine values of τ_c and k. Values for sites along the Kalamazoo River are shown in Table 2. Erosion of bank-toe materials for the Kalamazoo River was calculated using an excess shear stress approach (Figure 6). 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.

2.4 Texture of Bed Materials

CONCEPTS requires information on sediment texture to determine sediment routing and sorting processes. Bulk samples of bed materials were collected for this reason. The composition of bed material for each study site was taken from cores obtained by the USGS.

2.5 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 Aldridge and Garrett (1973) and Jarrett (1985). Calibration was carried out to match observed water surface elevations downstream of the dams. In general, roughness values for the channel bed and banks ranged from 0.03 to 0.06; for the floodplain, from 0.05 to 0.13.

2.6 CONCEPTS Values Used

Cross sections specify the boundary geometry and material properties. Cross sections are comprised of left and right floodplains, banks, and the streambed. Each of these channel surfaces is associated with material properties and flow-resistance characteristics. Table 3 gives the bank data and Table 4 gives the bed data for each modeled cross section along the study reach. In the depth of layer column, zero (0) is the top of the bank and the dash (-) indicates that the material remains the same down to the bedrock layer, which was arbitrarily set at 2 m below the thalweg elevation.

Table 3. Bank material and physical properties data used in the CONCEPTS simulations.

XS Name	Distance (km)	Bank material composition and physical properties									
		Bank	No. Layers	Depth (m)	Silt/Clay (%)	Sand (%)	Gravel (%)	c' (Pa)	φ'	τc (Pa)	*n*
P3	91.182	L	1	0-	6.30	45.70	48.00	2150	23.0	12.2	0.06
		R	1	0-	6.30	45.70	48.00	2150	23.0	12.2	0.06
P4	91.005	L	1	0-	6.30	45.70	48.00	2150	23.0	12.2	0.06
		R	1	0-	6.30	45.70	48.00	2150	23.0	12.2	0.06
P5	90.748	L	2	0-1.34	49.800	50.200	0.000	1000	24.2	11.7	0.06
				1.34-	81.700	18.300	0.000	10600	15.9	11.7	0.06
		R	2	0-1.34	49.800	50.200	0.000	1000	24.2	11.7	0.06
				1.34-	81.700	18.300	0.000	10600	15.9	11.7	0.06
P6	90.571	L	2	0-1.34	49.800	50.200	0.000	800	40.6	11.7	0.06
				1.34-	81.700	18.300	0.000	1400	27.9	11.7	0.06
		R	2	0-1.34	49.800	50.200	0.000	800	40.6	11.7	0.06
				1.34-	81.700	18.300	0.000	1400	27.9	11.7	0.06
P7	90.394	L	1	0-	1.400	85.400	13.200	8200	21.2	11.70	0.06
		R	1	0-	1.400	85.400	13.200	8200	21.2	11.70	0.06
P8	90.152	L	1	0-	1.400	85.400	13.200	8200	21.2	2.00	0.06
		R	1	0-	1.40	85.40	13.20	8200	21.2	2.00	0.06
Hwy131	89.895	L	1	0-	0.70	93.55	5.75	8200	21.2	9.80	0.06
		R	1	0-	0.70	93.55	5.75	8200	21.2	9.80	0.06
P10	89.653	L	1	0-	0.70	93.55	5.75	4000	23.8	18.0	0.06
		R	1	0-	0.70	93.55	5.75	4000	23.8	18.0	0.06
P11	89.493	L	2	0-0.4	55.20	44.80	0.00	2100	23.2	7.88	0.06
				0.4-	1.70	96.20	2.10	4000	18.7	7.88	0.06
		R	2	0-0.4	55.20	44.80	0.00	2100	23.2	7.88	0.06
				0.4-	1.70	96.20	2.10	4000	18..7	7.88	0.06
P12	89.348	L	2	0-0.4	55.20	44.80	0.00	2100	23.2	7.88	0.06
				0.4-	1.70	96.20	2.10	4000	18.7	7.88	0.06
		R	2	0-0.4	55.20	44.80	0.00	2100	23.2	7.88	0.06
				0.4-	1.70	96.20	2.10	4000	18.7	7.88	0.06
P14	89.219	L	1	0-	34.10	64.30	1.60	1900	23.5	3.76	0.06
		R	1	0-	34.10	64.30	1.60	1900	23.5	3.76	0.06
P15	89.026	L	1	0-	85.30	14.70	0.00	6130	20.4	66.0	0.06
		R	1	0-	24.70	38.17	37.13	6130	20.4	5.30	0.06
P17	88.817	L	1	0-	87.70	12.30	0.00	10700	14.6	72.2	0.06
		R	3	0-0.37	19.26	78.30	2.44	1900	23.5	5.01	0.06
				0.37-0.65	1.30	70.60	28.10	0	35.0	5.01	0.06
				0.65-	2.30	93.60	4.10	10700	14.6	3.30	0.06
P20	88.592	L	1	0-	75.20	24.80	0.00	3300	11.2	6.24	0.06
		R	1	0-	75.20	24.80	0.00	3300	11.2	6.24	0.06
P23	88.382	L	1	0-	64.80	35.20	0.00	1900	21.1	6.00	0.06
		R	1	0-	64.80	35.20	0.00	1900	21.1	3.90	0.06
USPWD	88.290	L	1	0-	64.80	35.20	0.00	1500	24.6	6.00	0.06
		R	1	0-	64.80	35.20	0.00	1500	24.6	3.90	0.06
PW DAM	88.270										
POC1	88.238	L	2	0-0.84	14.00	86.00	0.00	1500	24.6	2.50	0.05
				0.84-	45.99	54.01	0.00	1500	24.6	2.50	0.05
		R	1	0-	9.90	85.00	5.10	1500	24.6	2.50	0.05
POC3	88.173	L	2	0-0.84	14.00	86.00	0.00	1500	24.6	2.50	0.05
				0.84-	45.99	54.01	0.00	1500	24.6	2.50	0.05
		R	1	0-	9.90	85.00	5.10	1500	24.6	2.50	0.05
POC4	88.061	L	1	0-	18.65	81.30	0.05	1500	24.6	2.50	0.05
		R	1	0-	19.27	80.67	0.06	1500	24.6	2.50	0.05
POC6	87.932	L	1	0-	1.60	96.90	1.50	7600	19.8	2.50	0.05
		R	1	0-	1.60	96.90	1.50	7600	19.8	2.50	0.05
POC8	87.755	L	2	0-0.9	54.00	46.00	0.00	2100	31.4	2.50	0.05
				0.9-	27.19	72.51	0.30	5700	35.0	2.50	0.05
		R	2	0-0.9	54.00	46.00	0.00	2100	31.4	2.50	0.05
				0.9-	27.19	72.51	0.30	5700	35.0	2.50	0.05
POC11	87.546	L	1	0-	9.65	87.80	2.55	4400	24.0	2.50	0.05
		R	1	0-	9.65	87.80	2.55	4400	24.0	2.50	0.05
POC15	87.304	L	1	0-	94.30	5.70	0.00	6230	16.9	2.50	0.05
		R	1	0-	94.30	5.70	0.00	6230	16.9	2.50	0.05

POC16	87.079	L	1	0-	94.30	5.70	0.00	6230	16.9	1.40	0.05
		R	1	0-	94.30	5.70	0.00	6230	16.9	1.32	0.05
G9	86.918	L	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
		R	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
G8	86.709	L	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
		R	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
G7	86.452	L	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
		R	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
G6	86.210	L	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
		R	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
G5	85.969	L	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
		R	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
G4	85.711	L	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
		R	1	0-	95.05	4.95	0.00	3200	19.4	2.50	0.05
G2	85.486	L	1	0-	95.80	4.20	0.00	3200	19.4	2.50	0.05
		R	1	0-	95.80	4.20	0.00	3200	19.4	2.50	0.05
USOCD	85.297	L	1	0-	95.80	4.20	0.00	3200	19.4	2.50	0.05
		R	1	0-	95.80	4.20	0.00	3200	19.4	2.50	0.05
OC DAM	85.277										
DSOCD	85.257	L	1	0-	6.80	66.20	27.00	3200	19.4	4.37	0.05
		R	1	0-	6.80	66.20	27.00	3200	19.4	4.37	0.05
FS BRDG	84.955	L	1	0-	6.80	66.20	27.00	3400	29.3	3.50	0.05
		R	1	0-	19.80	79.60	0.60	3400	29.3	3.50	0.05
OC1	84.617	L	1	0-	6.80	66.20	27.00	3400	29.3	4.37	0.05
		R	1	0-	19.80	79.60	0.60	3400	29.3	4.37	0.05
OC2	84.312	L	1	0-	6.80	66.20	27.00	3400	29.3	4.37	0.05
		R	1	0-	19.80	79.60	0.60	3400	29.3	4.37	0.05
OC3	84.070	L	1	0-	1.00	74.70	24.30	1000	11.2	4.37	0.05
		R	1	0-	22.45	69.30	8.25	1000	11.2	4.37	0.05
OC4	83.700	L	1	0-	1.00	74.70	24.30	1600	21.3	4.37	0.05
		R	1	0-	22.45	69.30	8.25	1600	21.3	4.37	0.05
OC5	83.394	L	1	0-	1.15	67.15	31.70	1600	21.3	4.37	0.05
		R	1	0-	1.15	67.15	31.70	1600	21.3	4.37	0.05
OC6	83.089	L	1	0-	1.15	67.15	31.70	1600	21.3	4.37	0.05
		R	1	0-	1.15	67.15	31.70	1600	21.3	4.37	0.05
OC7	82.751	L	1	0-	68.20	31.80	0.00	1600	21.3	4.37	0.05
		R	1	0-	68.20	31.80	0.00	1600	21.3	4.37	0.05
OC8	82.429	L	1	0-	68.20	31.80	0.00	1600	21.3	4.37	0.05
		R	1	0-	68.20	31.80	0.00	1600	21.3	4.37	0.05

c' Effective cohesion
φ' Effective angle of internal friction
τc Critical shear stress
n Manning's roughness

Table 4. Bed material properties used in the CONCEPTS simulations.

XS Name	Distance (km)	Bed Material Properties					
		No. of layers	Depth (m)	Silt/Clay (%)	Sand (%)	Gravel (%)	*n*
P3	91.182	1	0-	0.44	78.39	21.17	0.06
P4	91.005	1	0-	0.44	78.39	21.17	0.06
P5	90.748	1	0-	0.44	78.39	21.17	0.06
P6	90.571	1	0-	0.44	78.39	21.17	0.06
P7	90.394	1	0-	44.88	53.82	1.30	0.06
P8	90.152	1	0-	18.73	76.47	4.80	0.06
Hwy131	89.895	1	0-	18.73	76.46	4.81	0.06
P10	89.653	1	0-	18.73	76.46	4.81	0.06
P11	89.493	2	0-0.15	0.00	59.23	40.77	0.06
			0.15-	0.00	85.06	14.94	
P12	89.348	2	0-0.31	0.00	30.63	69.37	0.06
			0.31-	0.00	88.34	11.66	
P14	89.219	2	0-0.31	0.00	30.63	69.37	0.06
			0.31-	0.00	88.34	11.66	
P15	89.026	1	0-	0.00	57.01	42.99	0.06
P17	88.817	3	0-0.31	0.00	77.86	22.14	0.06
			0.31-0.61	0.00	96.09	3.91	
			0.61-	0.00	86.80	13.20	
P20	88.592	4	0-0.31	0.00	96.67	3.33	0.06
			0.31-0.61	0.00	84.67	15.33	
			0.61-1.52	0.00	98.00	2.00	
			1.52-	0.00	85.10	14.90	
P23	88.382	4	0-0.46	0.00	98.28	1.72	0.06
			0.46-0.91	0.00	24.17	75.83	
			0.91-1.37	0.00	98.62	1.38	
			1.37-	0.00	72.44	27.56	
USPWD	88.290	4	0-0.46	0.00	98.28	1.72	0.06
			0.46-0.91	0.00	24.17	75.83	
			0.91-1.37	0.00	98.62	1.38	
			1.37-	0.00	72.44	27.56	
PW DAM	88.270						
POC1	88.238	1	0-	0.00	69.62	30.38	0.07
POC3	88.173	1	0-	0.00	69.62	30.38	0.07
POC4	88.061	1	0-	0.00	69.62	30.38	0.07
POC6	87.932	1	0-	1.60	96.90	1.50	0.07
POC8	87.755	1	0-	0.00	97.00	3.00	0.06
POC11	87.546	3	0-0.31	0.00	99.91	0.09	0.05
			0.31-0.61	0.00	74.67	25.33	
			0.61-	0.00	68.94	31.06	
POC15	87.304	3	0-0.91	0.00	79.27	20.73	0.04
			0.91-1.37	0.00	93.91	6.09	
			1.37-	0.00	98.73	1.27	
POC16	87.079	3	0-0.91	0.00	79.27	20.73	0.03
			0.91-1.37	0.00	93.91	6.09	
			1.37-	0.00	98.73	1.27	
G9	86.918	2	0-1.10	0.01	77.68	22.31	0.03
			1.10-	0.00	92.31	7.69	
G8	86.709	3	0-0.76	0.00	41.54	58.46	0.03
			0.76-2.13	0.00	77.59	22.41	
			2.13-	0.00	79.81	20.19	

G7	86.452	3	0-0.31	0.01	94.89	5.10	0.03
			0.31-0.82	0.00	72.02	27.98	
			0.82-	0.00	89.25	10.75	
G6	86.210	3	0-0.31	0.01	94.89	5.10	0.03
			0.31-0.82	0.00	72.02	27.98	
			0.82-	0.00	89.25	10.75	
G5	85.969	3	0-0.31	0.00	49.27	50.73	0.03
			0.31-1.22	0.00	72.95	27.05	
			1.22-	0.00	83.86	16.14	
G4	85.711	3	0-0.15	0.00	53.73	46.27	0.03
			0.15-1.22	0.00	67.78	32.22	
			1.22-	0.00	86.00	14.00	
G2	85.486	3	0-0.15	0.00	53.73	46.27	0.03
			0.15-1.22	0.00	67.78	32.22	
			1.22-	0.00	86.00	14.00	
USOCD	85.297	2	0-0.15	0.00	77.54	22.46	0.04
			0.15-	0.00	93.26	6.74	
OC DAM	85.277						
DSOCD	85.257	1	0-	0.00	1.00	99.00	0.06
FS BRDG	84.955	1	0-	0.00	1.00	99.00	0.04
OC1	84.617	1	0-	0.00	1.00	99.00	0.04
OC2	84.312	1	0-	0.00	24.06	75.94	0.04
OC3	84.070	1	0-	0.00	47.12	52.88	0.04
OC4	83.700	1	0-	0.00	27.56	72.44	0.04
OC5	83.394	1	0-	0.00	8.00	92.00	0.04
OC6	83.089	1	0-	3.17	8.71	88.12	0.04
OC7	82.751	1	0-	6.32	9.43	84.25	0.04
OC8	82.429	1	0-	6.32	9.43	84.25	0.04

3.0 RESULTS of CONCEPTS MODELING

CONCEPTS is a one-dimensional unsteady flow model that can adjust channel morphologies both laterally and vertically (Langendoen, 2000). The POC sub-reach of the Kalamazoo River poses a challenge because it is a multi-thread channel in this sub-reach.

3.1 Evaluation of POC Reach

The Kalamazoo River is a braided channel along the upper half of the POC reach. CONCEPTS simulates flow in a single-thread channel. To model this part of the Kalamazoo River we can: 1) combine the various threads (channels) into a single channel with approximately the same conveyance, or 2) only simulate the flow in the largest thread that conveys the majority of the water and sediment.

We decided to select the second option allowing for "real" boundary characteristics and conveyances to be used. Selecting the first option would have entailed synthesizing an entirely new channel with a different wetted perimeter and boundary characteristics. There is a dominating thread that conveys about 75 to 90 % of the flow (Syed, A. 2003, pers. comm., Aug 26). Hence, this thread should be the main contributor and conveyor of sediment from the upper end of the POC reach in case the POC reach is a source of sediment. The branching of the Kalamazoo River downstream of the Plainwell Dam was simulated by withdrawing water and sediment at cross section POC3 and returning it to the channel at cross section G9. Simulations with withdrawal rates of 10%, 15%, and 30% were performed for the "Dams-In" baseline scenario to determine the effects of withdrawal on sediment loads and channel morphology. Results of this sensitivity analysis showed negligible differences in sediment loads and morphologic changes within the sub-reach.

3.2 Interpretation of Bank-Erosion Results along Upper Half of POC Reach

The morphology of the upper half of the POC reach (from cross section POC1 to POC16) is depositional (braided) and is markedly different than that of the sections upstream of Plainwell Dam and near the Otsego City Dam (single-thread channel). Significant deposition is simulated along the upper half of the POC reach. Deposition on bars or bank toes resulted in the formation of berms, protecting the banks from eroding initially in the simulation. In cases where the top of the berm reached the top of the bank, the CONCEPTS simulation was halted to redefine the location of the bed, bank, and floodplain segments of the affected cross section. CONCEPTS was then re-started to complete the simulation. Possible, consecutive erosion of these berms will, therefore, show up as bank erosion in tables of results though erosion of deposited bed-material is actually being modeled.

3.3 Dams In (DI) - Baseline

The Dams In (DI) modeling scenario represents a baseline condition with existing channel geometries (including the low-head dams) and boundary characteristics. In general, the Plainwell reach is erosional (except just upstream of Plainwell Dam), the POC reach is depositional with sediments emanating from the reach upstream, whereas the OC reach is mainly a transport reach (Figure 8). Results show that over the entire study reach there is a net annual erosion of material (3670 T/y). Silts and clays are eroded from the reach at an average annual rate of 3570 T/y. Table 5 and Figure 9 summarizes the mass of material eroded (positive) or deposited (negative) from the channel boundary for each cross section. Results shown in Table 5 are broken down by location (bed or banks) and by general particle-size class, because it is the finer fractions (<65μm and <10μm) that are of particular interest. The last row "Passing outlet" represents the average annual sediment loads transported past OC8 in T/y (Figure 8).

Figure 8 shows simulated annual loads of total sediment at the downstream boundary of the study reach (OC8). As one might expect, years with high runoff correspond to years with high annual sediment loads and low percentages of silt/clay transport. Years of peak sediment for peak-flow years after 1985 do not show the great increases from low and moderate flow years as occurred in 1985. This is probably due to a 1985 flushing of sediment stored in the reach. For the Dams In case, the simulated average-annual sediment load (suspended and bed load) at the downstream boundary of the study reach (OC8) was 5010 T/y with almost 64% of this material (3200 T/y) finer than 65μm.

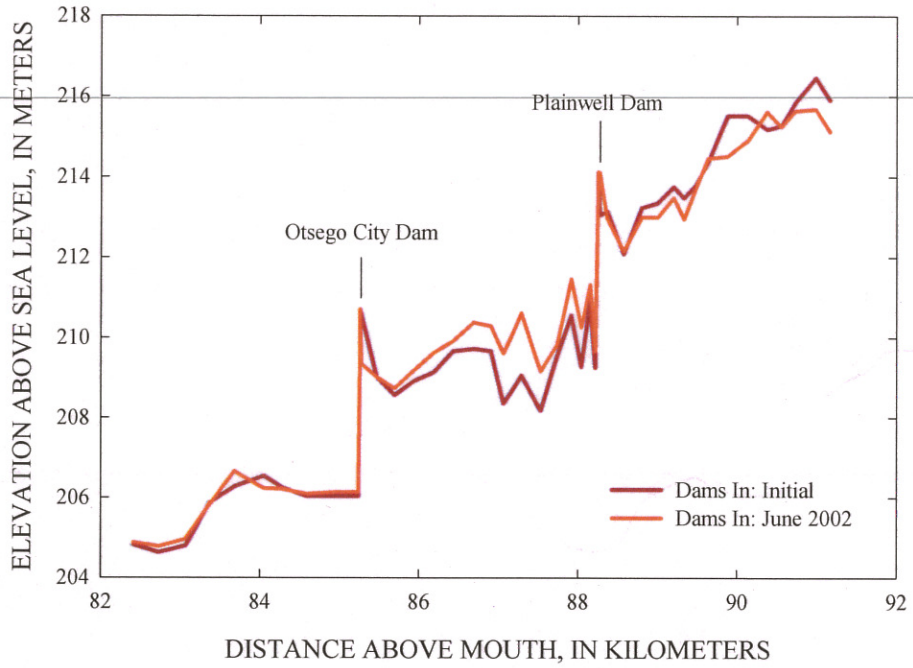

Figure 7 – Initial and final thalweg profiles for the Dams In (DI) baseline modeling scenario.

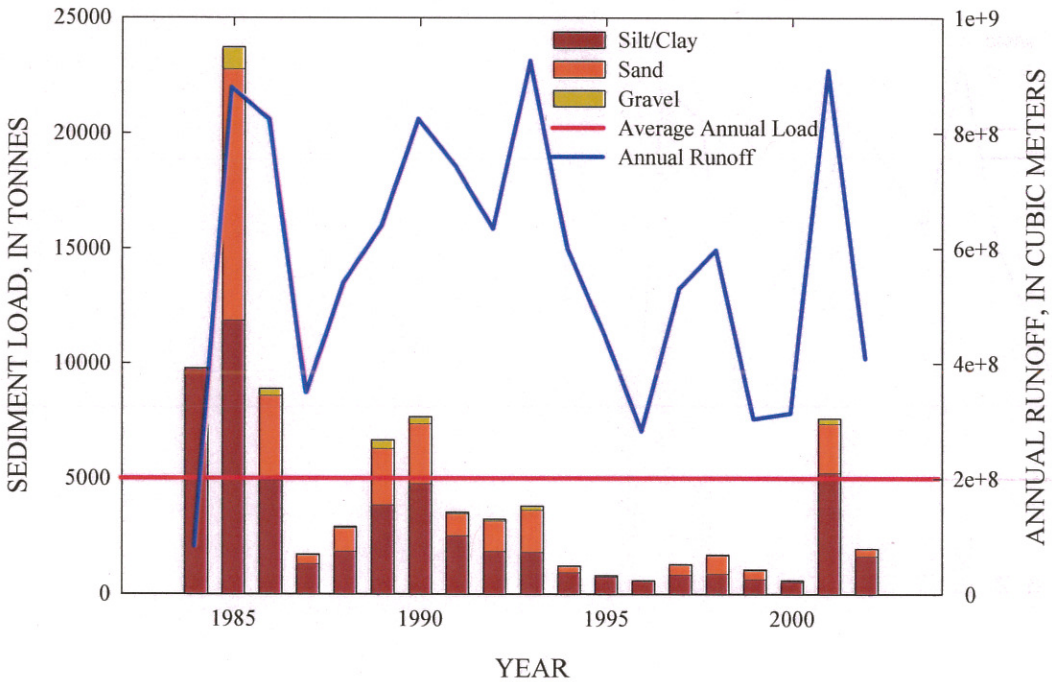

Figure 8 – Sediment load at the downstream boundary of the study reach (OC8) for the Dams In (DI) baseline modeling scenario.

Table 5. Dams In (DI) baseline modeling results.

XS Name	Distance (km)	Mass of Sediment Eroded (+) or Deposited (-) from/on the Channel Boundary								
		Total (T/y)			Bank (T/y)			Bed (T/y)		
		Total	Silt/Clay (<65μm)	Clay (<10μm)	Total	Silt/Clay (<65μm)	Clay (<10μm)	Total	Silt/Clay (<65μm)	Clay (<10μm)
P3	91.182	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P4	91.005	1620	5.83	0.17	9.47	0.58	0.17	1610	5.24	0.00
P5	90.748	2100	4.71	0.00	0.00	0.00	0.00	2100	4.70	0.00
P6	90.571	-413	1.35	0.00	0.00	0.00	0.00	-413	1.35	0.00
P7	90.394	1440	259	0.00	0.00	0.00	0.00	1440	259	0.00
P8	90.152	6950	221	0.00	0.00	0.00	0.00	6950	223	0.00
Hwy131	89.895	-2090	274	0.00	0.00	0.00	0.00	-2090	273	0.00
P10	89.653	3080	49.6	0.00	0.00	0.00	0.00	3090	53.3	0.00
P11	89.493	-147	-3.77	0.00	0.00	0.00	0.00	-140	1.07	0.00
P12	89.348	-431	-0.21	0.00	0.04	0.00	0.00	-431	-0.21	0.00
P14	89.219	761	7.20	4.75	19.0	6.24	4.75	747	3.55	0.00
P15	89.026	-385	10.8	5.98	40.9	9.72	5.98	-426	1.11	0.00
P17	88.817	-518	2.39	0.18	4.65	0.27	0.18	-523	2.12	0.00
P20	88.592	-1010	10.7	6.83	12.1	9.01	6.83	-1020	1.67	0.00
P23	88.382	-520	-0.68	0.00	0.00	0.00	0.00	-520	-0.68	0.00
USPWD	88.290	-787	-251	0.00	0.00	0.00	0.00	-787	-251	0.00
Plainwell Reach		9660	592	17.9	86.1	25.8	17.9	9590	577	0.00
PW DAM	88.270									
POC1	88.238	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POC3	88.173	1210	55.1	26.0	567	55.1	26.0	640	0.00	0.00
POC4	88.061	76.4	18.4	2.31	90.8	17.0	2.31	-14.4	1.35	0.00
POC6	87.932	-656	0.35	0.00	110.6	1.74	0.00	-761	1.68	0.00
POC8	87.755	-857	148	93.2	337	159	94.4	-1150	4.47	0.00
POC11	87.546	-235	23.2	18.0	398	35.6	18.7	-628	-10.9	0.00
POC15	87.304	556	546	367	565	531	367	-7.19	16.3	0.00
POC16	87.079	-2460	434	326	502	472	326	-2970	-38.2	0.00
G9	86.918	-970	0.15	-0.07	0.13	0.13	0.09	-965	4.36	0.00
G8	86.709	-173	-33.4	-20.0	0.00	0.00	0.00	-127	12.2	0.00
G7	86.452	-2270	2.78	0.00	0.00	0.00	0.00	-2270	2.78	0.00
G6	86.210	-1820	-20.9	-5.56	0.20	0.19	0.14	-1810	-13.9	0.00
G5	85.969	-910	-44.1	-10.3	3.53	3.35	2.38	-892	-25.5	0.00
G4	85.711	-965	63.0	0.00	0.00	0.00	0.00	-965	63.0	0.00
G2	85.486	-22.3	6.79	-0.64	0.00	0.00	0.00	-21.7	7.46	0.00
USOCD	85.297	1020	2.61	1.85	2.65	2.54	1.85	1020	0.07	0.00
POC Reach		-8480	1200	798	2580	1280	839	-10900	25.1	0.00
O DAM	85.277									
DSOCD	85.257	0	0.0	0.00	0	0.0	0.00	0.00	0.00	0.00
FS BRDG	84.955	172	-15.6	0.00	0.00	0.00	0.00	172	-15.6	0.00
OC1	84.617	477	71.2	3.05	53.5	5.91	3.05	423	65.3	0.00
OC2	84.312	1720	407	1.33	27.8	2.65	1.33	1690	405	0.00
OC3	84.070	1250	652	0.00	0.00	0.00	0.00	1250	652	0.00
OC4	83.700	-1350	219	3.67	43.3	7.35	3.67	-1400	212	0.00
OC5	83.394	-596	-2.82	0.02	7.80	0.09	0.02	-604	-2.91	0.00
OC6	83.089	-120	-128	5.54	478	5.33	1.13	-597	-133	4.39
OC7	82.751	2790	338	29.5	0.00	0.00	0.00	2790	339	29.8
OC8	82.429	-2170	216	125	234	157	117	-2400	56.9	7.28
OC Reach		2170	1760	168	840	179	126	1330	1580	41.5
Study Reach		3350	3550	986	3510	1480	983	6.44	2180	41.5

Passing Outlet	5010	3200

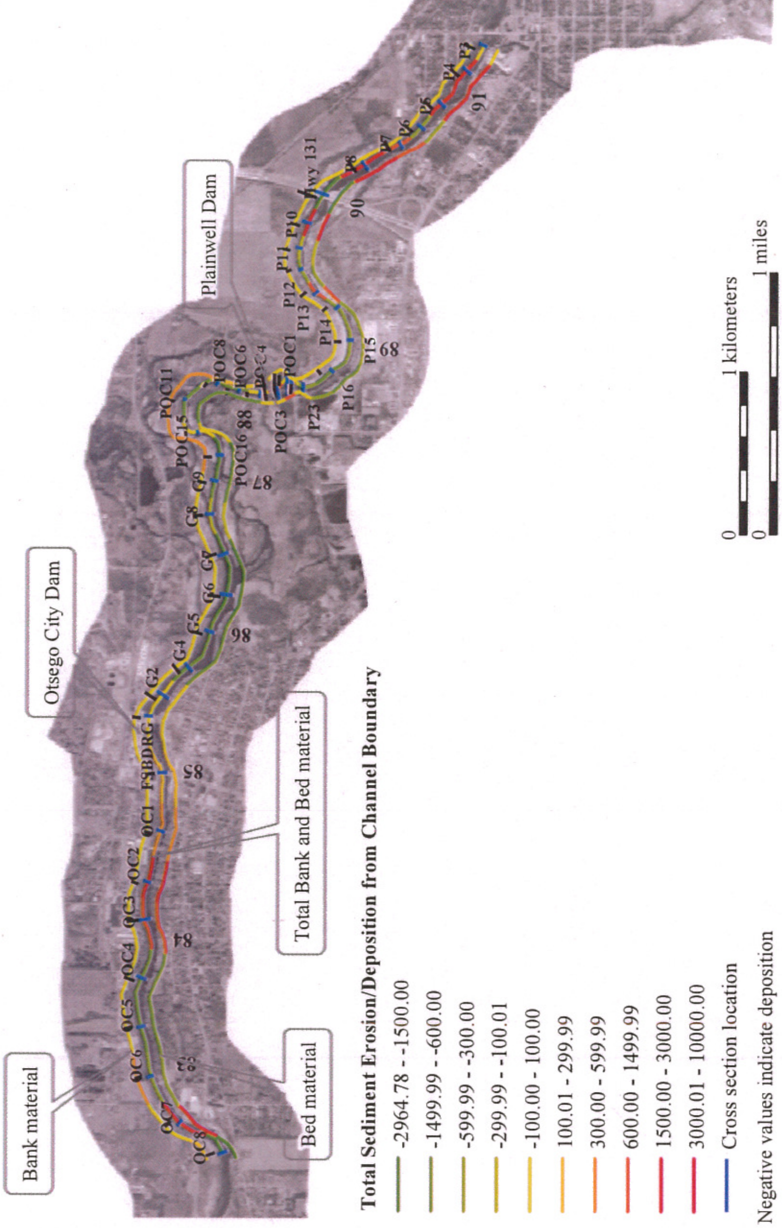

Figure 9 – Map of the study reach showing bed, bank, and total erosion/deposition for the DI scenario from data in Table 5.

3.4 Dams Out (DO)

The Dams Out scenario was simulated 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 Plainwell and POC sub-reaches occurred as knickpoints migrated headward through these sub-reaches as a direct result of simulated dam removal (Figure 10). In the Plainwell reach, bed erosion increased from 9590 T/y for the baseline (DI) scenario to 29,300 T/y for the DO scenario. In the POC reach, net deposition of 8480 T/y for the DI scenario to net erosion of 27,700 T/y for the DO scenario (Table 6 and Figure 12). Bank erosion also increased greatly from about 2670 to 4400 T/y on average, due to higher shear stresses exerted by the flow caused by the initial steepening of the channel. The relatively flatter slopes of the OC reach (being just upstream of Otsego City Dam) make this area a net sink (15,600 T/y) for sediment eroded from upstream (Figure 10).

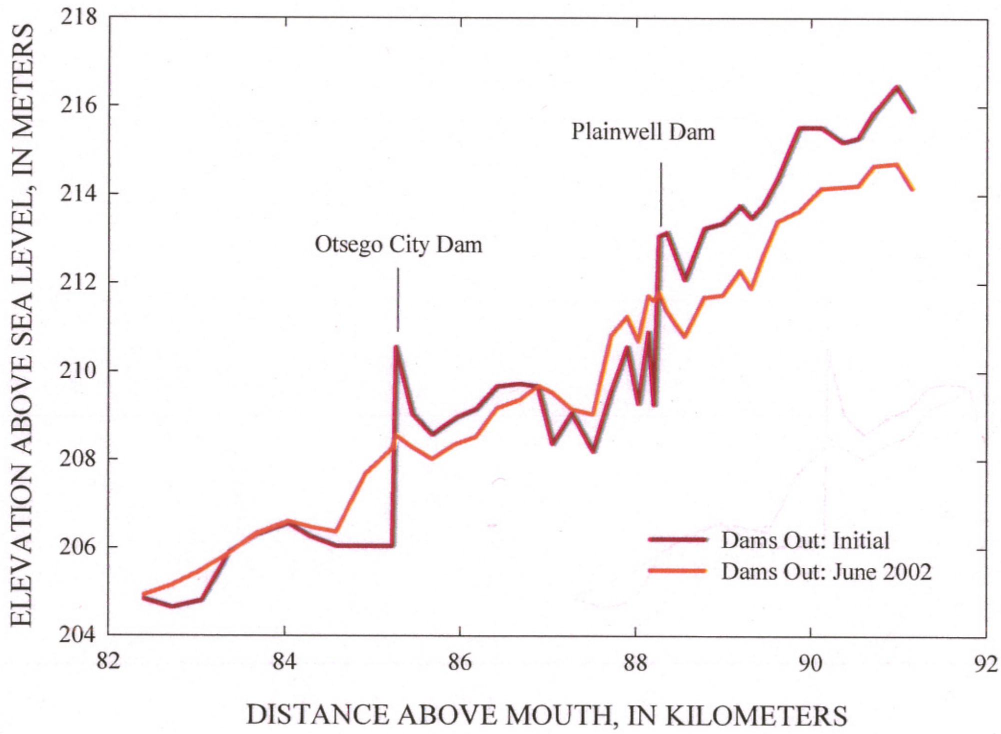

Figure 10 – Initial and final thalweg profiles for the Dams Out (DO) modeling scenario.

Simulated average-annual sediment load for the Dams Out case was 59200 T/y, more than 12 times greater than the baseline case (Figure 11). Although the percent contribution of fine-grained materials to this annual rate is much lower than in the case of the baseline (about 13%), the mass of fine-grained materials (finer than 0.065mm) transported beyond the downstream boundary at OC8 is 7500 T/y. This is about 2.3 times the amount transported under the baseline (DI) condition. Delivery of even finer sediments from the channel boundary (<10μm) is 2.2 times greater, reflecting greater amounts of bank erosion. Table 6 provides details regarding the mass of sediment eroded and deposited during the DO scenario for each of the simulated cross sections and sub-reaches.

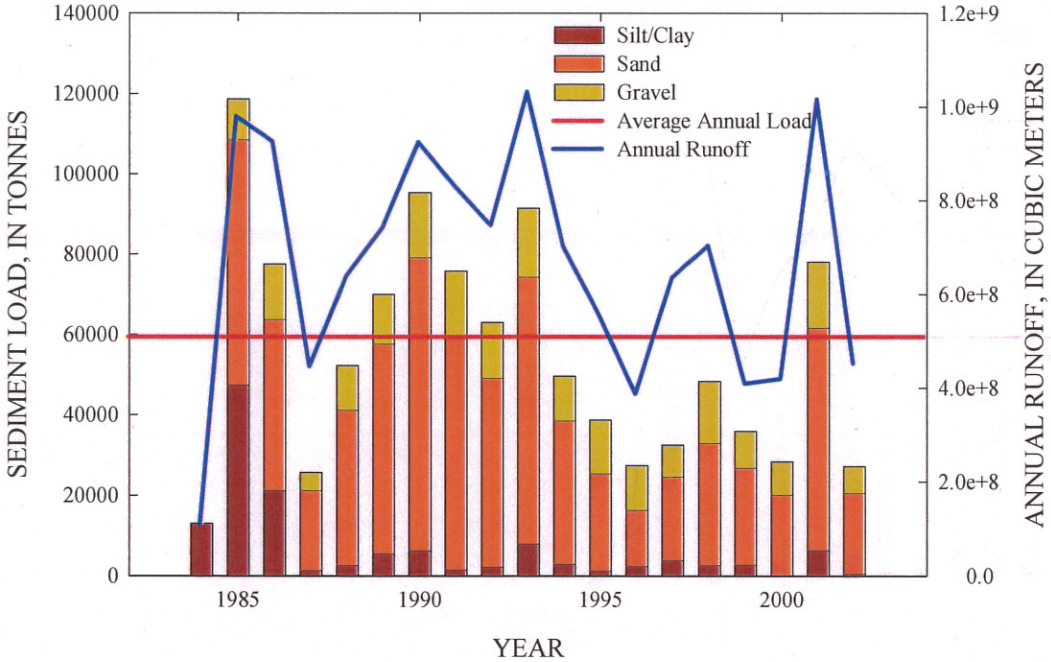

Figure 11 – Sediment load at the downstream boundary of the study reach (OC8) for the Dams Out (DO) modeling scenario.

Table 6. Dams Out (DO) modeling results.

XS Name	Distance (km)	Mass of Sediment Eroded (+) or Deposited (-) from the Channel Boundary								
		Total (T/y)			Bank (T/y)			Bed (T/y)		
		Total	Silt/Clay (<65μm)	Clay (<10μm)	Total	Silt/Clay (<65μm)	Clay (<10μm)	Total	Silt/Clay (<65μm)	Clay (<10μm)
P3	91.182	35.2	2.14	0.62	35.2	2.14	0.62	0.00	0.00	0.00
P4	91.005	3170	9.83	0.05	0.00	0.00	0.00	3170	9.82	0.05
P5	90.748	5300	13.1	0.04	0.00	0.00	0.00	5300	13.1	0.04
P6	90.571	570	30.0	19.4	31.1	24.0	19.2	538	5.98	0.11
P7	90.394	318	619	0.03	0.00	0.00	0.00	3170	619	0.03
P8	90.152	798	558	0.16	0.00	0.00	0.00	7980	559	0.16
Hwy131	89.895	610	507	0.34	0.00	0.00	0.00	609	506	0.34
P10	89.653	3370	372	0.03	0.00	0.00	0.00	3370	374	0.03
P11	89.493	562	20.7	0.00	0.00	0.00	0.00	566	23.1	0.00
P12	89.348	254	2.84	1.75	36.8	2.94	1.76	217	-0.10	0.00
P14	89.219	1190	63.0	38.2	152	50.2	38.2	1040	14.1	-0.01
P15	89.026	952	4.38	0.92	5.15	1.23	0.76	947	3.16	0.16
P17	88.817	1720	8.44	0.68	2.47	0.05	0.04	1720	8.39	0.64
P20	88.592	344	3.25	0.36	0.00	0.00	0.00	344	3.25	0.36
P23	88.382	389	18.6	6.66	0.00	0.00	0.00	389	18.6	6.66
USPWD	88.290	-65.7	8.23	3.68	0.02	0.01	0.01	-68.0	8.22	3.67
Plainwell Reach		29600	2240	72.9	263	80.6	60.6	29300	2170	12.2
POC1	88.238	119	4.71	1.30	20.5	2.28	1.16	96.7	2.43	0.14
POC3	88.173	1480	16.1	0.65	12.5	1.19	0.56	1470	14.9	0.10
POC4	88.061	3540	6.38	0.44	18.1	3.42	0.19	3530	2.96	0.25
POC6	87.932	260	-15.3	0.61	130	2.05	0.00	166	-0.52	0.61
POC8	87.755	830	516	341	1100	564	341	-158	2.09	0.35
POC11	87.546	107	19.1	15.3	324	29.1	15.2	-217	-10.0	0.04
POC15	87.304	23.5	452	317	488	459	317	-443	5.73	2.14
POC16	87.079	2530	1100	763	1170	1100	762	1360	-0.14	0.73
G9	86.918	2960	310	218	324	307	218	2640	3.49	0.29
G8	86.709	-1940	295	210	314	297	212	-2240	11.8	5.02
G7	86.452	5200	30.2	17.8	26.0	24.7	17.6	5170	5.47	0.28
G6	86.210	4730	31.2	17.5	27.0	25.6	18.2	4700	7.96	0.73
G5	85.969	607	172	123	194	184	131	427	2.03	0.34
G4	85.711	2950	20.3	7.31	4.41	4.18	2.97	2950	16.1	4.35
G2	85.486	1910	27.8	15.9	16.1	15.4	11.2	1900	12.4	4.63
USOCD	85.297	2380	5.04	2.11	0.42	0.40	0.29	2380	4.64	1.81
POC Reach		27700	2990	2050	4170	3020	2050	23700	81.4	21.8
DSOCD	85.257	13.9	23.1	10.7	361	23.6	10.7	-348	-0.51	0.00
FS BRDG	84.955	-3730	-16.2	-1.68	9.66	1.12	0.58	-3740	-17.3	-2.26
OC1	84.617	-4810	43.5	1.71	40.6	5.07	2.67	-4850	38.5	-0.96
OC2	84.312	-4380	-25.0	-4.67	53.6	5.93	3.06	-4360	26.2	25.2
OC3	84.070	2090	70.0	19.4	1.36	0.01	0.00	2090	70.0	19.4
OC4	83.700	1050	227	16.1	15.3	2.98	1.50	1040	224	14.6
OC5	83.394	-3580	41.8	2.83	3.19	0.04	0.01	-3570	53.6	9.59
OC6	83.089	-3410	11.2	14.7	336	3.75	0.80	-3710	38.6	31.7
OC7	82.751	1750	22.5	-31.8	0.00	0.00	0.00	2090	281	110
OC8	82.429	-633	157	69.6	107	71.8	53.4	-742	83.6	15.4
OC Reach		-15600	555	96.8	927	114	72.7	-16100	798	223
Study Reach		41600	5790	2220	5370	3220	2180	36900	3040	257

Passing Outlet	59200	7500

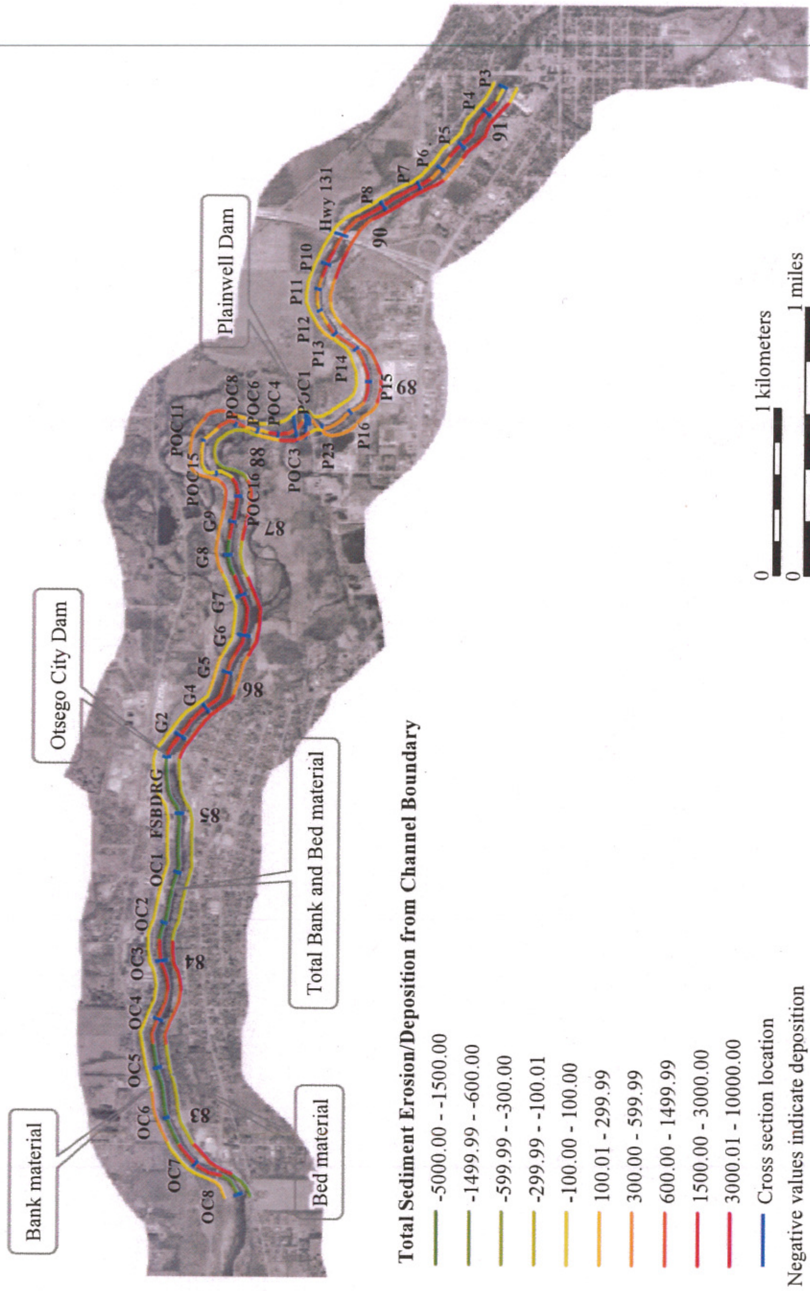

Figure 12 – Map of the study reach showing bed, bank, and total erosion/deposition for the DO scenario from data in Table 6.

3.5 Design Channel (D)

The USGS designed a channel to minimize the scour of PCB-laden channel sediments after the removal of the Plainwell and Otsego City Dams. Figure 13 shows the differences between the current thalweg profile and that of the design channel. Design gradient is 0.00127 m/m, about 1% flatter than the existing overall gradient between cross sections P3 at the upstream boundary and OC8 at the downstream boundary of the study reach. For comparison, the final simulated channel gradient is XX. 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 section POC3 and "returned" to the channel at section G9 (Figure 1). Excavated cross sections were assigned material composition and properties found at the level of excavation.

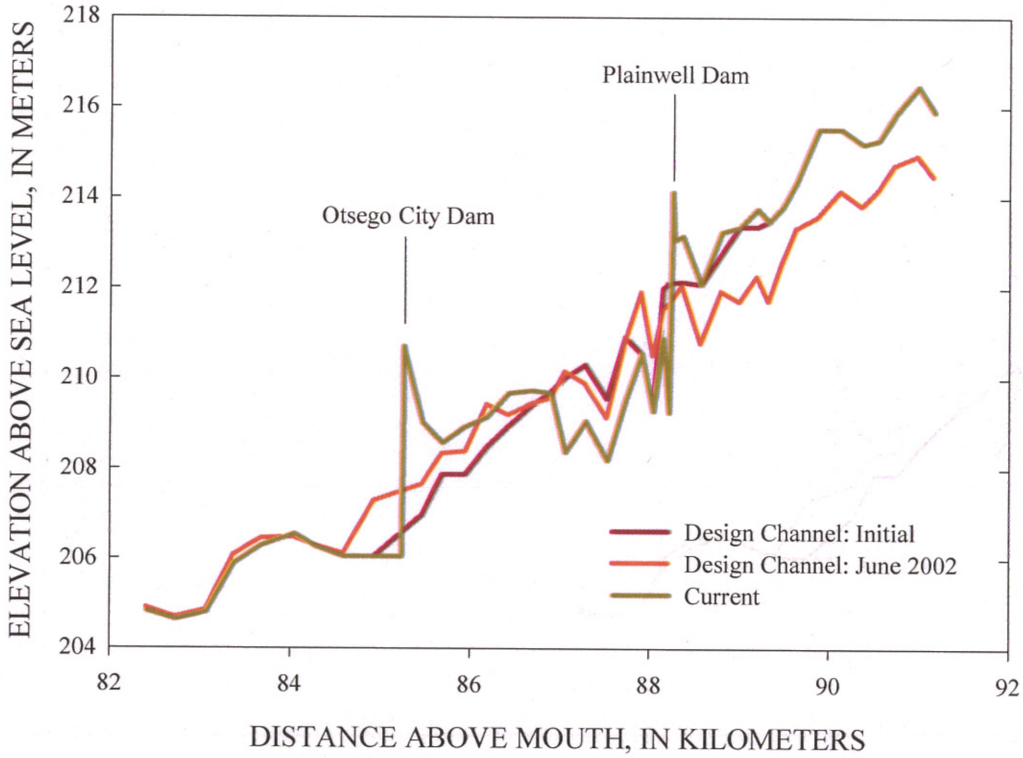

Figure 13 – Initial and final thalweg profiles for the Design Channel (D) modeling scenario shown in relation to the current configuration.

Simulation of the design channel resulted in channel incision in the Plainwell reach and net aggradation in the downstream POC and OC sub-reaches (Figure 13). Channel erosion simulated under this scenario is similar to the DI scenario (3870 T/y) but the net erosion in the Plainwell reach was 2.6 times greater than the DI scenario and the annual-average sediment load passing OC8 was 4 times greater than the DI scenario. This is not surprising given that both the DO and D scenarios include the removal of the dams.

The simulated average-annual total sediment load for the Design Case was 20,100 T/y, less than one-third of the DO scenario (Figure 14). On average, however, fine-grained sediment loads at the downstream boundary (5560 T/y) are greater than for the DI scenario.

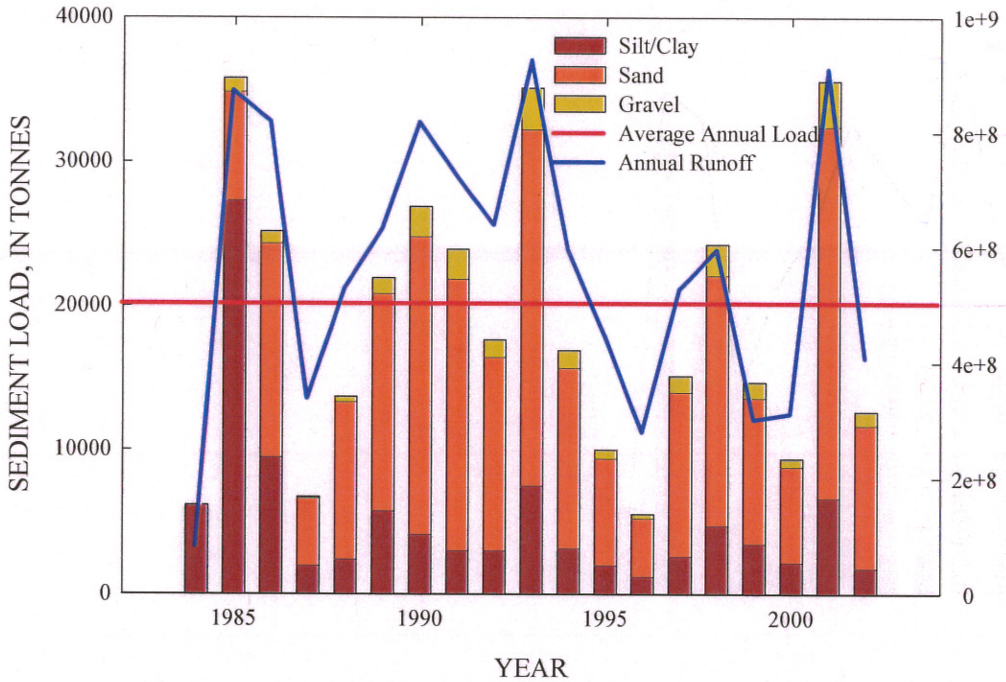

Figure 14 – Sediment load at the downstream boundary of the study reach (OC8) for the Design channel (D) modeling scenario.

Fine-grained materials made up a much greater percentage (132%) (5100 T/y) of the total mass eroded from the channel boundary (3870 T/y) but were similar in magnitude to the mass eroded under the DO scenario (5790 T/y). Most of these materials come from the channel bed in the Plainwell reach (Table 7 and Figure 15).

Table 7. Design Channel (D) modeling results.

XS Name	Distance (km)	Mass of Sediment Eroded (+) or Deposited (-) from/on the Channel Boundary								
		Total (T/y)			Bank (T/y)			Bed (T/y)		
		Total	Silt/Clay (<65µm)	Clay (<10µm)	Total	Silt/Clay (<65µm)	Clay (<10µm)	Total	Silt/Clay (<65µm)	Clay (<10µm)
P3	91.182	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
P4	91.005	3230	7.97	0.00	0.00	0.00	0.00	3230	7.96	0.00
P5	90.748	7790	12.9	0.00	0.00	0.00	0.00	7790	12.9	0.00
P6	90.571	-297	4.44	0.00	0.00	0.00	0.00	-297	4.44	0.00
P7	90.394	-483	414	0.00	0.00	0.00	0.00	-483	414	0.00
P8	90.152	6050	509	0.00	6.65	0.09	0.00	6050	509	0.00
Hwy131	89.895	-33.7	451	0.00	0.00	0.00	0.00	-34.9	450	0.00
P10	89.653	2900	350	0.00	0.00	0.00	0.00	2900	349	0.00
P11	89.493	686	21.4	0.00	0.00	0.00	0.00	687	22.1	0.00
P12	89.348	328	-0.29	0.00	0.25	0.00	0.00	328	-0.29	0.00
P14	89.219	1020	16.9	4.45	17.7	5.84	4.45	1000	11.3	0.00
P15	89.026	903	2.37	0.00	0.00	0.00	0.00	903	2.37	0.00
P17	88.817	929	9.95	0.48	5.74	0.75	0.48	923	9.20	0.00
P20	88.592	210	38.0	27.9	49.7	36.9	27.9	160	1.07	0.00
P23	88.382	1550	16.3	0.00	0.00	0.00	0.00	1550	16.3	0.00
Plainwell Reach		24800	1850	32.9	80.0	43.6	32.9	24700	1810	0.00
POC1	88.238	-106	3.15	1.68	5.31	2.36	1.68	-112	0.79	0.00
POC3	88.173	-133	-0.91	0.00	0.00	0.00	0.00	-133	-0.91	0.00
POC4	88.061	1120	-2.61	0.05	0.56	0.10	0.05	1120	-2.71	0.00
POC6	87.932	-228	-70.6	0.00	0.16	0.00	0.00	-228	-70.6	0.00
POC8	87.755	-1130	-10.7	0.01	0.10	0.03	0.01	-1130	-10.7	0.00
POC11	87.546	-330	10.2	5.47	116	10.4	5.47	-446	-0.22	0.00
POC15	87.304	-1650	272	186	287	269	186	-1940	3.72	0.00
POC16	87.079	-103	44.1	29.6	49.7	46.8	32.3	-146	2.60	0.00
G9	86.918	605	69.2	47.9	71.0	67.3	47.9	534	1.86	0.00
G8	86.709	1260	139	91.4	142	134	95.4	1120	12.6	0.00
G7	86.452	-1780	238	167	249	236	168	-2030	3.02	0.00
G6	86.210	5320	600	428	643	610	433	4690	0.83	0.00
G5	85.969	-2530	425	312	463	439	312	-2990	-13.6	0.00
G4	85.711	-1600	10.6	7.34	10.9	10.3	7.34	-1620	0.23	0.00
G2	85.486	-3500	-3.67	0.00	0.00	0.00	0.00	-3500	-3.67	0.00
POC Reach		-4790	1720	1280	2040	1820	1290	-6800	-76.7	0.00
FS BRDG	84.955	-10900	286	0.00	0.00	0.00	0.00	-10900	286	0.00
OC1	84.617	-2130	24.8	2.91	52.2	5.66	2.91	-2190	19.2	0.00
OC2	84.312	-3730	74.2	-12.2	29.8	2.68	1.33	-3740	97.2	0.00
OC3	84.070	2800	126	0.00	0.00	0.00	0.00	2800	126	0.00
OC4	83.700	723	14.8	1.34	18.2	2.72	1.35	704	12.1	0.00
OC5	83.394	-2680	-8.18	-3.53	7.06	0.08	0.02	-2680	-0.73	0.00
OC6	83.089	-1320	636	21.2	398	4.43	0.94	-1710	644	25.5
OC7	82.751	1450	257	11.9	0.00	0.00	0.00	1530	339	37.5
OC8	82.429	-300	116	164	209	140	104	-511	-26.4	58.7
OC Reach		-16100	1530	186	714	156	111	-16700	1500	121.7
Study Reach		3870	5100	1500	2830	2020	1430	1200	3230	121.7

Passing Outlet	20100	5560

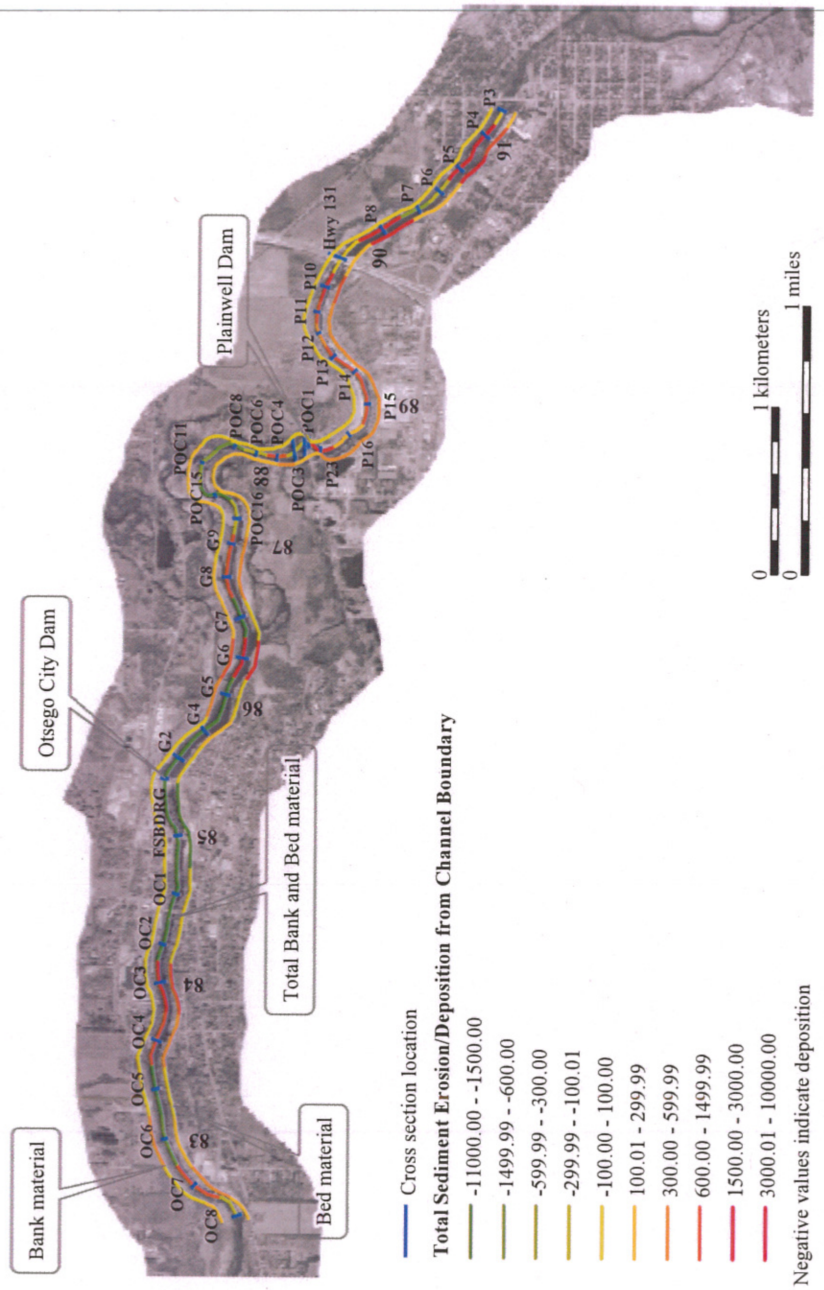

Figure 15 – Map of the study reach showing bed, bank, and total erosion/deposition for the D scenario from data in Table 7.

3.6 Comparison of the Three Modeling Scenarios: General

A comparison of the sediment loads at the downstream boundary and the final, June 2002 thalweg profiles are shown for the three modeling scenarios in Figures 16 and 17. The DI, baseline case clearly provides the smallest loads for both total and fine-grained sediment transport (Figure 16). This is not surprising given that the dams provide a basin for deposition and storage of all sediment sizes, and control channel grade.

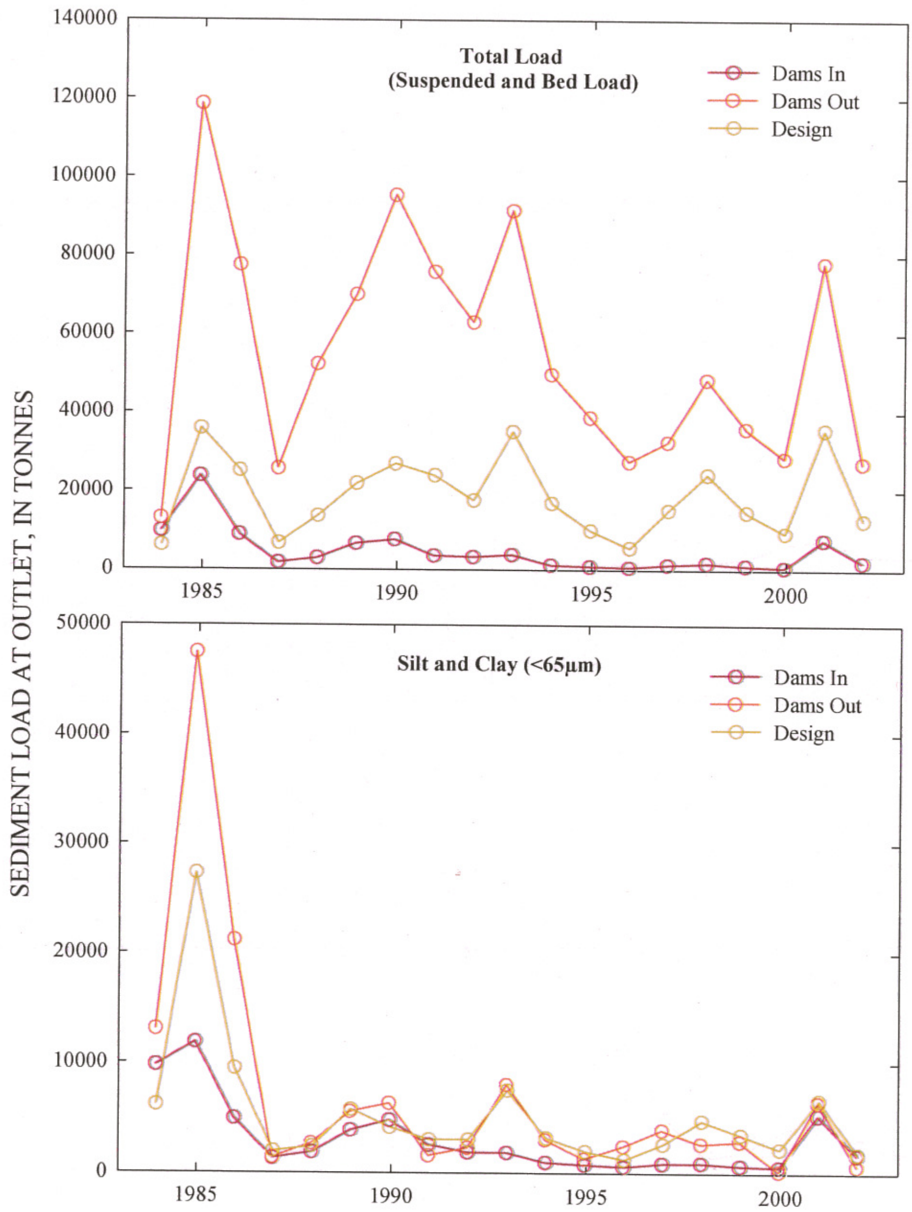

Figure 16 – Sediment loads broken out by size class at the downstream boundary (OC8) for the three modeling scenarios.

Comparison of the final (June 2002) thalweg profiles (Figure 17) shows significant differences in downcutting between the DI, baseline scenario and the two alternative modeling schemes. Responses in the Plainwell and OC reaches are almost identical for the DO and D scenarios. The POC reach is erosional under both alternative schemes as a result of the removal of the Otsego City Dam.

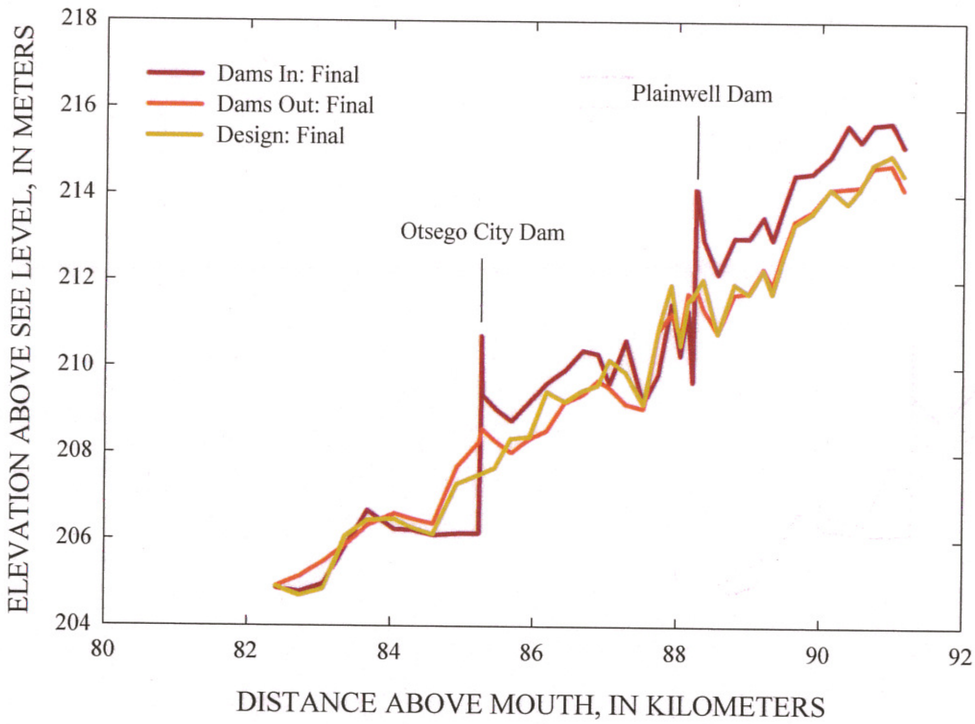

Figure 17 - Final thalweg profiles for the three modeling scenarios.

3.7 Comparison of the Three Modeling Scenarios: By Sub-Reach

Figures 19 – 24 graphically display much of the erosion/deposition data presented previously in Tables 5-7 by sub-reach. Data are plotted by river kilometer. Cross section names can be obtained from Figure 1. Graphs are presented in groups of three representing the average annual mass of sediment eroded or deposited during each simulation scenario and for each cross section as a total mass (in T/y), and as fractions finer than 65 μm and 10 μm. Because of concerns over streambank erosion, data are presented in Figures 20, 22 and 24 representing contributions from bank processes alone. Where possible, y-axis scales were kept identical for ease of comparison. This, however, was not always possible because of the range of the data and the reader is cautioned to take particular note of these scales.

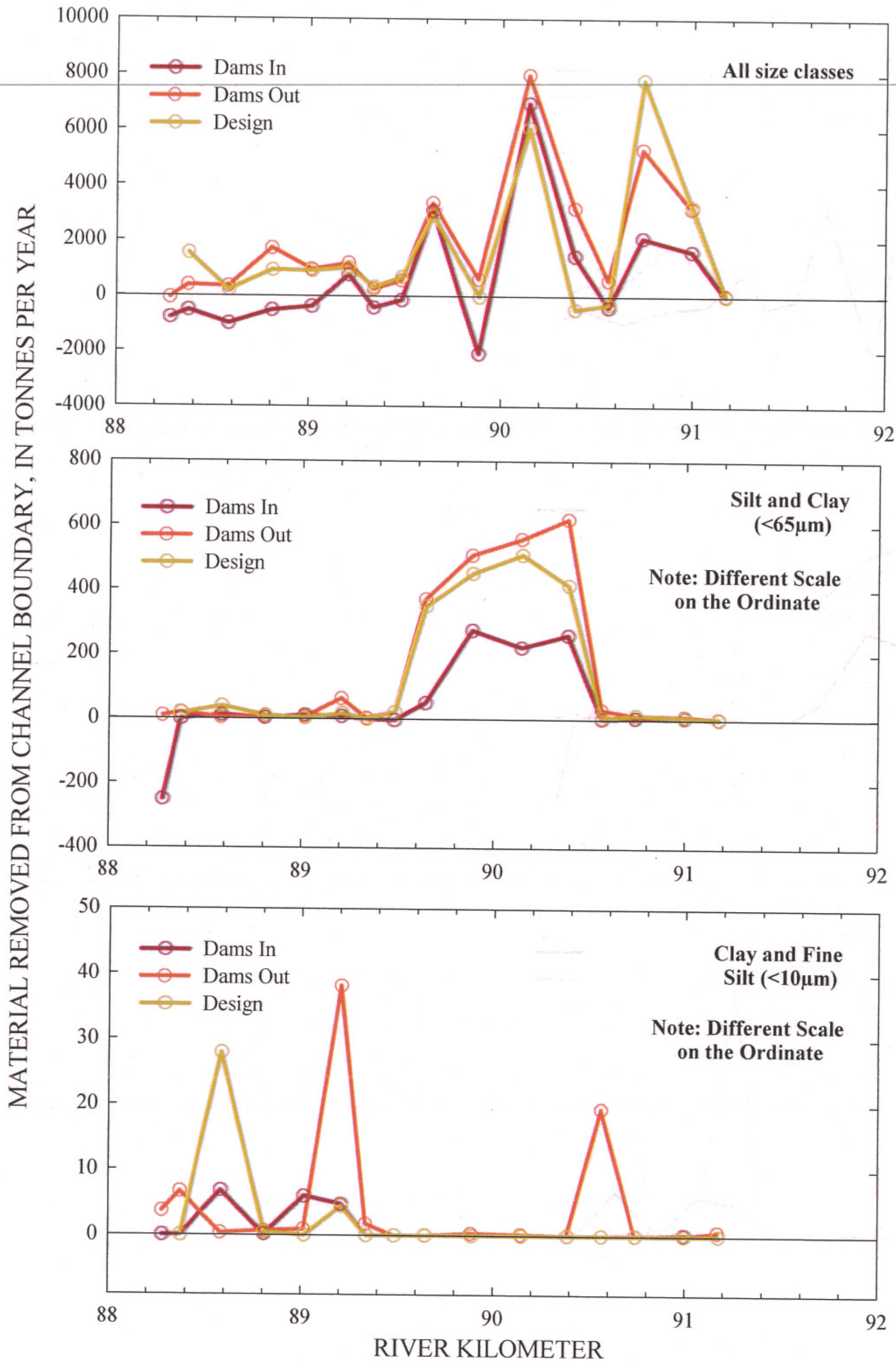

Figure 19 – Contributions from the channel boundary for the three modeling scenarios, by size class in the Plainwell reach.

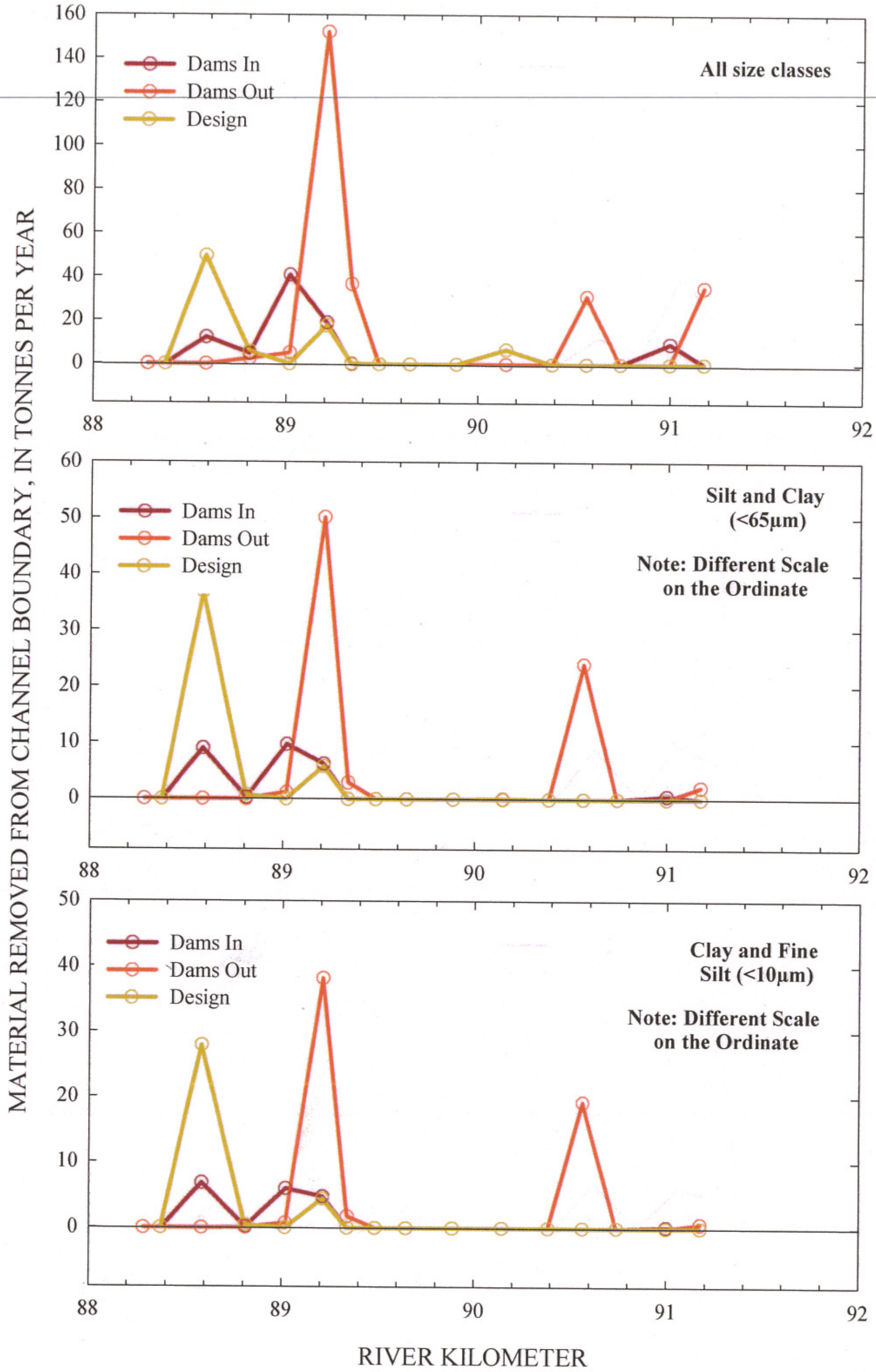

Figure 20 - Contributions from the channel banks for the three modeling scenarios, by size class in the Plainwell reach.

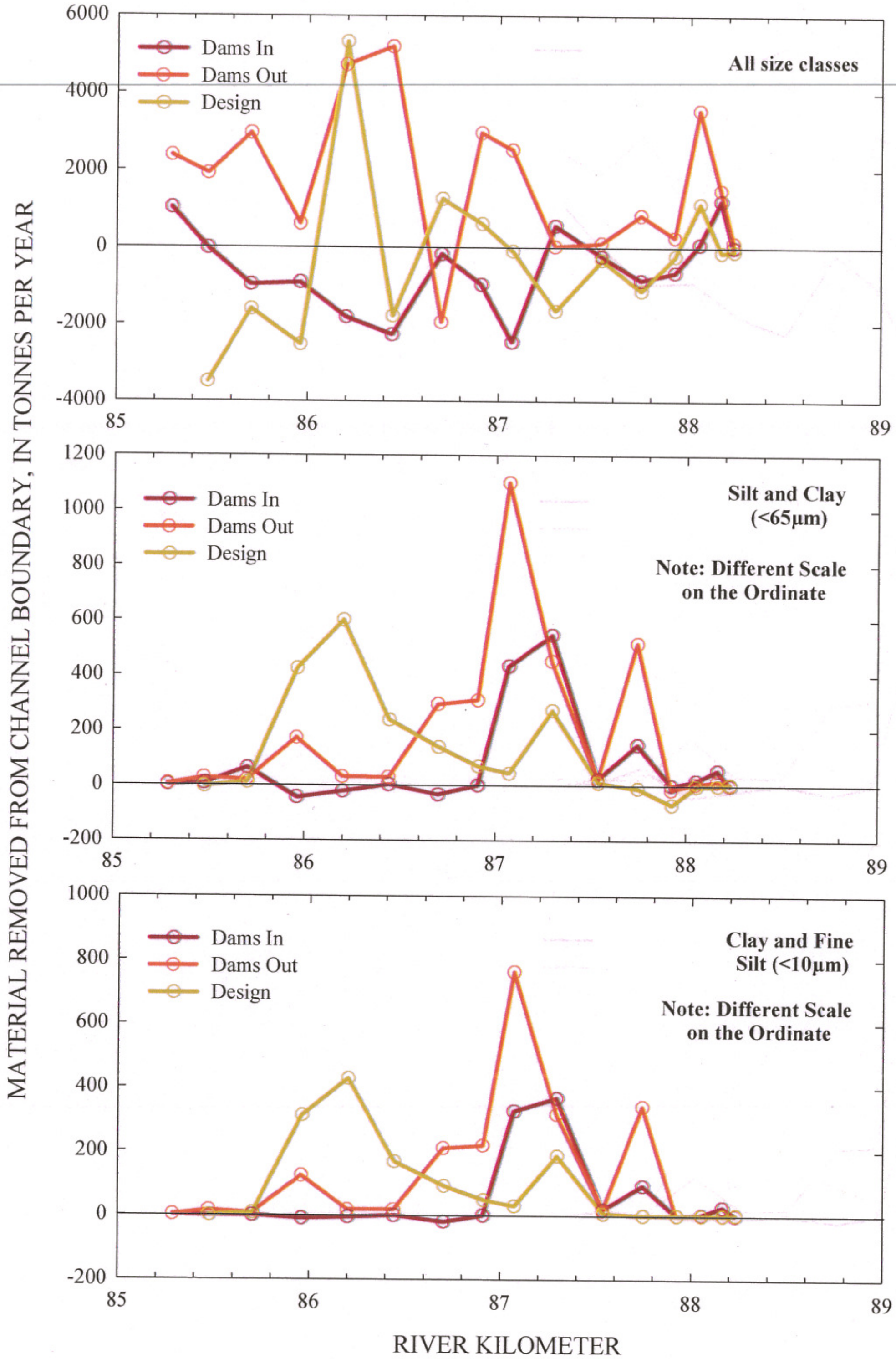

Figure 21 – Contributions from the channel boundary for the three modeling scenarios, by size class in the Plainwell to Otsego (POC) reach.

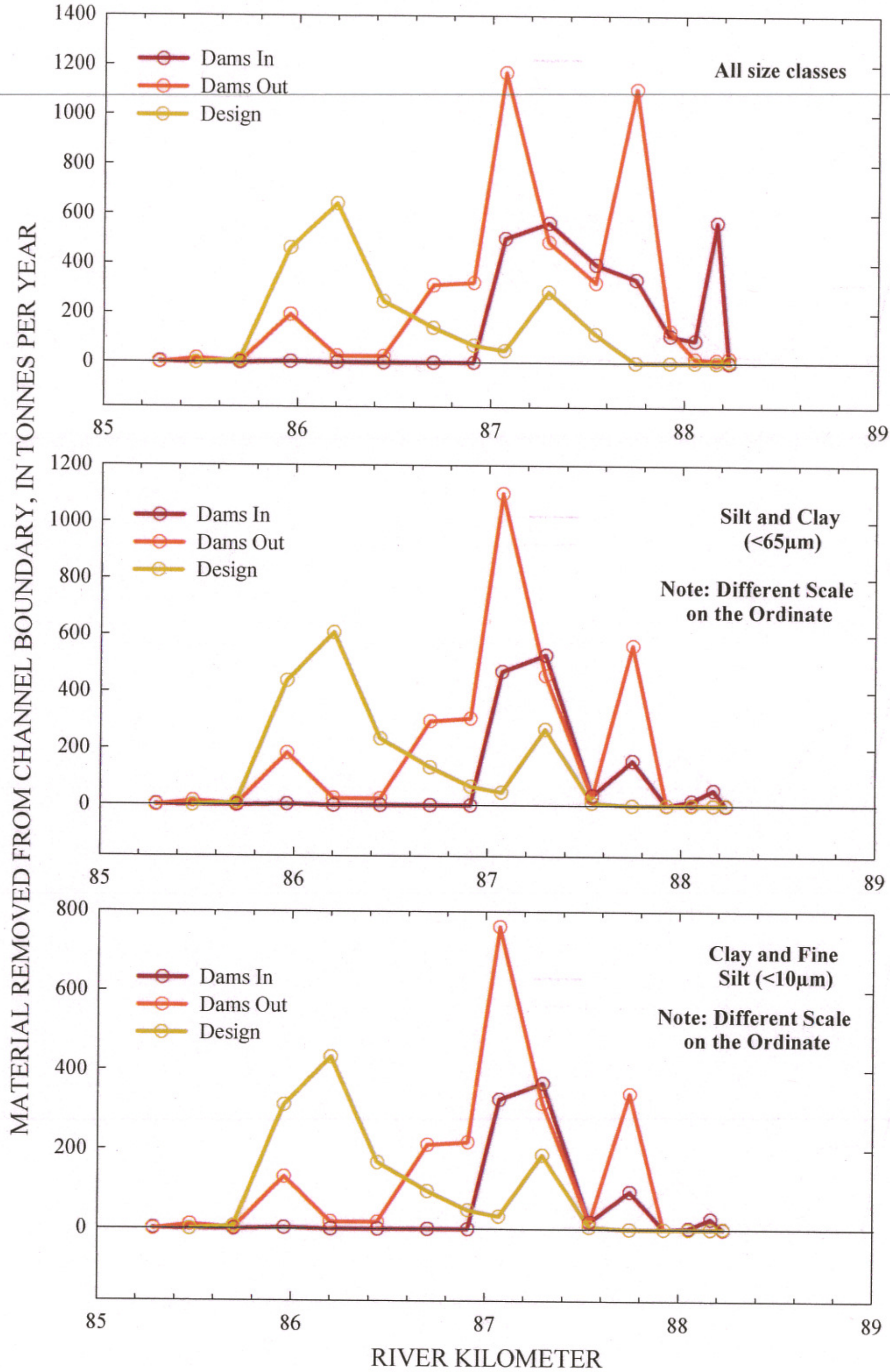

Figure 22 - Contributions from the channel banks for the three modeling scenarios, by size class in the Plainwell to Otsego (POC) reach.

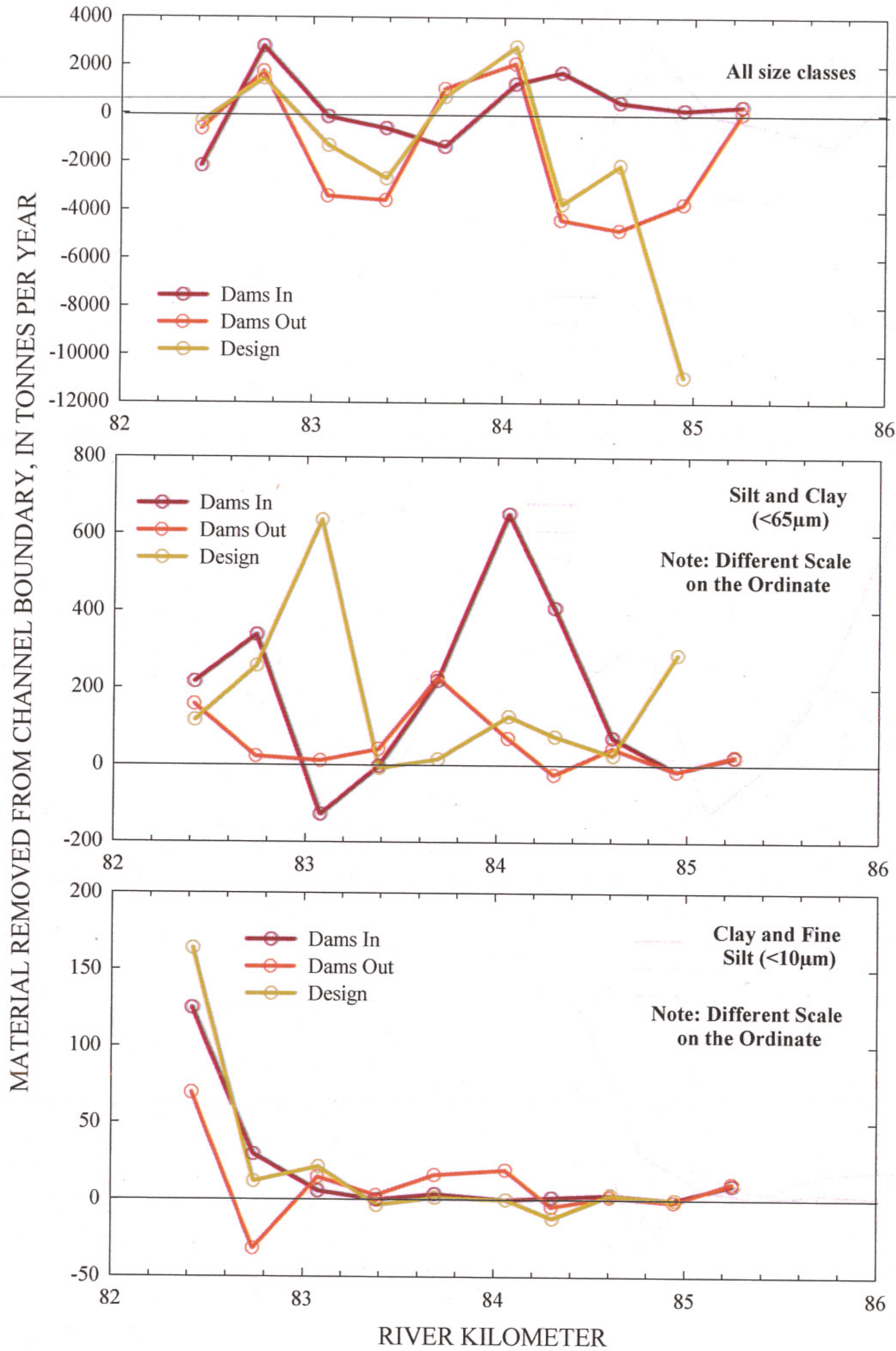

Figure 23 – Contributions from the channel boundary for the three modeling scenarios, by size class in the Otsego (OC) reach.

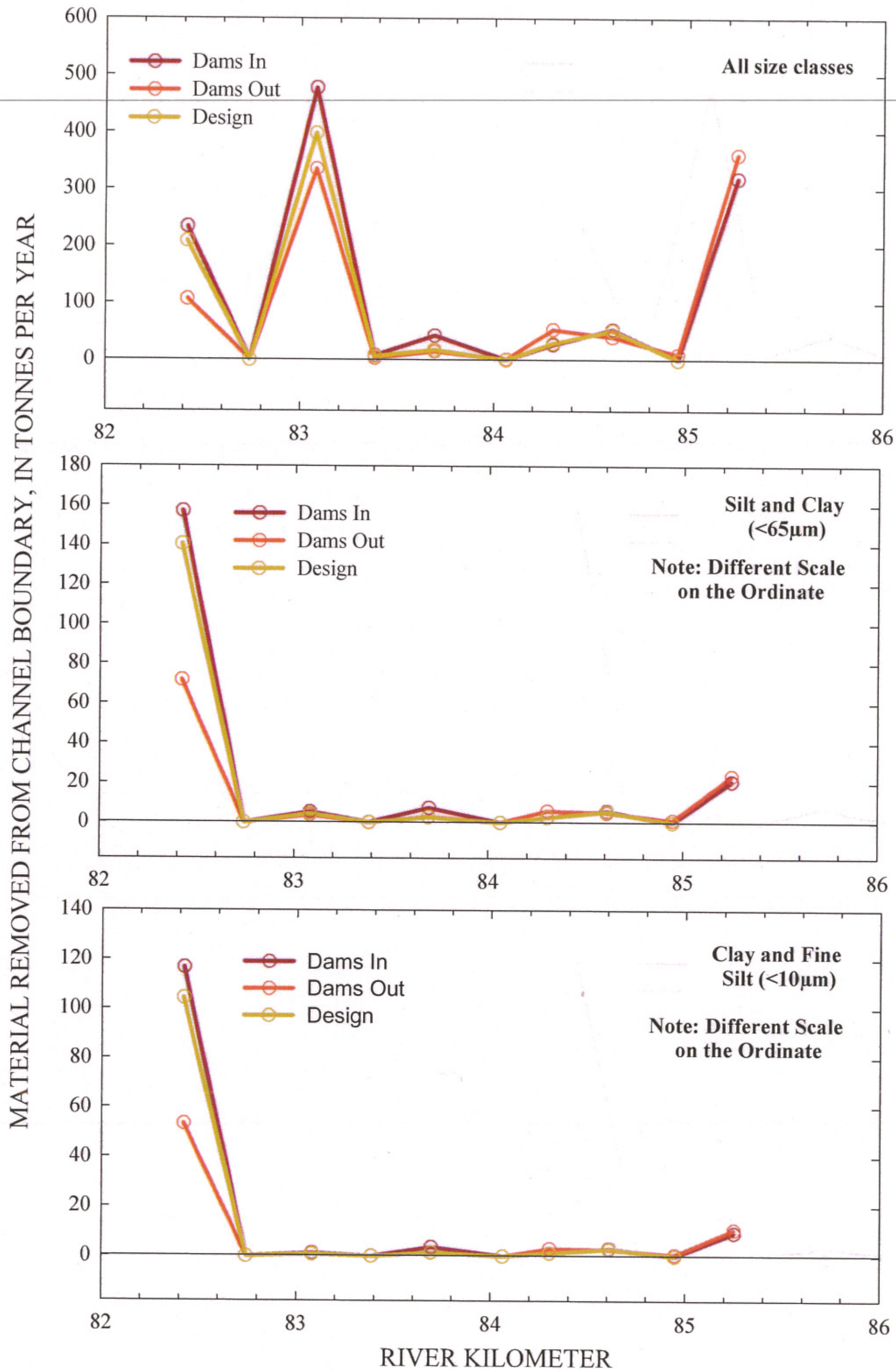

Figure 24 – Contributions from the channel banks for the three modeling scenarios, by size class in the Otsego (OC) reach.

4.0 SUMMARY and CONCLUSIONS

Three numerical simulations were carried out over a 17.7-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).

Total change in boundary sediments for the DI case show a net erosion of 3670 T/y at the downstream boundary. The Plainwell reach contributed 9660 T/y (erosion), the POC reach contributed 8480 T/y (deposition), and the OC reach contributed 2490 T/y (erosion). The average annual sediment load (suspended and bed load) at the downstream boundary is 5010 T/y. Total change in boundary sediments for the DO case show a net erosion of 41,600 T/y at the downstream boundary. The Plainwell reach contributed 29,600 T/y (erosion), the POC reach contributed 27,700 T/y (erosion), and the OC reach contributed 15,600 T/y (deposition). The average annual sediment load (suspended and bed load) at the downstream boundary is 59,200 T/y. Total change in boundary sediments for the D case show a net erosion of 3870 T/y at the downstream boundary. The Plainwell reach contributed 24,800 T/y (erosion), the POC reach contributed 4790 T/y (deposition), and the OC reach contributed 16,100 T/y (deposition). The average annual sediment load (suspended and bed load) at the downstream boundary is 20,100 T/y.

Fine-grained loads (<65μm and <10μm) show a similar pattern as total loads with the DI case contributing 3570 T/y and 993 T/y, the DO case contributing 5790 T/y and 2220 T/y, and the D case contributing 5100 T/y and 1500 T/y. For the DI case, the banks contributed 42% of the total in the 65μm class and 99% of the total in the 10μm class. For the DO case, the banks contributed 56% of the total in the 65μm class and 98% of the total in the 10μm class. For the D case, the banks contributed 40% of the total in the 65μm class and 95% of the total in the 10μm class.

Bank erosion and bed erosion increased significantly with the DO case, where bed erosion in the Plainwell reach increased from 9590 T/y to 29,300 T/y. Bank erosion increased from 86.1 T/y (DI) to 263 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 12 times, the erosion of material finer than 10μm 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 (20,100 T/y) the DO case but still 4 times greater than the DI case. The relative contribution to the 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.

5.0 ACKNOWLEDGMENTS

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