MULTIPLE APPROACHES TO ASSESSING THE IMPACT OF DAMS ON SEDIMENT DELIVERY IN THE ST. JOSEPH RIVER WATERSHED, MICHIGAN/ILLINOIS

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Abstract: The rates at which sediment moves through the St. Joseph River and its tributaries and watershed have been subject to significant human modification over the past 200 years. These modifications include logging, development of agricultural land, dam construction, urbanization and river channel alteration. The first major dam was constructed in 1850 and 66 large dams now exist in the watershed. Only 13% of the watershed now drains directly to the river mouth, and dams form a significant trap for sediment sourced from the remaining 87% of the watershed.

This study was undertaken as part of the US Army Corps of Engineers Great Lakes Tributary Modeling Program. A wide variety of techniques were used to assess the role of dams in altering sediment movement through the St. Joseph River watershed. Trap efficiency analysis was undertaken using the capacity-watershed and the capacity-inflow methods. Watershed sediment yield and delivery were under changing land uses were assessed using the Watershed Characterization System (EPA) and the Soil Water Assessment Tool (USDA-ARS). Acoustic bathymetric sediment surveys were taken of the larger downstream reservoirs in the watershed along with samples of trapped sediment. Historic dredging records of the navigable area of the lower river over a 150-year period were also evaluated to determine sedimentation rates in the lower river channel. A two-dimensional hydrodynamic and sediment transport model (RMA2-SED2D) was set up to examine the effects of modified upstream sediment delivery on the morphodynamics of the harbor and river mouth and to use the dredging data to test the sediment delivery model result over the last 150 years (i.e. by establishing the trapping rate of the harbor area).

The combination of the varied techniques outlined above allowed a detailed analysis of the role of dams in modifying watershed sediment movement in the face of changes to other watershed characteristics such as land use, BMPs and soil conservation practices. Evaluation using only one or two of the above techniques would have precluded identification of the role of dams in reducing sediment delivery to the lower river as their likely effect would not have been isolated from other factors. Dams were found to be effective in trapping up to 80% of sediment supplied from the upper watershed, with other factors such as in-channel sedimentation further reducing sediment supply to the river mouth. The merits of the various methods are discussed, along with challenges and benefits of their integration for assessment of sediment delivery.

INTRODUCTION

The U.S. Army Corps of Engineers is directed to develop sediment transport models for tributaries to the Great Lakes that discharge to Federal navigation channels or Areas of Concern (AOCs). These models are being developed to assist State and local resource agencies in evaluating alternatives for soil conservation and non-point source pollution prevention in the tributary watersheds. The ultimate goal is to support State and local measures that will reduce the loading of sediments to navigation channels and AOCs, and thereby reduce the costs for navigation maintenance and sediment remediation. A suite of models including the Soil and Water Assessment Tool, SWAT and the RMA2/SED-2D hydrodynamic and sediment transport models were developed to further understand sediment movement through the St. Joseph River Watershed. SWAT was constructed for the entire watershed so that significant sediment source areas could be identified, and the effects of land use change, best management practices (BMPs) and the impact of dams on sediment movement through the watershed could be evaluated. RMA2-SED2D model construction enabled upstream sediment delivery rates and harbor sediment trapping and throughput to be evaluated, allowing construction of a sediment budget, which formed the primary long-term sediment delivery calibration points for the SWAT model.

STUDY AREA

The St. Joseph River Watershed is a part of the Lake Michigan Basin, comprising 1.6 percent of its contributing area. The St. Joseph River main channel is 210 miles long and has over 1,641 miles of significant tributaries. The watershed covers 4,685 square miles-3,000 in Michigan and 1,685 square miles in Indiana. The river has a fall of over 600 feet from the source to its discharge into Lake Michigan.

METHODOLOGY

The Soil and Water Assessment Tool (SWAT) is a watershed-scale numerical model for the simulation of water, sediment, nutrient and pesticide movement in surface and subsurface systems. SWAT aids in prediction of the impacts of climate and vegetative changes, reservoir management, groundwater withdrawals, water transfer, land use change and watershed management practices on water, sediment and chemical dynamics in complex watershed systems. Land use and management conditions can be varied over long time periods, making the model a particularly useful tool to aid in the evaluation of BMPs. SWAT is a continuous-time model, intended for the prediction of long-term water and sediment yields from a watershed.

A detailed hydrodynamic model (RMA2) and an associated sediment transport model (SED2D) were set up to evaluate sediment movement through the harbor and into the nearshore zone. The main objectives of this exercise were to provide estimates of sediment movement through the harbor over long time periods and to evaluate the impact of dredging the inner harbor on sediment discharges to the nearshore zone. RMA2 is a two-dimensional, depth-averaged, finite element hydrodynamic numerical model. It computes water surface elevations and horizontal velocity components for subcritical, free-surface flow in two-dimensional flow fields. The original model was developed by Norton, King and Orlob (1973) for the US Army Corps of Engineers. Many subsequent enhancements have been made, culminating in the current version of the code. The program has been applied to calculate water levels and flow patterns in rivers, reservoirs, and estuaries.

The sediment transport model, SED2D is coupled with the RMA2 model. SED2D is a sediment transport numerical model developed by the U.S. Army Corps of Engineers Waterways Experiment Station. It has the ability to compute sediment loadings and bed elevation changes when supplied with a hydrodynamic solution computed by RMA2. SED2D can be used to model sand bed types or clay/silt bed types. It is possible to model both steady-state and transient flow types, just as with RMA2. The RMA2-SED2D model domain was set up for an area including the lower St. Joseph River up to approximately 3 miles upstream from the inner harbor; the Paw Paw River for approximately 2 miles upstream from the inner harbor; the inner and outer harbor; and the lake for approximately 2.5 miles upstream and downstream from the harbor, and for 1 mile offshore. Full details of setup, calibration and verification of these models are available on request from the authors.

RESULTS

Effect of Land Use Change: The pre-European settlement delivery rate to the harbor was estimated by SWAT to be 28,000 cy/yr (Table 1). The estimate was generated with SWAT using land use circa 1800-1830 for Michigan, and an estimated 1830 land use for Indiana. The estimated pre-development sediment delivery value of 28,000 cy/yr suggests that sediment transport in the St Joseph watershed was much lower than modern values. Soil erosion and sediment delivery to the harbor mouth were much higher for the 1978 model runs than for the pre-European settlement scenario. Since the 1978 land cover data did not divide agricultural land into subcategories, two sets of model runs were created using this dataset. One run used a generic agriculture term and the second run categorized all unclassified agricultural land as row crops to provide the upper limit to soil erosion and sediment yield predictions. These two runs predicted sediment delivery to the inner harbor of 68,000 cy/yr and 79,000 cy/yr respectively.

Table 1 Summary of SWAT Model Output.

Year	Model Conditions	Total Soil Erosion in Watershed (cy per year)	Total Sediment at Inner Harbor (cy per year)
1830	Pre-development	72,000	28,000
1978	Generic Agriculture;	850,000	68,000
1978	Row Crops	1,118,000	79,000
1992	Reference Condition	884,000	57,000

For the 1992 land cover data (which was classified into component agricultural uses), sediment delivery was predicted to be 57,000 cy/yr. This is lower than the 1978 values because land has been taken out of agricultural production in the intervening years, causing a drop in soil erosion and sediment supply to the harbor.

Effect of Dams: There are 190 dams in the St. Joseph River Watershed (Michigan Department of Natural Resources, 1999). Since 1850, 65 major dams have been constructed in the St. Joseph

Watershed (Table 2). In 1850 the first major dam was constructed at South Bend, with 76% of the watershed located upstream of the dam. Dam construction continued from this time, with the large Twin Branch Dam in 1903, and the Berrien Springs Dam in 1908, resulting in the 87% of the watershed being above major impoundments (Figure 1).

Table 2 Number of dams categorized by reservoir size from EPA (2005).

Dam Size	Storage (ac-ft)	Normal Storage	Maximum Storage	High Hazard	Significant Hazard	Low Hazard
Small	1-100	20	12	2	3	7
Medium	100-10,000	43	51	19	12	20
Large	10,000-1,000,000	1	1	1	0	0
Very Large	>1,000,000	0	0	0	0	0
Unknown		2	2	0	2	0

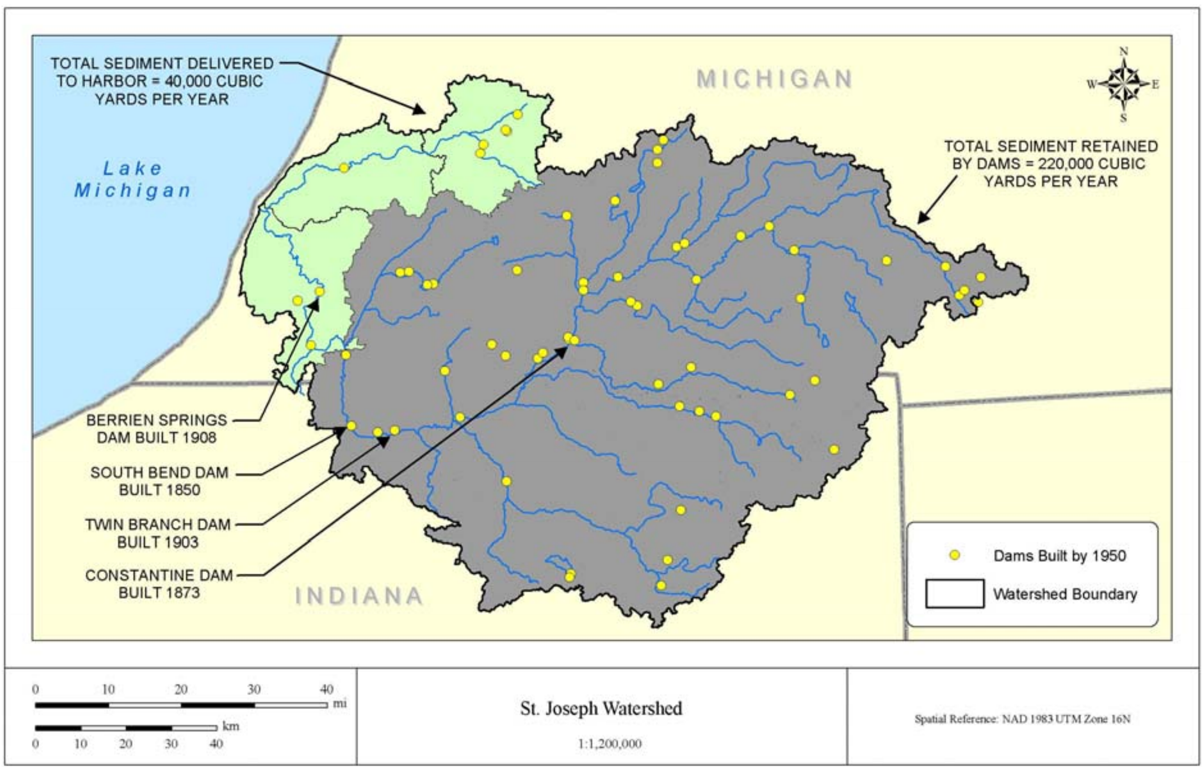

Figure 1 Influence of Dams on Sediment Supply From the River to St. Joseph Harbor.

These large dams are efficient sediment traps, regardless of whether they are underspill or overspill in construction. Either type of dam is an efficient trap because the sediment is not only trapped by the physical structure of the dam, but settles out in the slow moving water impounded for distances reaching several miles upstream from the dam. For example, the Twin Branch Dam impounds over 9 miles of main river, and has velocities that rarely exceed 1.5 ft/s. River flow data from 1930 was compared with a sediment transport capacity curve to determine an average annual sediment transport capacity of 20 tonnes per year in the Twin Branch Reservoir for particles in excess of 0.25 mm diameter. This means that any sediment delivered in excess of this amount will be trapped in the reservoir above Twin Branch Dam.

In addition to using standard empirical relationships to examine trapping efficiency, the SWAT model was set up to evaluate the effect of dams on sediment movement through the watershed and sediment delivery to the harbor mouth. There are several options for estimating reservoir outflow in SWAT. The option used for simulating the effect of dams in the St. Joseph SWAT model requires an average annual spillway release rate. If the volume in the reservoir exceeds the principle storage, then water is released at the average annual rate. If the volume exceeds the emergency spillway, the difference between that and the principal volume is released within one day.

Table 3 shows a summary of the SWAT model results for the influence of dams on sediment delivery to the harbor mouth. These runs were undertaken for the 1992 land cover data as it is the most recent complete dataset. Table 3.3 shows that the presence of dams in the watershed reduces total sediment supply to the inner harbor from 283,000 cy/yr to 57,000 cy/yr: a reduction of 226,000 cy/yr, or 80%, between the two scenarios. Sediment supply from the Paw Paw River, a tributary to the harbour, remains at approximately 15,000 cy/yr due to the negligible influence of dams on this tributary. Figure 2 shows the effect of dams on sediment delivery downstream through the watershed, showing high amounts of sediment delivered downstream without the dams, but a low sediment delivery throughout the catchment with dams present.

Table 3 SWAT model output showing influence of dams on total sediment delivery to the St. Joseph harbor.

Year	**Model Conditions**	**Total Soil Erosion in the Watershed (cy/yr)**	**Total Sediment at Inner Harbor (cy/yr)**
1992	Reference Condition	884,000	57,000
1992	No dams or reservoirs	884,000	283,000

The estimate of reservoir sedimentation compares well with empirical estimates from other sources. Chanson (1999) provides reservoir sedimentation rates in the continental US with a mean value of 10,310 cy/mi^2/yr. With the surface area of BASINS dams in the St. Joseph watershed being 15.94 square miles, multiplication of these values gives an empirical estimate of reservoir sedimentation of 165,000 cy/yr. This value compares well to the 226,000 cy/yr predicted by the SWAT model.

In summary, 65 major dams now exist within the St. Joseph River and only 13% of the watershed is able to drain directly and carry sand freely to the river mouth area. According to the SWAT model output, of the current total supply from the entire watershed of about 884,000 cy/yr of sediment (of which about 50% is sand), 226,000 cy/yr is trapped by dams and reservoirs and 601,000 cy/yr is held in other sediment sinks, such as in-channel deposition. Only 57,000 cy/yr (of which about 50 % is sand) is able to reach the inner harbor and river mouth (with a considerable portion of this delivered by the Paw Paw River tributary that feeds directly into the inner channel).

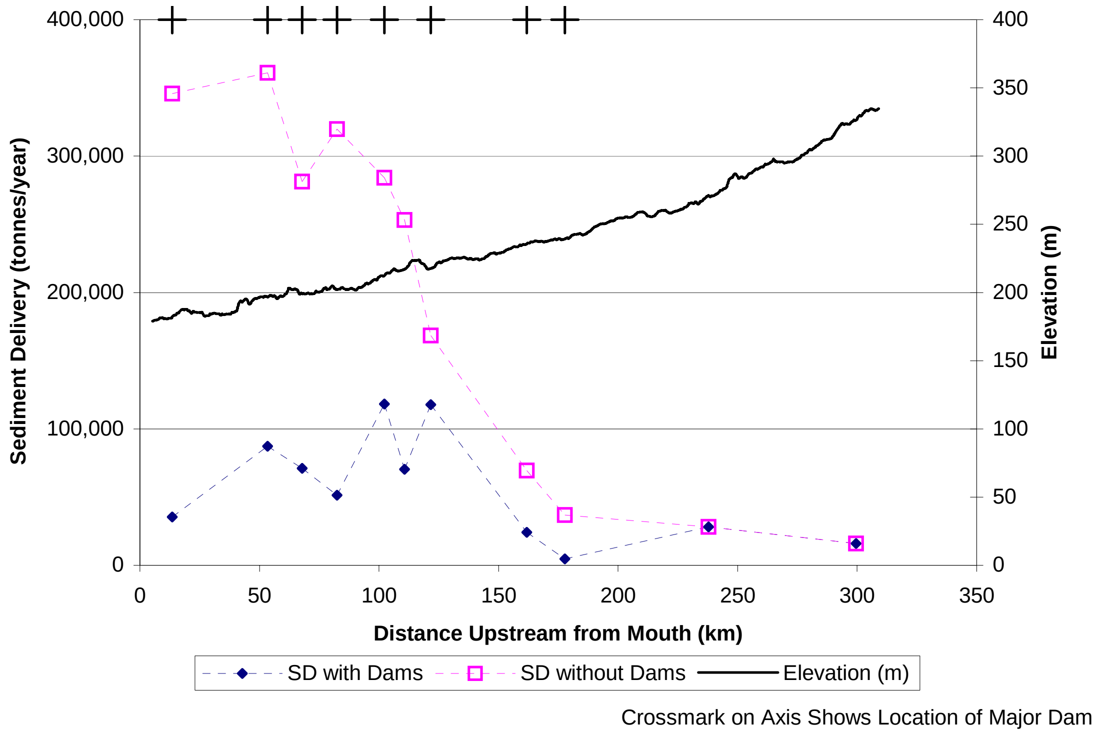

Figure 2 Effect of Dams on Watershed Sediment Delivery.

Harbor Sediment Trapping: A detailed hydrodynamic model (RMA2) and an associated sediment transport model (SED2D) were set up to evaluate sediment movement through the harbor and into the nearshore zone. In addition, an empirical analysis of river discharge and sediment load data produced a distribution of the amount of sediment transported by river flows of different magnitude. This showed that most sediment is transported in flows ranging from 3,500-4,900 ft^3/s. These flows have return periods in the range of 0.5-1.0 years.

Under mean flow conditions, most deposition is upstream from the inner harbor, and no sand reaches the harbor or lake (Figure 3). This is primarily due to the wide, deep, low gradient channel upstream from the harbor acting as a very efficient sediment trap under these conditions. It is only once flow is above the 1-year return period level that sand is transported into the inner harbor, and even at this stage, the amount deposited in the inner harbor is small compared to that deposited in the main channel upstream.

Figure 3 Velocity and Sediment Concentration in the St. Joseph Harbor.

Output from SED2D was then used to produce a set of look-up tables of sediment load for different flow and lake level scenarios. Daily sediment load from 1930 to present was derived by cross-referencing the look-up tables with the time series of river flows and lake level, thus giving a long-term prediction of sediment transport through the harbor. For the 2002 bathymetry, over the long term, the inner harbor traps approximately 50% of the sediment that enters, and 50% is transported to the outer harbor and lake. However, during the period from January 1988 to December 1997, the inner harbor trapped 67% of the entering sediment. This likely reflects an increased occurrence of flood events with a 1 to 3 year return period during this time.

CONCLUSIONS

Use of the SWAT model to evaluate watershed hydrology, sediment yield and sediment delivery in the St. Joseph Watershed greatly aided evaluation of a number of key topics in this watershed. Watershed sediment yield has increased approximately ten-fold since pre-settlement conditions, due to conversion of land from primarily forested to agricultural, and subsequently to urban land uses. Sediment delivery to the lake has approximately doubled as a result of these activities. However, watershed sediment delivery would be much higher were it not for the influence of many large dams and reservoirs in this watershed. SWAT proved to be a valuable tool in evaluating these parameters in such a large watershed. The use of harbor dredging data were vital as a measure of long-term sediment load in the St. Joseph River, and this provided valuable long-term calibration points for the SWAT model. However, it was only possible to link the dredging data to watershed sediment delivery by the use of the RMA2-SED2D model system to evaluate harbor sediment dynamics and sediment trapping efficiency over a long-term period.

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