BUILDING A BETTER UNDERSTANDING OF SEDIMENT ISSUES THROUGH THE APPLICATION OF A LONG-TERM FLUVIAL AND LITTORAL SEDIMENT BUDGET

Jim Selegean, Ph.D., P.E., P.H., Hydraulic Engineer, U.S. Army Corps of Engineers, Detroit, MI, james.p.selegean@usace.army.mil; Rob Nairn, Ph.D., P.Eng., Principal, Baird and Associates, Oakville, ON, rnairn@baird.com; Travis Dahl, P.E., Hydraulic Engineer, U.S. Army Corps of Engineers, Detroit, MI, Travis.A.Dahl@usace.army.mil; Calvin Creech, P.E., Hydraulic Engineer, U.S. Army Corps of Engineers, Detroit, MI, Calvin.T.Creech@usace.army.mil

Abstract Prior to European settlement, the St. Joseph River watershed was enveloped in a closed forest and produced very little sediment. Throughout the 1800s, the forests were cleared, agricultural activities began to dominate the landscape and dams were constructed. All of these activities affected sediment delivery to the federal harbor at St. Joseph, Michigan, USA and to the Lake Michigan littoral zone. A fluvial sediment budget was constructed by combining sediment yield model results with historic data sets and historic maps to examine the effects of land cover changes and dams from pre-European settlement to the present.

Simultaneously, changes were occurring along the shoreline, such as jetty construction, shoreline armoring and dredging, that altered the sediment supply to the littoral zone. A littoral sediment budget was similarly constructed. To build a better understanding of sediment supply to the littoral zone and how its components have affected coastal erosion over a 170-year time span, the fluvial and littoral sediment budgets were combined with the use of a multidimensional hydrodynamic and sediment transport model to quantify temporal changes in the sediment supply.

INTRODUCTION

The U.S. Army Corps of Engineers, Detroit District has build 92 harbors in Lakes Michigan, Huron, Superior and Erie. One of the Corps major missions is to maintain the navigability of these harbors. In 2008, the Detroit District dredging over 2 million cubic yards of sediment from federal navigation channels. Field data, numerical models and historical accounts were employed to build a better understanding of the sources of sediment delivered to the harbor at St. Joseph, Michigan, USA, with the goal of reducing dredging costs.

At the mouth of the St. Joseph River a sediment budget was constructed that consisted of littoral and fluvial sources that span a temporal range from pre-European settlement to the present. A set of computational tools were used to evaluate watershed hydrology, net erosion, sediment delivery, river channel hydrodynamics and sediment transport in the St. Joseph River Watershed. These models were developed to gain a general understanding of the hydrologic and geomorphic behavior of the watershed and to predict the effects of changing land use on subwatershed scale erosion and sediment delivery and to evaluate the impact of dam construction on sediment delivery to the watershed outlet. Models were calibrated against river flow and sediment transport records, reservoir sedimentation surveys and harbor dredging records.

The Soil and Water Assessment Tool, SWAT (Arnold et al., 1996) and the RMA2-SED-2D hydrodynamic and sediment transport models (King et al., 2006; Letter Jr. et al., 1998) were

employed 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, and the impact of dams on sediment movement through the watershed could be evaluated. An application of the RMA2-SED2D model 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 validation 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 338 km long and has over 2,600 km of significant tributaries (EPA, 2005). The watershed covers 12,134 km^2 – 7,770 km^2 in Michigan and 4,364 km^2 in Indiana. The river has a fall of over 180 m from the source to its discharge into Lake Michigan (EPA, 2005).

The notes of the General Land Office section surveyors, summarized in Dickmann and Leefers (2003), and a Michigan land use coverage map based on original surveyors tree data and descriptions of the vegetation and land between 1816 and 1856 (Corner et al., 1995), indicate the early 19th century St. Joseph Watershed was heavily forested with meadows, lakes and wetlands. The first major human impact on land use was the large scale logging activities through the latter half of the 1800's (Dickmann and Leefers, 2003).

STUDY METHODS

A combination of empirical analysis and numerical modeling techniques was used to assess the roles of land-use change and dam construction in altering sediment movement through the watershed. Watershed sediment yield and delivery under changing land uses were assessed using the SWAT model. Historic dredging records of the navigable lower river over a 150-year period were evaluated to determine sedimentation rates. A two-dimensional hydrodynamic and sediment transport model, RMA2-SED2D, was used to examine the effects of upstream sediment delivery on the morphodynamics of the harbor and river mouth and to use the dredging data to evaluate the sediment delivery model through establishment of historic harbor sediment trapping rates. The combination of techniques allowed a detailed analysis of the role of dams in modifying watershed sediment movement in the face of changes to land use 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 estimated to trap up to 80% of sediment supplied from the upper watershed, with in-channel sedimentation further reducing sediment supply to the river mouth.

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. SWAT is a continuous-time model, intended for the prediction of long-term water and

sediment yields from a large watershed, and it is well suited to the evaluation of land use change and other conditions, such as dam construction, over long time periods. A detailed description of the set-up, calibration and validation of the SWAT model can be found in USACE (2007).

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 RMA2-SED2D model domain was set up for an area including the lower St. Joseph River up to approximately 5 km upstream from the inner harbor; the Paw Paw River for approximately 3 km upstream from the inner harbor; the inner and outer harbor; and the lake for approximately 4 km upstream and downstream from the harbor, and for 2 km offshore. The model bathymetry was set up to represent bathymetry from surveys taken in 2002 and 1907.

The primary inputs to the RMA2 model (in addition to bathymetry) are lake level data downstream and river flow data at the upstream boundaries in the St. Joseph and Paw Paw Rivers. The most complete set of continuous flow data is available from the USGS gage at Niles, with a record from 1930 to present. Records of Total Suspended Solids (TSS) or Suspended Sediment Concentration (SSC) are coincident with this record, both at Niles and in other nearby locations.

A broad range of conditions needed to be modeled using the RMA2-SED2D system. To increase the efficiency of analysis, RMA2 was run in steady-state mode under different lake level and river flow conditions. Ten different river flows in the St. Joseph River were modeled, along with 3 different lake levels and 3 different flows in the Paw Paw River, to give a total of 90 (10 x 3 x 3) model runs for each scenario.

Once the hydrodynamic solution has been created by running RMA2, sediment transport is computed using SED2D. 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. SED2D requires an initial sediment concentration and sediment input at the upstream boundaries of the model. These were calculated from a sediment rating curve established for Niles and nearby TSS and SSC data. SED2D was then run for each of the 90 flow/lake level scenarios examined by RMA2, and for each of the 3 bathymetric configurations.

RESULTS

Effects of Land Use Change The pre-development (i.e. pre-European settlement) delivery rate to the harbor was estimated using SWAT to be 21,400 m^3/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 suggests that sediment transport in the St Joseph watershed was much lower than modern values, which is corroborated by observations by the U.S. Army Topographic Engineering Bureau in 1835 (Berrien, 1835) that very little sediment was delivered to the river mouth, even under spring flood conditions. Predicted soil erosion and sediment delivery to the harbor mouth were much higher for the 1978 model runs. 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 51,990 m^3/yr and 60,400 m^3/yr, respectively. For the 1992 land cover data (which was classified into component agricultural uses), sediment delivery was predicted to be 43,600 m^3/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.

Table 1 Summary of SWAT Model Output.

Year	Model Conditions	Total Soil Erosion in Watershed (m^3 / yr)	Total Sediment at Inner Harbor (m^3 / yr)
1830	Pre-development	55,000	21,400
1978	Generic Agriculture	649,900	51,990
1978	Row Crops	855,000	60,400
1992	Detailed Agricultural Condition	676,000	43,600

The major human impact on sediment delivery was large scale logging activities through the latter half of the 1800's (see Dickmann and Leefers, 2003). With the removal of large areas of tree cover, runoff would have reached the tributaries and the St. Joseph River much more quickly, increasing the intensity of flood flows. This, combined with reduced infiltration and increased overland flow, would have caused flashier flood peaks in the river channels. Therefore, the elimination of large areas of tree cover would have resulted in increased riverbank and bed erosion and an associated significant increase in sediment eroded from the watershed.

The onset of agricultural development, taking advantage of land cleared through logging or through clearing new lands, would have followed the large scale logging activities. When agriculture reached its peak in the mid 1900's, the river sediment load would also have achieved its maximum. This is because the greatest intensity of soil erosion in the watershed takes place on agricultural lands, and without modern conservation measures, much of this eroded sediment is delivered to the river channel system.

Influence of Dams on Sediment Delivery 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 (EPA, 2005). In 1850 the first major dam was

constructed at South Bend and this would have intercepted most, if not all, of the sand generated from 76% of the watershed located upstream of the dam. Dam construction continued through this period and the construction of the large Twin Branch Dam in 1903, and the Berrien Springs Dam in 1908, resulted in the interception of sediment load from 87% of the watershed. The Twin Branch Dam impounds over 14 km of the main river, and has velocities that rarely exceed 0.5 m/s during extreme flood conditions. River flow data from 1930 was compared with a sediment transport capacity curve to determine an average annual sediment transport capacity of the reservoir. The Twin Branch Reservoir has an average annual sediment transport capacity of 20 tonnes per year for particles in excess of 0.25 mm diameter and any sediment in excess of this amount is likely to be trapped in the reservoir above Twin Branch Dam. The trapping capability of the Twin Branch reservoir was checked using the HECRAS model (USACE; unpublished data), which determined that more than 99.9% of the supplied sand is trapped.

Table 2 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 2 shows that the presence of dams in the watershed reduces total sediment at the harbor mouth from 216,000 m^3/yr to 44,000 m^3/yr, a reduction of 172,000 m^3/yr, or 80%, between the two scenarios.

Table 2 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 (m^3 per year)	Total Sediment at Mouth of Paw Paw (m^3 per year)	Total Sediment at Harbor Mouth (m^3 per year)
1992	Reference Condition	675,000	11,000	44,000
1992	No Dams or Reservoirs	675,000	11,000	216,000

Harbor Sediment Trapping The 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. Under low flows, no sand reaches the inner harbor from the St. Joseph River, and any sand in the Paw Paw River is deposited upstream from the inner harbor. Under mean flow conditions deposition is still upstream from the inner harbor, and no sand reaches the harbor or lake. 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 the 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. Once a flow approaching a 2- to 5-year return period occurs, sand is moved through the inner harbor and deposited in the outer harbor. Only rarely (during an event with a greater than 5-year return period) is sand transported out into the littoral zone, and an event of this magnitude was not observed between 1950 and 1980.

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 55% of the sediment that enters, and 45% 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. This would cause increased deposition in the inner harbor. For the 1907 scenario, trapping efficiency in the inner harbor is lower than in 2002, with approximately 46% of supplied sediment being trapped. This reflects the shallower conditions in the inner harbor at this time, so more sediment was moved through the inner harbor during lower magnitude events.

Dredging records dating back to 1879 were reviewed to determine the amount of maintenance dredging associated with the inner and outer channel areas. Over the last 35 years, the inner channel dredging has been in the range of 10,700 to 17,500 m^3/yr (sand only). The comparison of dredging records to watershed sediment supply and harbor sediment trapping was limited to the sand size fraction as this study was part of a larger study considering supply of sand to the littoral zone outside the harbor. The fraction of sand deposited in the inner channel varies with time from 30 to 60% of the total quantity of sediment delivered by the river (depending on the strength of flood flows in any given year). From the data available since about 1960, the rate of outer channel dredging has averaged about 22,900 m^3/yr of sand.

The inner channel dredging would appear to have been responsible for the peak in total maintenance dredging in the 1950's and 1960's, along with several very large precipitation and river flow events in the 1940s and 1950s that would have delivered large quantities of sediment to the inner channel, as demonstrated by the RMA2/SED2D predictions for flow events of similar magnitude. This peak is also consistent with SWAT model predictions of watershed sediment supply (see USACE 2007 for a full discussion). Observations by others also suggest that this period corresponded to the highest erosion of agricultural land, due to extensive agriculture and poor soil conservation practices (see Trimble and Crosson 2000).

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.

REFERENCES

Arnold J.G., Williams J.R., Srinivasan R., and King K.W. (1996). "SWAT – Soil and water assessment tool." SWAT User's Manual. Texas A & M University. Temple, TX.

Berrien, J.M. (1835). "Letter to Lt. Col. J.J. Abert, Chief of Topographical Bureau." Report from Secretary of War to U.S. Senate. 3rd Congress, 2nd Session.

Corner P.J., Albert D.A., Wells H.A., and Hart B.L. (1995). "Michigan's native landscape, as interpreted from the GLO surveys 1816-1856." Michigan Natural Features Inventory, Michigan Department of Natural Resources (MDNR).

Dickmann D.L., and Leefers L.A. (2003). "The Forest of Michigan." The University of Michigan Press, Ann Arbor, Michigan.

EPA. (2005). "BASINS data for the St. Joseph Watershed, HUC #04050001."

King I., Donnell B.P., Letter Jr. J.P., McAnally Jr. W.H., Thomas W.A., and LaHatte C. (2006). "Users Guide for RMA2 Version 4.5." US Army, Engineer Research and Development Center, Waterways Experiment Station Coastal and Hydraulics Laboratory. 296 pp.

Letter Jr. J.V., Roig L.C., Donnel B.P., Thomas W.A., McAnally W.H., and Adamec Jr. S.A. (1998). "Users Manual for SED2D-WES Version 4.3 Beta, A Generalized Computer Program for Two-dimensional, Vertically Averaged Sediment Transport." US Army Corps of Engineers Waterways Experiment Station Coastal Hydraulics Laboratory, Vicksburg, MS. 188 pp.

Trimble S.W., and Crosson P. (2000). "U.S. soil erosion rates - myth or reality", *Science* 289: 248-250.

USACE (2007). "St. Joseph River Sediment Transport Modeling Study." U.S. Army Corps of Engineers, Detroit District study report.