MODEL STUDY: SHEBOYGAN RIVER
PHASE I: DATA COLLECTION & MODEL SELECTION

PREPARED FOR:

USACE, DETROIT DISTRICT
GREAT LAKES HYDRAULICS AND HYDROLOGY OFFICE
477 MICHIGAN AVE
DETROIT, MICHIGAN 48226
For further information, contact:
Dr. James P. Selegean, P.E. (313)226-6791

PREPARED BY:

W.F. BAIRD & ASSOCIATES LTD.
2981 YARMOUTH GREENWAY
MADISON, WISCONSIN, USA 53711
For further information, contact:
Dr. Rob Nairn, P. Eng (905)845-5385

9 FEBRUARY 2001
(UPDATED 20 JUNE 2001)

TABLE OF CONTENTS

1 INTRODUCTION

This report describes a preliminary investigation in support of the application of a hydrodynamic, sediment transport and erosion/deposition model for the Lower Sheboygan River. The work has been completed by Baird & Associates for the Detroit District office of the US Army Corps of Engineers to address the requirements of the USEPA. The purpose of the project is to develop a tool that is capable of evaluating erosion and deposition processes that can be used to evaluate alternatives being considered under the Record of Decision for this Superfund site. Specifically, the model will be applied to evaluate the scour potential of sediments in the lower 3 mile reach of the river under a 100 event and for a longer time period encompassing a series of events.

Phase I of this investigation consisted of a review of the available data and selection of an appropriate model. In order to apply a sediment transport model, data is required to describe the input or boundary conditions and to test the predictive capabilities of the model. Section 2 of this report summarizes a review of the available data, identification of data gaps and a proposed work plan to fill the data gaps. There is a wide range of possible models each with its strengths and limitations for given flow conditions, sediment characteristics and river morphology. Based on a consideration of these factors, the available models are reviewed and recommendations are made on an appropriate selection. Recommendations for the Phase II application of the data collection and modeling are summarized in Section 4.

2 REVIEW OF DATA

The data review is subdivided into three primary sections addressing:

1 Hydrographic and topographic survey data;

2 Flow conditions; and

3 Sediment characteristic (in-situ and dynamics).

Each of these sections is further divided into:

- description of the purpose of the data;
- summary of the available data;
- list of data gaps;
- proposed data collection plan.

2.1 Hydrographic and Topographic Survey Data

2.1.1 Data Requirements

Hydrographic and topographic survey data are required for two key reasons. First, an adequate description of the channel in plan and section is required to develop an accurate representation of the river course. This is boundary condition information. The second requirement is for snapshots in time of the river bed at the same locations to provide calibration and/or validation data. Specifically, this information provides an approximation of historic erosion/deposition to test the model.

2.1.2 Available Data

The following sources of hydrographic and topographic survey data are available within the project area:

1. Hydrographic information is available from the river mouth to Pennsylvania Avenue through the Corps of Engineers Kewaunee Office. This information includes cross sections located on 100 ft intervals with bank-to-bank coverage. This data is available digitally for 2000, 1999 and 1998. Hard copy prints are available for years 1979 through 1997. Elevations were gathered continuously

along each section for years 1998, 1999 and 2000 while elevations in previous years include elevations at 20-foot intervals.

2. Hydrographic information upstream of Pennsylvania Avenue to the USGS gaging station located at the Highway I43 crossing is available from a previous HEC-2 Model developed by the USACE. This information was also utilized by Blasland, Bouck & Lee, Inc. (BBL, 1998) for HEC-6 input to support a sediment transport investigation. Locations of these cross sections are indicated in Figure 1.

The HEC-2 Model has associated topographic information to the elevation of the 100 year flood for each section depicted in Figure 1. General topographic information is also available from the USGS 7.5 minute quadrangle map for the entire area.

2.1.3 Data Gaps

1. Existing hydrographic data from Pennsylvania Avenue to the river mouth is relatively comprehensive. Additional data requirements are not anticipated in this area to perform the proposed model investigation (i.e. with respect to either boundary condition information or validation data).

2. Existing hydrographic data from Pennsylvania Avenue upstream to the USGS gaging station located at I43 will need to be supplemented with additional data. These data are required to provided a better description of the river course, to update older data and to provide information on changes in river profile and section over the last 20 to 30 years.

3. Topographic information from Pennsylvania Avenue to the river mouth within the 100-flood plain is required to provide the boundary conditions for the 100 year flood.

2.1.4 Proposed Data Collection Plan

1. Perform approximately 17 new hydrographic sections between Pennsylvania Avenue and the USGS gaging station.

2. Gather topographic information at 7 sections located between the river mouth and the gaging station. Sections shall extend inland to include the 100-year flood elevation on each side of the river.

3. Repeat 10 sections that were originally performed as part of the USACE's HEC-2 Model Study for comparison analysis.

4. Locate and record the thalweg depth at all previously performed sections from the HEC-2 Study to update these boundary condition data.

A description of the proposed hydrographic and topographic data collection plan is provided in Figure 1.

Cost estimates to complete these surveys have been provided by Barr Engineering and by the USACE, Detroit District. It is planned that the surveys will be completed by April 30, 2001.

2.2 Velocity and Discharge Information

2.2.1 Data Requirements

The primary purpose of stage, discharge and velocity information is to define the upstream and downstream boundary conditions that drive the flow in the model. The use of measured velocities serves a secondary purpose of validating predicted flow velocity from the hydrodynamic model. Generally, this type of validation information is less essential than suspended sediment data owing to the higher confidence level and better parameterization of flow conditions. However, it is noted that detailed descriptions of velocity through the water column will be obtained from the University of Wisconsin instrumentation array in support of the sediment resuspension tests. This data will also be used to test the hydrodynamic predictions.

2.2.2 Available Data

1. The existing I43 gaging station, administered by the USGS, is currently active. It records data twice daily, Monday through Friday at approximately 8:00 am and 5:00 pm. Information is forwarded to the USGS website and is accessible to the public. Data can be reviewed for the current day in addition to the previous 6-day period. Real time discharge data can be obtained by comparing the river stage at the gage with a rating curve provided by the USGS. Historic data is also available in digital format.

2. Discharge and velocity data from a second gaging station located at the mouth of the river operated by the EPA during the Great Lakes PCB Loading Study in the mid 1990 may also be available. This information could provide downstream boundary information for the model. Lake level data is also available from gages at Milwaukee (9087057) and Kewaunee (9087068) Harbors and this will also be used to describe the downstream boundary condition, albeit to a lower level of accuracy and temporal resolution. It is our experience with hydrodynamic

modeling on several Great Lakes rivers that small changes in lake level have limited impact on flow conditions.

3. Information from a third gaging station operated by the USGS located at the 14th Street bridge between 1987 and 1991 may also be available.

2.2.3 Data Gaps

1. Some velocity data for validation of the hydrodynamic model.
2. Local downstream water level data with high temporal resolution.

2.2.4 Proposed Data Collection Plan

1. Velocity data will be collected through the vertical at one or two locations for one or two flow conditions.
2. Gather real time velocity/discharge information from the USGS gage during field investigations.
3. Gather water level information during the course of the field campaign to describe the downstream boundary condition and to compare to lake level records from other Milwaukee and Kewaunee to determine the extent of differences.

2.3 Sediment Characteristics and Dynamics

2.3.1 Data Requirements

Information on the sediment characteristics and dynamics are required to define boundary conditions and to provide calibration/validation data. The bed sediment grain size characteristics and the upstream boundary sediment load are essential input data. A ubiquitous weakness of these types of model investigations is a good definition of the incoming sediment load at the upstream boundary. Typically limited information is available on both the concentration and particle size distribution of the upstream sediment load and yet it can have a significant impact on predictions of future deposition (burial rates) and therefore, scour potential. Suspended sediment load measurements are required within the model domain to test the ability of the model to represent resuspension and settling characteristics. Finally, and importantly, an understanding of local sediment resuspension characteristics is required.

2.3.2 *Available Data*

The following suspended sediment data is available for the purposes of boundary condition definition and model validation:

1. Total suspended sediment measured by USGS at the I43 gaging station in 1980 (boundary condition data).

2. Total suspended sediment load measured at the USGS gaging station located near the mouth of the river from 1994-1995(validation data).

3. Total suspended sediment load measured at a USGS gaging station located at the 14th Street Bridge from 1987-1991 (validation data).

4. Total suspended sediment load measured by the WDNR at the 8th Street bridge from 1961-1976 (validation data).

5. Suspended sediment particle size data was collected by BBL (1998) at four locations along the river in 1991. Locations are not described in BBL's report.

6. Total suspended sediment measured by WDNR at South 28 from 1978-1986 (very few samples).

The following bed sediment data is available for definition of boundary conditions:

1. Bed material particle size measured by the WDNR in 1997 for 16 locations from I43 to the 8th Street bridge.

2. Bed material particle size distribution and specific gravity collected by RMT in 1993 at several locations in the 8th Street bridge area.

3. Bed material density collected at 8 locations near the mouth of the river in 1982 by USACE.

See Figure 2 and Table 1 for a description of the available data. The available information and the preliminary model tests with HEC-6 (a steady state one-dimensional sediment transport model) indicate the predominant sediment type both on the bed and in suspension is medium to coarse silt. It appears that the finer clay particle fraction is not abundant on this river. This observation has important implications for the proposed field work and model evaluation as described later.

2.3.3 Data Gaps

As is almost always the case, one of the key limitations in the existing data is one of the most important parameters: sediment load at the proposed upstream boundary of the model. An important requirement of the model setup is to develop a relationship between discharge (which is available continuously through an established stage-discharge relationship and suspended sediment load). It is possible that some of the historic suspended load measurements internal to the model domain could be used to help establish this key relationship. Another key limitation is the limited amount of particle size distribution data for suspended sediment. A limitation of the suspended sediment data internal to model domains is that it is erratic in coverage in both time and space and is not ideal for validation. Another key data gap is information on resuspension and settling characteristics for the sediment in this river. However, this limitation is not as critical as it might be for rivers with more clay in the flow and on the bed. A final limitation is the absence of information on bed load rates in this river for validation of the model. This type of information is very difficult to measure and generally does not account for a significant fraction of total transport.

2.3.4 Proposed Data Collection Plan

1. Measure sediment particle size distribution utilizing a horizontal sampler at the USGS I43 gaging station. Collect approximately 10 samples at this location for approximately 10 different flow events. Conduct tests to obtain particle size information for sand, silt and clay. This will fill a key gap in upstream boundary condition data.

2. In addition to these tests, conduct approximately 150 total suspended sediment tests. Collect samples at three river sections and include samples from 3 elevations in the water column. Collect samples for these separate flow events. This will provide important validation data.

3. Measure current and concentration profile characteristics and resuspension utilizing a laboratory-based sediment flume.

4. Gather additional data for parameterization of resuspension and settling utilizing Shaker tests (Tsai and Lick, 1986). While the Shaker Tests are now considered outdated (Lick, personal communication) and superfluous considering the detailed field apparatus being deployed, these tests will provide benchmark data for comparison to other rivers.

5. Gather two core samples at each of the one to three deployment locations (for a maximum of 9 samples) to obtain sediment characterization and bed properties.

Grain size analyses will be performed for several horizontal slices for each core. Laboratory tests will include bulk density, particle size distribution and organic content. Accurate core sample locations and elevations will be recorded.

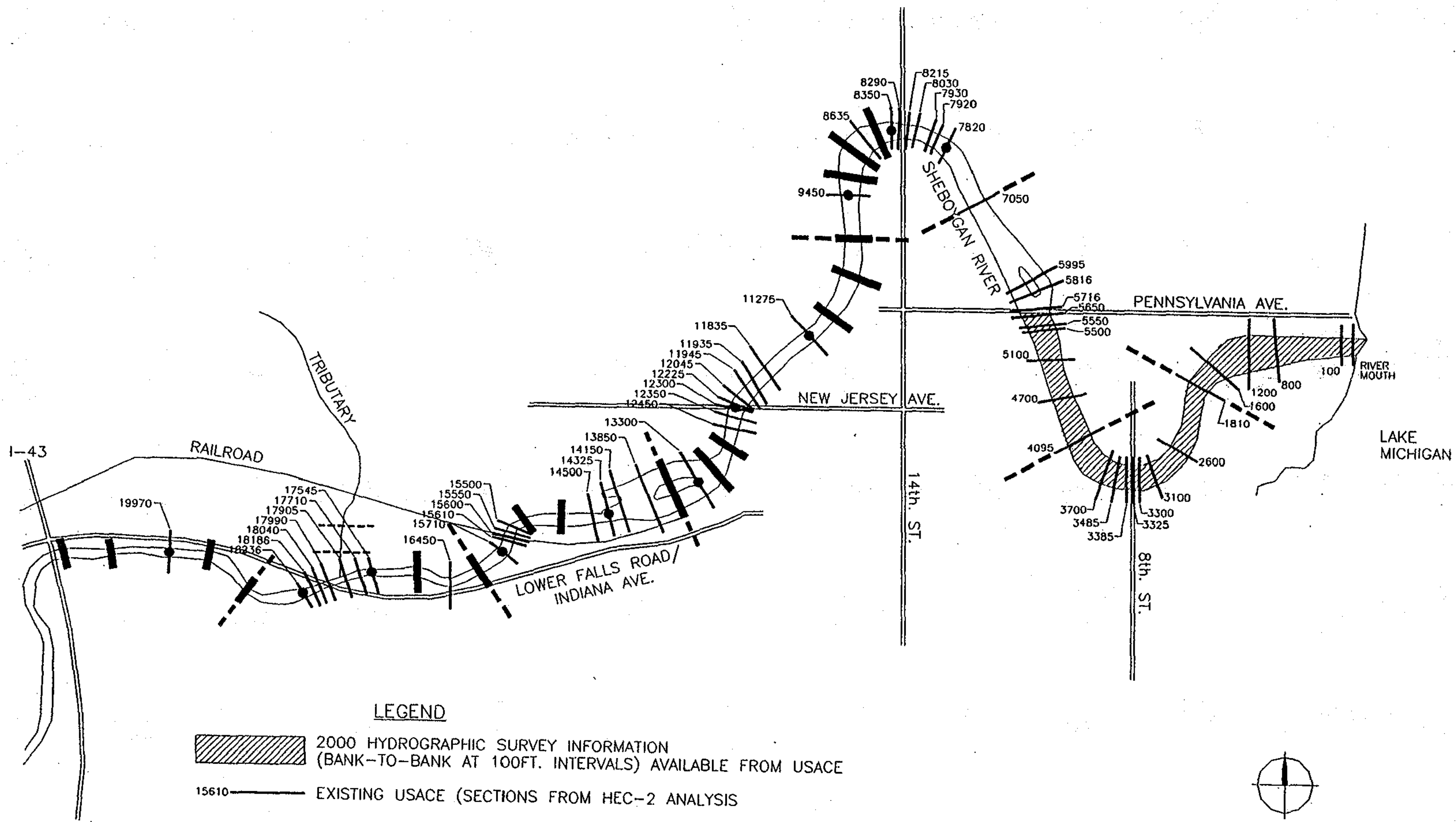
It is noted that a proposal for laboratory tests of the river bed sediment was received from the University of Wisconsin. The lab tests would provide resuspension information for a wider range of those that may encountered during the field campaign.

TABLE 1

SHEBOYGAN RIVER SEDIMENT TRANSPORT MODELING - PHASE 1
AVAILABLE DATA SUMMARY

Year(s)	Description	Measured Items	Location Description	Notes	Source
1961-1976	WDNR total suspended sediment data	TSS	8th St. Bridge		WDNR - STORET
1980	USGS total suspended sediment data	TSS	USGS gaging station at I43		USGS
6/1987 - 10/1991	USGS Gaging Station 14th Street Bridge	TSS	14th street bridge	mentioned in BBL report	WDNR
10/1991	BBL collected water samples at four locations	suspended sediment size distribution	*project area		BBL report
1994 - 1995	USGS Gaging Station at mouth	TSS, flow, temperature	USGS gaging station at mouth	Water Resources Data Wisconsin	USGS
1982	EPA Fields Database	bed material: density	near mouth		USACE - FIELDS database
1993	8th Street Bridge Data from 1993 RMT study	bed material: boring logs/locations, particle size/distribution, specific gravity	8th St. Bridge		RMT
1997	EPA Fields Database	bed material: sand, fine sand, gravel	mouth to I43		EPA fields
1999	BBL report	bed material: particle size distribution	mouth to 8th Street Bridge		BBL report
6/30/1916 - 9/30/1924 & 10/1/1950 - present	USGS Gage records - Station 04086000	discharge	USGS gaging station at I43	Water Resources Data Wisconsin	USGS
10/1/1993 - 10/31/1995	USGS Gage records - Station 04086041	discharge, water quality data for 1995	USGS gaging station at mouth	Water Resources Data Wisconsin	USGS
**?	USACE HEC2 cross-sections	river cross-sections	Pennsylvania Ave. to I43	cross-sections used in 1998 BBL study	BBL report
1979, 1991, 1995, 1997, 1999	EPA Bathymetry data	bathymetry figures comparing sediment deposition + bathymetry points for those years	inner harbor	bathymetry from USACE	EPA - FIELDS
1979-2000	Dredge sounding data	bathymetry	inner harbor	digital data from 1998-2000	USACE Kewanee Office
1993-1994	WDNR has collected sediment trap data	PCB concentration	USGS gaging station at mouth		WDNR-STORET
1988	FEMA Study	Flood elevations/profiles	project area		FEMA
1999	PCB Hot Spots - Inner Harbor	PCB hot spots	inner harbor		BBL report

*sample locations not described in BBL report
**date of initial study not known at this time



LEGEND

2000 HYDROGRAPHIC SURVEY INFORMATION (BANK-TO-BANK AT 100FT. INTERVALS) AVAILABLE FROM USACE

15610 —— EXISTING USACE (SECTIONS FROM HEC-2 ANALYSIS

PROPOSED HYDROGRAPHIC SECTIONS (BANK-TO-BANK)

EXTERNAL TOPOGRAPHY TO 100-YEAR FLOOD PLAIN ELEVATION

REPEAT BBL/USACE EXISTING CROSS SECTION

TRIBUTARY SECTION HDYROGRAPHIC BANK-TO-BANK, PLUS TOPOGRAPHIC TO 100-YEAR FLOOD ELEVATION

NOTE:
DOCUMENT THALWEG DEPTHS AT ALL PREVIOUSLY PERFORMED HEC-2 SECTIONS

FIGURE 1 – HYDROGRAPHIC & TOPOGRAPHIC SURVEY DATA

SHEBOYGAN RIVER SEDIMENT TRANSPORTATION MODELING
PHASE I
SHEBOYGAN, WISCONSIN

10115.01

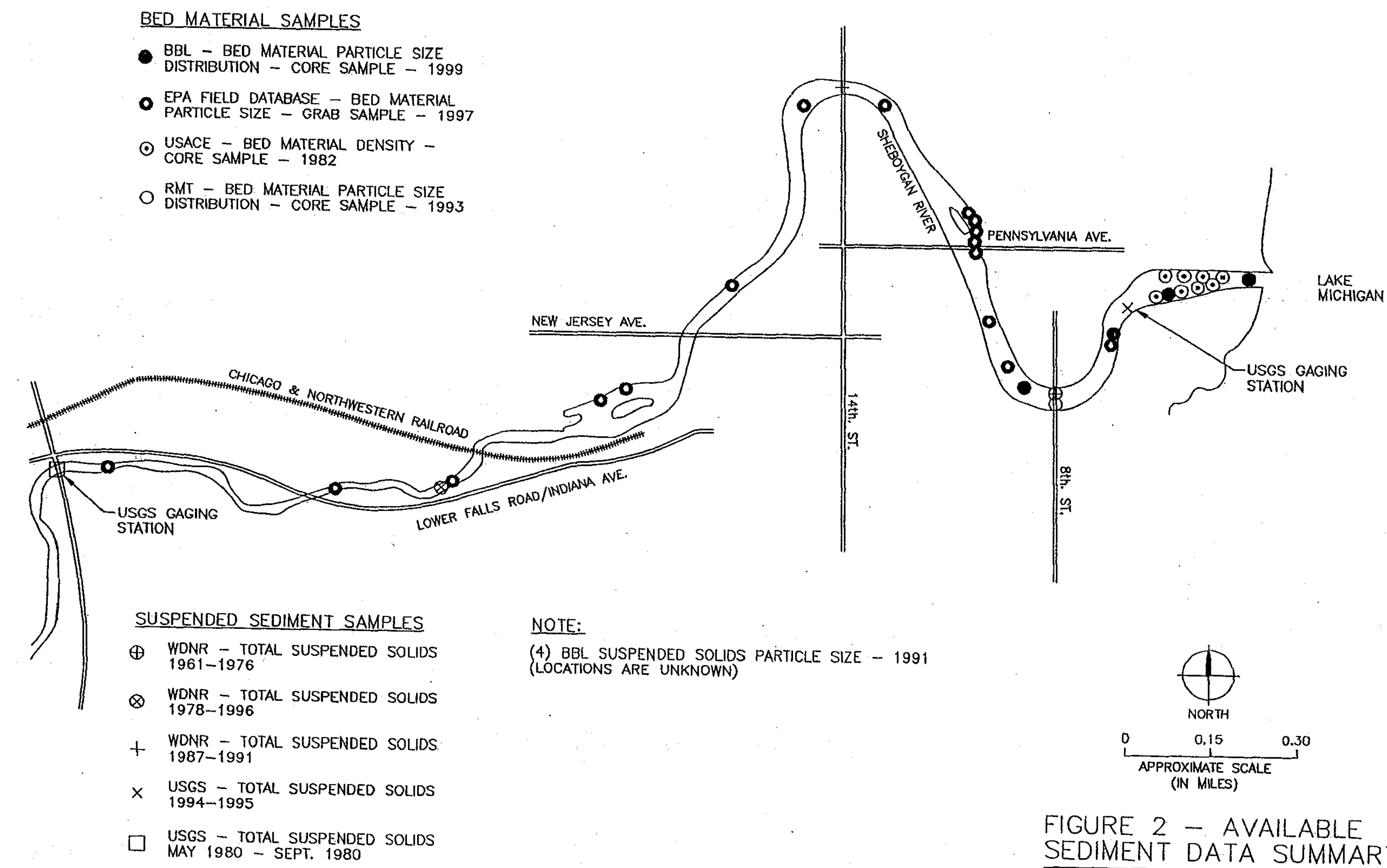


FIGURE 2 – AVAILABLE SEDIMENT DATA SUMMARY

SHEBOYGAN RIVER SEDIMENT TRANSPORTATION MODELING PHASE I
SHEBOYGAN, WISCONSIN

10115.01

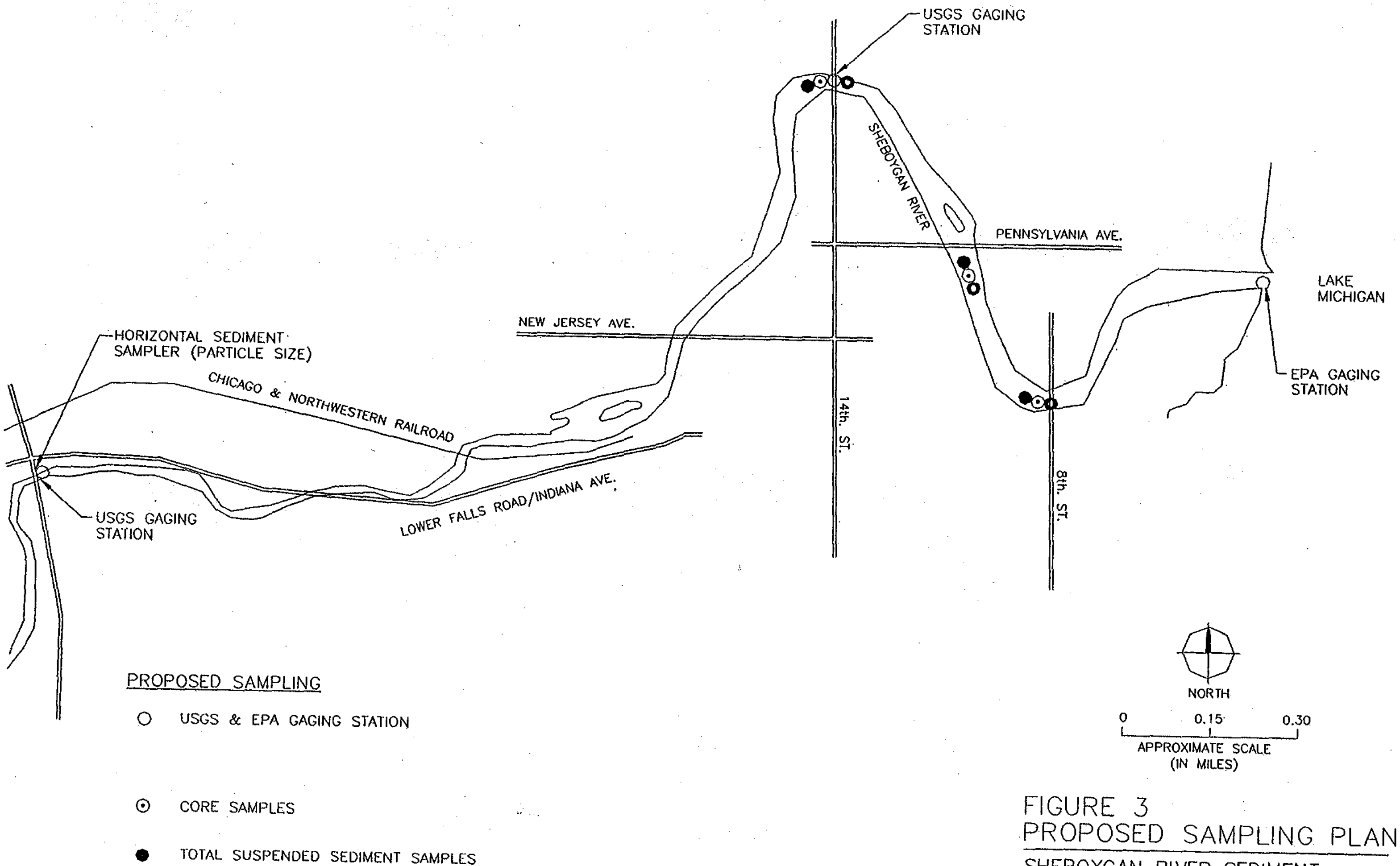


FIGURE 3
PROPOSED SAMPLING PLAN

SHEBOYGAN RIVER SEDIMENT
TRANSPORTATION MODELING
PHASE I
SHEBOYGAN, WISCONSIN

10115.01

3 MODEL SELECTION

There are several 2D/3D models available to simulate hydrodynamics, sediment transport and erosion/deposition in rivers, such as CH3D (WES), ECOM-SED (HydroQual), MISED (Lu, 1998), RMA10 (WES), HSCTM2D (EPA), etc. Each of these models has distinct features. The objective of this task is to select the most appropriate model considering the physical conditions of Sheboygan River, strengths and limitations of the models and the purpose of this investigation. This section describes hydrologic conditions and sediment features in the Sheboygan River, main features of the models, and criteria for model selection.

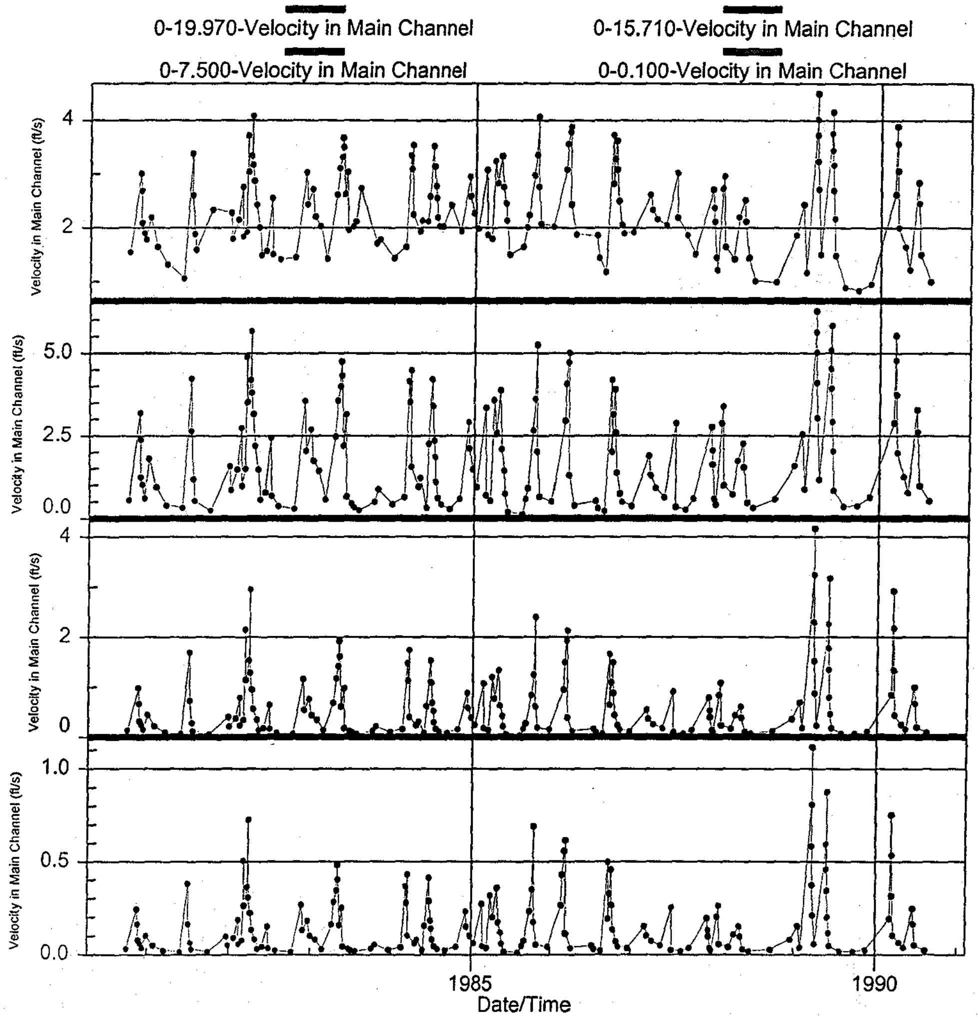
It is appropriate to apply a 2D or 3D model (vs a 1D model) owing to the relatively isolated locations of hot spots on the river. A 3D model preferred owing to the fact that some of the hot spots are located immediately downstream of the large bend at the 14 St. bridge. Flow dynamics are known to be 3-dimensional in nature at river bends and this has been shown to influence scour and sedimentation processes using CH3D-SED (Gessler et al., 1999). Furthermore, 3D models are now widely applied and do not present the problem they once did with respect to computational efficiency and computer resources.

3.1 Criteria for Model Selection

The study area for the model application is the lower reach of the Sheboygan River from the river mouth extending upstream to River Mile 3. Sediment transport in this area has been modelled using HEC-6, a one-dimensional hydraulic model (BBL, 1998). The model was applied to determine the sediment deposition and erosion over a 10 year period. Using the same model, Baird assessed the efficiency of a sediment trap in the river (Baird 1999). Model results indicate that the flow velocity in this area reaches more than 5 ft/s in large storm events (see Figure 4 showing velocity results along the river from the Baird HEC-6 model runs). One objective of the present model investigation is to examine bed changes in a 100-year flow event. The water depth upstream of the Pennsylvania Avenue bridge is shallow, about 3 ft. To model such high flows in a shallow river it is required that the selected model have good performance with respect to numerical stability. Since the river is narrow and meandering, the model requires fine grids to provide the necessary resolution to complete a detailed assessment of scour potential. Considering these factors, a finite difference model is not suitable for this application. Finite element models or finite difference models with curvilinear grids are required. Also, the presence of the bends implies that a 3D hydrodynamic model would be best.

Figure 4

Flow Velocity Calculated by HEC-6 model
River Mile: 3.8; 3.0; 1.4; 0.0

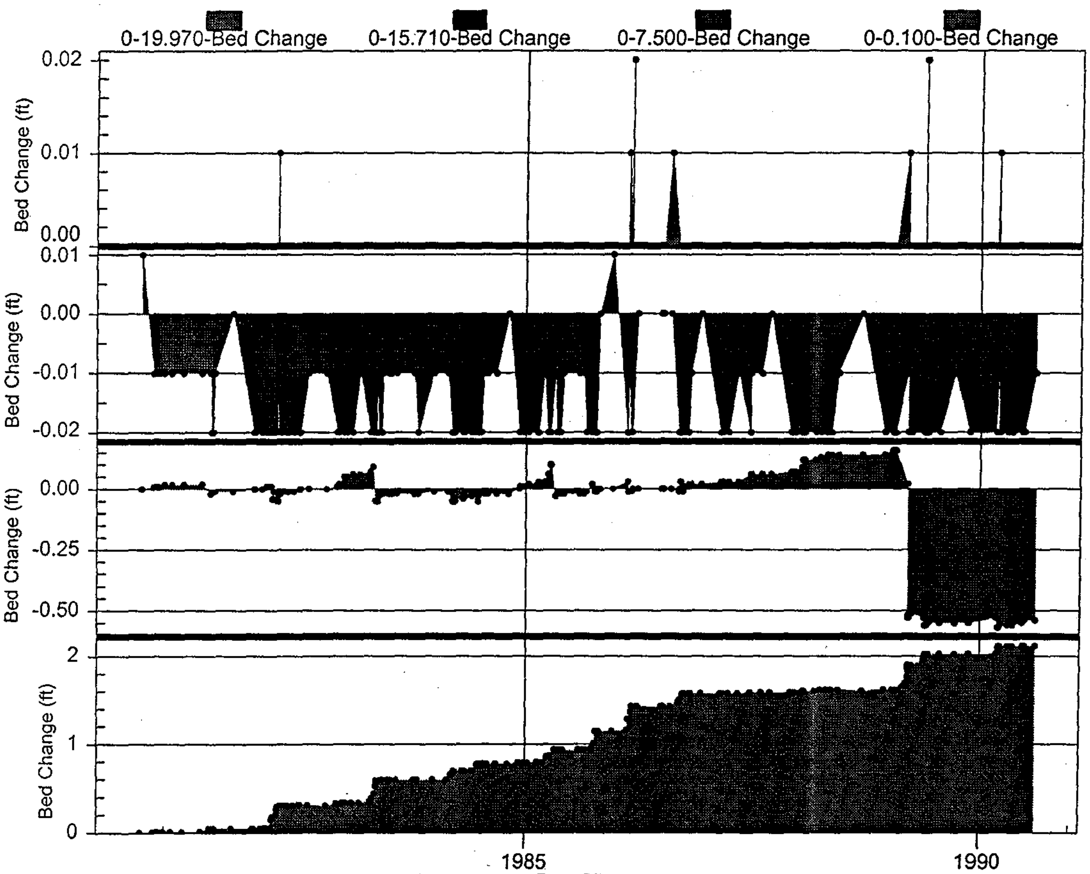


The predominant sediment on the bed and moving through the Lower Sheboygan River is coarse silt. The investigation of BBL (1998) documented that coarse silt occupies more than 70% of the total sediment load. If further geotechnical investigations indicate that the bed material contains a significant fraction of cohesive particle, the model will be modified to account for cohesive sediment scour and transport. Silt is non-cohesive and easily scoured and its settling velocity is small. The project specifically must assess the scour potential of buried sediment with high PCB concentration during high flows. It is likely that consolidation of freshly deposited sediment may not be an important process for this assessment. It would definitely be important if the sediment featured a higher clay content. The available information suggests that clay content is almost always less than 20% (i.e. relatively low). Therefore, models without consolidation may be suitable for this project. However, bed armoring must be considered in the simulation of the scour process. This process is particularly important where there is a wide range of grain sizes in the bed sediment. The HEC-6 model results completed by Baird indicated that erosion and deposition occurred alternately during high flow conditions. Erosion was predicted in the upstream section of the river and deposition was predicted near the mouth (See Figure 5). Therefore, the ideal model should perform well in predicting both erosion and deposition.

Figure 5

Bed Changes Over 10 Years Computed by HEC-6 Model

river mile: 3.8; 3.0; 1.4; 0.0



In summary, the ideal model for the Lower Sheboygan River should have the following characteristics:

- 3D model is preferred;
- FEM model or FDM model with curvilinear grids;
- good stability in high flow;
- non-cohesive sediment transport module (this assumption will be tested with both experimental data and modeling);
- soil consolidation can probably be neglected;
- bed armoring must be considered;
- perform well in sediment erosion and deposition calculations;
- efficient for long-term simulations.

3.2 Model Description and Comparison

The short list of models that were considered are as follows:

- ECOM-siz-SEDZL (HydroQual proprietary)
- MISED (Baird/Lu proprietary)
- CH3D-SED (IIHR & WES)
- SED-2D (CHL)
- RMA10 (CHL)
- HSCTM2D (EPA)
- TELEMAC (LNH)

Finite difference models using rectilinear grids such as MIKE21 and MIKE3 were not considered in this model selection process owing to the meandering form of the river.

The models are compared on the following aspects:

- Hydrodynamic and Sediment Transport Theory;
- Numerical techniques;
- Capabilities;
- Erosion potential method;
- History of use;
- Cost and documentation.

The features of these models are summarized in Table 2 at the end of this section. Details of the models that are qualified for model selection are described in the following sections.

3.2.1 ECOM-SIZ-SEDZL model

ECOM-siz-SEDZL is a version of the SEDZL code that has been integrated with the hydrodynamic solvers contained in the ECOM-si model, which is in turn a modification of the Princeton Ocean Model (POM). SEDZL is a two-dimensional sediment transport and bed dynamics model developed by Wilbert Lick, Joe Gailani, Kirk Ziegler and others at the University of California-Santa Barbara (Ziegler, 1986). The current version of ECOM-siz-SEDZL has been modified by Baird (Baird, 2000). The model is a 2D or 3D curvilinear finite difference model. If running in 3D, the σ-grid system is used in the vertical direction. The model applies Lick's theory (Lick, *et al*, 1995) to calculate cohesive sediment erosion and van Rijn's theory (van Rijn, 1986) to calculate non-cohesive sediment erosion. Bed consolidation is considered by dividing the bed into seven layers in the vertical. Three grain size fractions, sand, clay and biotic material, are considered in the sediment transport calculations. The model is suitable for sediment transport simulations in which both cohesive and non-cohesive sediment have to be considered. The model has been applied in the Fox River (Baird, 2000). One disadvantage of this model is that there is a stability problem at high flow owing to the dated numerical techniques used in the model. No significant modifications are necessary to apply this model to the Sheboygan River. The model is proprietary.

3.2.2 MISED model

MISED is a 3D hydrodynamic and sediment transport model newly developed by Lu (1997) of Baird. The model can simulate hydrodynamics, cohesive sediment transport or non-cohesive sediment transport in rivers, estuaries and coastal areas. Two new numerical techniques are included in the model. One is a new numerical method (Lu, 1998) which features unconditional stability, high efficiency and second order accuracy. The method integrates the advantages of the Eulerian-Lagrangian method, finite element method and finite difference method. Curvilinear finite element grids are applied in the horizontal plane. The other unique feature is the Gradient-Adaptive-Sigma (GAS) grid system (Wai and Lu, 1999) which can automatically adjust the grids based on vertical gradients in sediment concentration in order to increase vertical resolution. GAS automatically concentrates girds where the vertical gradient of concentration is large so that a high resolution numerical solution can be obtained in the area where it is most required. Lick's formula (Lick, *et al*, 1995) and van Rijn's formula (van Rijn, 1986) are used to calculate cohesive and non-cohesive sediment transport, respectively. A newly developed Pre-conditional Conjugate Gradient (PCG) method that is highly efficient for solving linear algebraic equation systems is used in the model. MISED has good stability characteristics, high resolution and fast computation. The disadvantages of the model are: a) no consideration of bed consolidation or bed armoring; and b) only one grain size may be represented. For application to the Sheboygan River the model would have to be modified to address bed armoring and possibly, multiple grain sizes. This model is proprietary.

3.2.3 CH3D-SED

CH3D-SED merges the 2D mobile bed modeling techniques developed by the Iowa Institute of Hydraulic Research (IIHR) and the CH3D three-dimensional hydrodynamic simulation code (USACE-WES) (Gessler, *et al* 1999; Spasojevic and Holly, 1994; and Chapman and Johnson, 1996). It is a finite difference model with curvilinear grid transformation in the horizontal plane and standard σ-grids in the vertical direction. It is well suited to the investigation of erosion and sedimentation in rivers and estuaries. In addition, the model has the ability to simulate freshwater and salt-water interface, thermal diffusion, contaminant transport, and wind stress. The sediment transport module of CH3D-SED in a strict sense is applicable only to sand-bed rivers. However, personal communication with van Rijn indicated that his transport algorithm would be valid down to medium silt sized particles and has been successfully applied to fine silts where good calibration data is available. Moreover, the model developers at the Corps' Waterways Experiment Station indicated it was their experience that the model would be applicable where the cohesive fraction of sediment was less than 20%. Given existing grain-size data, CH3D-SED is expected to competently model the sediments in Sheboygan River. Bed consolidation, bed armoring and bed load are considered in the model. It is a public domain model but with restricted distribution. The model applies an older numerical technique that this may cause some numerical problems such as inaccuracy and instability (Singh & Ghosh, 2000). Some modifications may be required to address these issues.

3.2.4 HSCTM2D (EPA)

HSCTM2D (Hayter, *et al*) is a two-dimensional (2D) finite element hydrodynamic and sediment transport modeling system, consisting of HYDRO2D, a 2D depth-integrated finite element hydrodynamic model which is a modified version of RMA2, and CS2D, a 2D depth-averaged finite element model for sediment and contaminant transport. It can be used to predict the fate of sediments and contaminants in riverine and estuarine environments. The model only accounts for cohesive sediment transport and is therefore not suitable for the Sheboygan River. Also, the standard Galerkin numerical method used in the RMA2 based hydrodynamics may lead to numerical instability at high flows for this river.

3.2.5 RMA10

RMA10 is a multi-dimensional (combining 1D, 2D either depth or laterally averaged, and 3D elements) finite element numerical model (King, I. P., 1992). It is capable of steady or dynamic simulation of three dimensional hydrodynamics, salinity, and sediment transport. It utilizes an unstructured grid with a Galerkin based finite element numerical scheme. The WES Coastal & Hydraulics Laboratory version is based upon the work of Dr. Ian King of Resource Management Associates. RMA10 assumes that the flow can be characterized as hydrostatic, i.e., vertical acceleration is neglected. There is a multi-grain size version of the model but it only simulates non-cohesive resuspension and tranport. The sediment transport module does not account for the impact of bed changes on the hydrodynamics at the time of this writing. The standard Galerkin numerical method used in RMA10 may cause instability problems during high speed flows on this river. These latter two limitations are important ones and essentially led us to the selection of CH3D-SED over RMA10.

3.2.6 SED2D

The TABS finite element model for sediment transport prior to 1995 was called STUDH. The STUDH model underwent considerable improvement and modernization in June 1995 and was renamed SED2D (CHL, 2000).

SED2D can be applied to clay or sand bed sediments where flow velocities can be considered two-dimensional in the horizontal plane. It is useful for both deposition and erosion studies and to a limited extent for stream width studies. The program simulates cohesive and non-cohesive sediment transport. The program does not compute water surface elevations or velocities; these data must be provided from an external calculation of the flow field. For most problems, the RMA2 model is used to generate the water surface elevations and velocities. SED2D does not couple with RMA2. An implicit assumption of the SED2D model is that the changes in the bed elevation due to erosion and/or deposition do not significantly affect the flow field. When the bed change calculated by the model becomes significant and the externally calculated flow field supplied by the user is no longer valid, then the SED2D run should be stopped, a new flow field calculation should be made using the new channel bathymetry generated by SED2D, and the SED2D run should be restarted with the new flow field as input. This process limits the model application to relatively stable bed conditions. Owing to the stability issues related to RMA2 and the lack of feedback from bed change to hydrodynamics, this model is not suitable for the Sheboygan River investigation.

3.2.7 TELEMAC

TELEMAC is a modeling system for hydrodynamics, sediment transport, and water quality in rivers, estuaries and coastal waters, developed by Electicite France and presently used and marketed by HR Wallingford. The TELEMAC system uses the latest finite element techniques to solve the shallow water equations either vertically averaged in two dimensions, or layered in three dimensions. This is an excellent river model however, the license fee is prohibitively expensive for this application.

3.3 Model Selection

In summary, the most suitable models for the Lower Sheboygan River are ECOM-siz-SEDZL, CH3D-SED and MISED. Based on the available sediment data that has been collected, cohesive (clay) sediment transport is probably not important on this river (at least for the section under consideration upstream of the river mouth). The CH3D-SED model is selected for the Lower Sheboygan River model because of the advantage of being public domain. However, there may be an issue with model stability in high flows and with respect to the efficiency and run time. In the event that the issues of model stability and efficiency negatively influence the ability to complete the project, the MISED model, which is more stable, accurate and faster could be applied. If cohesive sediment must be considered in the model (which is unlikely based on our current understanding of the site conditions), the ECOM-siz-SEDZL model is recommended for this application. In any event, further geotechnical investigation should provide information necessary to test and even modify thc resuspension algorithms in the selected model.

Table 2 - Summary of Model Comparison

Model	Ecom-siz-Sedzl	MISED	CH3D-SED	SED-2D	RMA10	HSCTM2D	TELEMAC
Author	A.F. Blumberg & C.K. Ziegler	Q.M. Lu	IIHR & WES	CHL, WES	CHL, WES	EPA	LNH
Theoretical							
Hydrodynamic Model Linked to	ECOM-siz	Built-In	CH3D	RMA2	Built-in	Hydro-2D (RMA2 modified)	Built-in
Coupled with Hydrodynamic Model	Yes	Yes	Yes	No	Yes	Yes	Yes
Numerical Techniques	2D/3D Curvilear FDM	3D 2nd order FEM	3D Curvililear FDM	2D FEM	3D FEM	2D FEM	2D/3D FEM
Capabilities							
Cohesive Sediment	Yes	Yes	No	Yes	Yes	Yes	Yes
Non-cohesive Sediment	Yes	Yes	Yes	Yes	Yes	Limited	No
Multiple Grain Sizes	Three Grain Sizes	No	Yes	No	Yes	No	No
Suspended Load	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bed Load	No	No	Yes	No	???	No	No
Erosion Process	Included	Included	Included	Included	Included	Included	Included
Deposition Process	Included	Included	Included	Included	Included	Included	Included
Bed Consolidation	Yes	No	No	Yes	???	Yes	???
Bed Armoring	Yes	No	Yes	No	???	No	No
Erosion Potential Method							
for Cohesive Sediment	Lick's	Lick's	N/A	???	No	Partheniades	???
for Non-cohesive Sediment	van Rijn (1984)	van Rijn	van Rijn	???	Van Rijn	Ackers/Einstein	N/A
History of Use							
General Usage	Sea, Rivers	Sea, Rivers	Rivers	Rivers	Rivers, Sea	Sea, Rivers	Rivers,Estuaries, Sea
Wide Variety of Application	Yes	No	Yes	Yes	No	Yes	Yes
Graphic Interface	No	Limited	Under Development	Yes (SMS)	Yes (SMS)	No	Yes
Documentation	Limited	No	Yes	Yes	No	Yes	Yes
Source Code Available	Yes/Limited	Yes/Limited	Yes	Yes	Under Development	Yes(???)	No
Cost							
Full License Cost	Proprietary	negotiable	WES Internal	Public Domain	WES Internal	Public Domain	$42,000
Site License Cost	Proprietary	negotiable	WES Internal	Public Domain	WES Internal	Public Domain	$21,000
Comments							
Advantages	Can to be customized	Good stability	Originally designed for river application	Fit to complicated boundary	Fit to complicated boundary	Coupled model	Many river/estuary applications
	Flexible input	Good computional speed		Many users			Designed for river application application
Disadvantages	Possible stability problems with high flow	Constant diffusion coefficient	Model is under development	Deals separately with cohesive and non-cohesive sediment transport	Need more documentation to confirm.	Possible slow computational speed	cost
			Possible problems of transport calculation due to neglect of high order terms in grid transformation.	Bed change does not automatically influence hydrodynamics	Bed change does not automatically influence hydrodynamics	2D hydrodynamics	
				Steady flow and 2D	2D hydrodynamic		
Likelihood of Success	Medium-High	Medium-High	Medium-High	Low	Undeternined	Medium-Low	High
Suitability for Intended	May be suitable	Suitable	Suitable	Suitable	May be suitable	May be suitable	Not suitable

4 CONCLUSION AND RECOMMENDATIONS

This report presents recommendations on collection of additional field data and the selection of an appropriate model to evaluate scour during the 100 year flow and other events. These activities will be performed in Phase II of this project.

Based on a review of the existing data, and a consideration of the requirements to complete the numerical model simulations, a recommended work plan was developed and presented in Section 2. The key new data sets that will be collected include:

- Hydrographic and topographic data to support the application of a 3D model;
- Application of a sediment flume to define sediment resuspension properties;
- Additional data on suspended sediment concentration and particle size for a better definition of upstream boundary condition and for internal validation.

It is proposed that the data collection be completed in April and May 2001.

A range of available numerical models of hydrodynamics, sediment transport and erosion/deposition were evaluated against a set of selection criteria. CH3D-SED was selected as the most appropriate model for this investigation (see Section 3 of the report). Two alternatives were designated in the event that CH3D-SED fails to perform satisfactorily in this environment. The modeling will be performed between May and August 2001.

A report describing the combined efforts of Phase I and II will be submitted in September 2001.

REFERENCES

Baird (1999). *Sediment Trap Assessment for Sheboygan River and Harbor, Wisconsin,* Technical Report prepared for USACE, Detroit District.

Baird (2000). *ECOM-SED model application: Lower Fox River below DePere*, Technical Report prepared for the Fox River Group of Companies and Wisconsin DNR.

Baird (2000). *ECOM-SED Model Application: Upstream Lower Fox River From Lake Winnebago To De Pere Dam*, Technical Report prepared for the Fox River Group of Companies and Wisconsin DNR.

BBL (Blasland, Bouck & Lee, Inc.) (1998). *Feasibility Study Report Sheboygan River and Harbor Site.* Technical Report prepared for Tecumsen Products Company.

Chapman, R.S. and B.H. Johnson (1996). User's Guide for the Sigma Stretched Versio of CH3D-WES. US Army Corps of Engineers Technical Report HL-96-21.

Coastal & Hydraulic Laboratory (WES) US Army Corps of Engineers (2000). *Users Guide to RMA2 WES Version 4.5,* User Manual.

Coastal & Hydraulic Laboratory (WES) US Army Corps of Engineers (2000). *Users Guide to SED-2D WES Version 4.5,* User Manual.

Gailani, J. C.K. Ziegler, and W. Lick (1991). Transport of Suspended Solids in the Lower Fox River, *J. Great Lakes Res.* 17(4), 479-494.

Gessler, D. B. Hall, M. Spasojevic, F. Holly, H. Pourtaheri, and N. Raphelt (1999). Application of 3D Mobile Bed, Hydrodynamic Model. *J. Hydr. Engrg.,* Vol. 125, No. 7, pp 737 – 749.

Hayter J. E. M.A. Bergs, R. Gu, S.C. McCutcheon, S.J. Smith and H.J. Whiteley. *HSCTM-2D, A Finite Element Model for Depth-Averaged Hydrodynamics, Sediment and Contaminant Transport*, User Manual.

HydroQual Inc.(1998). *A Primer for ECOMSED*, User Manual.

King, I. P. (1992). *A Finite Element Model for Stratified Flow-RMA10-User's Guide-Version 4.3*. Report prepared by Resource Management Associates for U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, MS.

Lick, W. Y.J. Xu, and J. McNeil (1995). Resuspension Properties of Sediments from the Fox, Saginaw, and Buffalo Rivers. *J. Great Lakes Research,* 21(2): 257-274.

Lu, Q. (1997). *Three-Dimensional Modeling of Hydrodynamics and Sediment Transport with Parallel Algorithm*. Ph.D. Dissertation, The Hong Kong Polytechnic University

Lu, Q. and O.W.H. Wai (1998). An efficient operator splitting scheme for three-dimensional hydrodynamic computations. *Int. J. Numer. Fluids,* Vol. 26, 771-789.

Singh, B.C. and L.K. Ghosh (2000). Discussion on "Application of 3D Mobile Bed, Hydrodynamic Model" by Gessler et al. *J. Hydr. Engrg.,* November, p 858-860.

Spasojevic, M. and F. M. Holly, Jr. (1994). Three-Dimensional Numerical Simulation of Mobile-Bed Hydrodynamics. US Army Corps of Engineers Contract Report HL-94-2.

Tsai, C. and W. Lick (1986). A portable device for measuring sediment resuspension. Journal of Great Lakes Research, 12 (4), 314-321.

Van Rijn, L.C. (1986). Mathematical Modeling of suspended sediment in nonuniform flows, *J. Hydr. Engrg.*, ASCE, 117, 433-455.

Wai O. W.H., and Q. Lu (1999), Gradient-Adaptive Sigma (GAS) Grid for 3D Mass-Transport Modeling, *J. Hydr. Engrg.,* Vol. 125, No.2, 141-151.

Zeigler, C. K. (1986). *A Numerical Analysis of Sediment Transport in Shallow Water*, Ph.D. Dissertation, University of California, Santa Barbara.