Sediment Transport Study

Sheboygan River and Harbor
Sheboygan, Wisconsin

Tecumseh Products Company
Sheboygan Falls, Wisconsin

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Glossary of Acronyms

BBL	Blasland, Bouck & Lee, Inc.
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CTF	Confined Treatment Facility
cfs	cubic feet per second
FS	Feasibility Study
HEC	Hydrologic Engineering Center
IGLD	International Great Lakes Datum
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NPL	National Priorities List
PCBs	polychlorinated biphenyls
RI/ES	Remedial Investigation/Enhanced Screening
RI/FS	Remedial Investigation/Feasibility Study
RI	Remedial Investigation
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Executive Summary

The Sheboygan River and Harbor Site is located approximately 55 miles north of Milwaukee, Wisconsin (Figure 1-1). The site, which includes approximately 14 miles of river and 100 acres of harbor, was placed on the National Priorities List (NPL) in May 1986 and as such, required preparation of a Remedial Investigation/Feasibility Study (RI/FS). The two-fold purpose of the RI/FS was to delineate the nature and extent of the constituents of concern associated with the site and identify remedial measures for mitigating potential site-related human health or environmental risks. The RI for this site was conducted from May 1987 to June 1988 by Blasland & Bouck Engineers, P.C., on behalf of Tecumseh Products Company (Tecumseh) (the only participating potentially responsible party). The main chemical constituents studied during the RI include polychlorinated biphenyls (PCBs) and eight heavy metals. The RI work efforts were summarized in the Remedial Investigation/Enhanced Screening (RI/ES) report dated May 1990.

Metals and PCBs were detected in Lower River and Inner Harbor sediment samples during the Sheboygan River and Harbor RI. The net deposition of progressively cleaner sediment generally was noted through the assessment of incremental depth sediment core samples. Navigation channel dredging, previously performed by the U.S. Army Corps of Engineers (USACE) within the Inner Harbor area (downstream of the Pennsylvania Avenue bridge), appears to have placed this stretch of riverbed in disequilibrium. The disequilibrium favored deposition of sediment as evident in the greater depths at which PCBs were found in the sediment. The deposition of progressively cleaner sediments has sequestered much PCB mass in the Inner Harbor well below the present day sediment surface. An important issue to be addressed with respect to the need for or potential types of remedial measures in the Inner Harbor is whether extreme events could reverse ongoing natural recovery by eroding a substantial portion of the sediment bed.

Evaluating the practicability, feasibility, and effectiveness of potential remedial measures in the Inner Harbor is the next phase of the RI/FS process. In order to provide more information for the evaluation of one alternative, on-going sedimentation within the Inner Harbor through natural armoring, a study was undertaken to model sediment transport in the Lower River and Inner Harbor (Figure 1-2).

Objectives of the Study

This sediment transport study involves using a mathematical modeling and analysis tool to understand and predict sediment movement under various River and Lake Michigan (Lake) conditions. The study was undertaken by Tecumseh with several objectives in mind, including:

- Apply the data collected during the RI to finding appropriate approaches to the Inner Harbor;
- Evaluate the effectiveness of natural sediment armoring and recovery;
- To the extent possible, estimate the effects of interactions among processes such as sediment erosion, deposition, or transport, and the influence of River (dis)equilibrium, floods, or changes in Lake levels; and

- Provide the U.S. Environmental Protection Agency (USEPA) and other involved parties with information to assist in assessing the feasibility of the natural armoring alternative, so as to reach a decision that protects the health of the community and surrounding environment.

Modeling the River and Harbor System

Scientific and engineering models, such as the one used in this study of the Lower River and Harbor, are computer-aided tools for describing, analyzing, and predicting the results of natural or human-induced changes in a "system." The model is one specifically selected because of its ability to use the RI data in simulating and evaluating the effects of natural sedimentation in the Inner Harbor. After comparison with other available models the "HEC-6 - Scour and Deposition in Rivers and Reservoirs" model was selected for this study. The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE) developed the HEC-6 model. HEC-6 is now one of the most widely used models for evaluating sediment transport and deposition, and it is best able to make use of the RI data collected for the Sheboygan River and Harbor system.

Results of the Study

Results of the sediment transport modeling discussed in this report are intended to aid the Agencies and the community in understanding the effects of both normal conditions and storm events on the natural armoring process. With this understanding and ability to estimate Inner Harbor conditions, all involved are better able to make decisions about the most appropriate approach for remediation of this site. Several of the study's central findings are summarized below.

Natural armoring is occurring through the process of sedimentation; that is, new cleaner sediments are being deposited on top of the older and deeper PCB- and metal-containing sediments. The study shows that the on-going net deposition of new sediments is the system's reaction to prior Harbor dredging by the USACE that placed the Lower River and Harbor out of balance and into "disequilibrium." The natural response of the system to the USACE's removal of sediments is to deposit and accumulate new sediments until a "dynamic equilibrium," or balance, is once again achieved. A river system is in dynamic equilibrium when there is no long-term net deposition or scour (erosion) of sediment.

Using current and historic data, the HEC-6 model shows that the natural armoring and recovery of the Inner Harbor will effectively isolate PCB- and metal-containing sediments as the system naturally restores itself. The modeling study also shows that although storm events are expected to cause localized short-term changes in sediment depths and transport rates, the protectiveness provided by the long-term net deposition of cleaner sediments has and will take place as the system strives toward renewed balance.

Conclusion

Overall, the sediment transport modeling study shows that the present and on-going natural armoring of the Inner Harbor is isolating the PCBs and metals contained in the deeper sediments as they are buried under fresh sediment.

In addition, this study shows that the natural recovery alternative, which takes advantage of the dynamic processes inherent in nature's tendency toward restoration, is expected to provide long-term stability and protectiveness as the Inner Harbor returns to a natural balance.

Section 1.0 - Introduction and Background

1.1 Overview

The Sheboygan River and Harbor Site is located approximately 55 miles north of Milwaukee, Wisconsin (Figure 1-1). The site, which includes approximately 14 miles of river and 100 acres of harbor, was placed on the National Priorities List (NPL) in May 1986 and as such, required preparation of a Remedial Investigation/Feasibility Study (RI/FS). The two-fold purpose of the RI/FS is to delineate the nature and extent of the chemicals of concern associated with a site and identify possible remedial measures for mitigating potential site-related human health or environmental risks. The RI for this site was conducted from May 1987 to June 1988 by Blasland & Bouck Engineers, P.C., on behalf of Tecumseh Products Company (the only participating potentially responsible party). The main chemical constituents studied during the Remedial Investigation (RI) for the Site include polychlorinated biphenyls (PCBs) and eight metals. The remedial investigation work efforts were summarized in the Remedial Investigation/Enhanced Screening (RI/ES) report dated May 1990. Additional site sampling results and the bench- and pilot-scale study results are included in the Alternative Specific Remedial Investigation Report (ASRI) (BBL) submitted to the Agencies in October 1995.

The next phase of the project involves the use of available site information collected thus far to identify and select potential remedial alternatives. The feasibility and potential effectiveness of these alternatives then will be evaluated and presented in the Feasibility Study (FS) report. An overall goal of the modeling work was to provide information which could be used to assess the feasibility of natural armoring as a remedial option for the Inner Harbor (Figure 1-2).

The Inner Harbor was the particular focus of the modeling for several related reasons. The Inner Harbor had been dredged historically, which would have created a disequilibrium favoring the deposition of sediments and associated chemicals. By contrast, no such "sink" was ever constructed in the Lower River, which historic and site investigation information suggest has been near or in dynamic equilibrium. PCB concentrations and sediment volumes are lower in this portion of the River than in the Inner Harbor. Consequently, the fate of PCBs and metals in the Inner Harbor was the primary focus of the modeling. Including the Lower River in the model served several purposes. It provided continuity from locations where sediment transport and flow data were collected (at the USGS gage) and similarly provided an upstream model boundary above possible backwater effects from Lake Michigan, as required. The location of the upstream model boundary also provided sufficient distance for model boundary effects to be equilibrated internally before modeling the area of interest. This is believed to be generally beneficial to the accuracy of estimates for areas within the Inner Harbor.

Demonstration of the natural armoring alternative in the Inner Harbor is effectively underway as evidenced by the results of previous segmented RI sediment core analyses and similar more recent analyses by the U.S. Army Corps of Engineers (USACE) which indicate the net deposition of progressively cleaner sediments covering older sediments containing PCBs and metals. The ability of naturally deposited sediment to armor and isolate PCB- and metal-containing sediments in the Inner Harbor over the long term is an important consideration with regard to remedial decision-making for the Site. Although natural armoring also has been shown to be effective at other sites, in this study its effectiveness was considered further with respect to the specific hydrodynamic conditions of the Lower River and Inner Harbor. A mathematical model of sediment transport, erosion, and deposition was used to estimate potential future changes in sediment bed elevations. In addition, the model was used to simulate extreme events, including the 100-year flood and low water levels in Lake Michigan to assess the stability of existing sediments under the natural armoring alternative.

1.2 Background

Dredging of the navigation channel in the Inner Harbor, prior to 1969, created a situation generally favoring the feasibility of the natural armoring alternative for Inner Harbor sediments. Deepening of Sheboygan's Inner Harbor via dredging has increased the cross sectional area and placed the riverbed in disequilibrium with the river's natural sediment load. The effect of this disequilibrium is to favor net deposition (aggrading) of fresh sediment on an annual basis. In addition, because of the larger cross-sectional area to convey flows, the river's minimum critical flow necessary to initiate bed sediment scour is greater after dredging than the critical flow prior to dredging.

1.3 Objective

The goal of the modeling work reported herein was to assess the effectiveness of the natural armoring alternative for the Inner Harbor. Simulation models provide a mechanism for evaluating the response of the sediment bed of the Inner Harbor on both a short-term, extreme event and relative long-term basis.

Section 2.0 - HEC-6 Model

2.1 Model Selection

A number of mathematical models have been developed to simulate sedimentation in alluvial channels. The unique assumptions and level of sophistication in each model govern the degree to which specific processes such as sediment erosion, transport, and deposition are represented.

Included among the criteria considered in selecting the most appropriate model for achieving the objective of this work effort were:

- The model's ability to realistically describe the most significant governing processes, and accurately simulate and represent natural events;
- Prior experience and established credibility of the model for this type of application; and
- The data requirements of the model in conjunction with the amount and type of available data.

Based on a comparative evaluation of various available models, the mathematical simulation model HEC-6, Scour and Deposition in Rivers and Reservoirs, was selected for use in this work effort. HEC-6 was developed by the Hydrologic Engineering Center (HEC) of the USACE. The model is a one-dimensional sediment transport model that calculates water surface and sediment bed surface profiles by mathematically simulating the interaction between sediment material in the stream bed and the flowing water-sediment mixture.

HEC-6 was selected for this work effort because it satisfies the criteria established for the effort and offers several advantages over other sediment transport models. Specifically, the advantages in using HEC-6 over other sediment transport models include:

- HEC-6 is one of the most widely used model to date for evaluating sediment transport and deposition in rivers.
- The model has been used in other Comprehensive Environmental Response Compensation Liabilities Act (CERCLA) remedial investigations.
- The model has been updated to accommodate the deposition and entrainment of silt and clay particles. This feature provides a real advantage for this study over many other sediment transport models because of the high percentage of silt and clay in the Lower Sheboygan River and Inner Harbor sediments (ranging from approximately 50 to 60 and 10 to 30 percent, respectively).
- The model can simulate a range of stream flow conditions such as peak flood events, multi-year simulations and baseflow sedimentation.

- HEC-6 has been developed to accept cross-sectional geometry in the same format as the USACE model HEC-2, Surface Water Profiles. Therefore, the model is compatible with previous Sheboygan River HEC-2 input data obtained from the USACE and used during the design of the Confined Treatment Facility (CTF).

As with any model, there are some limitations with HEC-6. However, these limitations are not considered significant given the characteristics of the Sheboygan River. For example, HEC-6 cannot simulate flow reversals and downstream tidal activity. Flow reversals and tidal activity are not significant phenomena affecting sediment transport in the Lower River and Inner Harbor. Due to the inability of any sediment transport model to accurately depict long-term and event-related sediment deposition in settings similar to the complicated circulation patterns in the Outer Harbor, the downstream boundary of the area to be modeled was selected as the junction of the Inner and Outer Harbors (Figure 1-2). (PCB levels in the Outer Harbor are generally less than 1 ppm, with the exception of deeper sediments located in the channel near the Inner Harbor. Given the dredging history shared by the Inner Harbor and this portion of the Outer Harbor, we expect that the model results for the nearby section of the Innder Harbor should be relevant to the assessment of fate of sedimentation in this portion of the Outer Harbor.)

In the HEC-6 simulations, scour and deposition processes are assumed to occur uniformly along a cross section and only sediment bed erosion, not bank erosion or sloughing, is assumed. Uniform deposition along a cross section and negligible bank erosion are reasonable assumptions, given the relatively efficient hydraulic radius (a relatively high ratio of cross-sectional area to length of the sediment-water interface) of the Sheboygan River cross sections in the Lower River and Inner Harbor. In addition, river walls are present through most of the Inner Harbor.

2.2 Data Requirements for HEC-6

HEC-6 is a one-dimensional numerical model of river mechanics that computes sediment scour and deposition by simulating the interaction between the hydraulics of the flow and the dynamics of sediment transport. HEC-6 can be used to predict the effect of changing the dynamic balance between sediment moving in the stream and sediment which has been deposited.

Input data required for the computations of sediment transport and deposition by the HEC-6 model can be grouped into three main categories: geometric, hydrologic and sediment data. Each data type is discussed in detail below.

2.2.1 Geometric Data

Geometric input data include cross sections, reach lengths and Manning's "n" roughness coefficients. Sets of coordinate points giving elevation and distance along the cross section are used to describe the shape of each cross section (Figure 2-1). The format is virtually identical to the HEC-2 format for geometric data. Each section of the model (representing the reach between adjacent cross sections) must include three reach lengths, one for the main channel and one each for the right and left overbank areas. Curvature of the channel can be simulated by setting the distances of the overbank areas different than that of the main channel. The Manning's "n" roughness coefficient also is specified for each model section. The coefficient may vary depending on the bed material, bank vegetation or abrupt changes in direction or flow velocity.

2.2.2 Hydrologic Data

Hydrologic input data include water discharge, downstream water surface elevation, duration of discharge, and water temperature.

The HEC-6 program treats a continuous hydrograph as a sequence of discrete steady flows, each having a specified time duration (Figure 2-2). The number and length of computational intervals for a given flow and duration sequence is selected by the user so as to minimize the total number of computation steps for the given period consistent with maintaining an accurate representation of both the water and sediment discharge. To best simulate river conditions, the time duration of computational interval specified are shorter for higher flows, when sediment transport and riverbed water interactions are greatest, shorter than for low flow periods when sediment processes are less dynamic. The computational period must be of a duration to allow for the full movement of a water particle through the study area.

A starting water surface elevation at the downstream model boundary must be specified for each time step. In an open river situation, a stage-discharge rating curve is typically used, which relates water elevation to flow rate at a specific location not affected by backwater conditions. In this application, the starting water surface elevation for each time step was set to the corresponding elevation of Lake Michigan for that time period. Hydraulic calculations then proceed in an upstream direction from section to section. Water surface profiles are calculated through the HEC-6 program using the standard step method to solve the one-dimensional energy and continuity equations. Frictional energy losses are calculated using Manning's equation.

2.2.3 Sediment Data

Sediment input data include information on inflowing sediment load, particle size distribution of inflowing sediment, particle size distribution of bed sediments, and the selected sediment transport capacity relationship. The recently revised 5.0 release of the HEC-6 program allows for user specification of critical shear stress thresholds for deposition and scour, and particle and mass erosion rates for fine-grained sediments.

The relative aggradation or scour of a stream bed depends on the amount and size of sediment flowing into a river reach relative to the transport capacity of the reach. Inflowing sediment loads are related to water flow by a sediment-discharge curve for the upstream end of the channel. The sediment load is specified as the loading rate in tons per day for up to nine selected river flows. Due to differences in the behavior of varying size particles, it is necessary to classify sediment into groups based on size, for application of different transport equations. The HEC-6 model accounts for up to 15 different size fractions which include one size for clay, four for silt, five for sands and five for gravel.

Particle size distribution also must be specified for stream bed sediments. The bed sediment size distribution can be defined for any of the cross sections used to define channel geometry. If no sediment particle sizes are specified for a cross section, a distance-weighted average of sediment size is computed from the nearest upstream and downstream cross sections with sediment size data specified computed. The total amount of sediment available for transport from a section is determined by the average depth of sediment in the streambed specified for that section.

There are ten sediment transport functions for bed sediment loads available within HEC-6, or the user can specify transport coefficients based on observed data. The transport function used for the Sheboygan River was Madden's modification of Laursen's (1958) transport function. This function has few restrictions and is suitable for situations with median grain sizes of a wide range of values from silts (0.011 mm) to coarse sands (4.0 mm). The transport capacity is computed by HEC-6 at each cross section using the hydraulic information from the water surface profile calculation (width, depth, energy slopes, flow velocity, etc.) and the gradation of bed material.

A recent improvement included in release 5.0 of the HEC-6 model is the ability to model both deposition and scour of fine-grained sediment. For clay- and silt-size sediment (up to 0.0625 mm), Krone's (1962) method for deposition is used and Ariathurai's (1976) adaption of Parthenaides' (1965) method is used for scour. The HEC-6 program has the option of computing only the deposition of silt-sized and clay-sized sediments or computing both the deposition and scour of these particles. To include the option of both the deposition and scour of the fine-grained sediment, the user must specify the shear stress threshold for deposition (the water velocity related stress below which deposition of fine-grained particles will begin to occur), the shear stress threshold for scour (the water velocity related stress above which scour or resuspension of fine-grained particles will begin to occur), the threshold for mass erosion, and the mass erosion rate (as shear stress increases, individual particle scour gives way to mass erosion of cohesive sediments; the stress at which mass erosion starts is the threshold, while the rate describes the extent of that mass erosion). Other parameters for silt and clay characterization such as specific gravity, unit weight and the compaction coefficient may be specified or default values may be used.

Section 3.0 - Input Data

This section describes the input data sources used to develop, calibrate and verify the sediment transport model for the Lower Sheboygan River and Inner Harbor. Where appropriate, necessary assumptions that were made in lieu of site-specific data are discussed.

3.1 Channel Geometry Data

Channel geometry data were obtained from a previously calibrated HEC-2 water surface profile model of the Sheboygan River that was developed by the USACE. The HEC-2 and HEC-6 programs use nearly identical methods to code cross-sectional geometry, so the data were easily transferred. Only those cross sections located within the 4 mile stretch of the river downstream of the U.S. Geological Survey (USGS) gaging station, to the River's mouth, were used in the HEC-6 model (Figure 3-1). Due to the minor differences in the formatting of bridge geometry between the HEC-2 and HEC-6 models, the bridge cross-section data were reformatted as necessary.

For model cross sections located in the Inner Harbor (starting about 100 feet downstream of Pennsylvania Avenue), date-specific channel geometry data were obtained from bathymetric surveys conducted by the USACE. Bathymetric survey data were available for September 1980, June 1982, May 1983, June 1984, July 1986, December 1987, October 1988, June 1989, and October 1990. During these surveys, data were collected at 55 transects spaced 100 feet apart. Water depth was measured across each transect at approximate 20-foot intervals. Channel geometry for cross sections in the Inner Harbor used in the HEC-6 simulations during the various starting times was adjusted to correspond to the results of the bathymetric survey for that time period. The most frequently used years to establish initial condition time periods were 1986 for calibration runs, and 1980 for verification runs and simulations (model predictions). Lacking other bathymetric data, Lower River cross sections located upstream of Pennsylvania Avenue obtained from the HEC-2 model were used for all simulations.

The water surface based International Great Lakes Datum (IGLD) of 1955 was used for the Lower River and Inner Harbor elevations. Elevations for Inner Harbor bed sediments (from USACE bathymetric surveys) and Lake Michigan water levels were originally presented in IGLD elevations. This datum is offset approximately 1.3 feet above the lower-based National Geodetic Vertical Datum (NGVD) of 1929 which was used as the reference elevation datum in the previous HEC-2 studies of the River. To place water- and land-based elevations on the same elevation measurement datum, the cross-sectional elevations upstream of Pennsylvania Avenue (originally in NGVD of 1929) were adjusted to reference the IGLD of 1955.

3.2 Hydrologic Data

3.2.1 Sheboygan River Discharge Data

Mean daily discharge data were available from the USGS gaging station (#04096000) located approximately 4 miles upstream from the River's mouth on the Sheboygan River near Interstate 43. Periods of record that were used from this station included 1916 to 1924 and 1951 to 1993. The mean daily flow for the period of record was approximately 250 cubic feet per second (cfs). The maximum discharge recorded was 7,680 cfs which occurred in 1975. A flow duration curve for the Sheboygan River is presented in Figure 3-2.

The computation technique used in HEC-6 requires that the continuous discharge data be converted into a step series of steady-flow events forming a discharge histograph (a step graph of river discharge as a function of time) to approximate the continuous discharge hydrograph. Before proceeding with the creation of the discharge histograph, the optimum computational intervals for the flow range to be simulated by the model were established by the methods suggested by Thomas et al. (1981) and Gee (1984). The computation time interval is optimal for a given flow when the largest number of days in an individual computation can be used without introducing instability, oscillation or error. The time duration for a steady discharge then can be set as a multiple of the computation interval.

Mean daily discharge records for the USGS gaging station were reviewed for individual years ranging from 1960 to 1990. For each year, representative discharges were selected for periods of similar daily flow, and a discharge histograph was synthesized to characterize the annual hydrograph. Consistent with the optimum computation intervals, lower flows were generally grouped into longer periods with a computation interval of 5 to 12 days, while for higher flows, time periods were shorter with computation intervals of 1 or 2 days. For extreme hydrologic events, 6-hour time steps were used in simulations. On average, 15 to 20 representative discharge values with 60 to 80 individual computational intervals were used to characterize an annual hydrograph in the model.

3.2.2 Lake Michigan Water Surface Elevation Data

The water surface elevation of Lake Michigan is the downstream boundary condition for the model. The elevation of Lake Michigan was used as the starting condition for the downstream-most cross section for each computation. For the period 1975 to 1990, monthly average lake elevations from the National Oceanic and Atmospheric Administration (NOAA) station at Kewaunee, Wisconsin were used. Prior to the establishment of the Kewaunee station in 1975, monthly data from the NOAA Milwaukee South station were used for the period 1970 to 1974. For the period before 1970, monthly data from the NOAA Milwaukee station were used (station moved in 1970 to Milwaukee South).

For each discharge value in the discharge histograph, an average lake level corresponding to the same time period was selected. For low flow periods when the duration of flow may have extended over two or more months, a time weighted average Lake level was calculated.

3.3 Suspended Bed Sediment Data

3.3.1 Suspended Sediment Load Curve

Total suspended solids (TSS) concentrations were available from water-column monitoring at the USGS gaging station and the 14th Street bridge conducted between June 1987 and October 1991. Although the 14th Street bridge is in the middle rather than the upper end of the reach to be modeled, changes in total suspended solids concentration measurements between the USGS gaging station and the bridge were minimal and supported inclusion of the data in developing the sediment load curve.

Instantaneous suspended sediment loads were calculated using TSS concentration and discharge data for 29 samples. The instantaneous sediment load, expressed in tons per day, was plotted against stream discharge and a best-fit curve drawn. The upper limit of the flow range for which TSS data are available is 950 cfs.

The suspended sediment load curve was extrapolated beyond the range of field observations to 10,200 cfs (the 100-year recurrence interval discharge) as a log-log linear relationship between sediment load, in tons per day, and water discharge in cfs. The slope of the log-log linear relationship was 1.27, in general agreement with Bennett (1982) who noted that the slope of this relationship is often a value near 4/3 or 1.33.

To assess the reasonableness of the extrapolated load curve, the estimated sediment yield for the Sheboygan River (taken from the extended relationship) was compared to suspended sediment yields from two other Wisconsin rivers for which high flow period data were available (Figure 3-3). One was the Menomonee River which is located near Milwaukee. Its basin is about one-third the size (132 mi^2) of the Sheboygan River basin. The other river basin used was the Nemadji River. The Nemadji River basin is forested and slightly larger (495 mi^2) than the Sheboygan. After normalizing for differences in basin area, sediment yield per square mile as a function of discharge per square mile was found to be comparable for the range of flow data from the other rivers being utilized (equivalent to approximately 4,000 cfs for the Sheboygan River). Therefore the sediment load curve developed for the Sheboygan River appears reasonable.

3.3.2 Suspended Sediment Size Distribution Data

In October 1991 water samples were collected at four locations for analysis of suspended sediment size distribution. Samples were collected during two separate days when flow at the gaging station averaged 280 cfs and 800 cfs, respectively. Samples were analyzed using a scanning electron microscope and particle counts for the 5 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 50, and 50 to 100 micron size ranges were determined. The mass distribution was estimated by assuming all particles could be represented by the mean value of their size range. An average particle volume for each range then was calculated, and the particle volume multiplied by the particle count and an estimated specific gravity of 2.6.

Coarse silts were the dominant particle size class, 72.3 ± 7.2 percent for 280 cfs and 70.5 ± 6.2 percent for 800 cfs. There were no sands present for 280 cfs. For 800 cfs, the 50 to 100 micron size range, which overlaps both the coarse silts and very fine sands, comprised an estimated 24 percent of the total sediment mass.

Medium silts were 21.3 ± 7.5 and 16.5 ± 6.0 percent by mass for the 280 and 800 cfs discharges, respectively. Fine silts were estimated to be 5.7 ± 0.3 and 10.4 ± 1.3 percent and very fine silt 0.75 ± 0.1 and 2.6 ± 0.4 percent, respectively.

For higher flows, the sediment size distribution was estimated. Coarse silt was kept as the dominant sediment size class for suspended sediments. The percent of sand in the suspended sediment was estimated based on the maximum predicted transport capacity in the upper reach of the study area, which was relatively limited. For example, at 6,300 cfs, approximately the 10-year recurrence flow, sand still accounted for only 13.7 percent of the inflowing suspended sediment mass. If the mass of sand in the incoming flow at the upstream model boundary was to be increased beyond the transport capacity computed by the model, the additional excess sand would be predicted to be deposited shortly after entering the modeled portion of the River; therefore, the incoming sand load was adjusted to more closely correspond to the computed transport capacity near the upstream boundary. This would tend to guard against the overprediction of sand deposition in the modeled reach.

3.3.3 Bed Sediment Data

As discussed earlier in Section 3.1, periodic bathymetric surveys conducted by USACE were used to define initial channel geometry in the Inner Harbor for various time periods.

The mean bed surface elevation was determined for each cross section for each bathymetric survey. A three cross-section moving average of mean bed surface elevation was computed to smooth some of the apparent random fluctuations observed in the bathymetric surveys. Changes in bed surface elevation between bathymetric survey periods then were calculated. The total volume of sediment deposited was calculated from the change in sediment depth, channel width and distance between cross sections. The computed depth and volume of sediments accumulated based on the bathymetric survey depths were used to evaluate the performance of the model during calibration and verification phases.

The depth of the movable bed (those sediments in the channel subject to possible scour and transport) was determined from field measurements. A total of 107 sediment cores were collected from the Sheboygan River under Phases I and II of the RI. The depth of sediment was recorded for each coring location. These recorded depths were used to define the initial depth of sediments and varied from 1-foot at the upper end of the study reach to greater than 10 feet (10 feet, however, is the maximum value the model allows) in and Inner Harbor.

The purpose of the sediment core sampling during Phases I and II of the RI was to determine the spatial distribution of chemical constituents in the sediments, and therefore, the areas selected for coring were primarily areas of thicker sediment accumulation (near banks, backwater areas, etc.). From field observation, much of the River from cross-section 14500 near South 23rd Street (14,500 feet upstream of the Inner Harbor mouth) to the USGS gage did not have appreciable sediment deposits. To avoid creating a large hypothetical initial reservoir of easily erodible sediments in the upper reach, which would lead to an overestimation of deposition rates in the Inner Harbor, the initial conditions for movable bed depths upstream of cross-section 14500 were modified and set equal to 0.1-foot. Preliminary hydraulic simulations based upon the predicted channel velocities indicated that large areas of sediment deposition in the main channel were unlikely between the USGS gaging station and cross-section 14500. In the model, any sediments which were deposited in the upstream portion of the modeled reach during the course of the simulation still would be available for later scour and transport.

Grain-size analysis to characterize the riverbed sediments as coarse sand (>2 mm), fine sand (0.075 - 2 mm), or silt and clay (<0.075 mm) were performed on samples from all sediment cores using ASTM sieve analysis method D422. A more detailed grain-size analysis was performed on 22 samples from 17 locations (Figure 3-4) using both sieve and hydrometric analyses to provide data to characterize the bed material size distribution into the 15 grain-size classes used in the HEC-6 program.

Section 4.0 - Model Simulations

4.1 Model Calibration and Verification

4.1.1 Fixed-bed Hydraulic Calibration

To calibrate the hydraulic portion of the HEC-6 model developed for the Sheboygan River, a series of "fixed-bed" simulations were performed. In the fixed-bed simulation, no sediment transport, erosion or deposition computations are performed.

The fixed-bed model was calibrated by comparing water surface elevations predicted at the model cross section representing the USGS gage to the elevation determined from the most current USGS stage-discharge rating curve for the gaging station. The stage-discharge rating curve at the station describes the observed relationship between water surface elevation (stage) and volume of flow (discharge) as measured by the USGS at the station. The water surface elevations computed by the model and those given by the rating curve were within 0.1-foot over the flow range for which the USGS rating curve had been developed.

Comparisons of the predicted water surface elevations and main channel velocities for each cross section were made between the HEC-6 fixed-bed model and the HEC-2 water surface profile model. The water surface elevations were in agreement, as were most channel velocities. The only notable differences were minor differences in predicted velocities near some of the bridges for extreme high flow events such as the 10- and 100-year recurrence interval flows. These differences appear to be artifacts of the computation methods used in each program to specify bridge geometry and friction losses associated with the bridge constrictions. The velocity differences were not carried beyond the immediate areas of the bridges.

As additional cross sections were added to obtain better spatial resolution of sediment deposition in the Inner Harbor, the predicted water surface elevation and channel velocities between the HEC-6 and HEC-2 models again were compared. When the maximum number of cross sections HEC-6 can accommodate was exceeded, the upper boundary of the model was moved from the USGS gaging station to cross-section 19970 located approximately 1,500 feet downstream of the gage. The addition of new cross sections in the Inner Harbor and the shortening of the model reach had no significant effect on either the computed water surface elevations or channel velocities.

4.1.2 Sediment Transport Model Calibration Runs

Model calibration was performed using a 4-year period with June 1986 as a starting time for the simulations. Channel geometry input data for cross sections between Pennsylvania Avenue bridge (within 5,550 feet from the Inner Harbor mouth) and the Inner Harbor mouth were set to reflect stream bed conditions determined by the June 1986 bathymetric survey. To improve resolution in the Inner Harbor, additional cross sections were added to the model to represent the channel at locations 1,200, 1,600, 2,600, 3,100, 3,700, 4,700, and 5,500 feet from the Inner Harbor mouth. The discharge histograph and monthly average Lake Michigan levels for the June 1986 to October 1990 period were used as time dependent input variables for each calibration run.

The 1986 to 1990 time period was selected for calibration purposes because it represented a period of somewhat lower than average water levels for Lake Michigan and average to above average River discharge. These characteristics would be conducive to both potential episodic scour during high flows as well as the general accumulation of sediments within the Inner Harbor for the majority of the time. The October 1988 to June 1989 time period was the only interval between consecutive USACE surveys where a net scour of sediments for several cross sections in the Inner Harbor were observed in the bathymetric survey records. As this was the only opportunity to calibrate scour-related parameters, the 1986 to 1990 period, and specifically the 1988 to 1989 period, represented an important time period for use in development of the model.

The results of the calibration simulations were evaluated against deposition/scour estimates developed using data from the December 1987, October 1988, June 1989, and October 1990 bathymetric surveys. Each simulation was evaluated based on total sediment deposition (in acre-feet) for the study area and the net deposition (in feet) at selected cross sections within the Inner Harbor.

The variables used to calibrate the model included:

- The shear stress threshold coefficient for deposition (below which deposition of fine-grain sediments can occur);
- The shear stress threshold coefficient for scour (above which scour of fine-grain sediment can occur); and
- The particle and mass erosion coefficients (which, along with shear stress, determine the mass of sediment eroded per hour).

HEC-6 incorporates a concept of an active and inactive portion of the sediment bed. The active bed is assumed to be the surface layer which is mixed by flow at any given time. The depth of the active layer changes depending on flow. The active layer depth also represents the thickness of sediment required to provide the minimum amount of larger size particles which could function as an armor layer (a layer of particles one diameter thick, which would not be scoured) for existing flow conditions. In general, the active bed thickness increases with increasing flow. The inactive layer is the bed sediment below the active bed. Bed material is moved within the model between active and inactive layers as the thickness of the active layer is adjusted by the model.

These variables were adjusted for both the active (surface layer) and inactive (deeper) sediments. Because there were multiple parameters to be adjusted, with multiple time periods for comparison of predicted to observed deposition, a range of values existed for each of the calibration coefficients for which numerous combinations could result in predictions of total sediment deposition in general agreement with observed deposition. The best calibration results for total sediment deposition were obtained when the threshold deposition coefficient was between 0.035 and 0.040 lb/ft^2, the threshold scour coefficient was between 0.040 and 0.050 lb/ft^2, and the mass erosion coefficient was 60 to 80 lb/ft^2/hr at a shear stress of 1.0 lb/ft^2, for the active bed. The optimum threshold scour coefficient for the inactive bed was between 0.20 and 0.25 lb/ft^2.

Results of a calibration simulation with a deposition coefficient of 0.040 lb/ft^2, active bed scour coefficient of 0.045 lb/ft^2, inactive bed scour coefficient of 0.20 lb/ft^2 and a mass erosion rate of 75 lbs/ft^2/hr are shown as the "higher coefficient" model calibration in Figure 4-1.

The various simulations were not as accurate in predicting deposition between individual surveys as they were for total deposition during the entire four year calibration period. The largest difference for each simulation was generally associated with the December 1987 to October 1988 period. The bathymetric survey data indicate a net deposition of 11.8 acre-feet in the Lower River and Inner Harbor between the 1987 and 1988 surveys, while most simulations using parameters in the range specified above predicted only a third of that amount (3.5 to 4.0 acre-feet). Part of the difference is attributable to the observation that the predicted total sediment inflow for the December 1987 to October 1988 period was only 5.2 acre-feet, which, based on the sediment loading curve developed for the model, was less than half the observed deposition. Thus, the model underpredicted deposition during this period.

Predicted depths of accumulated sediments at individual cross sections were compared to those observed based on bathymetric data. For those calibration runs which best predicted total volume of sediment deposited in the Inner Harbor, sediment deposition was generally overpredicted for cross sections upstream of the Eighth Street bridge and underpredicted for downstream cross sections. The spatial pattern of deposition within the Inner Harbor was better predicted by simulations with threshold deposition and scour coefficients in the 0.018 to 0.024 lb/ft^2 range. The total deposition of sediment predicted using these lower threshold coefficients were, however, underestimated by 20 percent for the June 1986 to October 1990 calibration period. Typical results for a simulation using the lower threshold coefficients are shown in Figure 4-1 as "lower coefficient" model calibration.

4.1.3 Initial Verification Run

Based on the calibration results, an initial model was selected for verification with an active bed threshold deposition coefficient of 0.040 lb/ft^2, active bed scour coefficient of 0.045 lb/ft^2, inactive bed scour coefficient of 0.20 lb/ft^2, and mass erosion rate of 75 lb/ft^2/hr at 1.0 lb/ft^2 shear stress. These values are reflective of the higher coefficient calibration run. The verification period used was September 1980 to October 1990. Initial geometry data for cross sections downstream of Pennsylvania Avenue bridge (cross-section 5550) were set to reflect channel conditions observed during the September 1980 bathymetric survey. Predicted volume of accumulated sediment was compared to that calculated from the bathymetric surveys for the period.

The initial verification run overestimated the volume of accumulated sediment for the 1980 to 1983 period by a substantial amount. During the September 1980 to June 1983 time period, a computed 62.41 acre-feet of sediment entered the upstream end of the study reach. Predicted accumulation was 30.34 acre-feet (Figure 4-2), but the observed deposition (based on bathymetric surveys) was only 4.85 acre-feet equivalent to a trap efficiency of only 7.8 percent.

After 1983, comparisons based on cumulative deposition from 1980 were better than the first few years, but comparisons between predicted and observed deposition on a survey-to-survey basis were still erratic (Figure 4-2). After overpredicting net deposition initially, the model results did start to approach the observed deposition as a result of underprediction for the 1987 to 1988 period and overprediction of net scour by over 10 acre-feet in the 1988 to 1989 period.

In addition, the spatial pattern of modeled sediment deposition on a cross-section basis was generally skewed until 1989, overpredicting for the area upstream of the Eighth Street bridge (cross-section 3325) and underpredicting for cross sections downstream of the bridge (Figure 4-3). During the 1988 to 1989 scour period, the simulation predicted the movement of newly deposited sediment above Eighth Street to downstream areas of the Inner Harbor resulting in a predicted 1990 sediment deposition profile similar to that observed from comparison of the 1980 and 1990 bathymetric data (Figure 4-3).

4.1.4 Final Verification Run

An alternative version of the model using lower threshold shear coefficients, which had better represented the spatial distribution pattern during calibration, but had underpredicted the total volume of sediment deposited, was used in a separate verification simulation. In this second model, the active bed threshold deposition coefficient was 0.020 lb/ft^2, the active bed threshold scour coefficient was 0.022 lb/ft^2, and the mass erosion rate was 65 $lbs/ft^2/hr$ at 1.0 lb/ft^2 shear stress. During the original calibration the "lower coefficient" simulation underpredicted total deposition in the Inner Harbor by nearly 20 percent, yet this simulation still greatly overpredicted deposition for the early 1980s during the verification run. The predicted accumulation was 27.20 acre-feet compared to an observed 4.85 acre-feet for the September 1980 to May 1983 period (Figure 4-2).

Comparisons between predicted and observed net deposition (between USACE surveys) generally improved with time. The model seemed to internally compensate for the overprediction during the 1980 to 1986 period by a decrease in deposition and an increase in scour during the verification simulation for the 1986 to 1990 period, relative to the same period in the calibration simulation using the same values for model parameters. This could be anticipated, as the overprediction of deposition for 1980 to 1986 raised the bed surface elevation above that which had been used as an initial condition for the calibration runs.

Although both models predicted similar net deposition volumes when the full 1980 to 1990 time period was considered (Figure 4-3), the spatial distribution of the predicted deposition for the second verification simulation (with the lower coefficient values for deposition and scour) better matched the observed pattern from bathymetric surveys than did the initial verification for the 1980 to 1988 period (Figure 4-3). Scour observed at individual cross sections in the Inner Harbor during the 1988 to 1989 period also was more closely predicted by the second verification simulation (Figure 4-3). The standard error for the second verification was 0.42 feet compared to 0.46 feet for the initial verification run for the 1980 to 1990 period. The standard error for the second verification was 0.44 feet compared to 0.96 feet for the initial verification of the 1988 to 1989 period, the only period where net scour was observed based upon bathymetric data.

The second (lower coefficient) version of the model was felt to represent the more conservative case, as the lower coefficients would predict lower deposition and higher scour rates than the initial model. The better representation of the spatial pattern of deposition and scour, especially for the 1988 to 1989 observed scour period, also weighed heavily in the selection process. This version was selected for use in the simulations to assess the effects of extreme hydrologic events on the stability of the stream bed under the natural armoring alternative. Minor modifications were made to the model after verification. These included raising the deposition coefficient and scour coefficient for the active bed from 0.020 and 0.022 lb/ft^2 to 0.019 and 0.020 lb/ft^2, respectively, and lowering the mass erosion rate from 65 to 63 lbs/ft^2/hr.

4.2 Extreme Hydrologic Event Simulation

The calibrated model was used to predict the potential for scour during extreme hydrologic events. Two sets of river flow conditions were evaluated for three varying Lake levels. The first set of flow data represented a 5-day event with a peak discharge equal to a 10-year recurrence flood flow of 6,400 cfs. The second set of hydrologic conditions represented a 5-day event with a 100-year recurrence interval having a peak flow of 10,200 cfs. (As noted earlier the maximum recorded discharge in 50 years of streamflow monitoring at the Sheboygan River is 7,680 cfs.) The step histograms used to represent these events are depicted in Figure 4-4. Based on the last 25 years of Lake Michigan water surface elevation data collected by NOAA, elevations of 577.4, 579.6 and 581.0 feet (IGLD of 1955) were selected to represent the low, average and high Lake level conditions. Separate simulations were performed for the 10- and 100-year recurrence interval floods with the downstream water surface elevation set to each of these three water levels.

The extreme event was programmed to occur at the end of a 1980 to 1990 simulation with minor alterations to the model. Due to uncertainties regarding the response of the stream bed in the upstream areas, the depth of sediment at each cross section upstream of the 14th Street bridge was limited to a maximum of 0.1-foot as an initial condition in the event simulations. This procedure limited the availability of sediments from the upper portions of the modeled reach to be scoured and redeposited in the Inner Harbor. The results of the extreme hydrologic event simulations therefore have a tendency towards a lower predicted value of net deposition and a maximum predicted value of scour in the Inner Harbor. In addition, to assure that the model represents a conservative estimate of the scour from extreme events (i.e., tending to overestimate potential scour in the Inner Harbor), the threshold scour coefficient for the inactive bed was lowered from 0.20 to 0.05 lb/ft^2. Hydraulic conditions (e.g., velocity and shear stress), trap efficiencies, bed surface elevation, and bed compositions were computed and analyzed for each day of the 5-day events.

HEC-6 is designed for analysis of long-term scour and deposition; however, it may be used with appropriate caution, to perform single-event simulations. Although the results of the extreme hydrologic event simulation will be discussed quantitatively here for comparative purposes, the interpretation and application to the river system should be viewed qualitatively. One of the assumptions of the HEC-6 model is that equilibrium between the river and sediment bed is achieved within each computational time step. This assumption is probably not maintained under the condition simulated during extreme events, during which the Sheboygan River is being influenced by unsteady, non-equilibrium conditions, which constantly change the dynamics between the bed and river hydraulics. In performing simulations for conditions where the actual system is in non-equilibrium during an extreme event, documentation for use of the model suggests that the results be viewed only qualitatively (HEC, 1991).

4.3.1 Net Deposition From Extreme Events

Figure 4-5 shows the predicted net deposition during the 10-year event under low, medium and high Lake conditions, as well as the predicted net deposition during the 100-year event. The difference in deposition is measured from the beginning of the event to the fifth day of the event (2,200 cfs or 3,500 cfs flow for the 10- and 100-year event, respectively).

The analysis of the simulations shows that net deposition in the Inner Harbor due to extreme events follows a general pattern consistent with those anticipated based upon the hydraulic characteristics of the Inner Harbor area. Four trends in the pattern of net deposition can be noted:

(1) Despite the extreme nature of the events, there was relatively minor (generally less than 0.5 feet) net change in the bed surface elevation estimated at river cross sections in the reach between Eighth Street and Pennsylvania Avenue bridges. This is perhaps an indicator that the reach is nearing its dynamic equilibrium.

(2) Deposition of sediments downstream of Eighth Street bridge results in a net increase in bed elevation during extreme events. Net deposition was always predicted downstream of cross-section 1600, and for most cases between cross-section 1600 and Eighth Street bridge. The deposition reflects the reduced velocity associated with the wider, deeper channel in this portion of the Inner Harbor.

(3) Deposition downstream of Eighth Street bridge was greater for the low-Lake level simulations than that for the medium- or high-Lake level simulations due to scour and reduced deposition in upstream areas, such as between the Pennsylvania Avenue and 14th Street bridges, during low Lake conditions. These areas between the Pennsylvania and 14th Street bridges are transitional flow areas, sometimes, during high-Lake level, affected by backwater conditions (water level determined by downstream Lake level) and sometimes, during low-Lake level, free flowing. In these transitional flow areas, the relative change in velocity with changing Lake-level is greatest, with highest velocities for a given flow during lower Lake levels when the channel cross-sectional area is least.

(4) The only areas in the Inner Harbor which are predicted to have a net scour during extreme events are those cross-sections at or very near the Eighth Street and Pennsylvania Avenue bridges. This reflects the increase in shear stress which occurs as flow is constricted near these structures.

4.3.2 Scour and Deposition of Distinct Grain Sizes

A detailed analysis was made of the behavior of distinct grain sizes during the 10- and 100-year events under high and low Lake conditions. Figure 4-6 shows the predicted sediment load transported past selected cross sections under low Lake conditions at flows of 10,200, 9,500 and 3,500 cfs, during a 100-year event. The erosion and deposition tendency of a select sediment size can be ascertained from these graphs. If the graph indicates sediment load is increasing with downstream distance, erosion is occurring in the intervening reach. A decreasing load moving downstream indicates that deposition is occurring between the cross sections.

During the simulated peak flow of 10,200 cfs, fine sands are scoured near the Eighth Street bridge but are deposited shortly downstream. However, the model predicts that during peak flow, very fine sands continue to be eroded downstream of Eighth Street bridge. Even during the 100-year event there is comparatively little transport of sediments with grain size larger than medium sand. There is little spatial change in the predicted transport load of silts and clays during the 100-year flood flow (10,200 cfs) because: 1) the silt and clay materials in the surface layer sediments have already been scoured from the active surface layer, and 2) the velocity is too great to allow for the deposition of silt and clay already in the water column.

As the flow starts to subside to 9,500 cfs, the quantities of suspended sediment transported are reduced by about a third, but somewhat the same pattern of deposition and scour is maintained.

By the time the flow subsides to 3,500 cfs, the sand sediment load is approximately 1 percent of the sand load at peak flow. Very fine sands begin to be deposited downstream of the Eighth Street bridge. Fine sands are deposited between cross-sections 4095 and 3100. The sediment load for silts is constant downstream of cross-section 8350.

The effect of the 100-year event shifts the spatial distribution of grain sizes in sediments by eroding finer grain sizes and either depositing them farther downstream in the Inner Harbor, or with the finest materials, transporting these particles into the Outer Harbor. Therefore, at a given cross section, the finer grain sizes are eroded from the cross section leaving behind or being replaced by coarser sediments. This results in surface sediments in the Inner Harbor becoming coarser and therefore more resistant to scour by the end of the 100-year event.

Figure 4-7 shows the net deposition of distinct sediment size fractions at selected cross sections as a result of the 100-year event with low Lake levels (negative values indicate net scour). For the 100-year event, fine sands in the active layer have replaced silts and very fine sands downstream of cross-section 3325. Also, medium sands have replaced fine sands in the active layer between cross-sections 5100 and 3700 for the 100-year event. Although this grain size shift is observed within the active layer for other event flow and Lake level scenarios, it was less pronounced than in the more extreme 100-year, low Lake simulation. The 10-year event under high Lake conditions has the lowest potential for sediment transport and thus the least observable change in active layer sediment characteristics during the simulated extreme events.

Figure 4-8 shows the predicted sediment load transported under high Lake conditions at the 6,400 cfs, 6,000 cfs, and 2,200 cfs flows for the 10-year event. As in the case of the 100-year event under low Lake conditions, clays and silts in the surface layers of sediment have been removed prior to the peak flow. At peak flow of 6,400 cfs for the 10-year event, very fine sands, some of which are eroded in the area around the Eighth Street bridge, are being deposited upstream of cross-section 3100. Fine sands are being deposited upstream of cross-section 3100, while medium sands are being deposited upstream of cross-section 4100. The point of deposition of each of these sediment sizes is farther upstream than for the 100-year event under low Lake conditions. Silts and clays are transported through the Lower River and Inner Harbor without being deposited.

At 2,200 cfs, no sands are being transported in the water column below cross-section 4700.

Figure 4-7 shows the change in grain size fractions at selected cross sections as a result of the 10-year event under high Lake conditions. The materials in the bed are finer than was the case for the 100-year event under low Lake conditions. Very fine sands have replaced silts below cross-section 3325, and fine sands have replaced very fine sands, between cross-sections 3700 and 3325.

The detailed analysis of the movement of sediment grain sizes helps to explain the resistance of the reach between the Eighth Street bridge and Pennsylvania Avenue bridge to erosion during high flow events. Even during the peak flow of the 100-year event under low Lake conditions, the sediment transport capacity of coarse sands and gravels is relatively small. These materials are thus left behind when finer sediments are scoured. As finer sediments are removed, coarse sands and gravels form a thin layer on top of the underlying finer material in the inactive bed. This layer of coarser material acts like a natural armor layer, shielding the underlying sediments from erosion. HEC-6 reflects a natural armoring process as it determines the amount of scour at a cross-section, and for this reason predicts limited scour occurring between the Eight Street bridge and the Pennsylvania Avenue bridge.

Section 5.0 - Sensitivity Analysis

A series of simulations were performed to assess the sensitivity of the predicted results to changes in model parameters which could not be directly measured and were estimated during the calibration procedure. This procedure is performed to assess the range of model response variations in estimates of certain parameters. This exercise tends to reveal the parameters of particular importance to the accuracy of model results and the consequences of uncertainty/certainty to parameter estimates. These simulations are designed to reveal model behavior and are not intended to characterize or represent the site. Model parameters for which a sensitivity analysis was performed included the active bed shear stress threshold deposition coefficient, the active bed shear stress threshold scour coefficient, the active bed mass erosion rate, and the inactive bed shear stress threshold scour coefficient. Simulations also were performed to evaluate the sensitivity of results to changes in the mass of inflowing suspended sediment, and the water surface level of Lake Michigan.

Each trial simulated hydrologic conditions for the 1980 to 1990 period. The simulations also calculated the effects of a 100-year flow event during low Lake level at the end of the 1980 to 1990 period. Results of both sets of sensitivity analyses are present for each parameter. The sensitivity analysis focused on the Inner Harbor downstream of Pennsylvania Avenue bridge.

5.1 Active Bed Shear Stress Deposition Threshold Coefficient and Scour Threshold Coefficient

Since the shear stress threshold for the scour of clays and silts must be larger than the shear stress threshold for their deposition, the effects of altering the deposition and scour threshold coefficients have to be considered jointly. The calibrated model used a deposition threshold of 0.019 lb/ft^2 and a scour threshold of 0.02 lb/ft^2. For the sensitivity analysis, a range of values between 0.01 lb/ft^2 and 0.06 lb/ft^2 were examined for both coefficients whenever the selected values would have produced a scour threshold less than the deposition threshold. Values were modified such that an approximate ratio of 0.95 between deposition and scour coefficients was substituted. Table 5-1 summarizes the parameters used for each trial. A follow-up set of trials examined the same range of coefficient values, but fixed the deposition coefficient at 0.0095 lb/ft^2 for scour variations and the scour coefficient at 0.063 lb/ft^2 for deposition variations. These fixed values represent the extremes of the previous set of trials, and were used to isolate and identify the source of variability in the results of the first set of sensitivity trials. This second set of parameter combinations also is listed in Table 5-1.

The range of variation in net deposition for the simulated time period 1980 to 1990 was minor. Figure 5-1A shows the predicted net deposition in the Lower River and Inner Harbor for the first set of sensitivity tests for the deposition coefficient, and Figure 5-2A shows the predicted net deposition for the first set of sensitivity tests for the scour coefficient.

The lack of a consistent deposition or scour pattern during the sensitivity analysis for the reach between cross sections 4095 and 5500 may reflect the fact that this area is close to its dynamic equilibrium. With no dominant trend towards either erosion or deposition, there is no consistent mechanism within the simulation for the modification of the threshold coefficients to significantly effect predicted bed elevations.

Between cross sections 1600 and 4095, the higher the deposition and scour thresholds, the less erosion in the reach and the higher the net deposition. This section of the River represents an area of general deposition with only rare scour during extreme high flows. With a higher scour coefficient, resuspension of the deposited sediment will occur less frequently.

Downstream from cross section 1600, lower scour coefficients and lower deposition coefficients lead to higher suspended sediment loads entering the downstream end of the Inner Harbor. These predicted higher loads are due to particles either scouring from or not depositing in upstream areas. This causes greater sediment deposition in the downstream portion of the Inner Harbor as streamflow velocities decrease with increasing cross-sectional flow area.

The sensitivity of the active bed threshold coefficients are not as important in the simulations of extreme events as for more typical flows, because shear stresses predicted in the extreme event simulations are significantly greater than any of the threshold coefficient values considered. The effects of the 100-year flow on net deposition levels are shown in Figure 5-1B for variations in the deposition threshold and in Figure 5-2B for variations in the scour threshold. The net deposition is measured as the total change in sediment bed elevation from the beginning of the simulation. For most of the study area, the differences caused by alterations to these parameters are minimal. The greatest effect during the 100-year event is noted for the 1,500-foot reach downstream of Eighth Street bridge (cross sections 1800 to 3300). In this area, scour of the sediment bed during the 100-year event is predicted to occur in the range of approximately 0.5 foot when the bed deposition or scour coefficient is greater than 0.04 lb/ft^2. However, the 0.5 feet of scour is approximately equal to the amount of increased deposition computed for these same cross sections during the 10-year runs under the same coefficient values. The resultant net difference in results after the simulation which includes the 100-year event is therefore insignificant for these parameters. In the portion of the Inner Harbor downstream of Eighth Street bridge, there is still 2 feet of net deposition after the 100-year flood. Between cross sections 4095 and 5500, sediment bed elevation is relatively unchanged by a 100-year event, although bed composition reflects the replacement of silt by coarser sands in the active layer. The fact that a 100-year flow has little effect on bed elevation in this reach over the range of coefficients tested indicates that between cross sections 4095 and 5500, the River is approaching dynamic equilibrium and that this equilibrium prediction is relatively insensitive to the value of the threshold coefficients.

5.2 Active Bed Mass Erosion Rate

The computed rate of clay or silt erosion is a linear function of shear stress. At or below the threshold coefficient for erosion, no scour of the bed is predicted. The rate increases to a specified mass erosion rate at the mass erosion threshold. The calibrated model uses a mass erosion rate of 63 $lbs/hr/ft^2$ at a mass erosion threshold of 1 lb/ft^2. The sensitivity analysis examined values for the mass erosion rate ranging between 30 $lbs/hr/ft^2$ and 120 $lbs/hr/ft^2$, thereby affecting the slope of the shear stress/erosion curve.

Figure 5-3A shows the predicted net deposition for the Inner Harbor during the 1980 to 1990 simulation. Between cross sections 1600 and 5500, predicted net deposition varied by less than a half a foot across the range of mass erosion rate values. Higher mass erosion rates lead to slightly more erosion during episodic high flow periods in this reach and thus lower net deposition. Downstream of cross section 1600, higher erosion rates are correlated with higher sediment loads and consequently greater redeposition of sediments as the velocities decrease in the downstream portion of the Inner Harbor. Overall trap efficiencies (percent of suspended material retained within the study reach) vary little for the period 1980 to 1990 as a result of variations in the mass erosion coefficient. Trap efficiencies for sand remain at 99 percent, while those for silts range from 28 to 35 percent, with lower mass erosion rates correlated with higher net trap efficiencies.

Figure 5-3B shows the net deposition predicted for different values of the mass erosion rate in the Inner Harbor in response to the 100-year flow. Lower erosion rates are generally correlated with greater net deposition. The exception to this general observation was the simulation predicting more deposition in the Inner Harbor with a mass erosion rate of 120 $lbs/hr/ft^2$ than was predicted for the simulation with 90 $lbs/hr/ft^2$. In this specific case, the deposition in the Inner Harbor from the greater upstream erosion at 120 $lbs/hr/ft^2$ outweighs the greater loss of silts and clays.

5.3 Inactive Bed Shear Stress Scour Threshold Coefficient

The model was calibrated with an inactive bed scour threshold coefficient of 0.20 lb/ft^2 compared to 0.02 lb/ft^2 for the active bed. The higher value for inactive bed sediments compared to active bed sediments reflects the increased resistance to scour which occurs when the deeper, older sediments become compacted. When it is assumed that the shear stress exceeds the inactive bed scour threshold and the active bed sediment are exhausted, predicted scour of consolidated sediments below the active layer is possible. Values for the inactive bed scour coefficient ranging between 0.05 and 0.50 lb/ft^2 were used in the sensitivity analysis.

The sensitivity analysis indicates that the model is insensitive to changes in the inactive bed scour threshold during normal flow conditions. As Figure 5-4A shows, there was little variation in the predicted net deposition for the period 1980 to 1990 in the Inner Harbor, partially because the threshold was exceeded relatively infrequently.

Figure 5-4B shows the change in bed elevation in the Inner Harbor during the simulated 100-year event. Sediment bed dynamics during the 100-year flow tend to counteract whatever differences in net deposition resulted from varying the inactive bed scour coefficient during the 1980 to 1990 flow simulation. Between cross sections 3325 and 5995, those simulations with coefficients which produced higher net deposition in the 1980 to 1990 simulation, eroded more in these same reaches during the 100-year event. Downstream of 3325, lower coefficients for the 100-year event simulation lead to more deposition as they also did for the 1980 to 1990 simulation.

5.4 Mass of Inflowing Suspended Sediment

The mass of suspended sediment entering the upstream end of the reach modeled was measured. During the period of measurement, flow was limited to less than 950 cfs. On the basis of these direct measurements and results from other Wisconsin rivers, a sediment load versus discharge curve was constructed and extended for River flows of greater than 950 cfs. To gauge the uncertainty introduced by extrapolating to high flow events, a sensitivity analysis examined the effects of uniformly raising or lowering the sediment loading rates to 50 percent, 75 percent, 90 percent, 110 percent, and 125 percent of their original values.

Figure 5-5A shows the predicted net deposition for the Inner Harbor for the simulated 1980 to 1990 time period. Predicted net deposition is nearly linearly correlated with upstream sediment loading. Trap efficiencies for silts are fairly constant, ranging from 29 to 31 percent despite differences in sediment loading. The differences in predicted net deposition between various sediment load scenarios are greatest for those cross sections where the sediment deposition was greatest downstream of Pennsylvania Avenue bridge (cross-section 5550) the range of the differences in predicted net deposition between the sediment load scenarios are from 0.36 feet at cross sections 5100 and 4700 to a maximum of 2.05 feet at cross section 3100.

The predicted change in bed elevation resulting from the 100-year flow tends to be similar, regardless of suspended sediment load. Figure 5-5B shows the difference in net deposition due to the 100-year flow. The erosion of previously deposited silts is responsible for the slightly lower net deposition for higher values of upstream sediment load.

5.5 Lake Elevation

Three model simulations for the 1980 to 1990 time period were performed to determine the effect of the water surface level in Lake Michigan on net deposition and trap efficiency in the Lower River and Inner Harbor. Each simulation used the identical flow data and maintained a constant Lake level of either 577.4, 579.0, or 581.0 feet (IGLD 1955) throughout the simulated period.

In Figure 5-6, the predicted net deposition from the three constant Lake level simulations are compared with the net deposition predicted using the Lake level record for the 1980 to 1990 period. The simulations with constant low and medium Lake levels had slightly less net deposition in the reach between cross sections 4095 and 5550.

The simulations which use the historic Lake level record or a constant low Lake level have greater deposition downstream of cross section 3100 (Eighth Street bridge). The simulation with the highest assumed Lake level had the highest deposition between Eighth Street and Pennsylvania Avenue bridges. These deposition patterns represent the distance downstream particles must travel before river velocities start to decrease sufficiently to allow for settling. With higher Lake levels, backwater effects, which decreases velocity, extend further upstream. The simulations with constant low, medium, and high Lake levels have silt trap efficiencies of 28 percent, 32 percent, and 34 percent, respectively. For comparison, the simulation using the historic Lake level record for the 1980 to 1990 period has a predicted silt trap efficiency of 31 percent. The trap efficiency of sand is insensitive to differences in Lake level for these simulations.

Section 6.0 - Results and Conclusions

Metals and PCBs were detected in Inner Harbor sediment samples during the Sheboygan River and Harbor Remedial Investigation. The net deposition of progressively cleaner sediment was generally noted, through the assessment of Inner Harbor sediment core samples by depth. Since prior navigation channel dredging has placed this stretch of the riverbed in disequilibrium, short-term extreme event and relative long-term dynamic equilibrium conditions are considerations in assessing the need for, and types of, potential viable remedial measures in the Inner Harbor, should these be deemed necessary.

The HEC-6 simulation model was selected as an appropriate mechanism for evaluating the response of the sediment bed of the Inner Harbor on both a relative long-term and short-term extreme event basis. An overall goal of the modeling work was to provide information which could be used to assess the feasibility of natural armoring as a remedial option for the Inner Harbor.

The results of the HEC-6 modeling efforts are summarized below.

6.1 Results

6.1.1 Results of Extreme Hydrologic Event Simulation

To assess the effects of extreme hydrologic events on the stability of the natural sediment cap, simulations were performed to represent 10-year (6,400 cfs) and 100-year (10,200 cfs) recurrence interval high flow events for low, average, and high Lake Michigan levels. The simulations indicated:

- During extreme event simulations the predicted bed elevation in the Inner Harbor either changes little or results in a net accumulation of sediments. There was little net change in bed surface between Eighth Street and Pennsylvania Avenue bridges during extreme events. Downstream of Eighth Street bridge, there was net accumulation of sediments predicted during extreme events.

- Lower Lake levels in the event simulations lead to a greater predicted rate of deposition downstream of the Eighth Street bridge. With upstream velocities increasing as lower Lake levels reduced the length of the River affected by backwater conditions, more sediments were predicted to be transported downstream of the Eighth Street bridge before deposition occurred.

- Some scour was predicted for *certain* ~~several~~ cross-sections in the vicinity of bridges. During extreme events, some scour of sediment was predicted in the vicinity of Eighth Street and Pennsylvania Avenue bridges. Scour during the event, however, was limited to 0.5 to 1.0 foot of sediment, and is still less than deposition predicted for the preceding 10 years.

- The texture of the surface sediments are coarser as a result of the extreme hydrologic events. The 10-year and 100-year extreme events shift the distribution of grain sizes in the surface sediments by scouring the finer-grain sizes, and leaving the coarser materials behind and/or, by replacing them with coarser material scoured from farther upstream. The coarser sediments (either those not scoured or those freshly deposited) act as a natural armor layer shielding the underlying sediments from erosion during later time steps of the simulated event. The replacement of finer materials with coarser materials during the extreme events explain why, although some scour of finer materials is predicted for cross-sections between the Eighth Street and Pennsylvania Avenue bridges, there is little or no net decrease in the overall sediment bed elevation. The exchange of coarser for finer material affects the upper 0.6-foot near the Eighth Street bridge and upper 0.3-foot between Eighth Street and the Pennsylvania Avenue bridge.

6.2 Conclusions

Natural armoring represents a viable remedial option for sediment in the Inner Harbor. Net accumulation of progressively cleaner sediment has been documented through the analysis of sediment cores. The HEC-6 simulation predicts continued sediment accumulation in the Inner Harbor sediment bed, as the system continues to move towards dynamic equilibrium. As such, the modeling results indicate that natural armoring is an appropriate remedial option for the Inner Harbor sediments.

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TABLE

Table 5-1
Sheboygan River and Harbor Site
Sediment Transport Investigation

Active Bed Deposition and Scour Threshold Coefficients for Sensitivity Analysis

First Set of Sensitivity Trials	
Sensitivity Analysis of the Deposition Coefficient	
Deposition Threshold (lb/sq ft)	Erosion Threshold (lb/sq ft)
.01	.02
.015	.02
.025	.026
.04	.042
.06	.063
Sensitivity Analysis of the Scour Coefficient	
Deposition Threshold (lb/sq ft)	Erosion Threshold (lb/sq ft)
0.0095	0.01
0.014	0.015
0.019	0.025
0.019	0.04
0.019	0.06
Second Set of Sensitivity Trials	
Sensitivity Analysis of the Deposition Coefficient	
Deposition Threshold (lb/sq ft)	Erosion Threshold (lb/sq ft)
0.01	0.063
0.015	0.063
0.025	0.063
0.04	0.063
0.06	0.063
Sensitivity Analysis of the Scour Coefficient	
Deposition Threshold (lb/sq ft)	Erosion Threshold (lb/sq ft)
0.0095	0.01
0.0095	0.015
0.0095	0.025
0.0095	0.04
0.0095	0.06

FIGURES

REFERENCE: WISCONSIN MAP, PROVIDED BY THE DEPARTMENT OF TRANSPORTATION (OFFICIAL STATE HIGHWAY MAP)

13 0 13

APPROXIMATE SCALE: 1"=13 MILES

QUADRANGLE LOCATION

L: (LAYER)
P: STD-PCP/AP
10/96-SYR-54-NES
17606D04/17606G01.DWG

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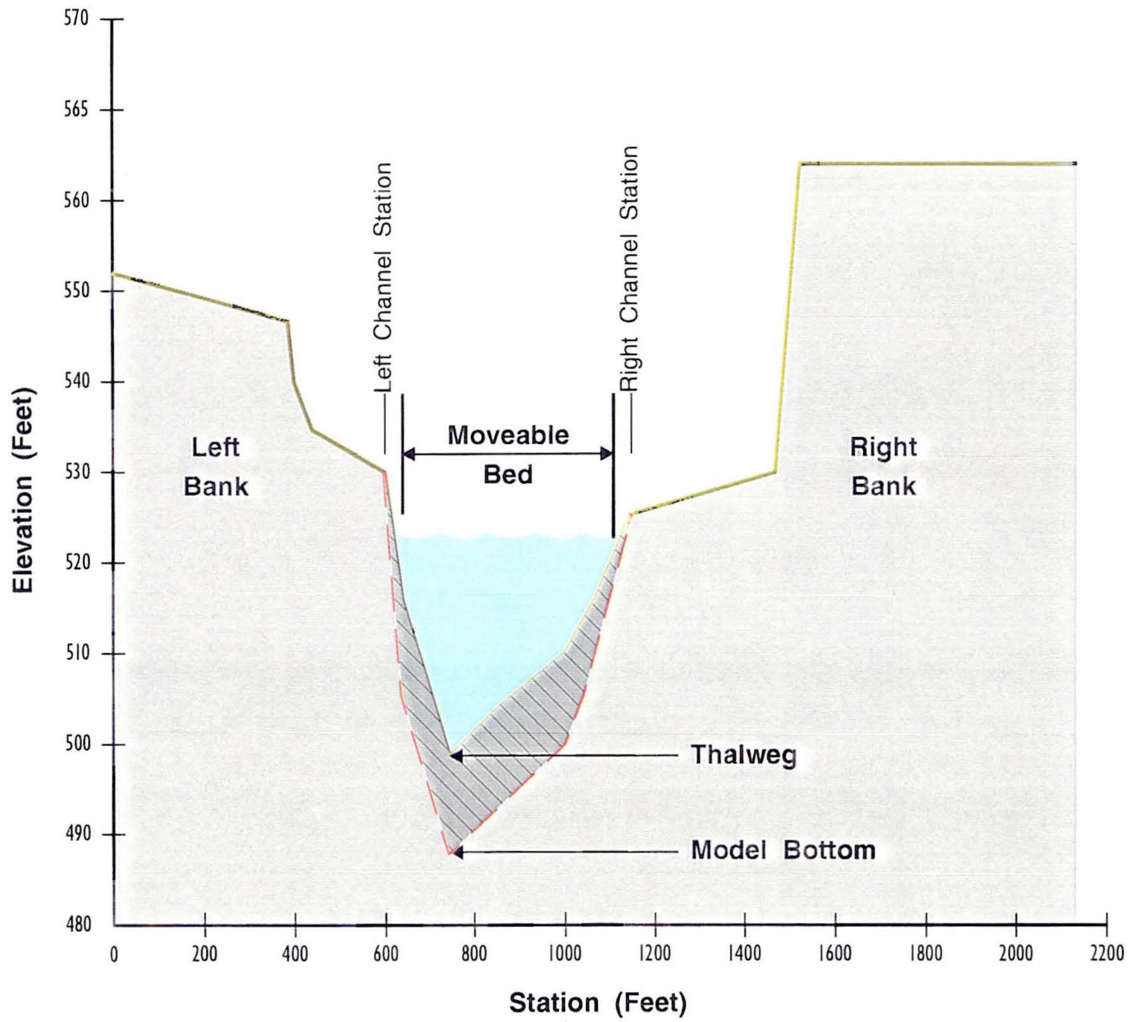
SHEBOYGAN, WISCONSIN

SEDIMENT TRANSPORT INVESTIGATION

GENERAL SITE LOCATION MAP

FIGURE **1-1**



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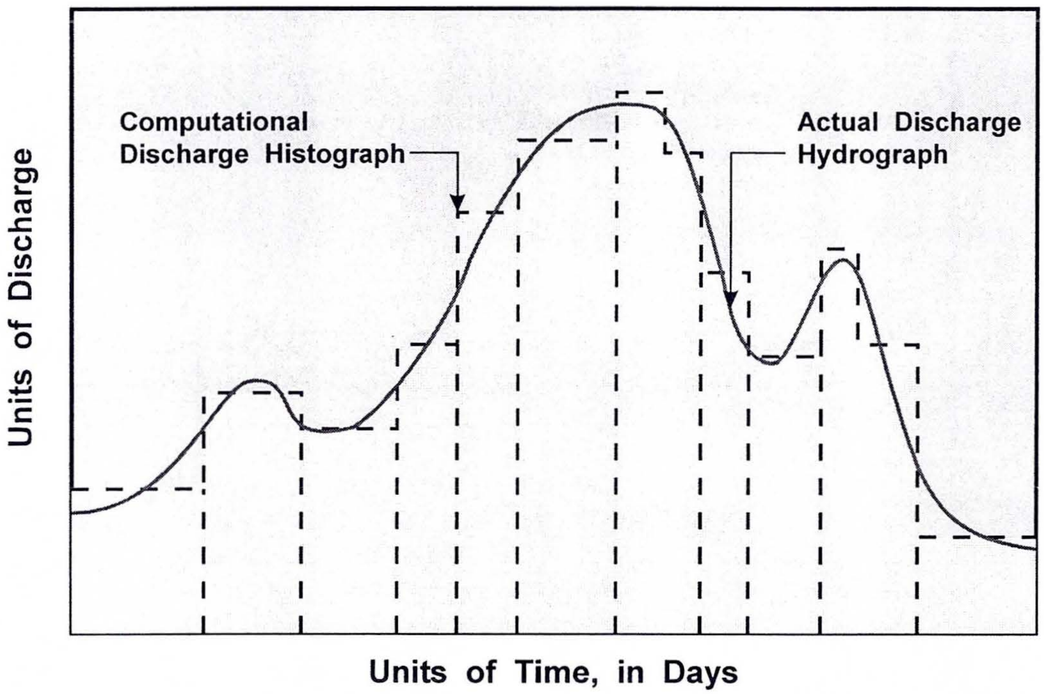
REPRESENTATION OF RIVER CROSS-SECTION IN HEC-6

FIGURE **2-1**

11/95 D54 DJH
1760703R/17607n02.cdr



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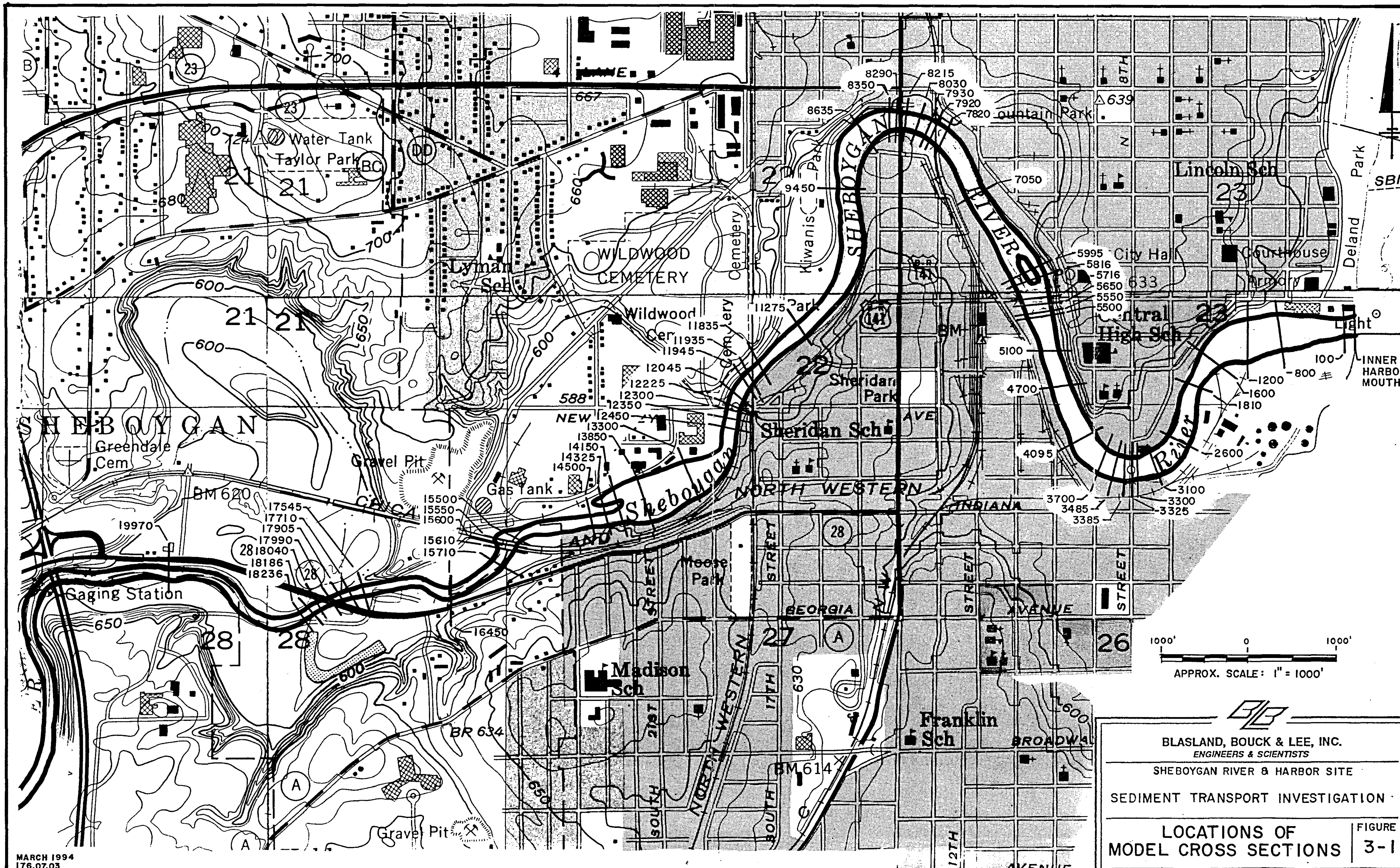
SEDIMENT TRANSPORT INVESTIGATION

REPRESENTATION OF HYPOTHETICAL DISCHARGE HYDROGRAPH IN HEC-6

FIGURE **2-2**

03/94 D54-DJH
1760703R/17607n01.cdr



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176.07.03

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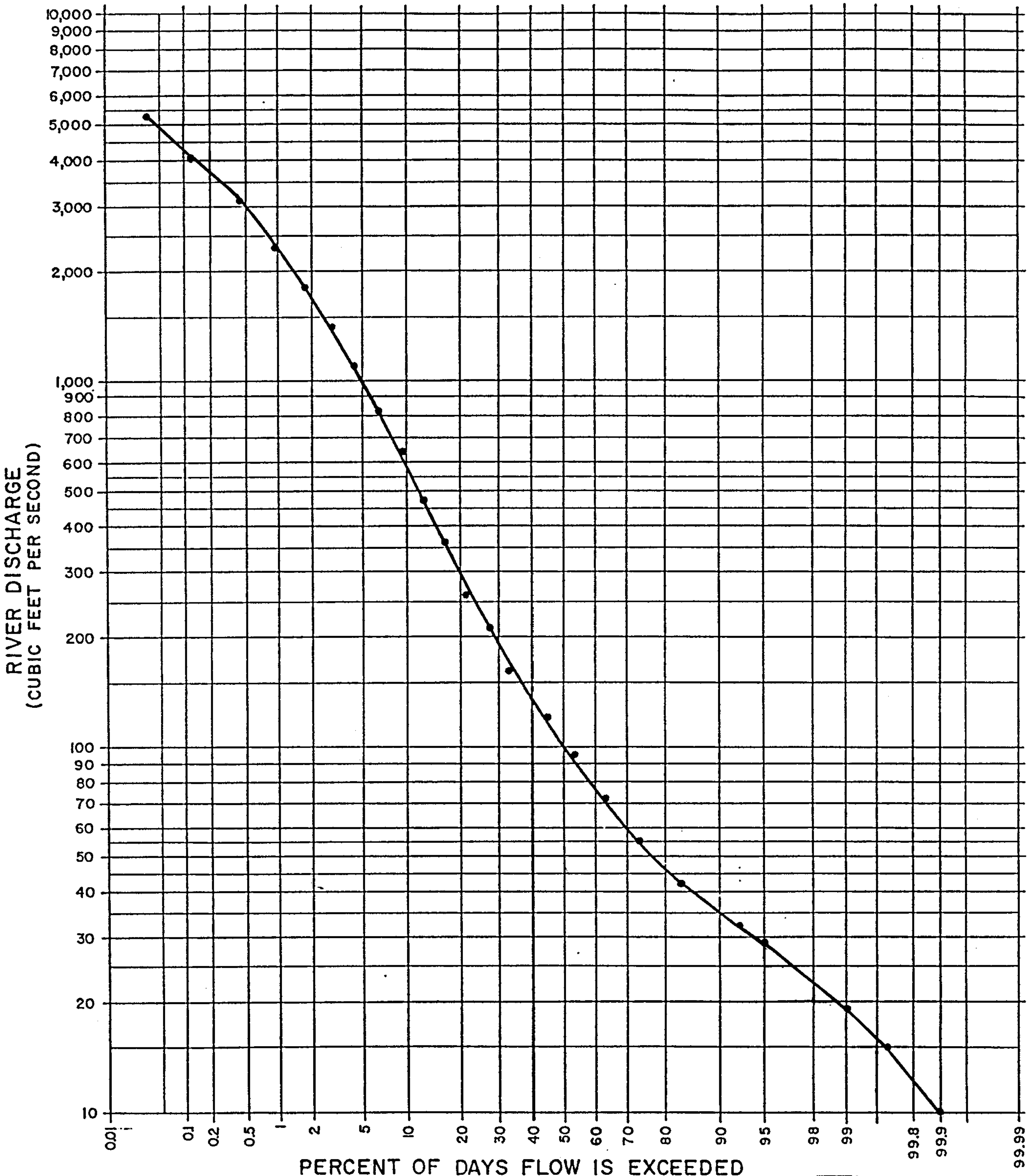
LOCATIONS OF MODEL CROSS SECTIONS

FIGURE 3-1



NOTE:

THIS FLOW DURATION CURVE REPRESENTS DATA FROM THE YEARS 1916 TO 1924, AND 1951 TO 1993

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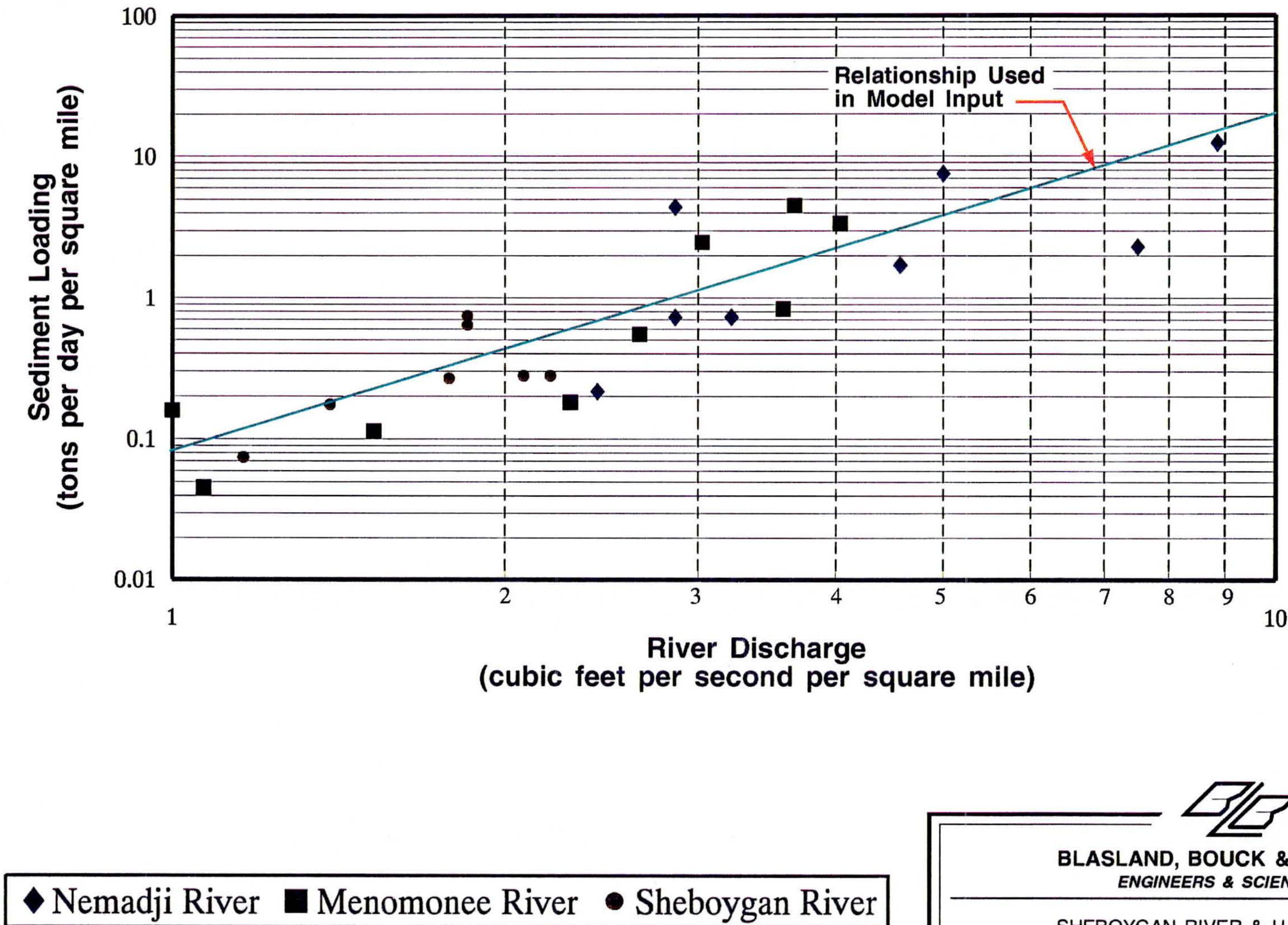
SHEBOYGAN RIVER FLOW DURATION CURVE

FIGURE 3-2

MARCH 1994
176.07.03

[redacted] [redacted] [redacted]



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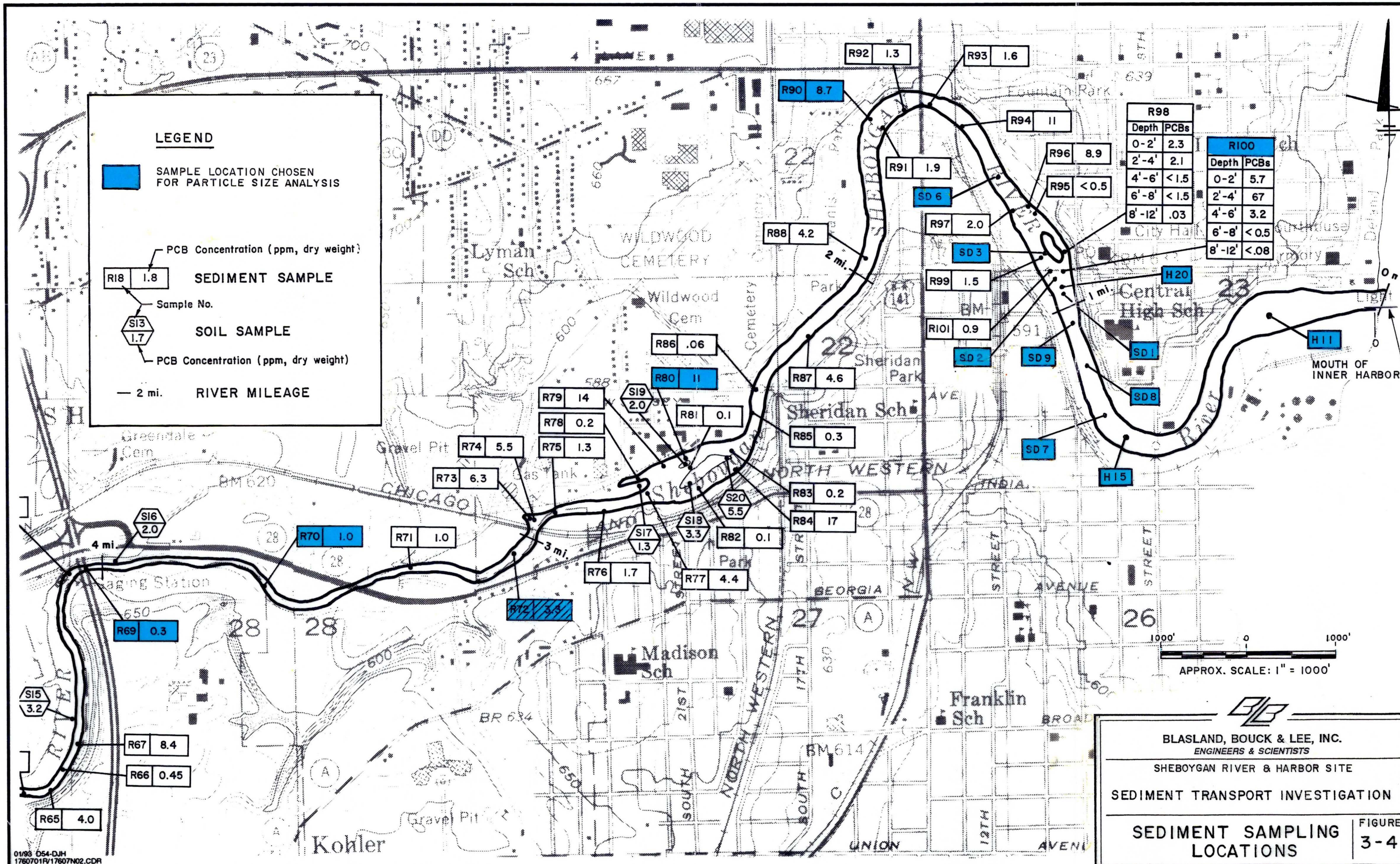
SEDIMENT TRANSPORT INVESTIGATION

SEDIMENT TRANSPORT COMPARISON TO OTHER WISCONSIN RIVERS

FIGURE **3-3**

11/95 D54 DJH
1760703R/17607N08.CDR



R98	
Depth	PCBs
0-2'	2.3
2'-4'	2.1
4'-6'	< 1.5
6'-8'	< 1.5
8'-12'	.03

R100	
Depth	PCBs
0-2'	5.7
2'-4'	67
4'-6'	3.2
6'-8'	< 0.5
8'-12'	<.08

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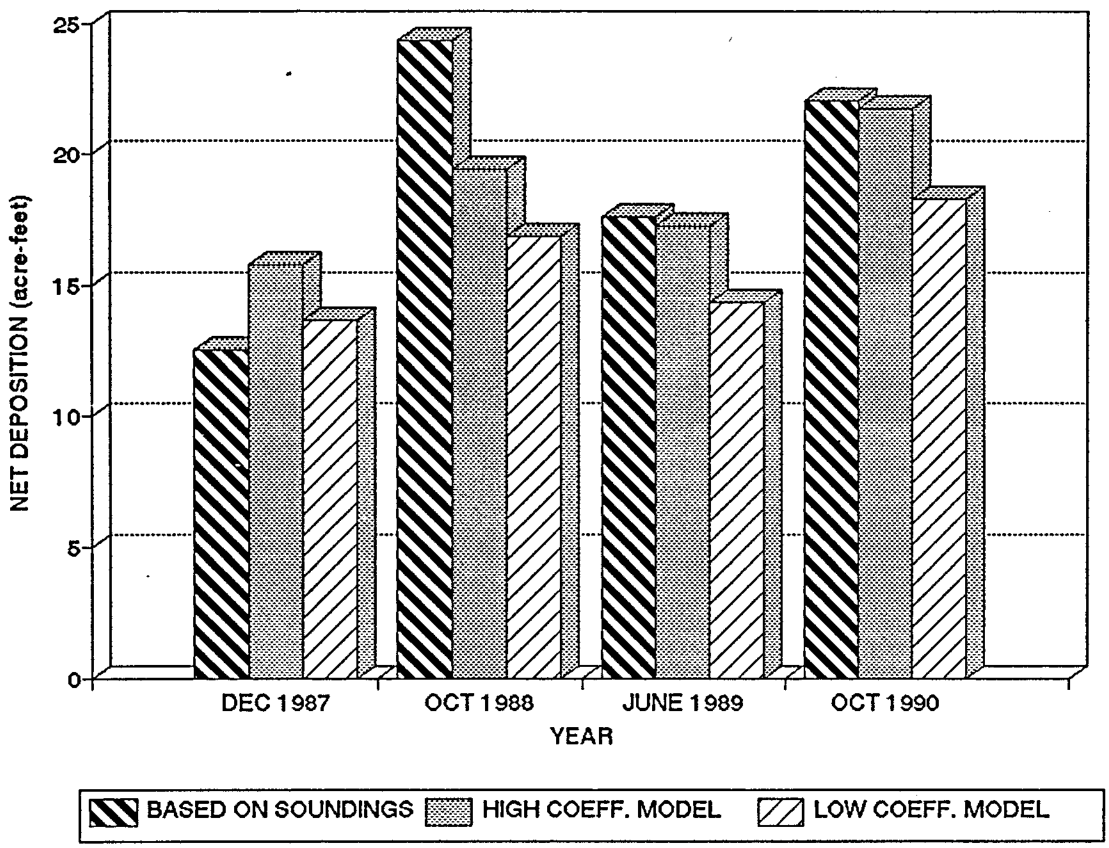
SEDIMENT TRANSPORT INVESTIGATION

SEDIMENT SAMPLING LOCATIONS

FIGURE 3-4



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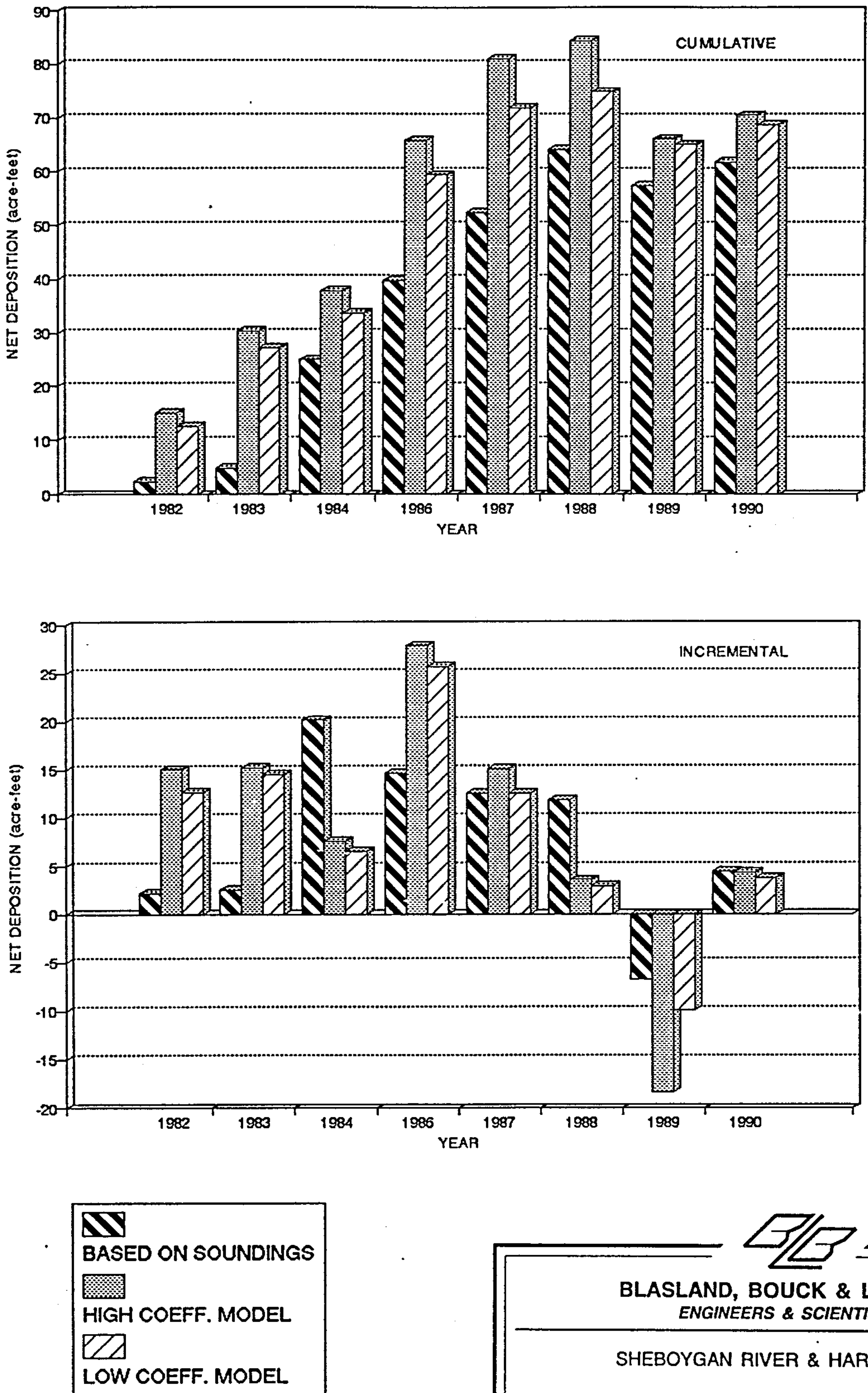
SEDIMENT TRANSPORT INVESTIGATION

RESULTS OF MODEL CALIBRATION CUMULATIVE DEPOSITION OF SEDIMENT

FIGURE **4-1**

11/95 D54-JVM
1760703R/17607n30.cdr



11/95 D54-JVM
1760703R/17607n31.cdr

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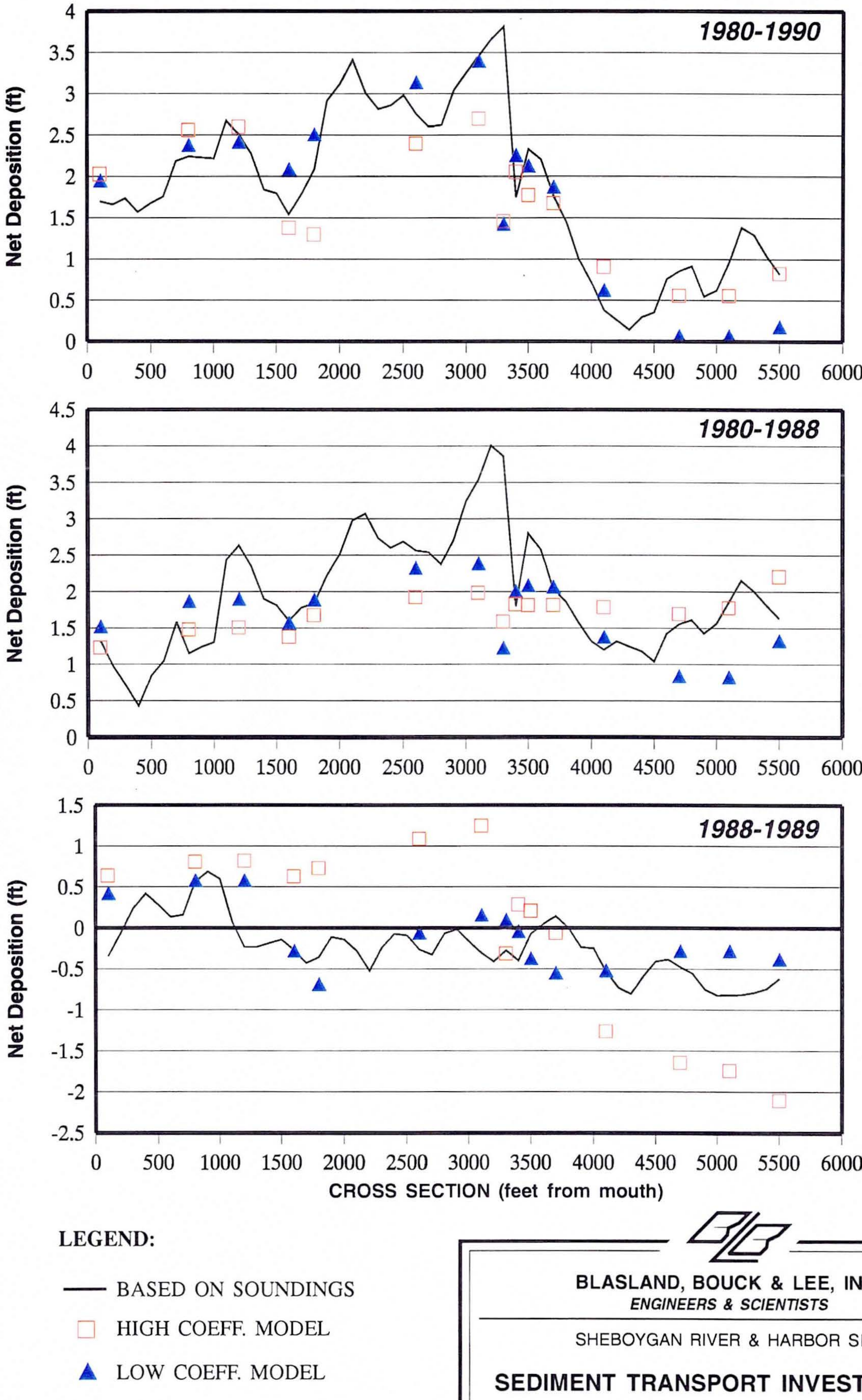
SEDIMENT TRANSPORT INVESTIGATION

MODEL VERIFICATION RESULTS

FIGURE **4-2**



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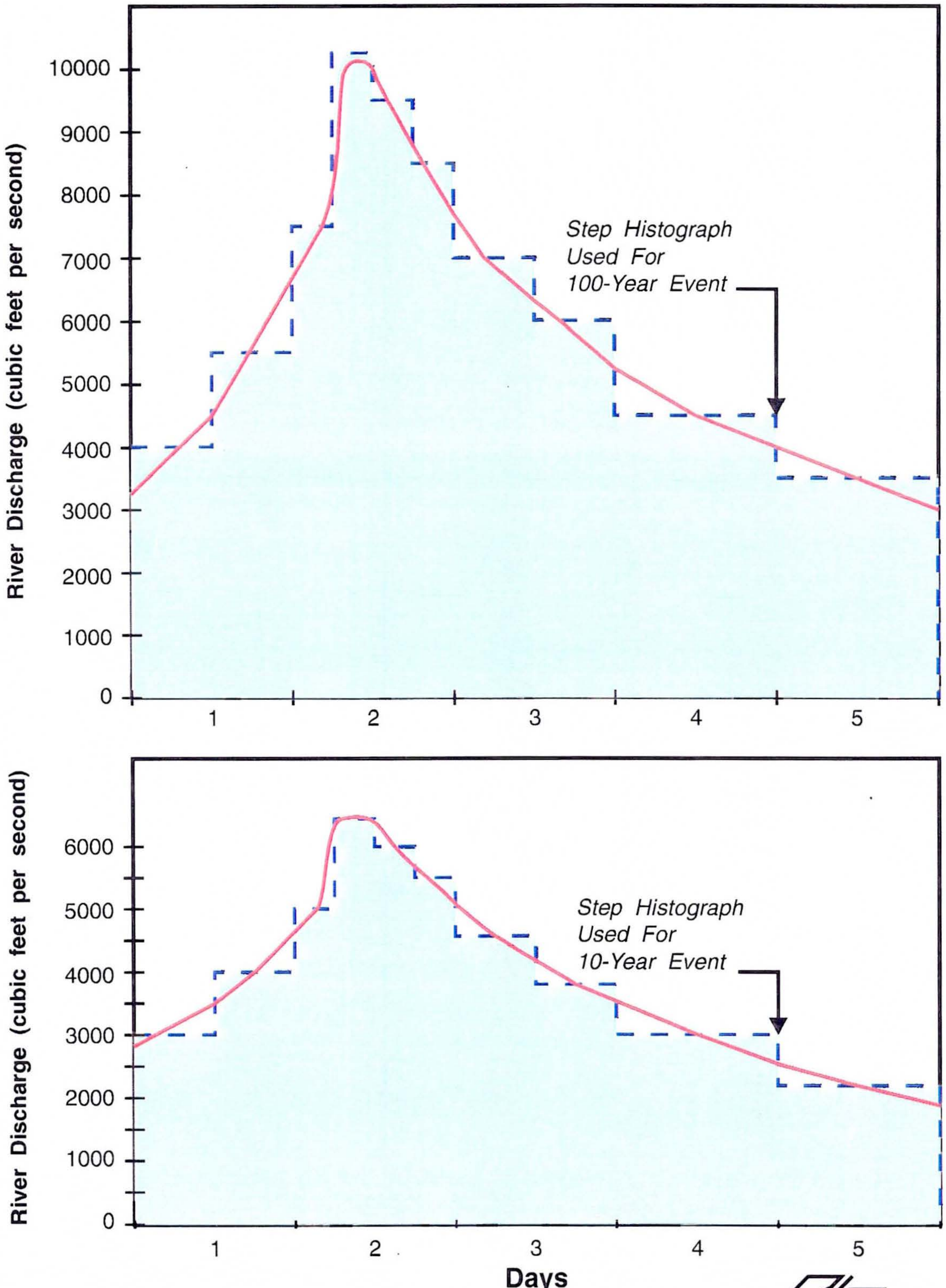
SEDIMENT TRANSPORT INVESTIGATION

SPATIAL DISTRIBUTION OF PREDICTED DEPOSITION DURING MODEL VERIFICATIONS

FIGURE **4-3**

11/95 D54 DJH
1760703R/17607n05.cdr



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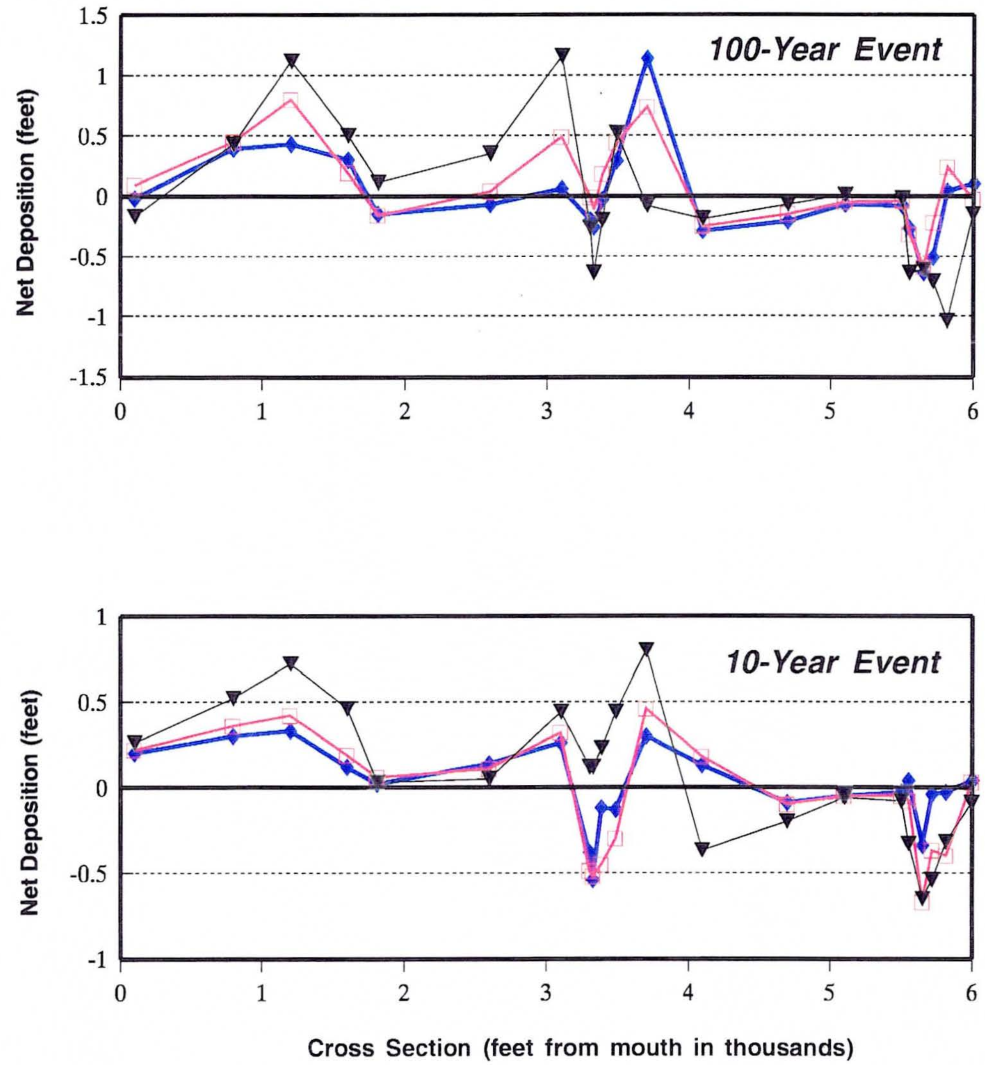
SEDIMENT TRANSPORT INVESTIGATION

FLOOD HYDROGRAPHS USED IN SIMULATIONS

FIGURE 4-4

11/95 D54 DJH
1760703R/17607n09.cdr



Legend:

Low Lake

Medium Lake

High Lake

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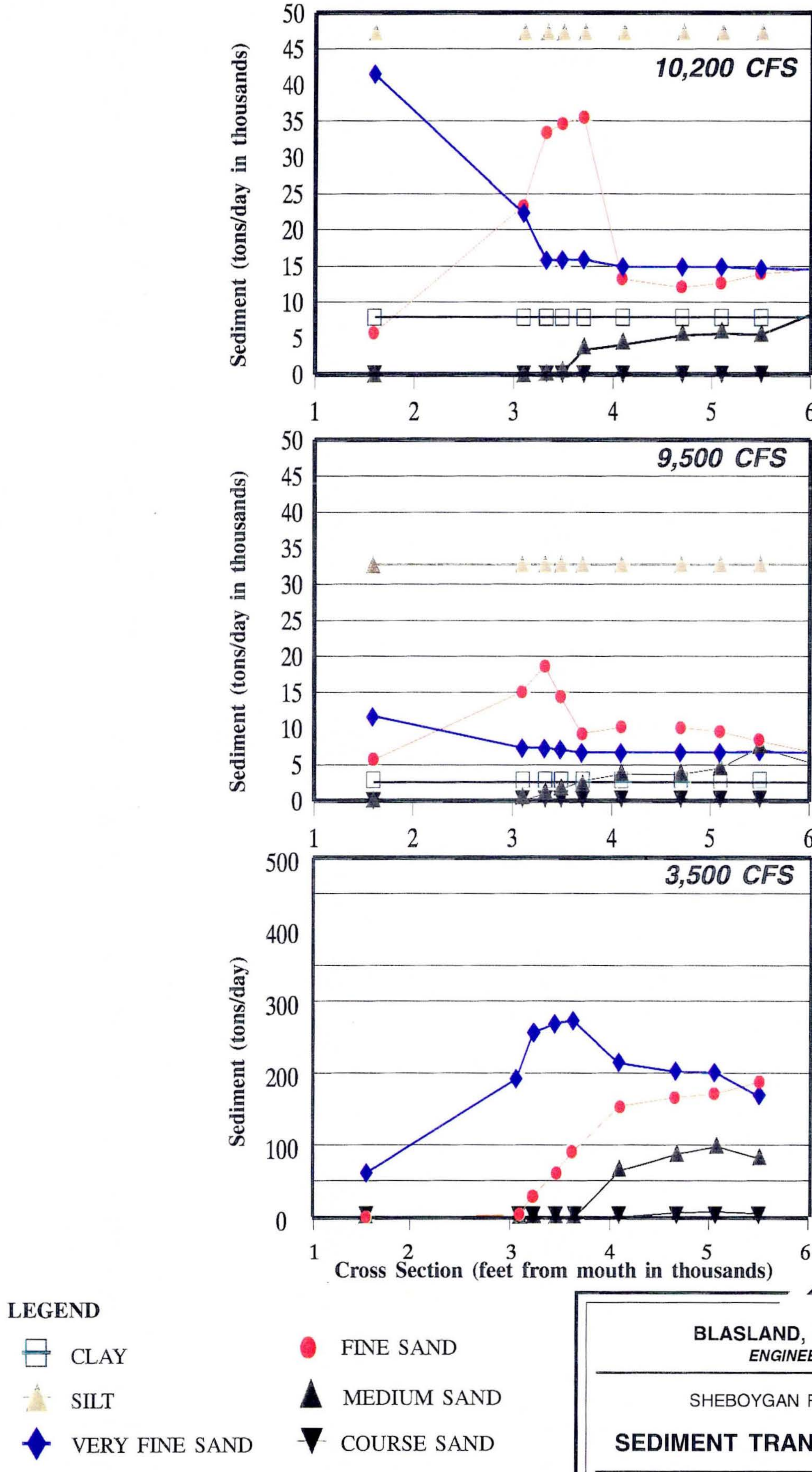
SEDIMENT TRANSPORT INVESTIGATION

NET DEPOSITION DURING EXTREME EVENTS

FIGURE **4-5**

11/95 D54 JVM
17607003/17607N10.CDR



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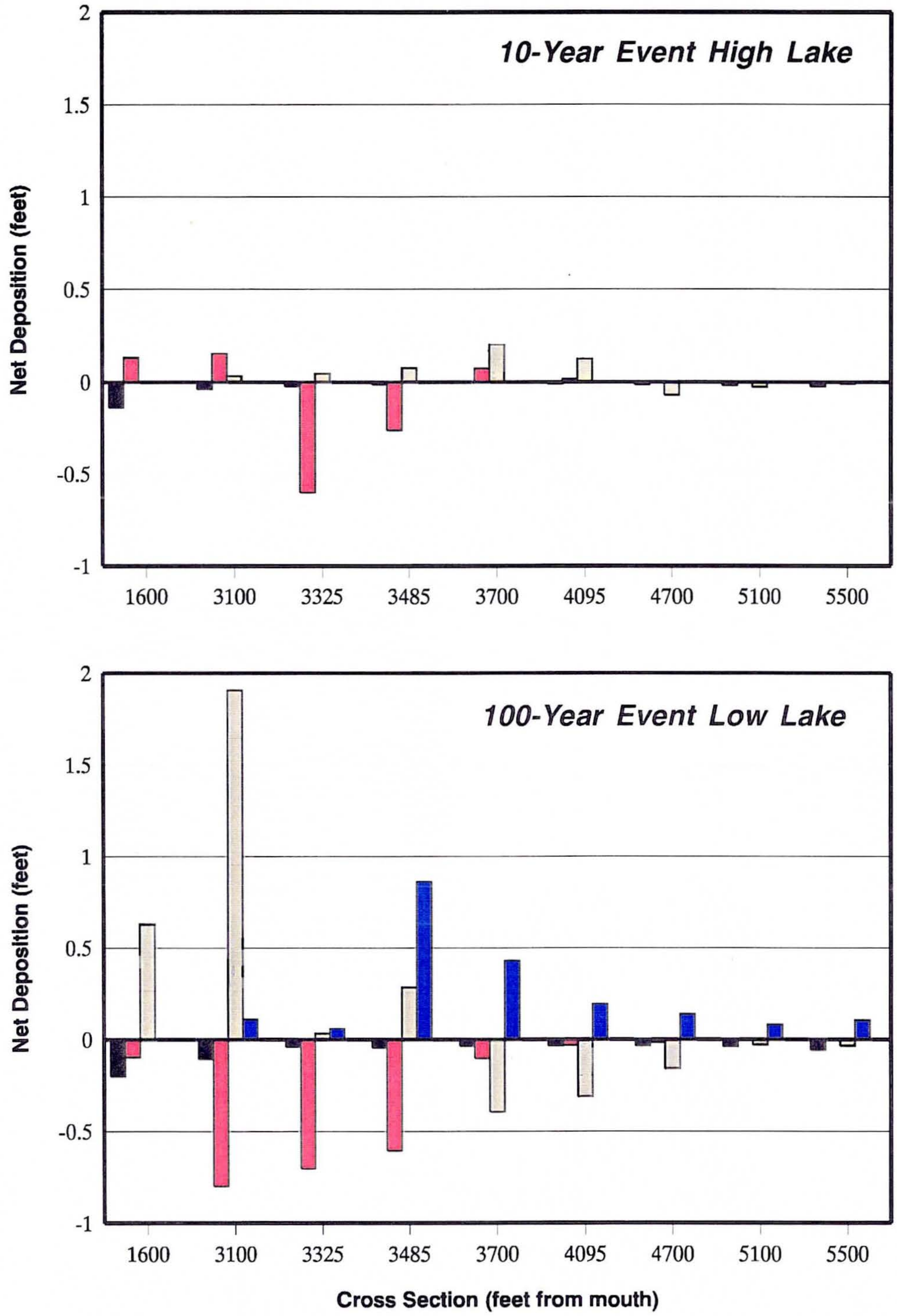
SEDIMENT TRANSPORT INVESTIGATION

SEDIMENT TRANSPORT 100-YEAR EVENT, LOW LAKE LEVEL

FIGURE **4-6**

11/95 D54 DJH
1760703R/17607n15.cdr



Legend:

- Silt
- Very Fine Sand
- Fine Sand
- Medium Sand
- Coarse Sand

11/95 D54 DJH
1760703R/17607N11.CDR

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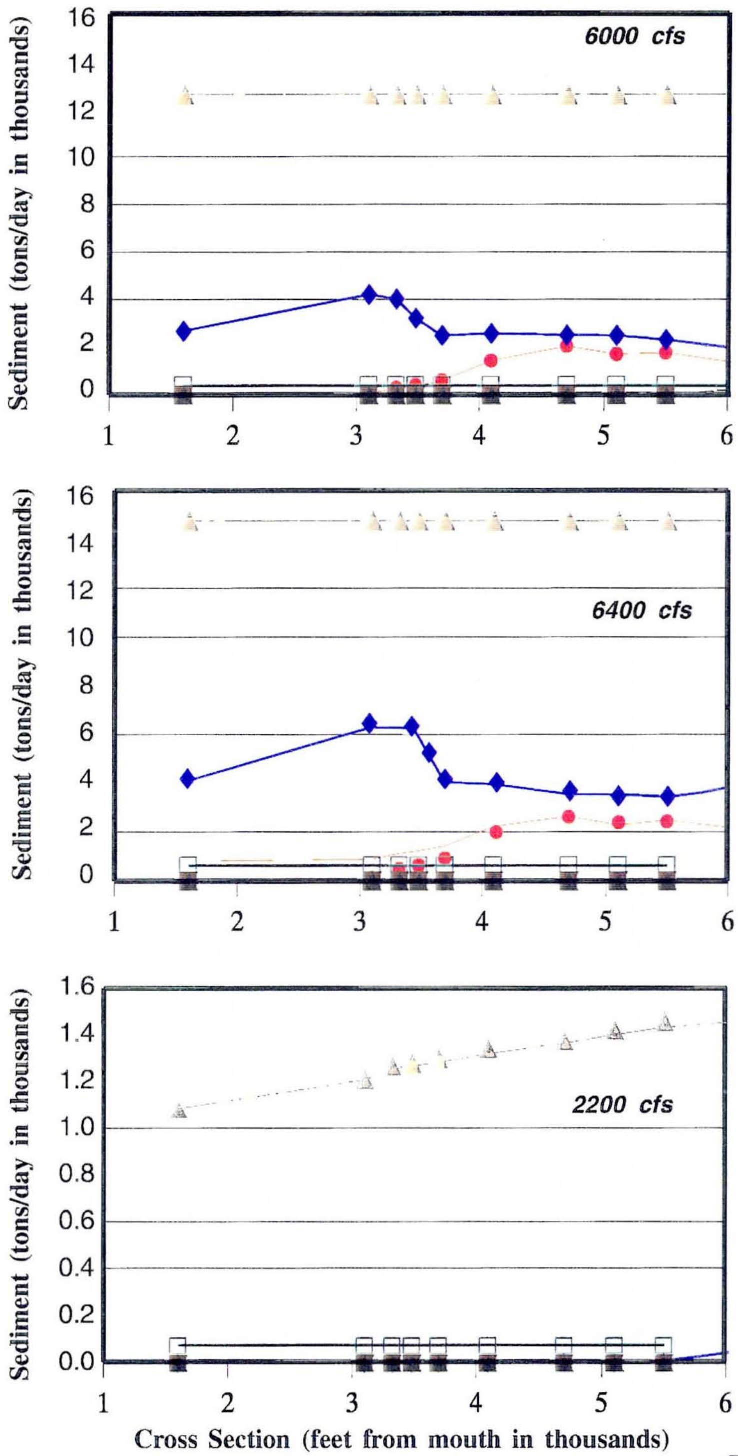
SEDIMENT TRANSPORT INVESTIGATION

NET DEPOSITION OF GRAIN SIZES

FIGURE **4-7**



LEGEND:

- CLAY
- SILT
- VERY FINE SAND
- FINE SAND
- MEDIUM SAND
- COARSE SAND

11/95 D54 DJH, JVM
1760703R/17607n12.cdr

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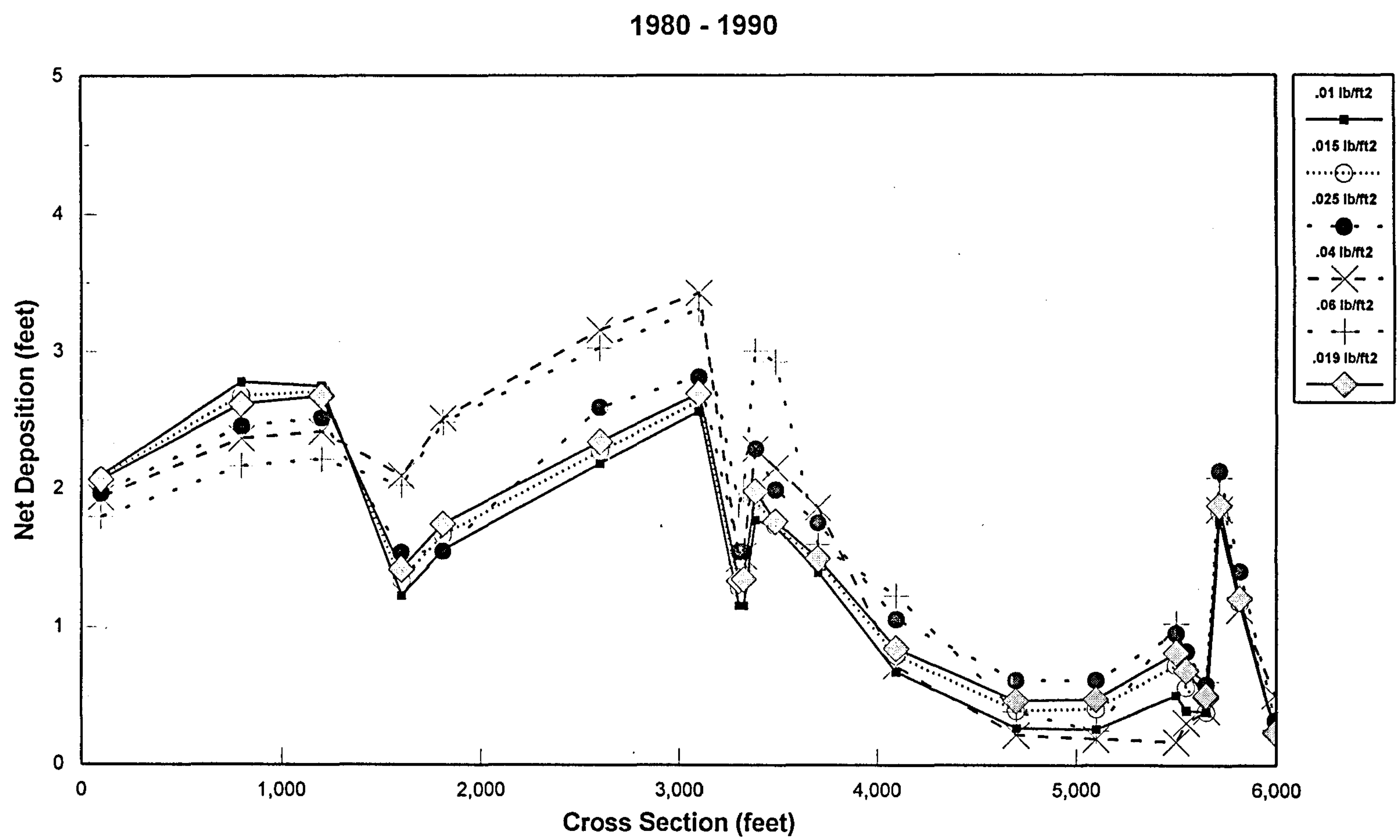
SEDIMENT TRANSPORT INVESTIGATION

SEDIMENT TRANSPORT 10-YEAR EVENT, HIGH LAKE LEVEL

FIGURE **4-8**

[redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted]



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Sheboygan River and Harbor Site

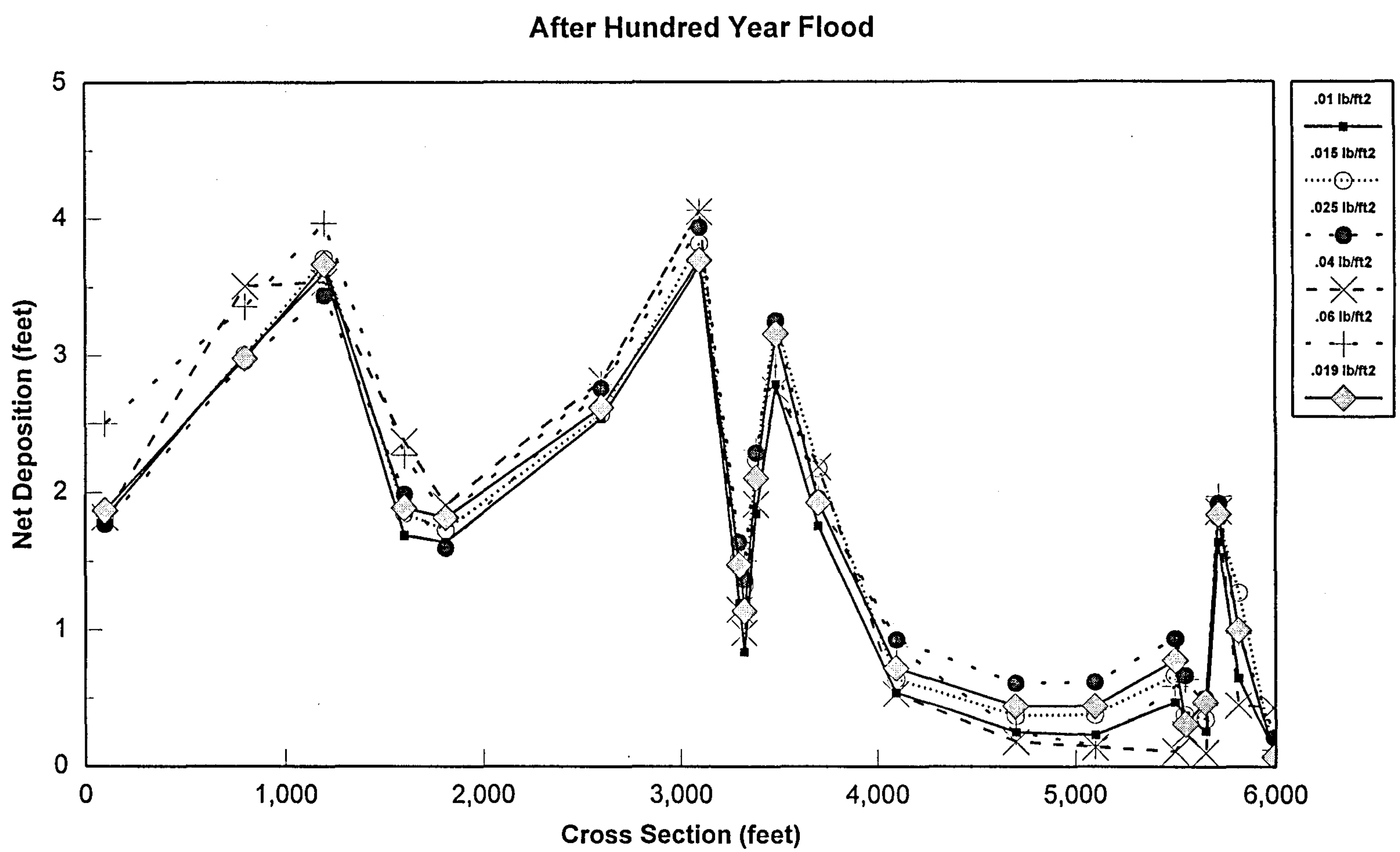
Sediment Transport Investigation

Sensitivity Analysis of Active Bed Deposition Threshold Coefficient

Figure 5-1A

10/96 - 03861081.PRE

[redacted]



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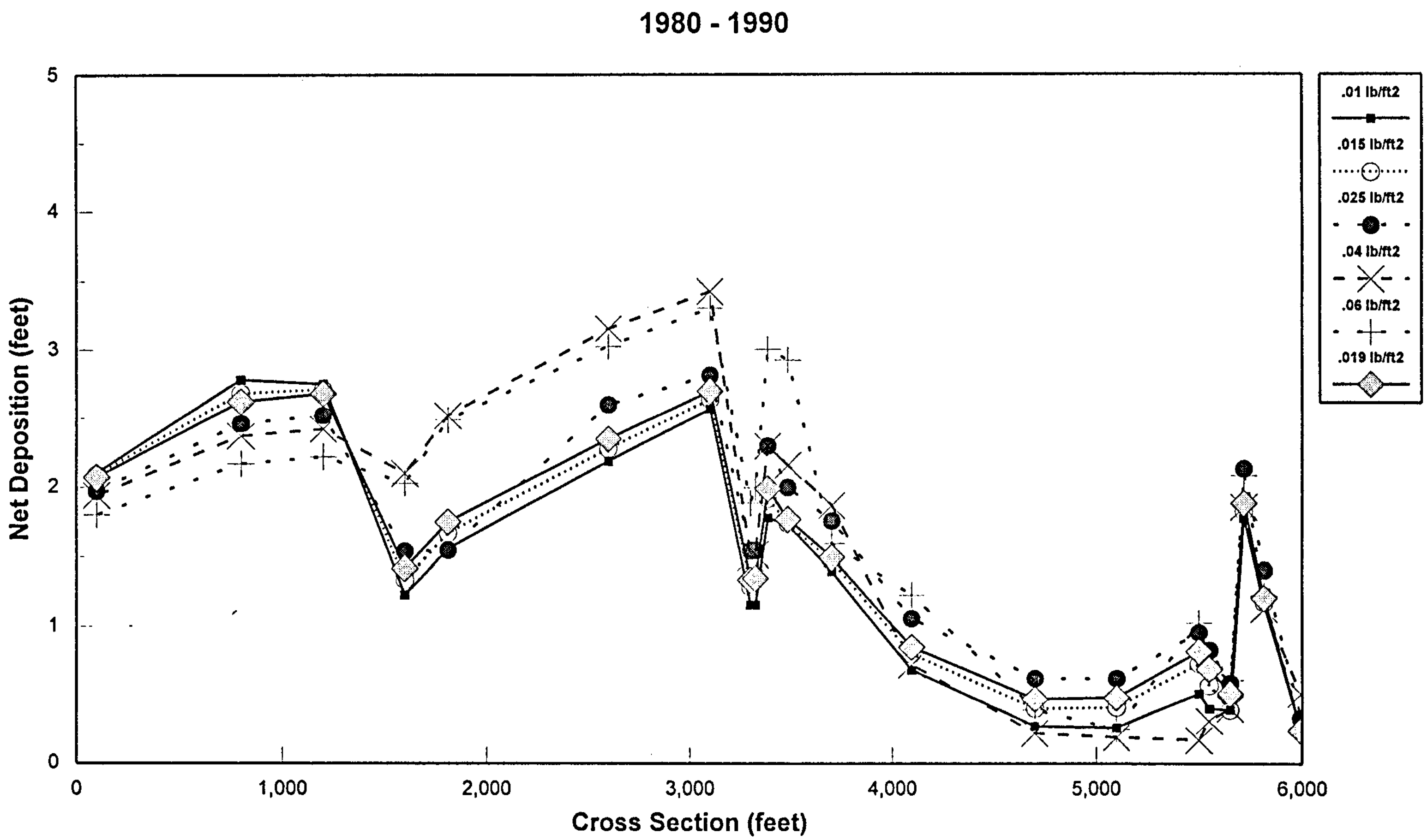
Sediment Transport Investigation

Sensitivity Analysis of Active Bed Deposition Threshold Coefficient

Figure 5-1B

10/96 - 03861081.PRE



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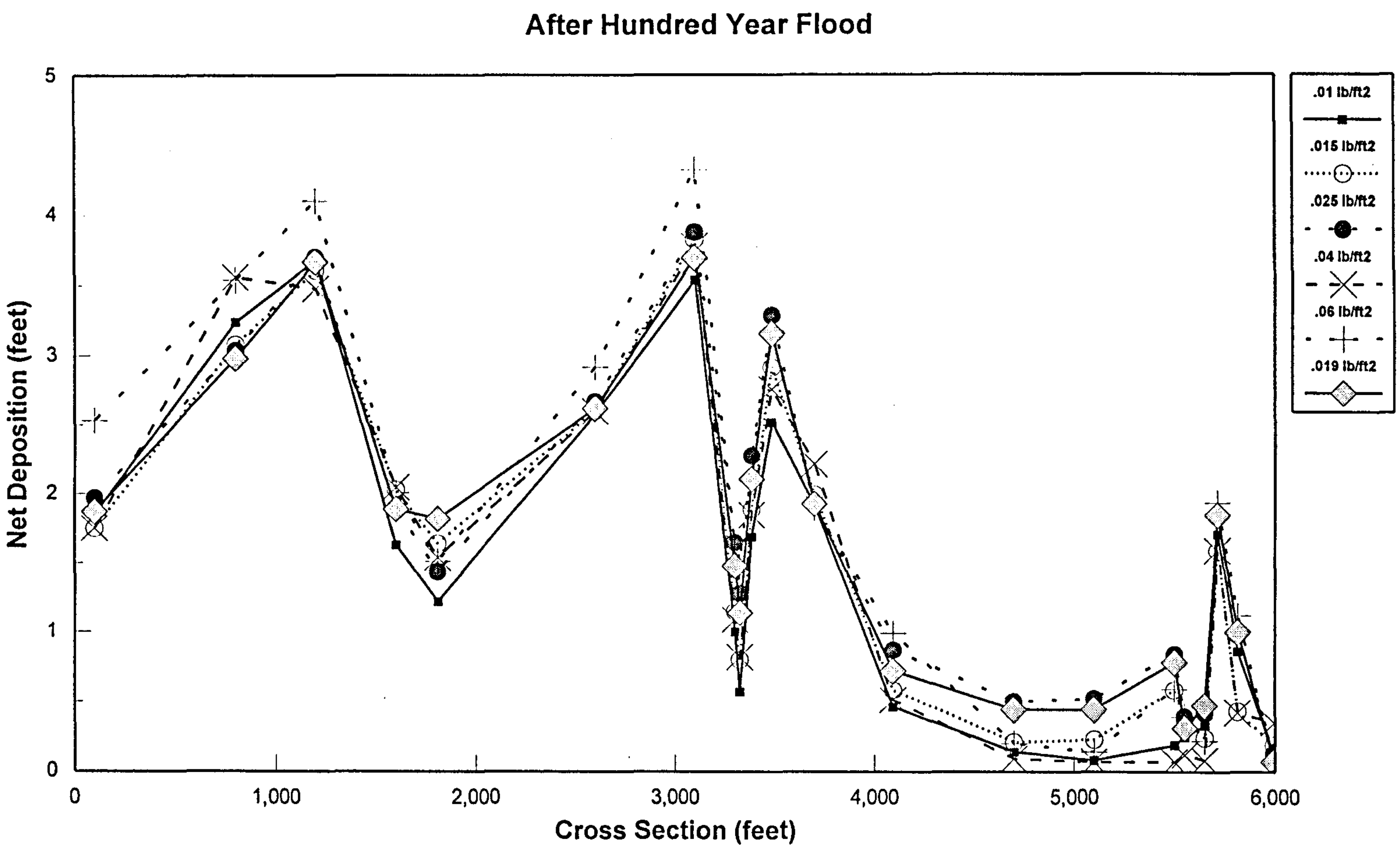
Sheboygan River and Harbor Site

Sediment Transport Investigation

Sensitivity Analysis of Active Bed Scour Threshold Coefficient	**Figure 5-2A**

10/96 - 03861081.PRE

[redacted]



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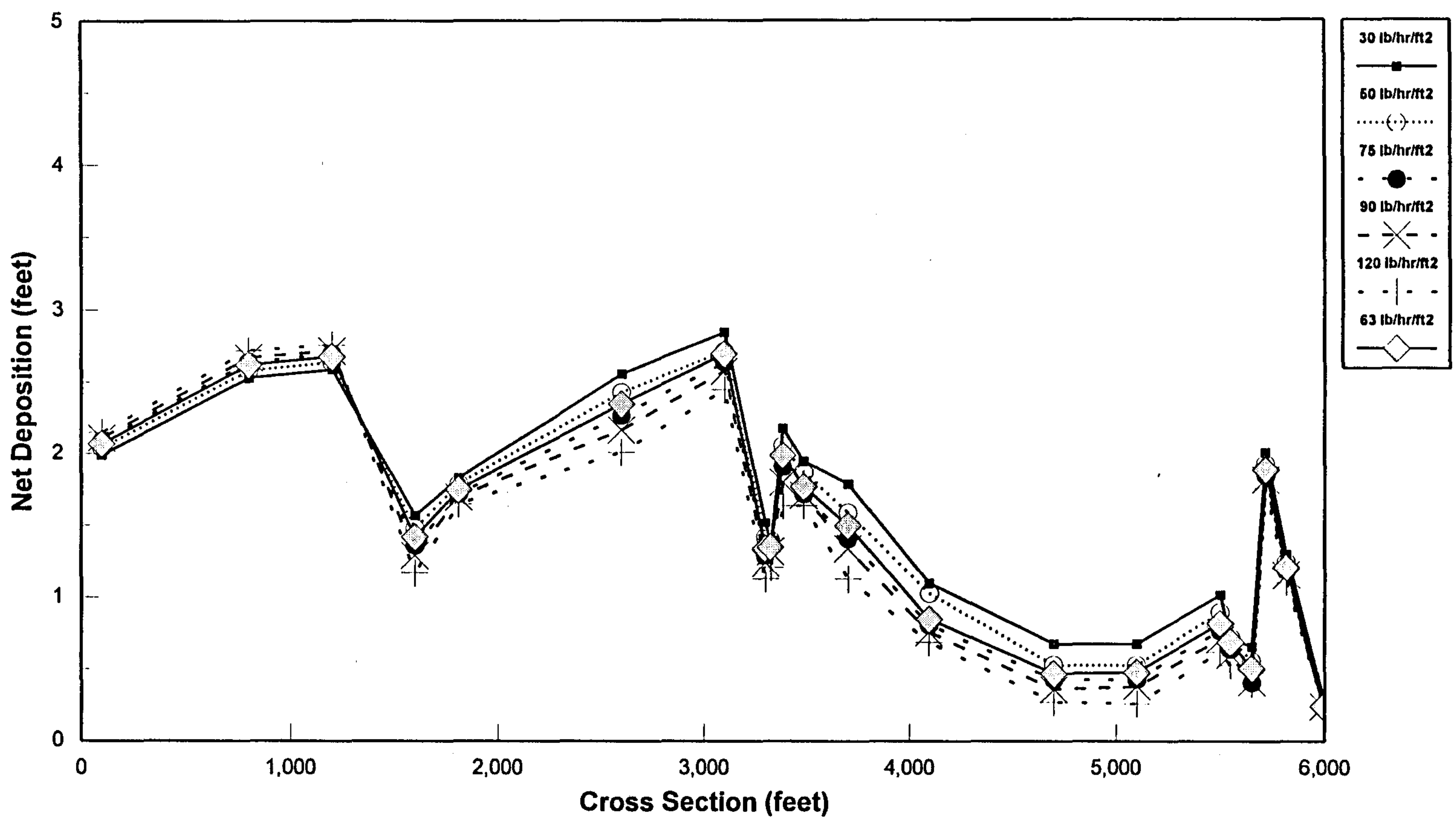
Sediment Transport Investigation

Sensitivity Analysis of Active Bed Scour Threshold Coefficient	**Figure 5-2B**

10/96 - 03861081.PRE

1980-1990



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Sheboygan River and Harbor Site

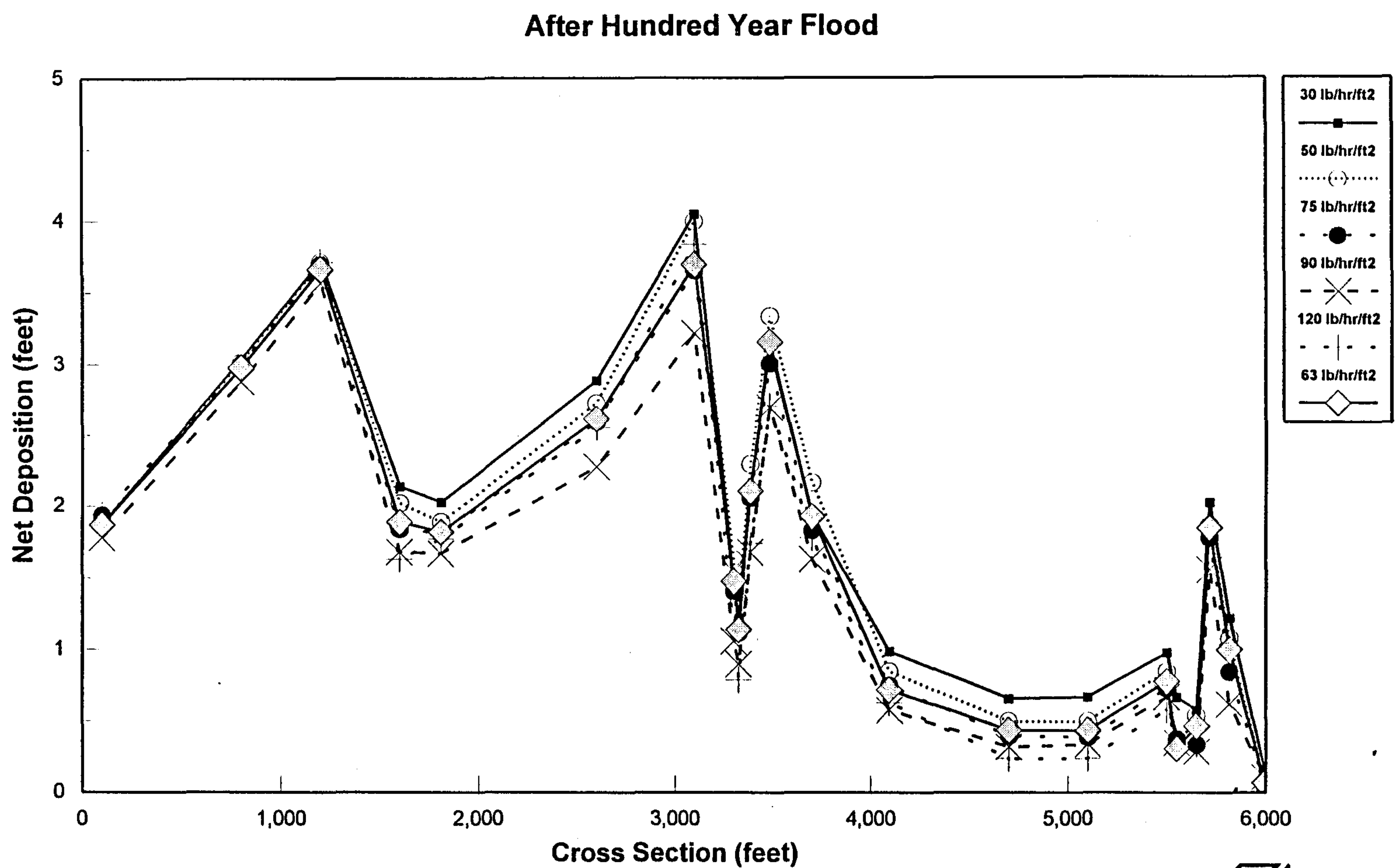
Sediment Transport Investigation

Sensitivity Analysis of Mass Erosion Rate at 1 lb/ft^2

Figure 5-3A

10/96 - 03861081.PRE

[redacted]



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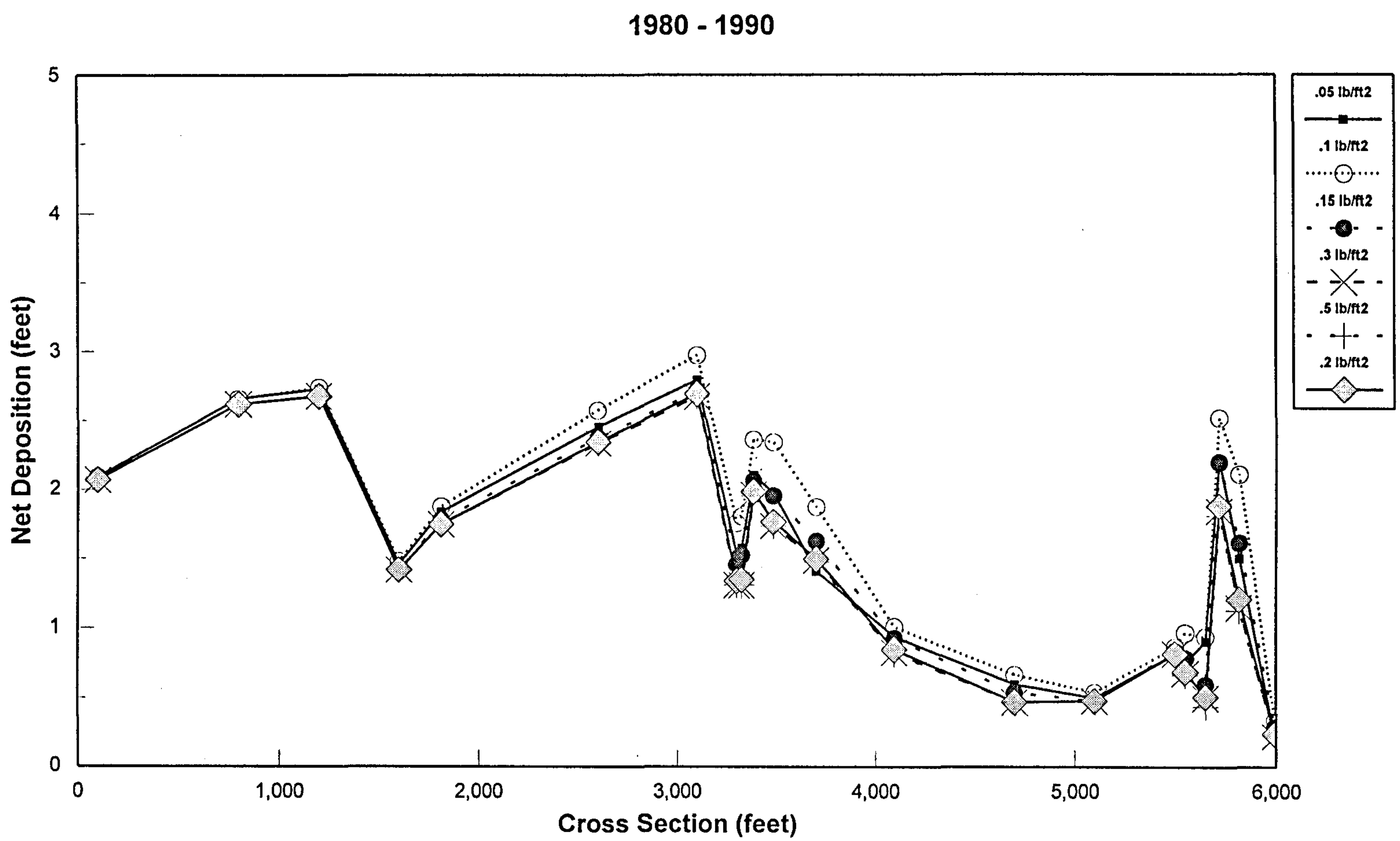
Sediment Transport Investigation

Sensitivity Analysis of Mass Erosion Rate at 1 lb/ft^2

Figure 5-3B

10/96 - 03861081.PRE



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Sheboygan River and Harbor Site

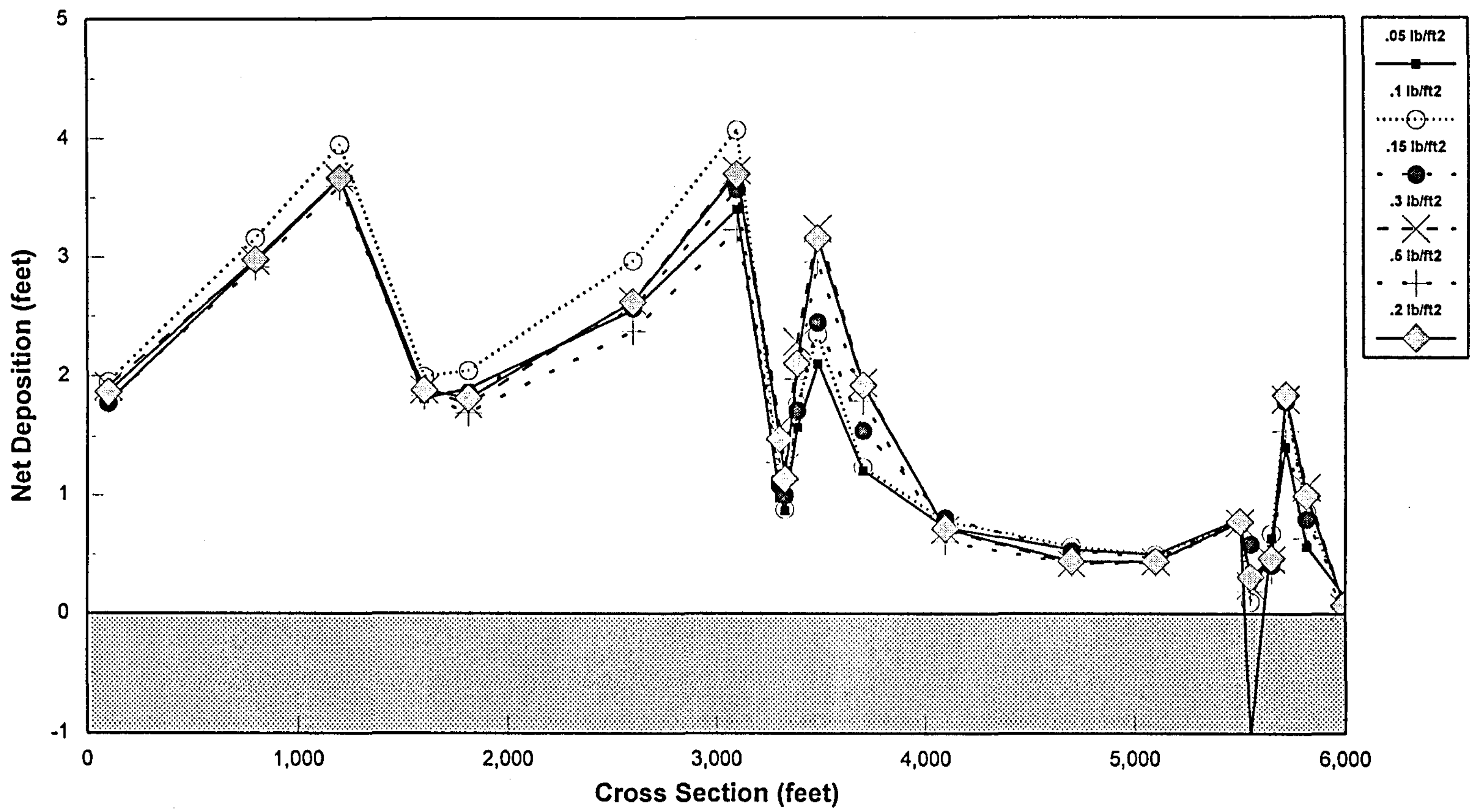
Sediment Transport Investigation

Sensitivity Analysis of Inactive Bed Scour Threshold Coefficient

Figure 5-4A

10/96 - 03861081.PRE

After Hundred Year Flood



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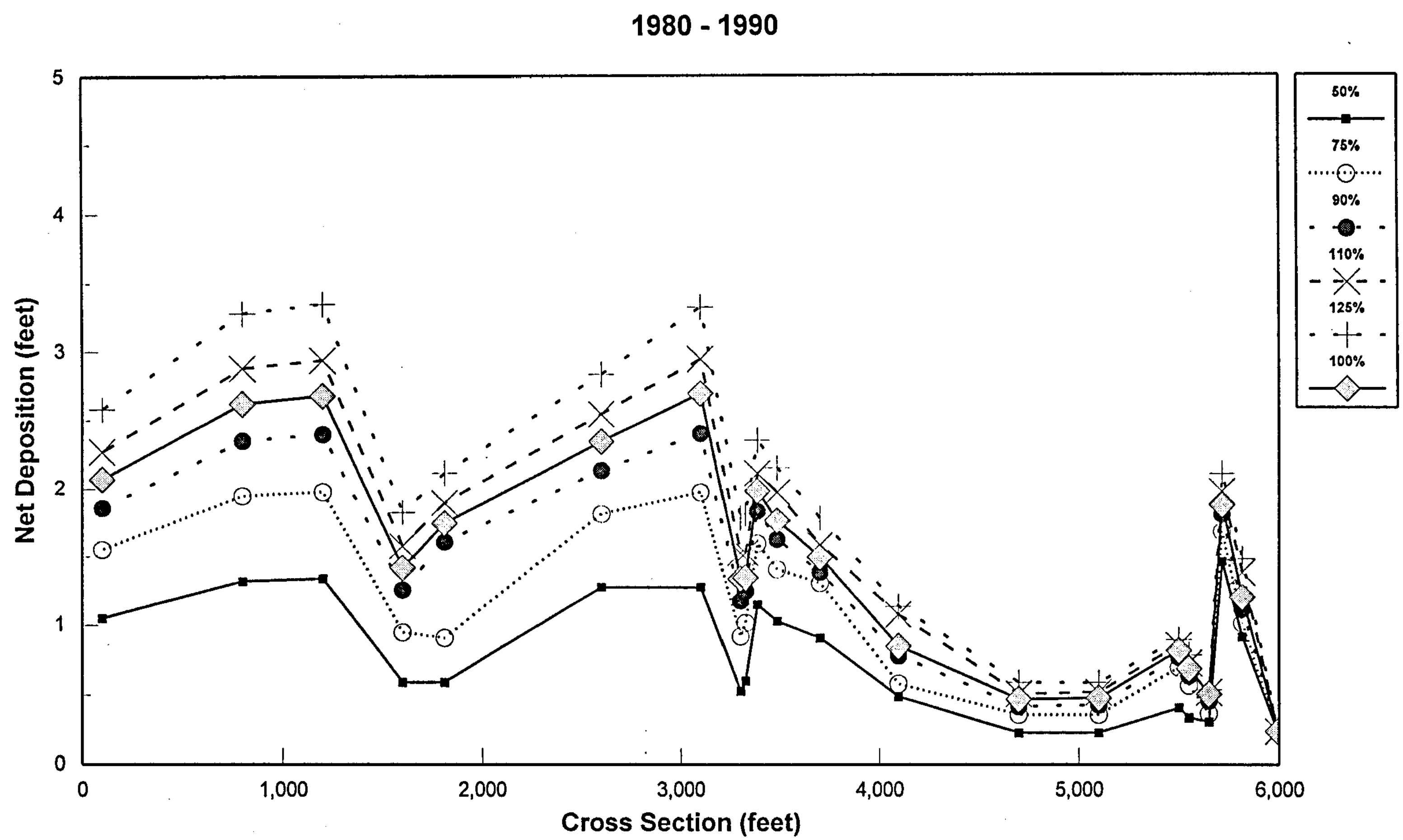
Sheboygan River and Harbor Site
Sediment Transport Investigation

Sensitivity Analysis of Inactive Bed Scour Threshold Coefficient

Figure 5-4B



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Sheboygan River and Harbor Site

Sediment Transport Investigation

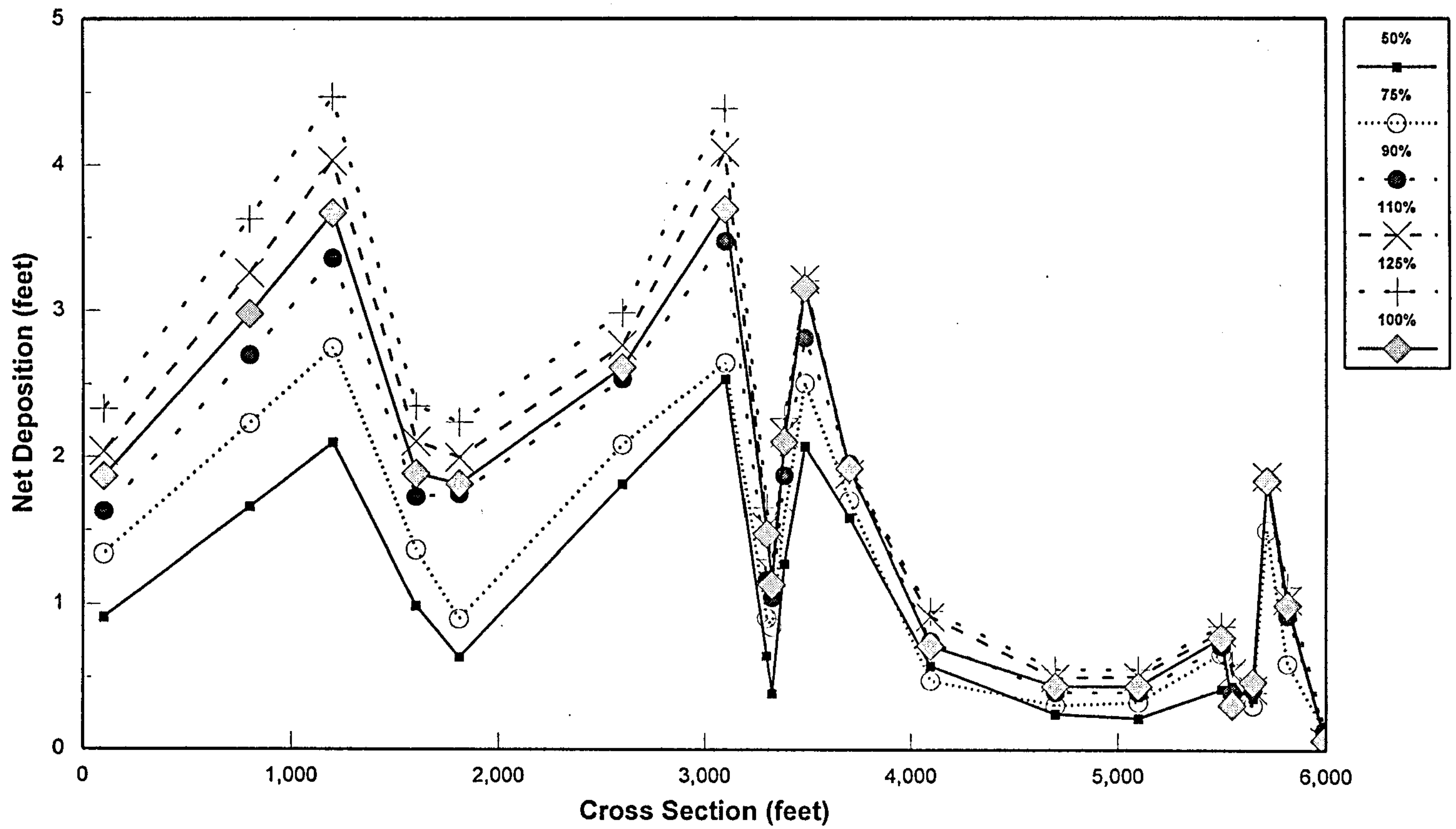
Sensitivity Analysis of Suspended Sediment Load

Figure 5-5A

10/96 - 03861081.PRE

[redacted]

After Hundred Year Flood



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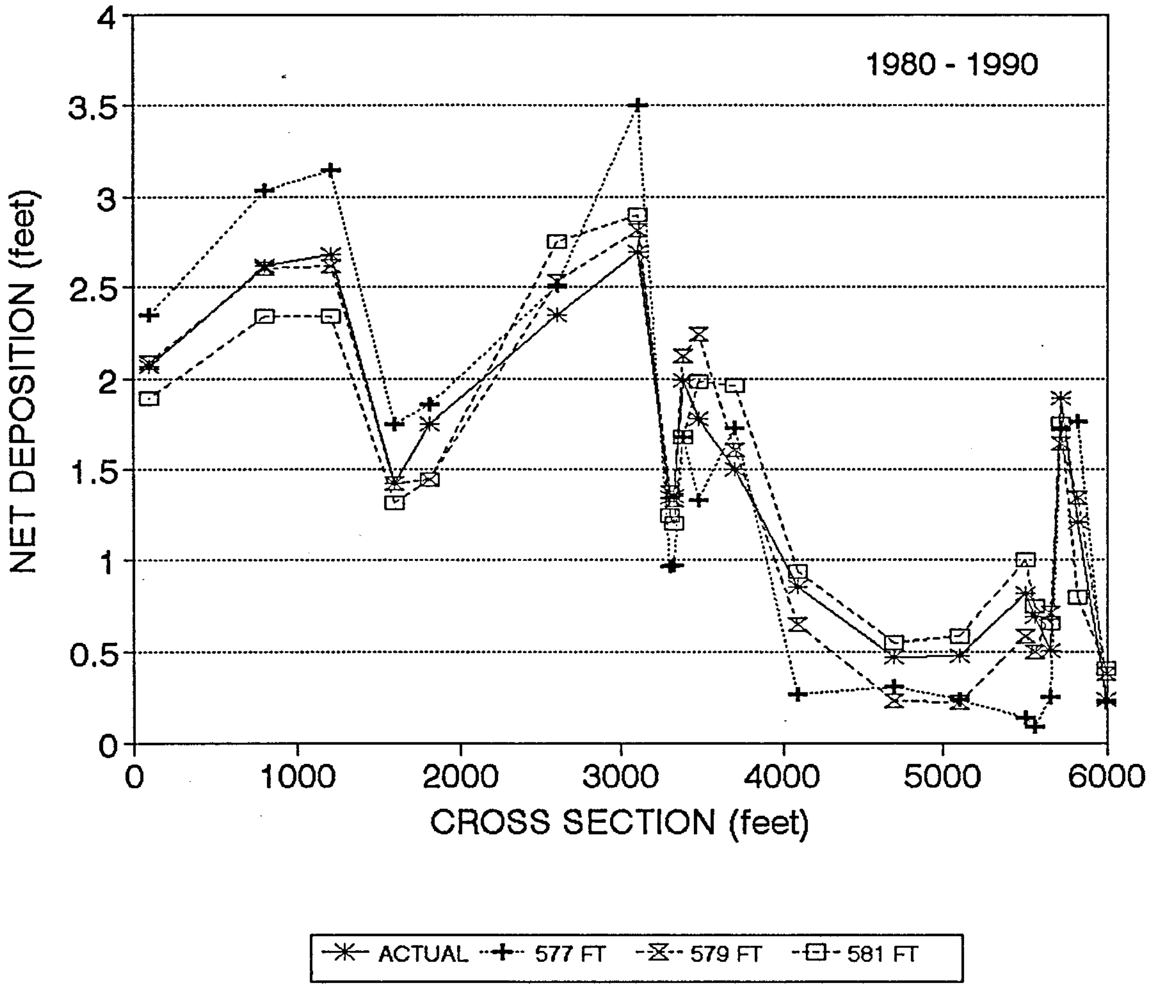
Sheboygan River and Harbor Site

Sediment Transport Investigation

Sensitivity Analysis of Suspended Sediment Load

Figure 5-5B

10/96 - 03861081.PRE



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SHEBOYGAN RIVER & HARBOR SITE

SEDIMENT TRANSPORT INVESTIGATION

PREDICTED NET DEPOSITION FOR CONSTANT LAKE LEVELS

FIGURE **5-6**

11/95 D54-JVM
1760703R/17607n32.cdr