MENOMONEE RIVER SEDIMENT TRANSPORT MODELING SYSTEM FINAL REPORT

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EXECUTIVE SUMMARY

This report describes the sediment and flow dynamics of the Menomonee River Watershed and the modeling system that was developed to analyze it. The Menomonee River Watershed is located near Milwaukee, Wisconsin, and encompasses approximately 140 square miles. This study was performed on behalf of the Detroit District of the U.S. Army Corps of Engineers by Baird & Associates. The authorization for this study is granted in Section 516(e) of the Water Resources Development Act of 1996, which directs the Corps to develop sediment transport models for tributaries to the Great Lakes that discharge into Federal navigation channels or Areas of Concern.

The modeling system components were selected on the basis of criteria that included ease of use and availability. The resulting system includes hydrologic and sediment modeling components that are available for download through the Internet, or can be purchased on digital media for a nominal cost. One of the graphical components, used to view spatial data, ArcView GIS, is proprietary, although it is widely used by hydrologic and hydraulic engineers for a variety of uses.

The input data for the modeling system that was developed for this study can be modified to evaluate the effects of a wide range of factors that contribute to the sediment delivered to and transported through the river system. The non-proprietary components of the modeling system are available for distribution, and will include instructions for modifying the input data and performing other model simulations.

The key findings of the study include the following:

- E*ach portion of the river system has a unique sediment delivery characteristic*. Several analyses were performed to develop generalized equations for sediment delivery that were used to generate input data for the sediment transport model.
- *Bank erosion as a sediment source is a minor contributor on this watershed* and is not expected to increase significantly with the accompanying increased urbanization.
- *Primary sources of sediment to the Menomonee River are first agricultural lands and second, urban non-point sources.*
- *The majority of the sediment delivered to the river system occurs during a relatively small number of rainfall/runoff events*. In a one-year period during 1975 and 1976, over 75% of sediment delivered to the river occurred during the 73 days (20% of one year) of the highest flows. This is an important consideration when assessing the benefits of flood peak mitigation projects.

INTRODUCTION AND BACKGROUND

The Menomonee River is a tributary of the Milwaukee River and has a watershed area of approximately 140 square miles. The watershed is primarily urban (less than 25% of the 1995 land use was categorized as agricultural) with residential, commercial and industrial development at a range of densities. The uppermost reach of the watershed is agricultural land that is being actively developed.

It has been postulated that the primary sources of sediment within the Menomonee River Watershed are: bank erosion, erosion from construction sites (land development and road building) and particulate washoff from urban areas. It has been suggested that bank erosion is becoming a more important issue with time as the urbanization of the watershed has created a flashier system with higher peak velocities and shear stresses. There are also important sediment quality issues on the Menomonee (e.g. the Moss American Superfund Site on the upstream end of the Little Menomonee).

The intention of the Section 516e program of WRDA96 is to assess the impact of land use and other management practices (e.g. flood control) on the production and delivery of sediment to federal navigation projects and Areas of Concern (AOCs). Therefore, it is necessary to develop a watershed-based sediment transport modeling system with hydrologic, hydrodynamic and sediment transport modules. It is important to link these modules together and to link the individual modules to input data layers (mostly in GIS format) to create an efficient and streamlined approach for assessing the impact of management practices on the delivery of sediment.

It has been identified that there are several other areas of interest and potential applications for an extended watershed-based modeling system on the Menomonee River, these include providing decision support on the following issues: sediment quality, water quality (possible TMDL application), flood control, and river restoration projects (for habitat improvements). While the WRDA Section 516e authorization does not provide a mandate to investigate these issues directly, other groups (such as local NGOs, MMSD, the City of Milwaukee, the Port Authority, Wisconsin DNR, USGS and the EPA) have indicated an interest in partnering on the project. Therefore, the flexibility of the system to address these other issues was considered during development.

METHODOLOGY

The watershed study consisted of several steps, which included varying degrees of quantitative and qualitative analyses. The basic steps included:

- *Hydrologic and hydraulic data collection and analysis;*
- *Channel geomorphological analysis;*
- *Sediment budget analysis;*
- *Sediment model calibration;*
- *Sediment modeling of other scenarios.*

These steps, which are described in detail in the following sections of the report, all play an important role in understanding the interaction between the hydrology of the watershed and the sediment delivery to the Menomonee River, and the transport of the sediment to its ultimate destination. Although there is a large degree of variability in erosion and sediment transport mechanisms, careful analysis of the system can provide a meaningful understanding of these processes. This understanding can provide a basis for developing engineering practices and land use policies that can effectively decrease the sediment delivered to and transported down the river.

HYDROLOGY AND HYDRAULICS

Flow and Sediment Data

The hydrologic data used in this study included measured river flow and suspended sediment data from ten USGS gage sites in the basin, shown in Table 1. Several of these gages sites were only operational for slightly over two years from 1975 to 1977. Although this is a relatively short period, the spatial coverage was adequate to provide a detailed analysis of the sediment delivery and transport for this period. The gage locations are shown in Figure 1.

Table 1. Menomonee River USGS Flow and sediment load measuring stations

Location	USGS Gage ID	Record Period	Basin Area (mi^2)
Menomonee River at Germantown	4087018	1975-1977	19.0
Menomonee River at Menomonee Falls	4087030	1975-2000	34.7
Menomonee River at Butler	4087040	1975-1979	60.6
Menomonee River at Falk Corporation	4087140	1975-1977	133.8
Menomonee River at Wauwatosa	4087120	1961-2000	123.0
Little Menomonee at Freistadt	4087050	1975-1980	8.0
Little Menomonee at Milwaukee	4087070	1975-1977	19.7
Underwood Creek at Wauwatosa	4087088	1975-1977	18.2
Honey Creek at Wauwatosa	4087119	1975-1981	10.3
Noyes Creek at Milwaukee	4087060	1975-1977	1.9

The first step in this analysis was to determine the flow frequency breakdown of the flows at the Menomonee River gage at Wauwatosa. Figure 2 is a histogram of the daily flow values for the water years of 1961 through 1999. An example interpretation of this chart is a daily average flow of 200 cfs is exceeded approximately 12% of the days. Although this statistic is not meaningful in itself, it was used as a basis for determining the flow pattern that would comprise a typical year.

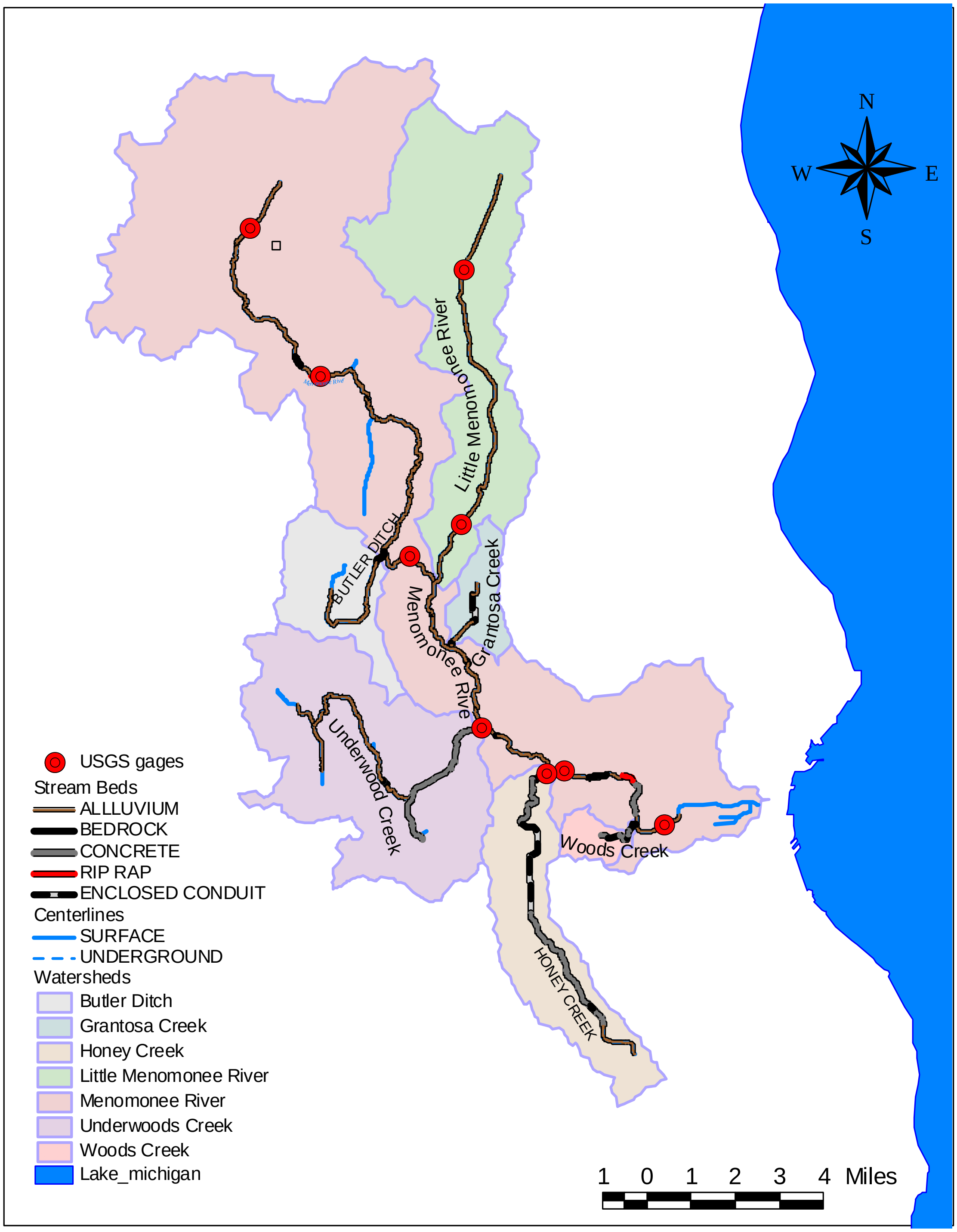


Figure 1. USGS gage locations.

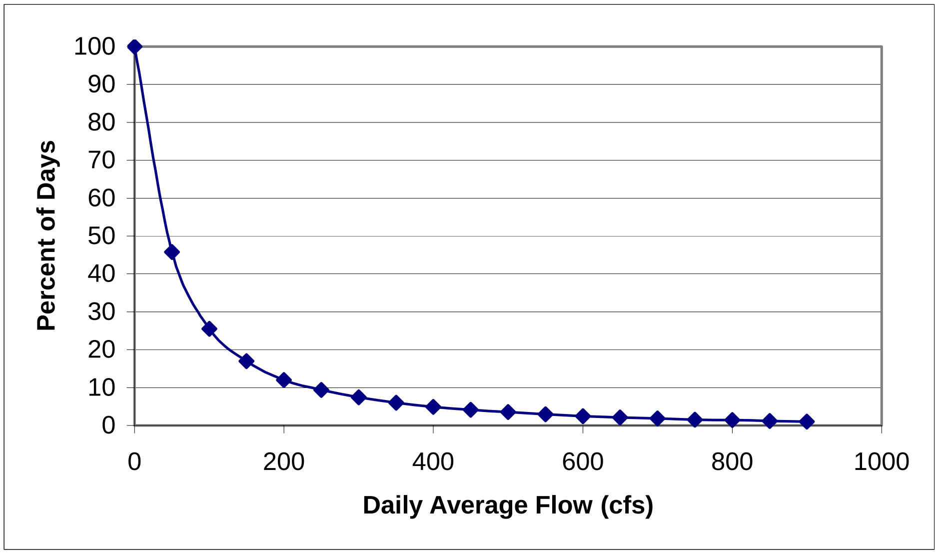


Figure 2. Flow histogram - Menomonee River at Wauwatosa (1961-1999).

Inspection of the data for the 1961 to 1999 period indicated that the one-year period from March 1, 1975 to February 28, 1976, represented a typical year. This period also coincided with the period that the basin was monitored for total suspended solids (TSS).

The data from this one-year period was analyzed for quantifiable relationships between flow, sediment, and land use. This analysis was a precursor to the in-depth analyses that will be described in subsequent sections of this report. The primary interest in this analysis was to determine the following:

- The frequency of flow events of varying magnitudes;
- The flow contribution from each of the gaged tributaries for events of varying magnitudes;
- The suspended sediment loads measured during flow events of varying magnitudes;
- The suspended sediment contribution from each of the gaged tributaries relative to the suspended sediment in the lower Menomonee.

Table 2. Flow and sediment statistics from selected gaging stations.

	Upper Menomonee River (above M. Falls gage)	Little Menomonee River (above Milwaukee gage)	Underwood Creek	Honey Creek
Drainage Area (sq. mi.)	34.7	19.7	18.2	10.3
Agricultural Land Use (% of basin, circa 1975)	49	48	1	6
Drainage Area Ratio to Wauwatosa Gage (%)	28.2	16.0	14.8	8.4
Flow Contribution to Wauwatosa Gage, all flows (%)	26.5	16.7	12.6	7.3
Flow Contribution to Wauwatosa Gage, low flows* (%)	26.2	17.4	12.7	7.4
Flow Contribution to Wauwatosa Gage, high flows* (%)	29.6	18.6	15.9	6.4
TSS Contribution to Wauwatosa Gage, all flows (%)	13.1	27.6	13.6	12.6
TSS Contribution to Wauwatosa Gage, low flows* (%)	12.6	27.0	13.7	12.7
TSS Contribution to Wauwatosa Gage, high flows* (%)	10.2	13.7	15.6	10.2
TSS Contribution from largest 20% of flow events	75.7	87.9	90.2	83.4

*Low flows are defined as lowest 50 percentile flows, high flows are highest 2 percentile.

Several conclusions may be drawn from this analysis and are summarized in Table 2. In terms of flow, it can be seen that the basins contribute nearly proportional to their drainage areas. Although the land use, specifically urban vs. agricultural, varied by tributary during this time period, this did not factor greatly into the flow contribution.

Another conclusion is that the sediment carried in each of these tributaries, when compared to the total sediment measured at the Wauwatosa gage site, is not as proportional to drainage area. It is evident that each subwatershed had a unique sediment-production regime, which will be described in subsequent sections of this report.

The last, and perhaps the most significant, conclusion from this data analysis is the relationship between the magnitude of the rainfall/runoff event and the sediment produced. The data indicates very clearly that the greatest proportion of the sediment delivered to and transported through the river system is produced by large rainfall/runoff events. In all cases, over 75% of the sediment was delivered by the largest 20% of the flow events. This relationship will also be described in more detail in subsequent sections of this report.

Modeling Data

A significant amount of data was obtained from a previous Menomonee River Watercourse Study performed for MMSD by Camp, Dresser and McKee (CDM). The data used from that study included the following: HSPF input and output files for the Menomonee River and four of its tributaries, a description of their work, GIS data including land use, soil and subbasin maps, and meteorological data.

Additional GIS data were downloaded from an EPA website (http://www.epa.gov/OST/BASINS/gisdata.html). This included a digital elevation map, river reach map, political boundary data, and USGS gage locations.

Meteorological data gathered at the Mitchell Field station were included in the information obtained from CDM. Included in this data were 15-minute precipitation, hourly solar radiation, hourly evaporation, hourly wind movement, daily dewpoint temperatures, and hourly temperature data for 1940 to 1997.

River cross-section data were obtained from the MMSD HEC-RAS model. This information was originally gathered and digitized for the Menomonee River Watershed Watercourse Planning Study.

Other cross section and GIS data was obtained from the Inter-Fluve Sediment Transport Study of the Menomonee River Watershed Report done for MMSD in 2001.

Other Studies

One previous study that was reviewed as part of the literature review for this study was Technical Report No. 4, "Estimating the Effect of Urbanization on the Discharge-Frequency Relationship" (Marquette University, 1999). This report included a description of the Oak Creek and Menomonee River Watersheds and a statistical analysis of the peak flows experienced on these waterways.

While it is well understood that the increased imperviousness that accompanies urbanization tends to increase runoff on a short-term basis, the effects of urbanization on annual peak flows is a complex phenomenon. The report contains a description of the statistical analysis of the annual peak flows that were measured over a period of years that also coincided with significant urbanization. The analysis also included predictions of the future shifts to the discharge-frequency relationship due to urbanization, as shown in Figure 3.

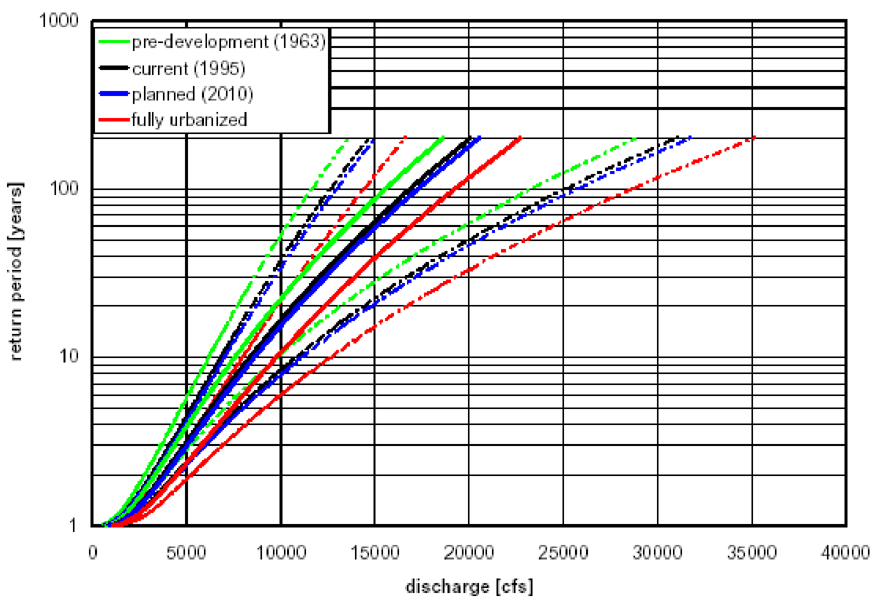


Figure 3. Effects of watershed conditions and future urbanization on the flood frequency distribution for the Menomonee River at Wauwatosa.

The significant findings from this report include the following:

- A shift of the flow-frequency relationship;
- At Menomonee Falls:
  - Slight increase for future land uses;
  - 50% increase on the 2-year flow for fully urbanized conditions;
  - 33% increase on the 100-year flow for fully urbanized conditions;
- At Wauwatosa:
  - Slight increase for future land uses;
  - 20% increase on the 2-year flow for fully urbanized conditions;
  - 11% increase on the 100-year flow for fully urbanized conditions.

It is important to note, however, that these conclusions do not account for the effects of potential land use controls or best management practices. It is accepted that this watershed will experience continued urbanization, but the actual shift in the flow-frequency relationship will depend on the combined effects of urbanization as well as runoff-controlling practices such as detention ponds, reservoirs, and others.

SEDIMENT DYNAMICS ASSESSMENT

Introduction

The Menomonee River is a tributary of the Milwaukee River near Milwaukee, Wisconsin, with a drainage area of approximately 35,200 ha (Figure 4). The lower part of the river is mainly commercial-industrial area with some residential sections. The central section is mainly residential with a few scattered agricultural sections. The land use in the upper section of the watershed is mainly agricultural with some residential sites. This portion of the watershed has changed notably since the late 1960s' from rural to residential areas.

One of the main objectives of this work was to understand the sediment dynamics of the Menomonee River Watershed, and its sensitivity to land use changes. Numerical models can be very useful in determining the amount of sediment that is transported into and along a river reach and the amount of erosion and deposition present in the system. Some of the advantages of using numerical models include the simplification of data required for the analysis, time of analysis and versatility of predicting possible future conditions.

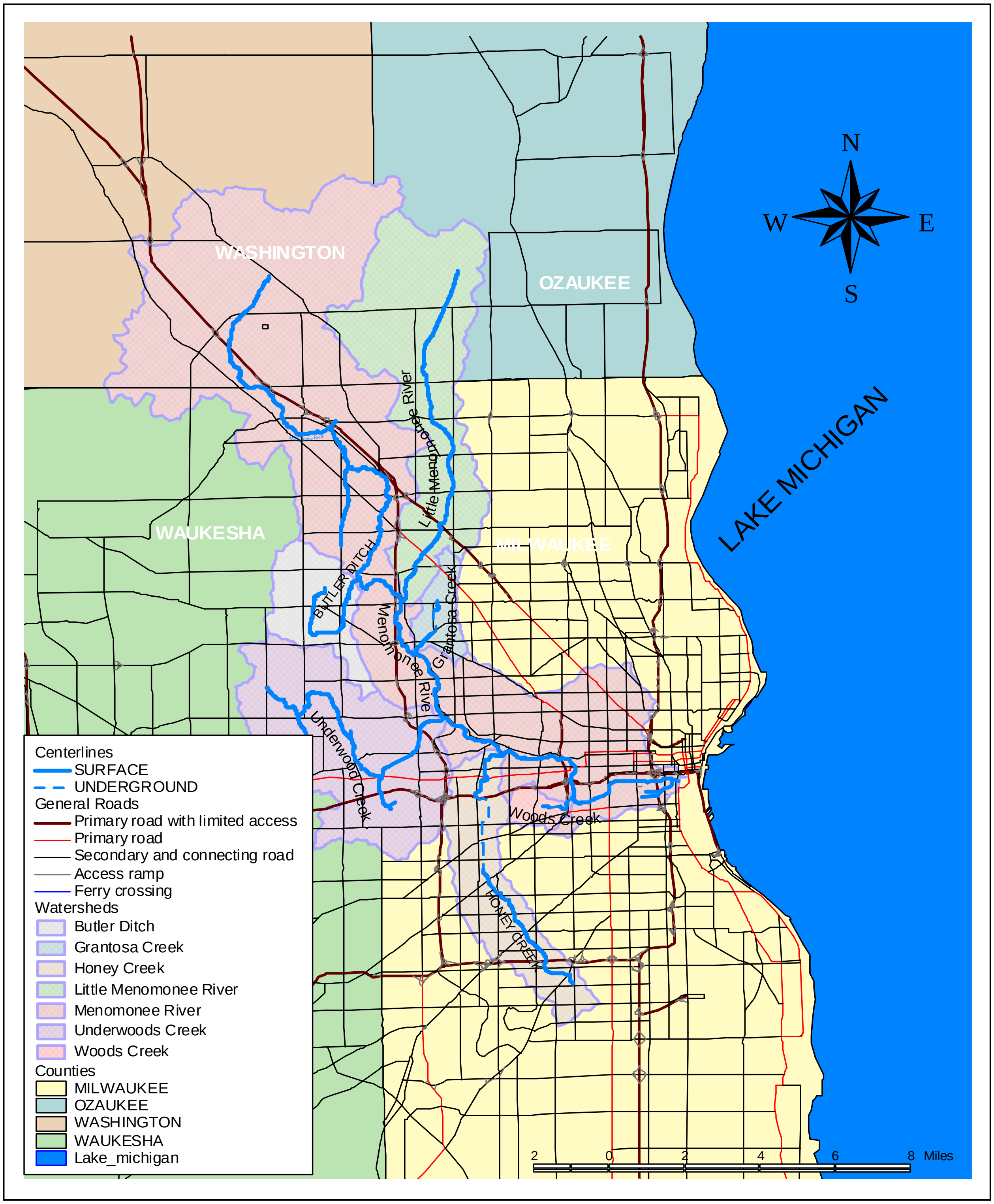


Figure 4. Project area map.

SEDIMENT BUDGET

In order to accurately determine the sediment transport and fate of suspended sediment within a river system, is very important to understand how the system behaves for different flow scenarios as well as the sources, sinks and types of sediment present within the watershed.

Sediment Sinks

Sinks of sediment are defined as areas where there is loss of suspended sediment (i.e. areas of deposition). These areas are usually associated with sections where the velocity is reduced due to cross section expansion, such as the widening and deepening, and dams. An example of this can be observed at Menomonee Falls (Figure 14).

The main sediment sink of this watershed is in the lower Menomonee River area and in particular, the dredged area.

Bannerman et al (Wisconsin DNR, 1979) conducted a study on the influence of tributary inputs to Lake Michigan during high flow events. After analyzing the total yearly load from the Milwaukee, Kinnickinnic and Menomonee Rivers, they concluded that the Menomonee River usually discharged about 50% (15,000 tons) of the total river loading reaching the Milwaukee Harbor. They found that the average grain size distribution (from 3 samples) for bottom sediments was 65% sand, 30% silt and 5% clay. A similar grain size distribution for bottom sediments was the reported by Dong et al (1979), and was composed of 84% sand, 10% silt and 6% clay. This suggested that the harbor area was not an efficient sediment trap although it was sporadically dredged. They also obtained a suspended sediment distribution of 28% silt and 72% clay and stated that this load would be transported further downstream and then deposit at the lake.

The USACE obtains particle size distribution from sediments dredged from the harbor. An analysis of the 1993 dredged sediment data from 3 sites in the harbor indicates that the average composition of the samples was: 8% sand and 92% silt/clay. Both data sets (1979 and 1993) appear to be very different, which may suggest that the sediment dynamics and the sediment sources of the site could have changed significantly in recent years.

Yearly bathymetric records from 1998 to 2000 were also provided by the USACE from which a yearly deposition volume was obtained.

The 1993 grain size distribution data was further analyzed by comparing it with results from a theoretical non-dimensional sedimentation model developed by Baird. The input parameters for this model were flow and sediment load from USGS data, and suspended sediment size distribution, which was obtained from the HEC6 output. The results are presented in Table 3.

Table 3. Measured and calculated sedimentation at Milwaukee Harbor.

Year	Input (tons/year)	Sedimentation (tons/year)	Total Water ft^3 $x10^7$	% Deposition	Measured Deposition (tons/year)
98-99	35121.61	11008.6	395.22	31.3	11269.88
99-00	28546.35	8947.63	385.62	31.3	7712.98

It appears that there is reasonable agreement between the deposited material and the dredged volume, and the deposited sediment is around 31% of the total load. This indicates that 69% is further transported downstream and eventually deposited. This might not be a high deposition percentage, but it represents approximately 9650 yd^3 of sediment deposited every year in the harbor.

The following table describes the percentage of deposition and the grain size distribution of the deposited material.

Table 4. Percentage of deposition per size class and grain size distribution.

Class	% Deposition	Size Distribution
Clay	3.4	3.90
Very fine silt	11.2	10.09
Fine silt	44.9	25.83
Medium silt	100	31.90
Coarse silt	100	15.95
Very fine sand	100	4.01
Fine sand	100	5.74
Medium sand	100	2.55

The percentages of sand and silt/clay particles are 12% and 88%, respectively. It can be noted that this distribution is similar to the one obtained from the 1993 dredged sediment data.

Sediment Sources

Within a watershed there are three main sources of sediment that contribute to the load transported by the river:

- bed erosion;
- bank erosion;
- runoff from the land (point source and non-point source).

Bed Erosion

The amount of sediment eroded from the bed is primarily determined by flow velocity, but is also affected by factors such as soil type, vegetation cover, bioturbation, organic matter content, and bed history.

The bed elevation from SWRPC (1975) was determined at each Inter-Fluve surveyed cross section and interpolated along the streams to obtain a bed elevation profile with data points at each one of the model cross sections.

By comparing these two data sets an erosion-deposition profile for the 1975-2000 time period was obtained for the Menomonee River and Little Menomonee River (Figure 5 and 6). From these figures it is evident that there are only localized areas of apparently significant bed erosion (e.g. River Mile 12-15 on the main stem and between River Mile 1 and 2 on the Little Menomonee).

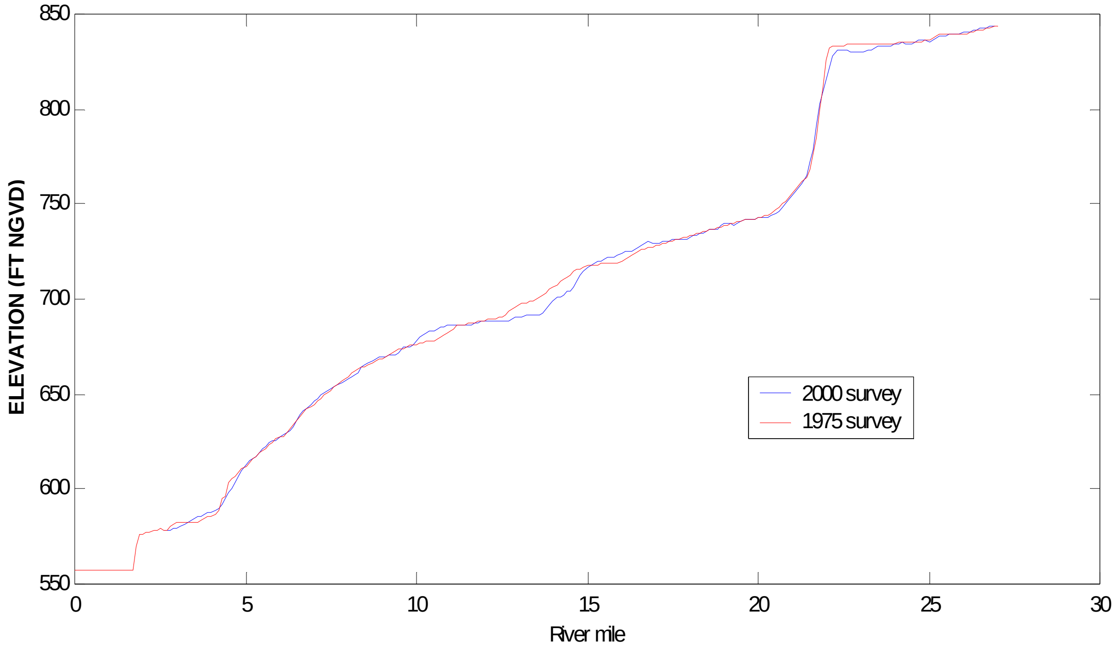


Figure 5. Bed Elevation profiles for the Menomonee River for 1975 and 2000.

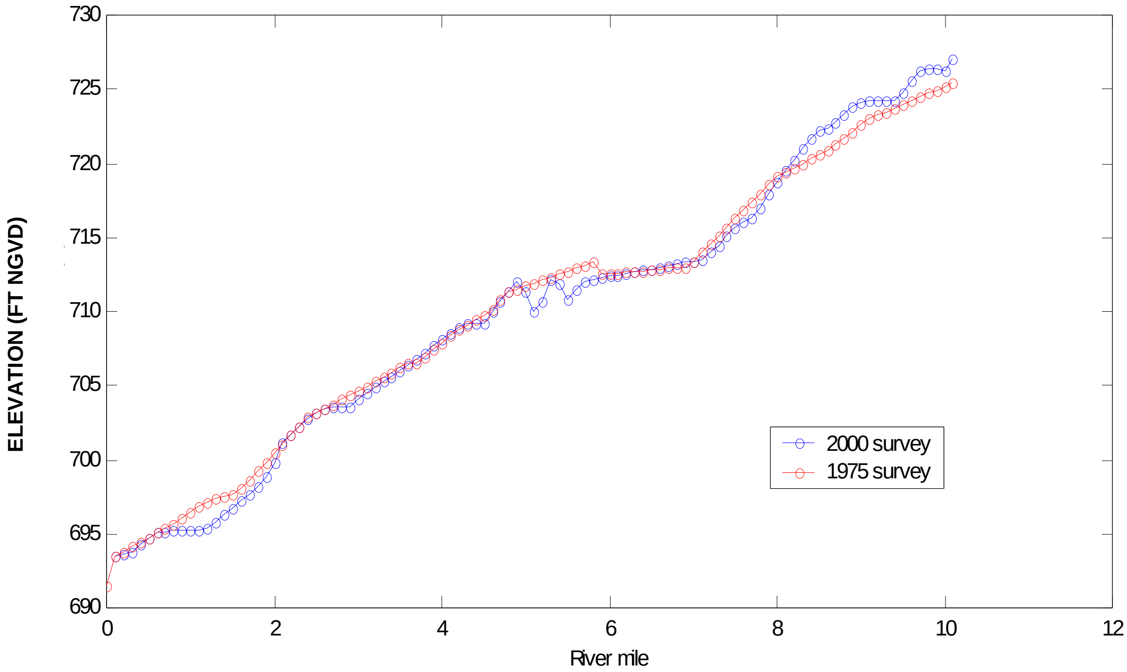


Figure 6. Bed elevation profiles for the Little Menomonee River for 1975 and 2000.

Bank Erosion

Bank erosion can be caused by either lateral instability in a river or vertical instability (i.e. bed erosion in the latter case). Therefore, in some, but not all, cases there may be a correlation between bed and bank erosion. The Inter-Fluve GIS includes a set of photographs of the rivers. This information was used to define the areas of bank erosion, which are generally associated with steep slopes, lack of vegetation, visible roots and fallen trees (Figure 7, 8 and 9).

The photographic sequence of the streams was also used to determine whether the eroded depth obtained from the profile analysis was congruent with direct visual observation. For example, in Butler Ditch the bed profile comparison suggested overall erosion (which was consistent along the stream) of approximately 6 ft. After looking at the photographs (Figure 10) it was determined that no erosion of such magnitude was possible in the area thus the bed change for this stream was not further analyzed for bank erodibility.

Figure 7. Example of bank instability. Abrupt slopes, exposed roots, lack of vegetation and bank failure.

Figure 8. Example of bank instability. Abrupt slopes, exposed roots, lack of vegetation and bank failure.

Figure 9. Example of bank instability. Abrupt slopes, exposed roots, lack of vegetation and land failure.

Figure 10. Butler Ditch at River Mile 1.3

The contribution of bank sediment to the river system was determined by plotting the bed erosion-deposition profiles for Menomonee and Little Menomonee Rivers and then superimposing the areas of bank erosion (Figure 11 and 12).

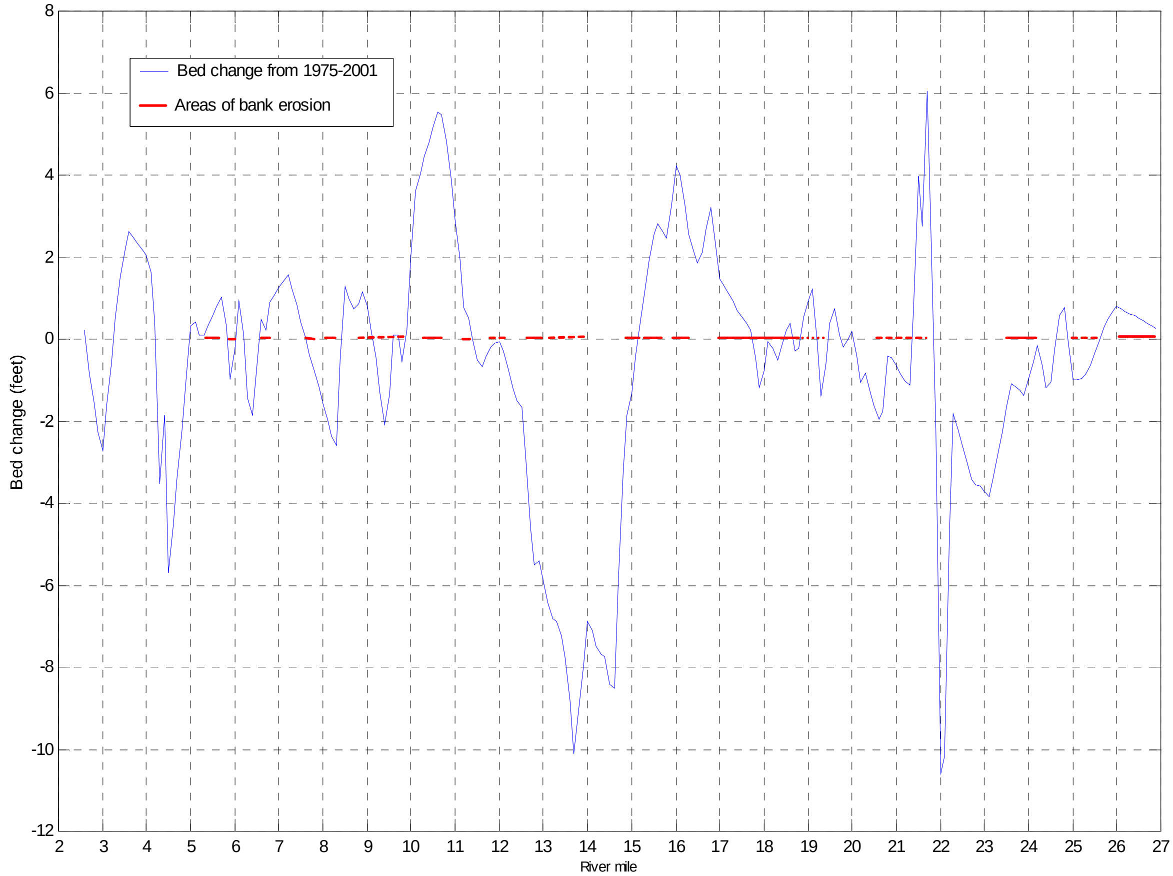


Figure 11. Erosion-deposition profile for Menomonee River and areas of bank instability.

The plots for the Little Menomonee River demonstrate that there is a correlation between bed erosion and areas of bank instability. For the Menomonee River, there are areas that show significant bed erosion (up to 10 feet). A visual comparison of the photographs for the river section between miles 13 and 15 (Figure 13) to the calculated bed change indicates that the erosion magnitudes are not apparently due to the geomorphology since there is no congruence between data sources. This indicates that the change could be associated with other factors.

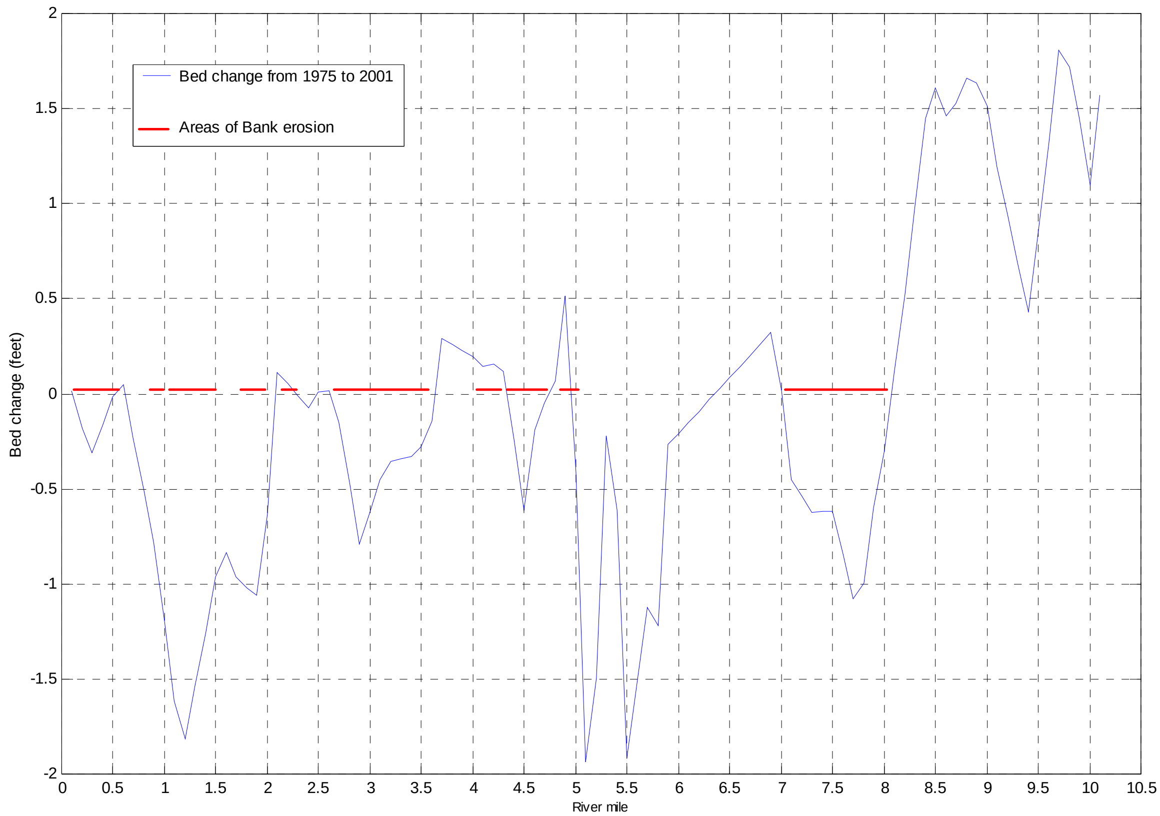


Figure 12. Erosion-deposition profile for Little Menomonee River and areas of bank instability.

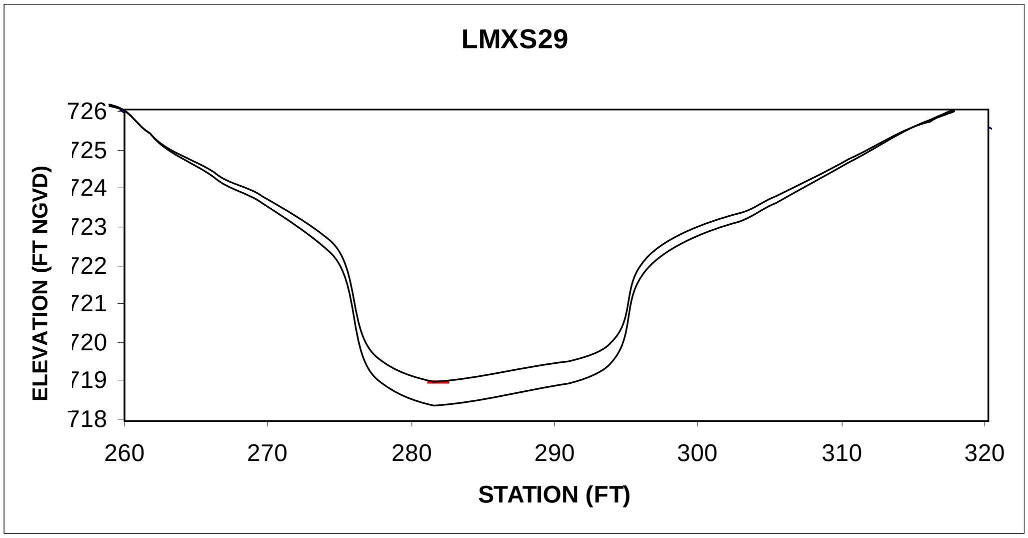
A similar erosion pattern is observed near river mile 22 of the Menomonee River, which corresponds to Main Street (which has had dredging activities and construction of bank walls and riprap, Figure 14), thus the calculated bed change is not natural.

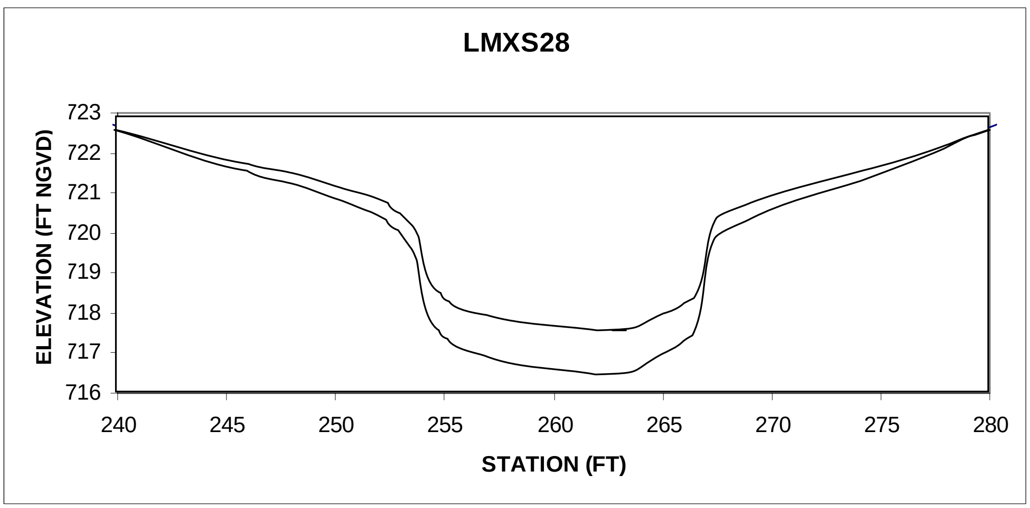
Therefore, only the Little Menomonee data was further analyzed to better define the bank erosion processes, where there was a correlation between bank stability and bed change.

The Inter-Fluve cross sections from the areas with bank instability were plotted, and the bed surface elevation from 1975 was labeled on each plot. The cross section was then elevated to this point (keeping the same ratio and dimensions as the newest cross section) and the area between both curves was determined, Figure 15).

Figure 13. Menomonee River at River Mile 14.4.

Figure 14. Menomonee River at River Mile 21.9.





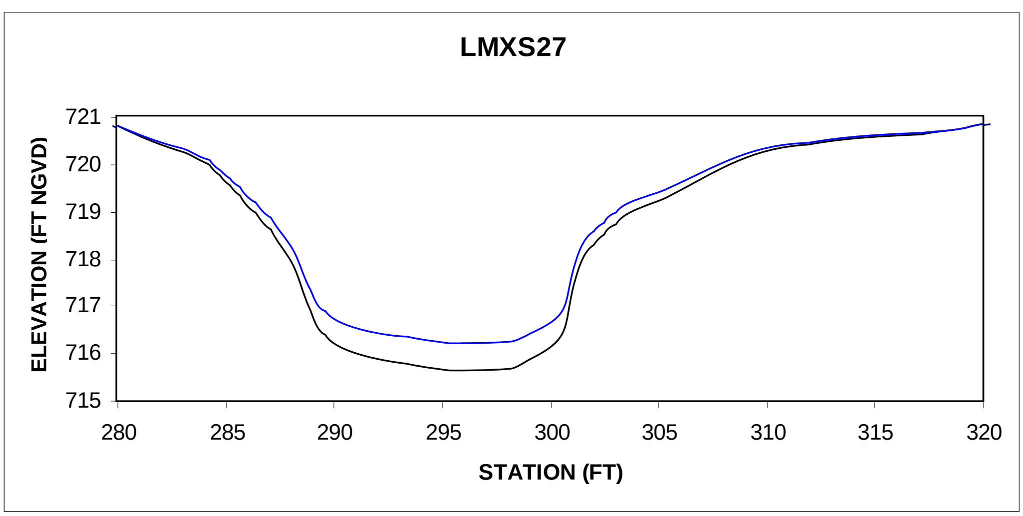
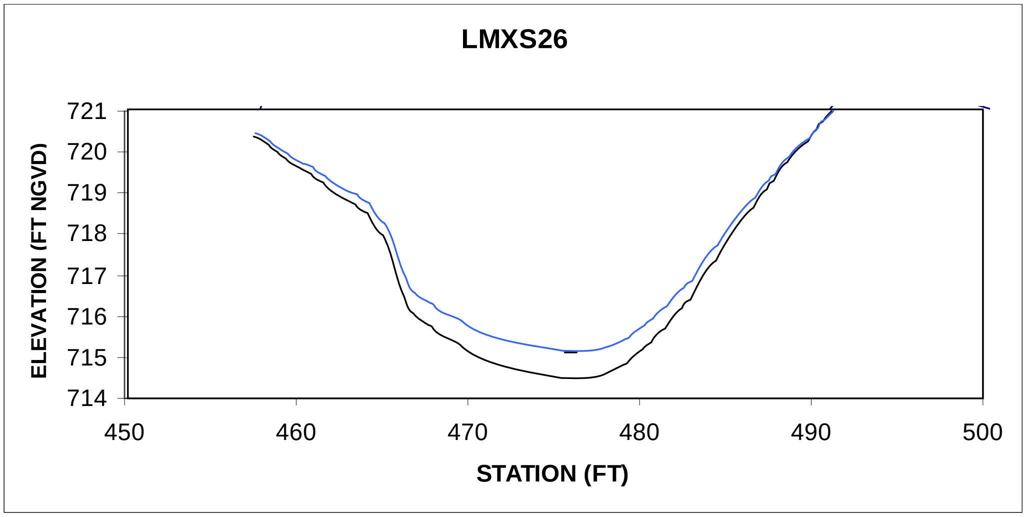
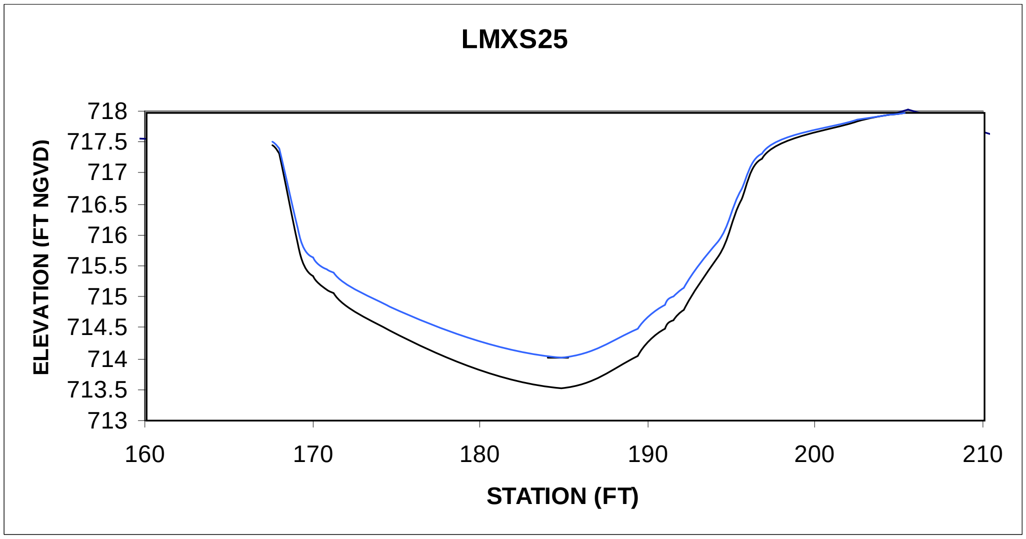


Figure 15a. Eroded area between 1975 and 2000 for several cross sections from the Little Menomonee River.





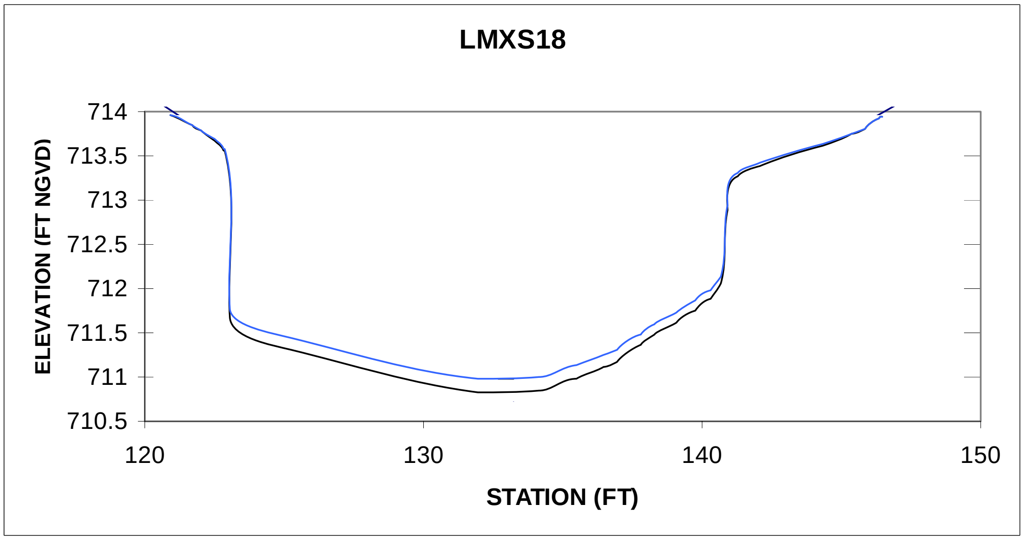
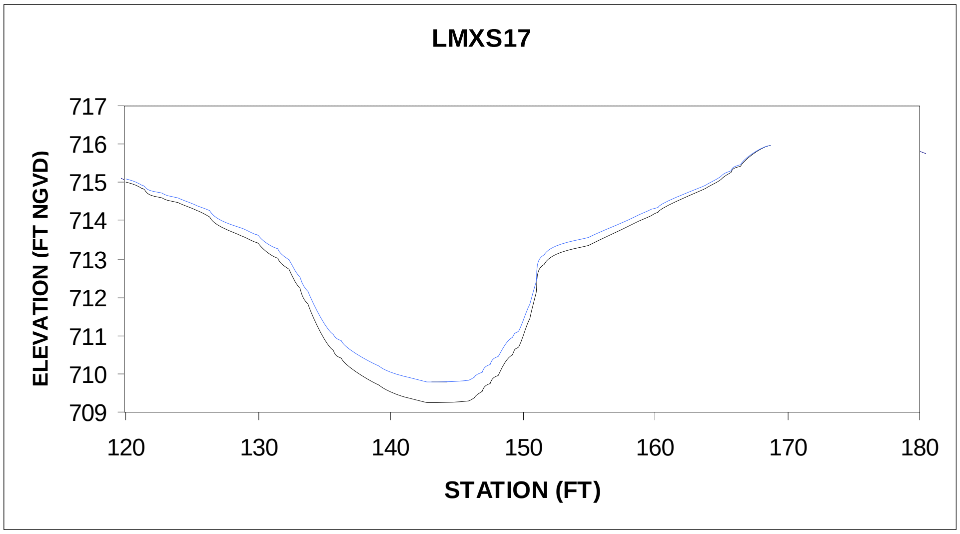
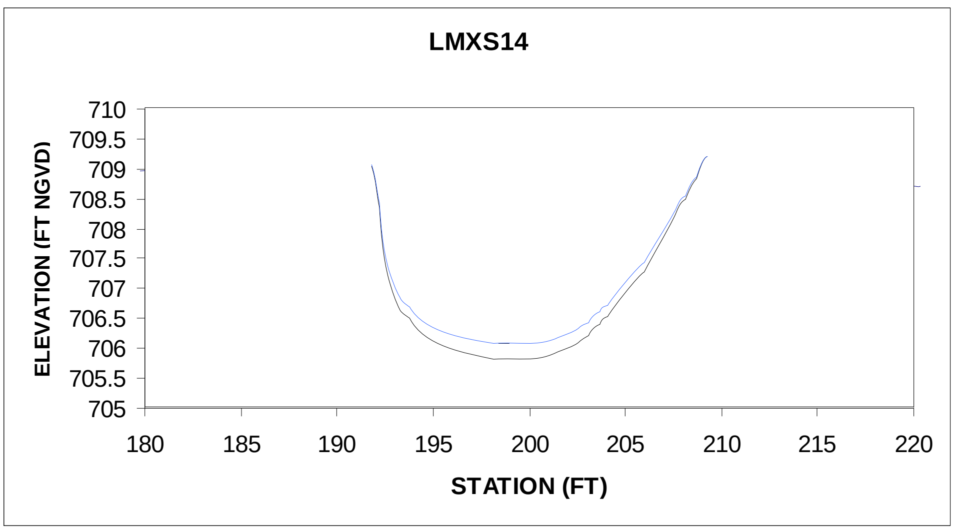


Figure 15b. Eroded area between 1975 and 2000 for several cross sections from the Little Menomonee River.





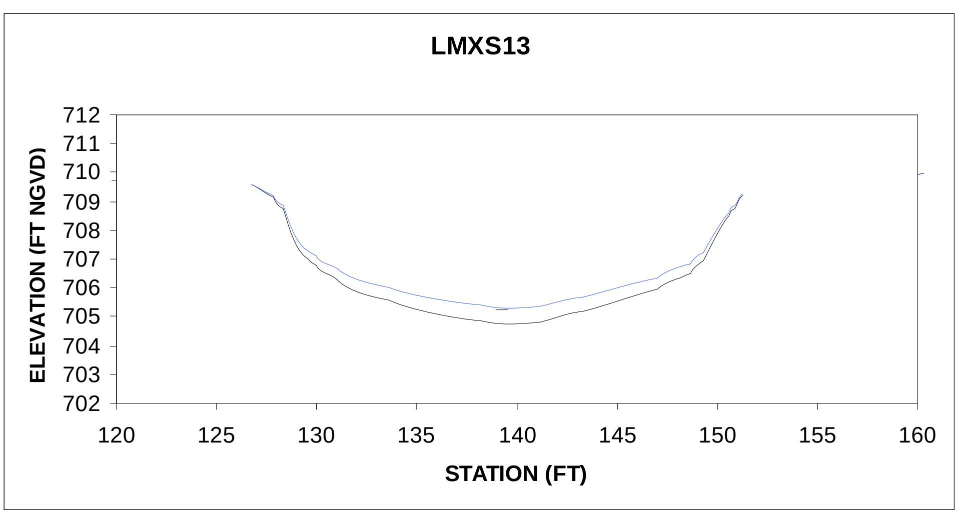
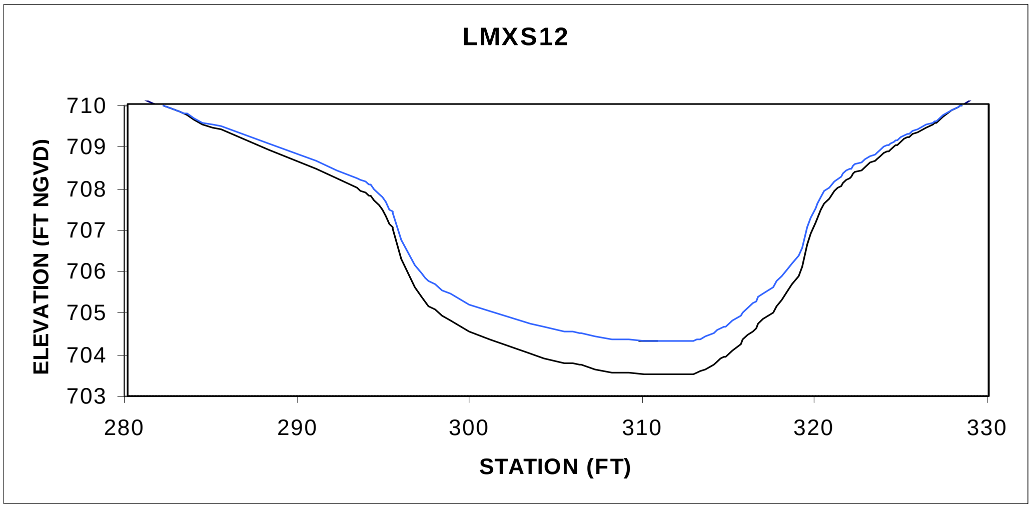


Figure 15c. Eroded area between 1975 and 2000 for several cross sections from the Little Menomonee River.



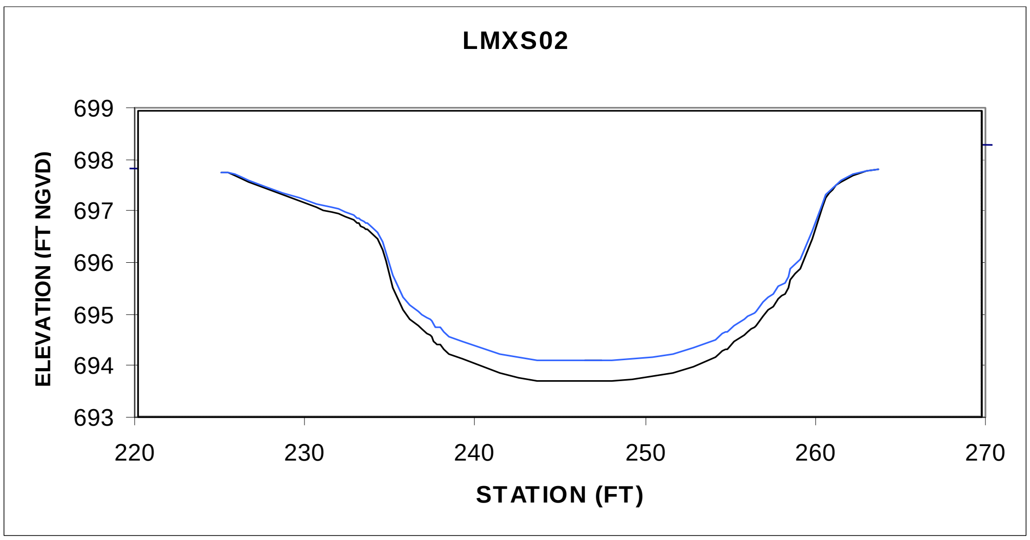


Figure 15d. Eroded area between 1975 and 2000 for several cross sections from the Little Menomonee River.

Since it was observed that the amount of bank erosion was influenced by bed erosion, they were plotted against each other (Figure 16) and a trend line was fitted through the data points. This curve was then used to determine the total volume of eroded sediment within the sections that showed congruent natural bed changes along the river. By using a bed density of 82 lb/ft^3, which corresponds to consolidated soils (HEC-6 manual), it was observed that the annual sediment mass (229 tons) corresponds to approximately 5% of the total yearly load (5056 tons) recorded at the Little Menomonee River mouth (Table 5), thus the sediment load contribution from bank erosion is not significant in this system. If the bank contribution was found to be significant, additional analyses would be necessary, either with another numerical model or a modification of the HEC-6 model.

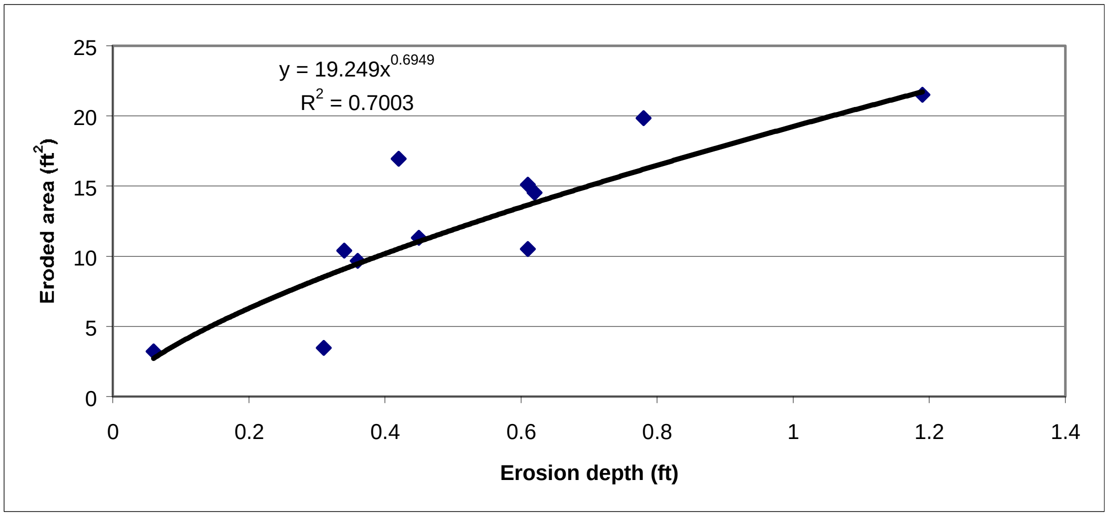


Figure 16. Relationship between erosion depth and eroded area obtained from measured data for the Little Menomonee River.

Table 5. Bank erosion contribution to sediment load for the Little Menomonee River.

RM	Bed Change (ft)	Area Change (ft^2)	Volume ('75–'00) (ft^3)	Yearly Vol. (ft^3)
0.2	-0.18	5.89	3111.93	124.48
0.3	-0.31	8.59	4534.15	181.37
0.4	-0.17	5.52	2911.97	116.48
0.5	-0.02	1.18	623.20	24.93
0.6	-0.15	5.18	2734.72	109.39
0.7	-0.47	11.38	6010.70	240.43
0.8	-0.79	16.31	8611.89	344.48
0.9	-0.62	13.78	7276.90	291.08
1	-0.45	11.03	5822.63	232.91
1.1	-0.36	9.40	4963.25	198.53
1.2	-0.34	9.13	4820.16	192.81
1.3	-0.33	8.86	4676.13	187.05
1.4	-0.28	7.94	4193.22	167.73
1.5	-0.15	5.04	2658.85	106.35
1.6	-0.25	7.27	3839.67	153.59
1.7	-0.61	13.67	7215.44	288.62
1.8	-0.19	6.07	3207.49	128.30
1.9	-0.05	2.29	1208.80	48.35
2	-0.45	11.08	5847.86	233.91
2.1	-0.54	12.51	6605.49	264.22
2.2	-0.62	13.87	7325.89	293.04
2.3	-0.62	13.82	7296.54	291.86
2.4	-0.62	13.76	7267.08	290.68
2.5	-0.85	17.17	9067.71	362.71
2.6	-1.08	20.31	10721.83	428.87
2.7	-1.00	19.21	10143.67	405.75
2.8	-0.60	13.50	7129.00	285.16
2.9	-0.30	8.35	4408.54	176.34

Seasonal Variability of Sediment Delivery

Another test that was carried out to determine the importance of bank erosion consisted of a temporal analysis of sediment load for the Menomonee main stem (Figure 17). It was found that during the winter and early spring months the amount of suspended sediment, at a constant discharge, was lower. As it can be observed in Figure 18, the low temperatures correspond to lower sediment discharges. This suggests that sediment yield and delivery from the land is significant, because the soil is frozen in the winter-spring months thus offering more resistance to being eroded than in the summer-autumn months. In contrast, bank erosion and certainly, bed erosion would be expected to occur throughout the year (at least for periods when the river is not frozen over).

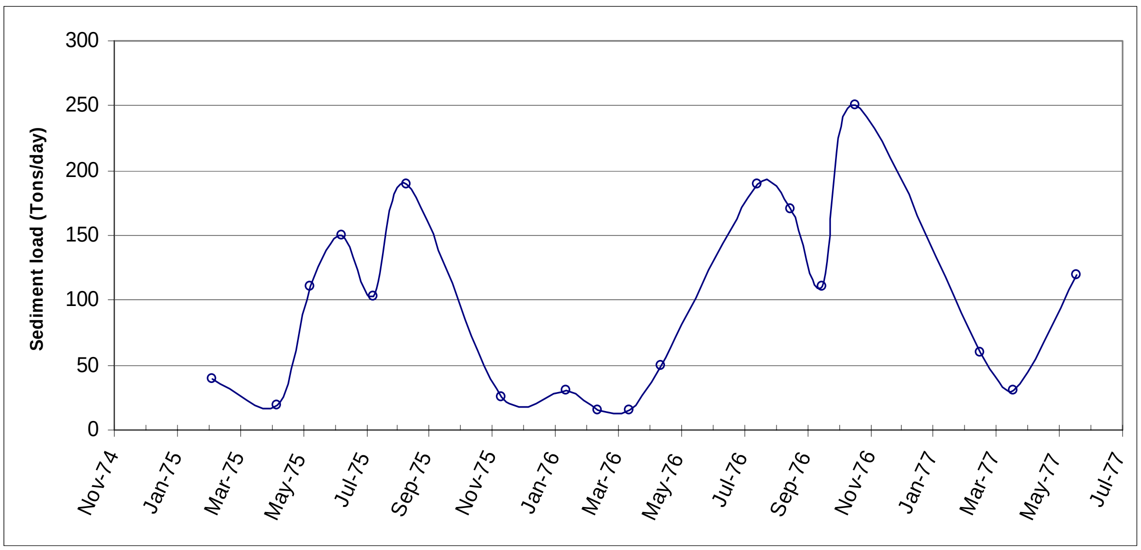


Figure 17. Calculated sediment load at Falk gage for a constant discharge of 200 cfs.

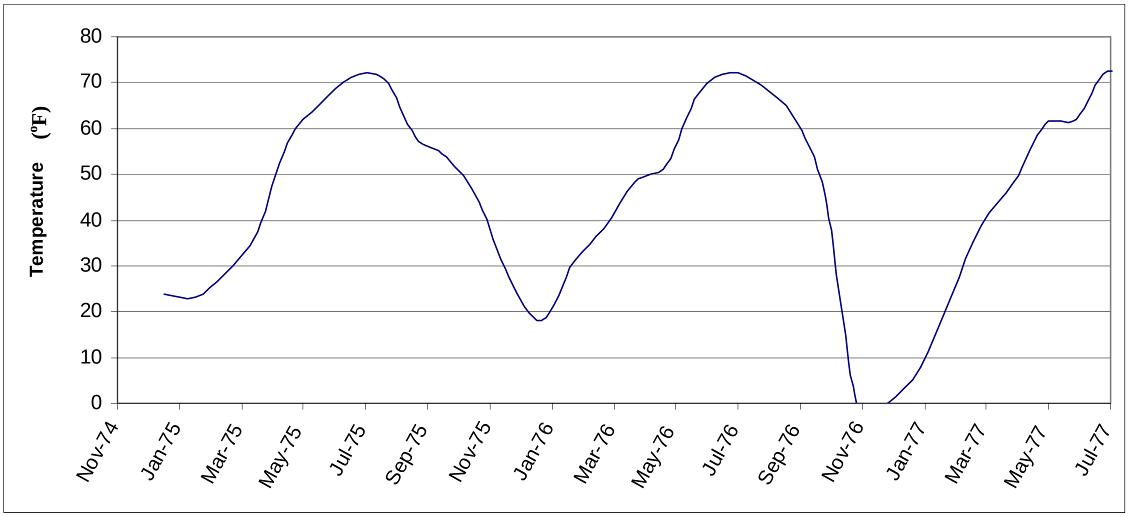


Figure 18. Temperature variation for November 1974 to July 1977.

Runoff from Land

Rainfall generates sheet and rill erosion of exposed soil in a watershed (i.e. sediment yield) and some fraction of this eroded sediment (i.e. sediment delivery) is introduced directly to the river. The amount and characteristics of this source of sediment is site-specific and is affected by several factors such as slope, land use, temperature, basin area and sediment composition.

Dong et al (1979) found seven major soil types within the Menomonee Watershed, which represent about 75% of the total area (Table 6). From these soil types it was determined that 41% corresponds to Ozaukee sil, 16% to Mequon sil, 4% to Hochheim sil, 3.5% to Pella sil, 3.5% to Theresa sil, 2.6% to Ashkum sicl and 3% to Houghton muck.

Table 6. Soil type distribution for Milwaukee area.

Soil type	Sand%	Silt%	Clay%
Ozaukee sil	24	57	19
Mequon sil	35	36	29
Hochheim sil	29	44	27
Ashkum sicl	21	44	35
Pella sil	14	49	37
Theresa sil	22	62	16
Houghton muck	1	38	61

(From Dong et al 1979; sil = silt loam, sicl = silty clay loam)

In October 1977 street sediments were collected at two locations (13th Street Bridge and 91st Street) by the Wisconsin Department of Natural Resources (WDNR). Theses samples showed an average of 86% sand, 8.75% silt and 5.25% clay (Dong et al 1979).

Bannnerman et al (Wisconsin DNR, 1983) conducted a study on nonpoint source pollution for the Milwaukee area and found that 6% of the sampled sediment was clay, 7% silt, 79% sand and 8% were organic particles. This sediment size distribution suggests that the finer particles are transported as runoff or by aeolian action. Greb and Bannerman (1997) determined that only 14% of the total sediment load that was discharged into a detention pond corresponded to the sand fraction, thus the remainder of the sand load was deposited in the street before entering the pond.

A sensitivity analysis related to grain size distribution changes was performed with the model. After several grain size distribution scenarios were simulated, it was found that the variability in deposition patterns and sediment load was insignificant (on the order of 0.5 cm over a 30 day period with a storm event).

Since the topography is similar throughout the model domain, slope changes were not considered as a significant factor for the sediment load that is introduced to the system.

SEDIMENT DELIVERY ANALYSIS

Sediment load and discharge data were obtained for several locations within the southeast area of Wisconsin (Table 7). The collected data corresponds to catchment basins with different areas and different land uses.

Table 7. Flow and sediment load measuring stations from the southeast Wisconsin area.

Location	USGS Gage ID	Record Period	Basin Area (mi^2)	Land Use (% urban)
Little Menomonee at Milwaukee	04087070	1975-1977	19.7	26.5
Underwood Creek	04087088	1975-1977	18.2	82.4
Honey Creek	04087119	1975-1977	10.3	94
Jefferson Park	04087019	1977-1978	1.8	19.6
Jackson Creek	054310157	1983-1984	4.3	39
Noyes Creek	04087060	1975-1977	1.9	79.5

The Menomonee River Falk Gage (Figure 1) represents the total amount of water captured by the watershed and the amount of sediment that leaves the system. After calculating the monthly load and discharge for this gage, it was found that the most significant sediment loads occur during the spring and summer months (
Figure 19).

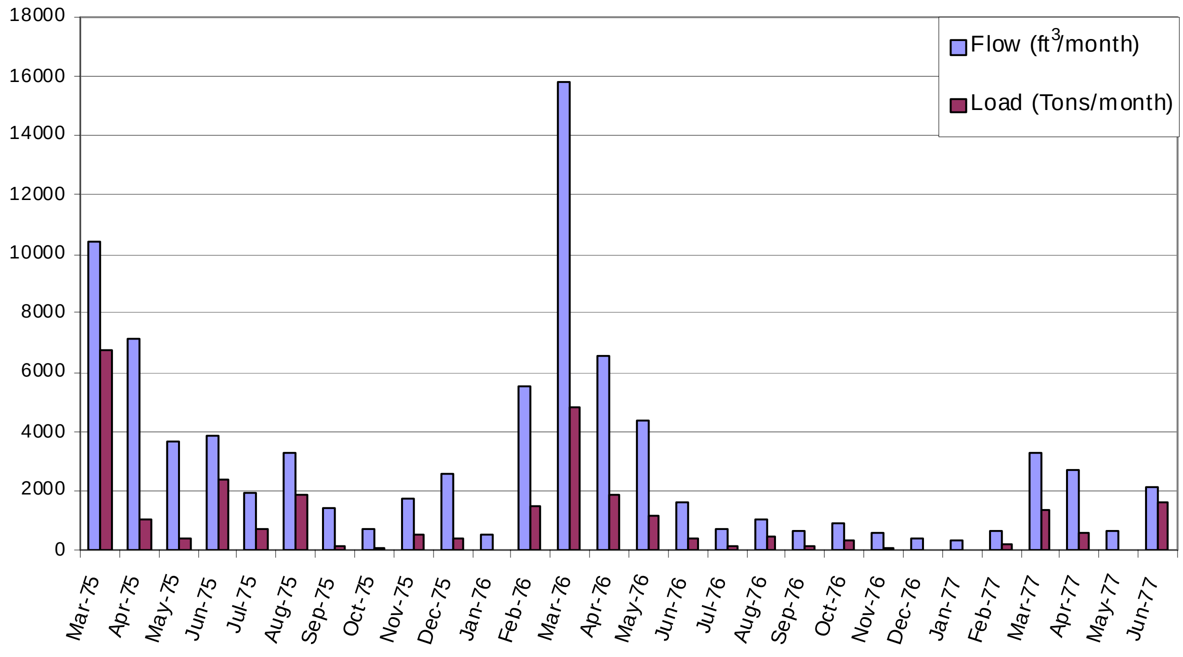


Figure 19. Monthly sediment load and river discharge at USGS Falk Gage Station.

The large quantity of sediment load present in March can be attributed to high precipitation events so the only time periods considered for determining the relationship between sediment load and flow magnitude, for the model input, were late spring (April-May) and early summer (June-July).

Data for each of the gages listed in Table 7 were analyzed for spring and summer. This was done by selecting single events within the selected seasons and then plotting the sediment load data against flow measurements. A rating curve of the form $y=ax^b$ was fitted through the data (Figure 20 - 31).

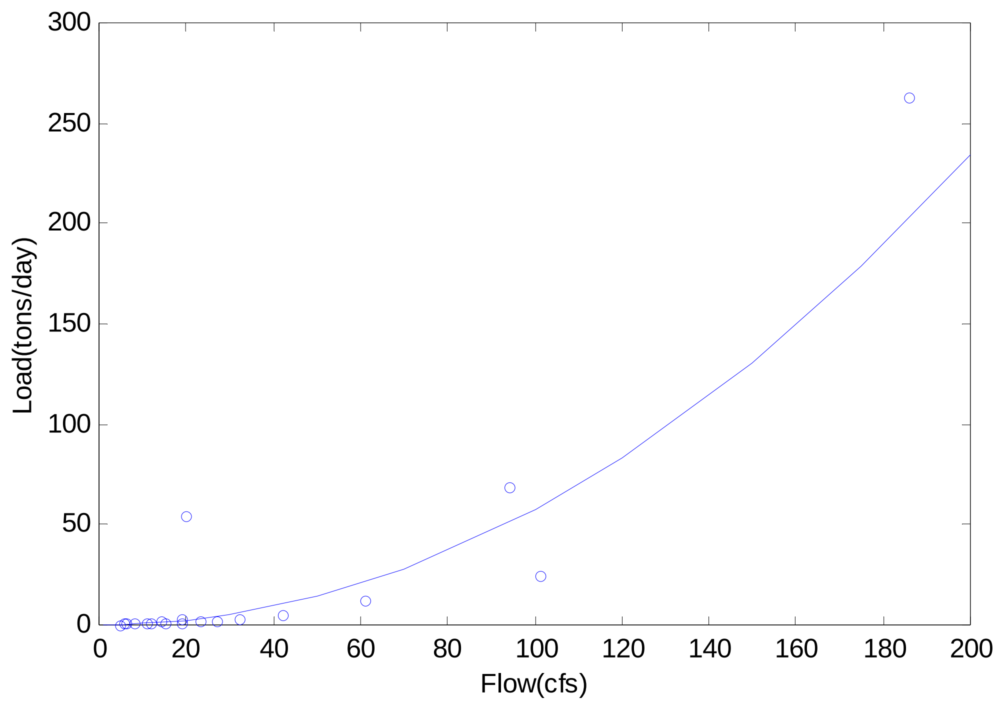


Figure 20. Sediment load vs. discharge for the Little Menomonee River (spring).

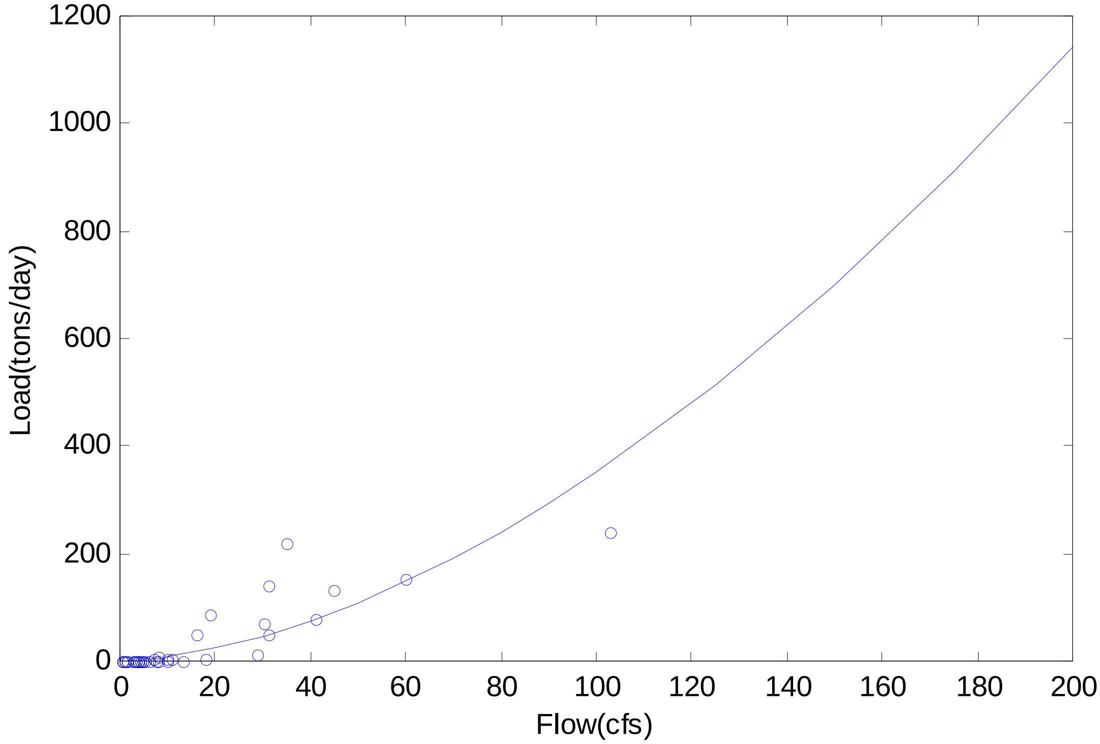


Figure 21. Sediment load vs. discharge for the Little Menomonee River (summer).

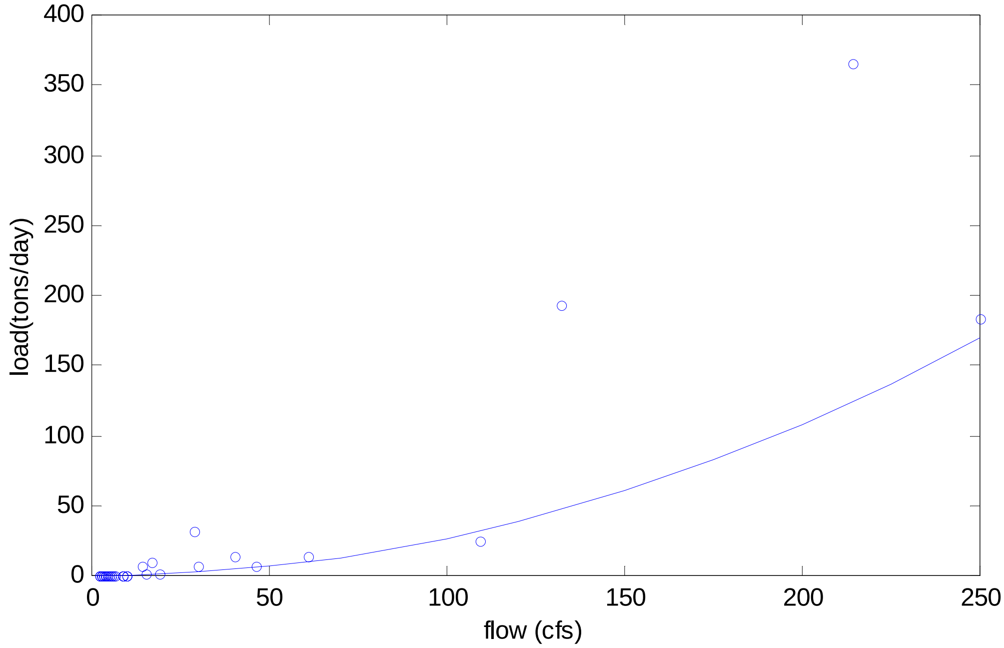


Figure 22. Sediment load vs. discharge for Underwood Creek (spring).

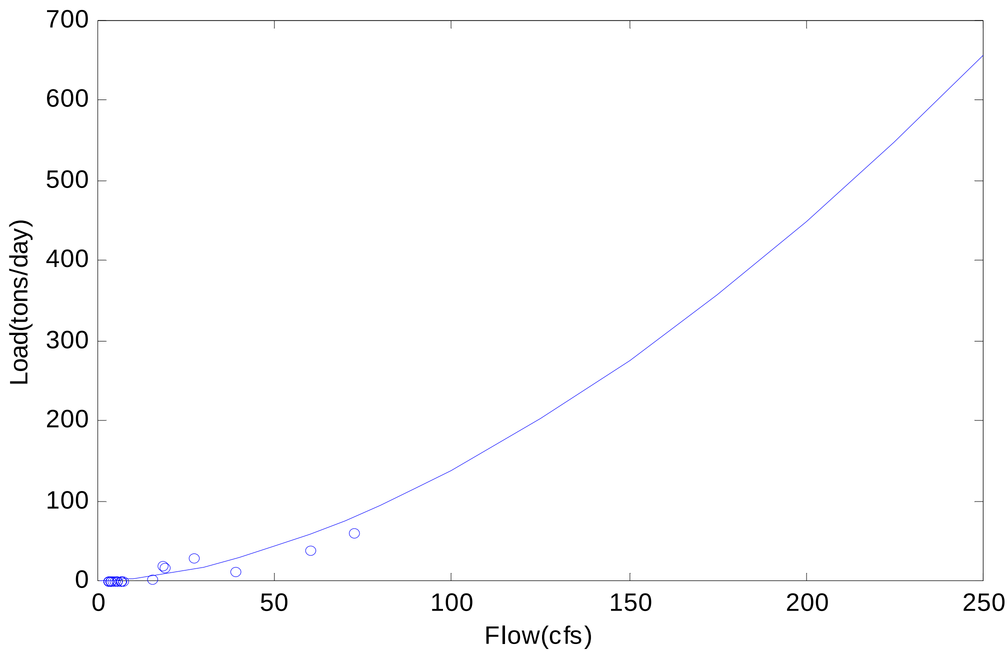


Figure 23. Sediment load vs. discharge for Underwood Creek (summer).

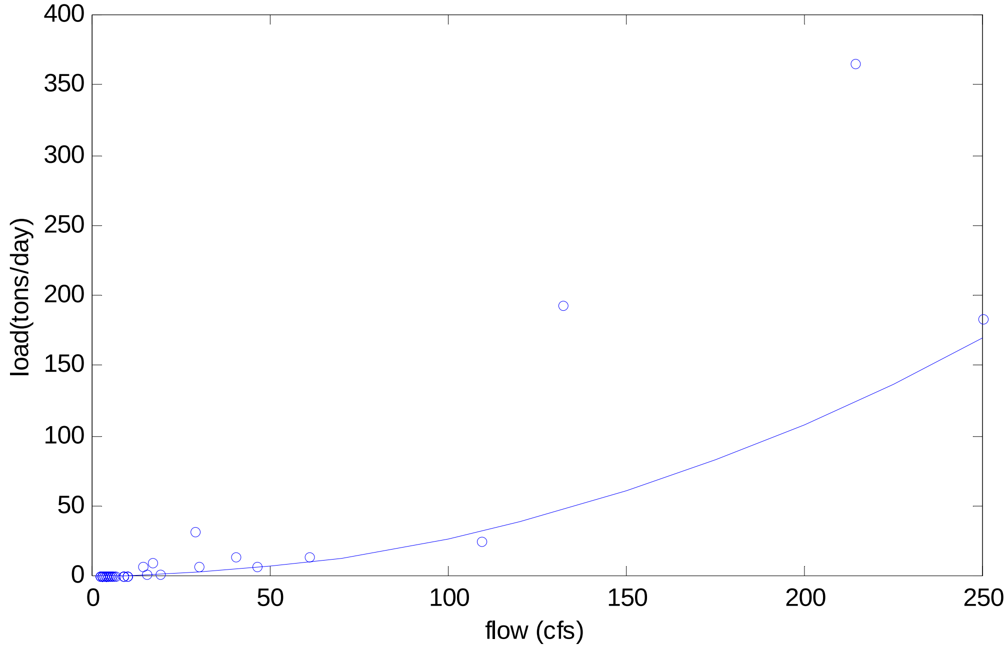


Figure 24. Sediment load vs. discharge for Honey Creek (spring).

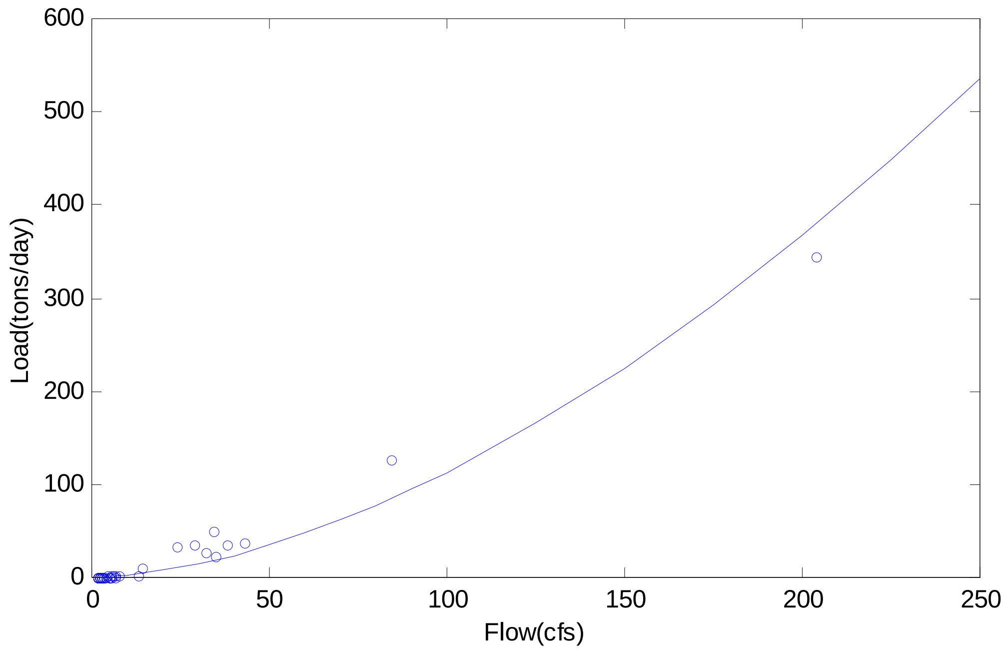


Figure 25. Sediment load vs. discharge for Honey Creek (summer).

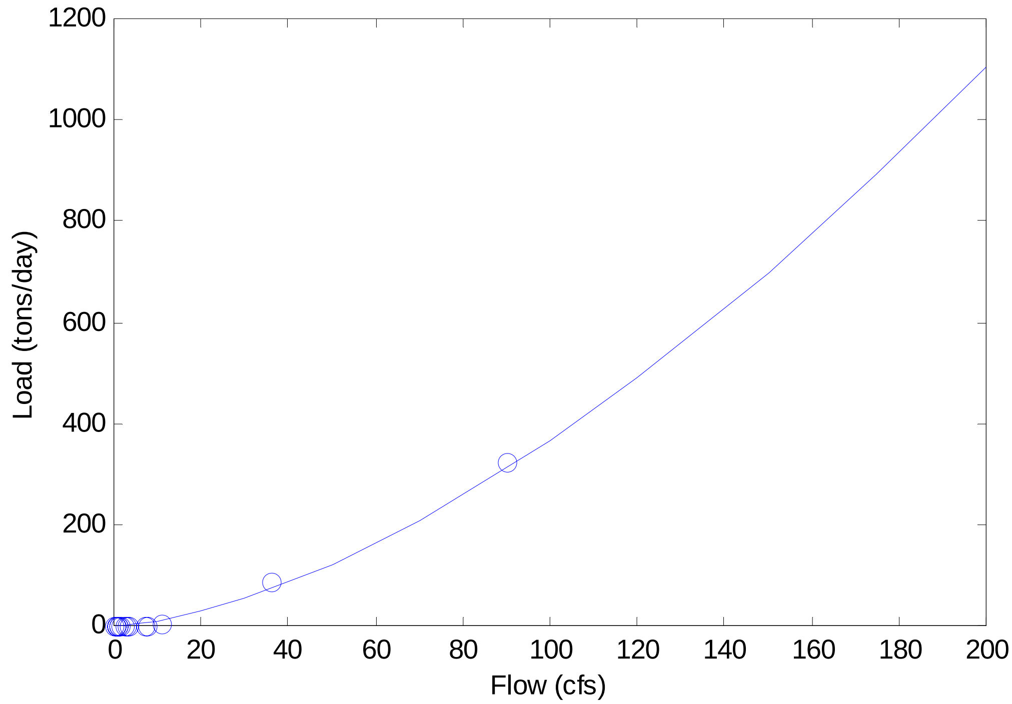


Figure 26. Sediment load vs. discharge for Jefferson Creek (spring).

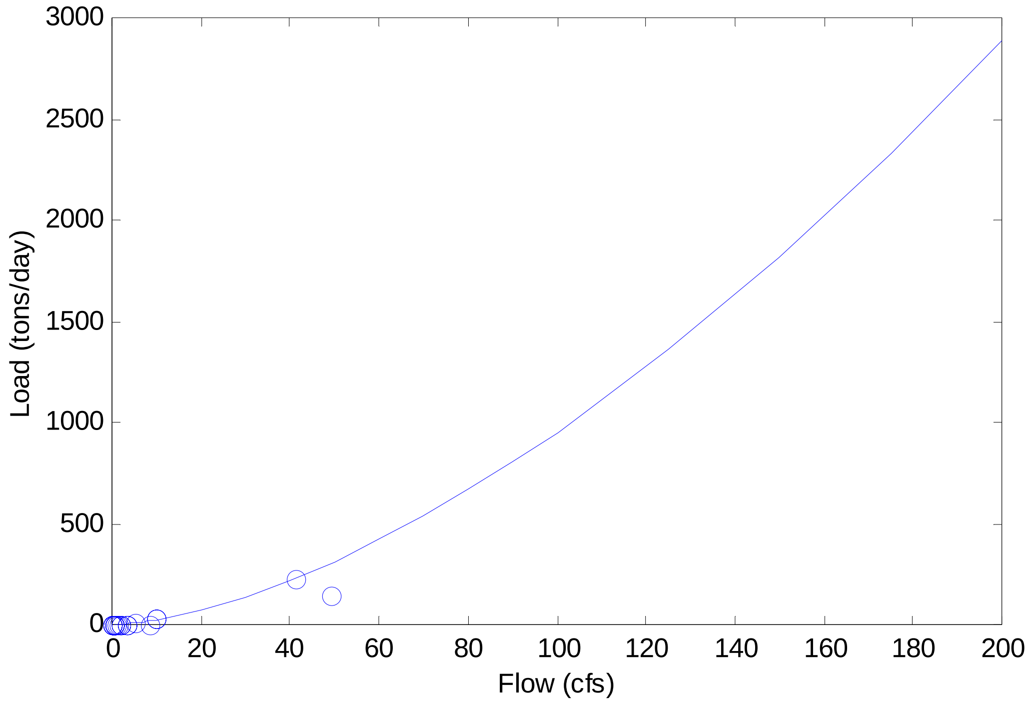


Figure 27. Sediment load vs. discharge for Jefferson Creek (summer).

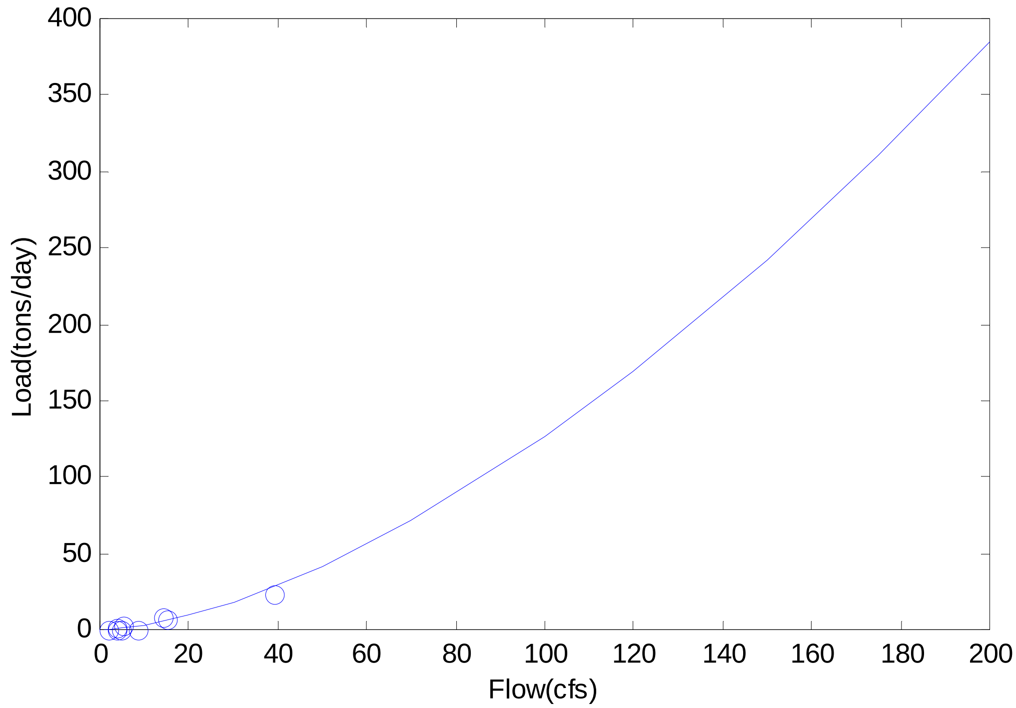


Figure 28. Sediment load vs. discharge for Jackson Creek (spring).

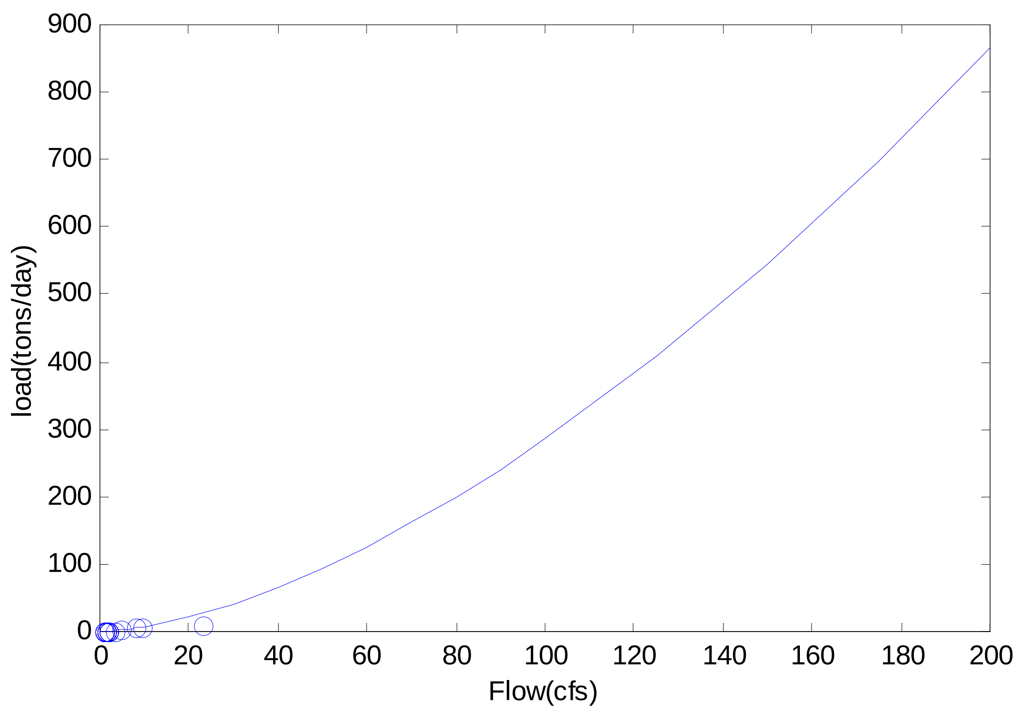


Figure 29. Sediment load vs. discharge for Jackson Creek (summer).

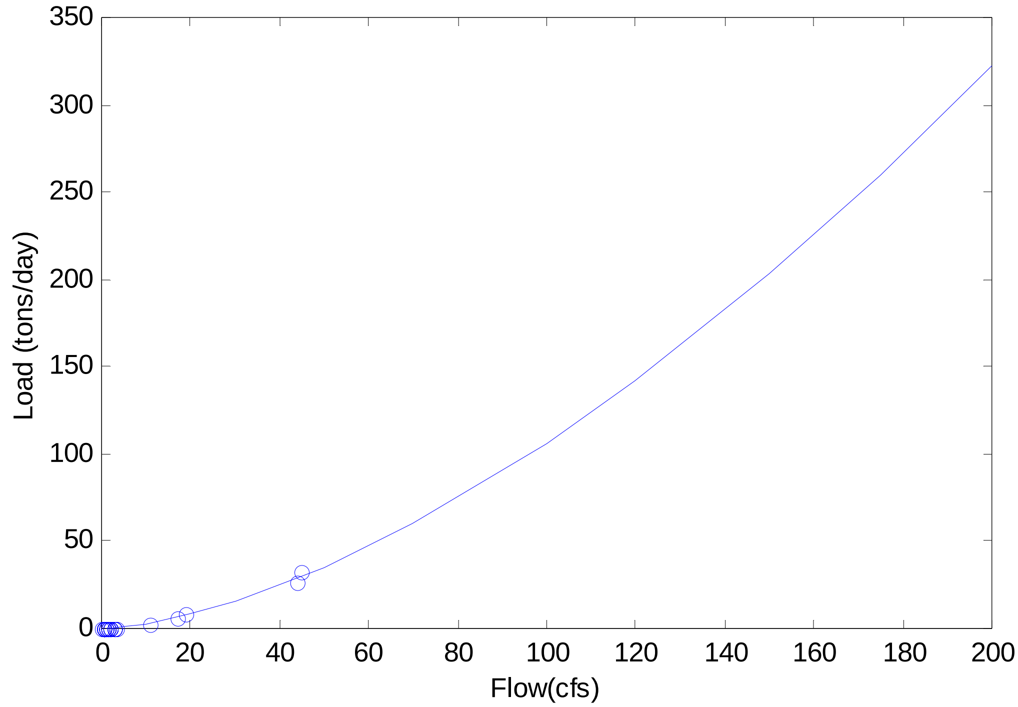


Figure 30. Sediment load vs. discharge for Noyes Creek (spring).

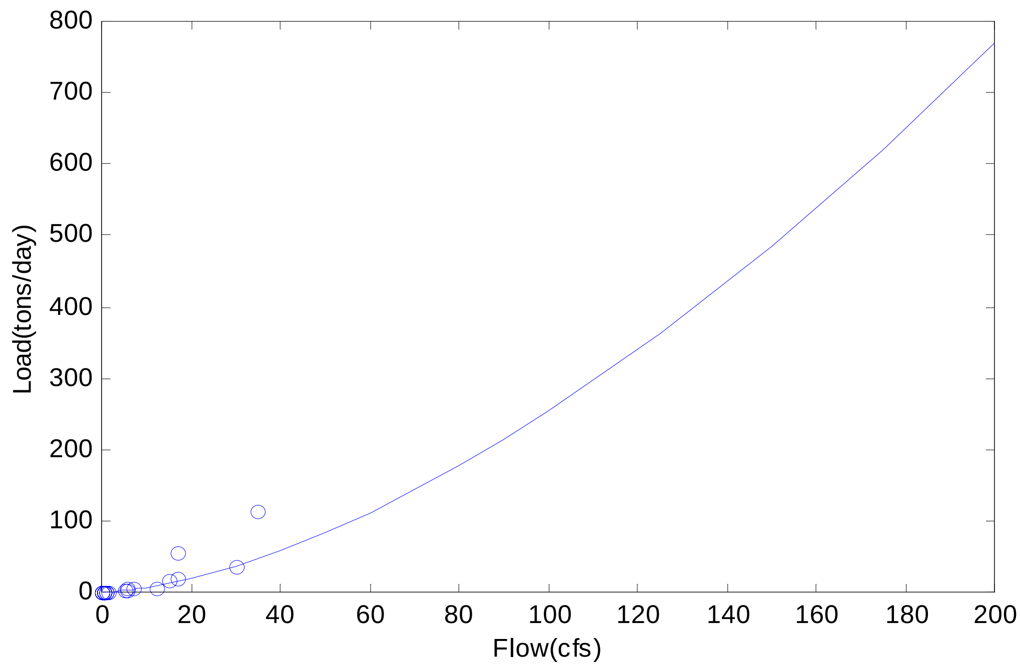


Figure 31. Sediment load vs. discharge for Noyes Creek (summer).

Figure 20 through 31 clearly reveal a relationship of increasing sediment load with increasing flow for the summer period. Previous curve fitting attempts using the regression tools in MS-Excel were discarded because the fit is based on obtaining the best r^2 possible and does not follow the theoretical mathematical relationship. In this case, some values had a significant influence on the trend line (e.g. Honey Creek - spring). When an automatic fit was used, the sediment load was overestimated.

The nature of the data is a limiting factor for accuracy and interpretation, owing to the fact that the sediment load and discharge were measured only once a day; the highest discharge values do not necessarily represent the highest discharge of the day. By using a manual fit, high sediment load values (in relation to flow) can be disregarded (e.g. Jefferson Creek spring) because peak load is not usually coincident with peak discharge.

By manipulating both of the coefficients from the equation, it was found that coefficient *b* had a similar value for the small basins and a similar value for the larger basins. Therefore, a fixed value for this coefficient was established according to the basin size and coefficient *a* was manipulated until a good fit was reached. When the summer curves were obtained, it was noted that the coefficient *b* for small basins used in the spring analysis also fit the data, but for large basins, this value was reduced (Table 8).

Table 8. *b* values for basin size and record period.

Basin Size (mi^2)	Record Period	*b* Value
<4.5	Spring	1.6
	Summer	2.03
>4.5	Spring	1.6
	Summer	1.7

It was noted that the rating curves for larger catchment basins (greater than 4.5 square miles) showed a proportionally lower sediment load than for small catchment basins (Figure 32 and 33). However, in nature it is not very probable to obtain such high flows in small streams due to the size of the catchment basin. This behavior may be explained by the distance the sediment travels before reaching the stream. As the basin gets larger, the load travels a longer distance and the probability of being deposited before reaching the stream is higher than for small basins. In other words, sediment delivery rates are lower (per unit area) for large watersheds.

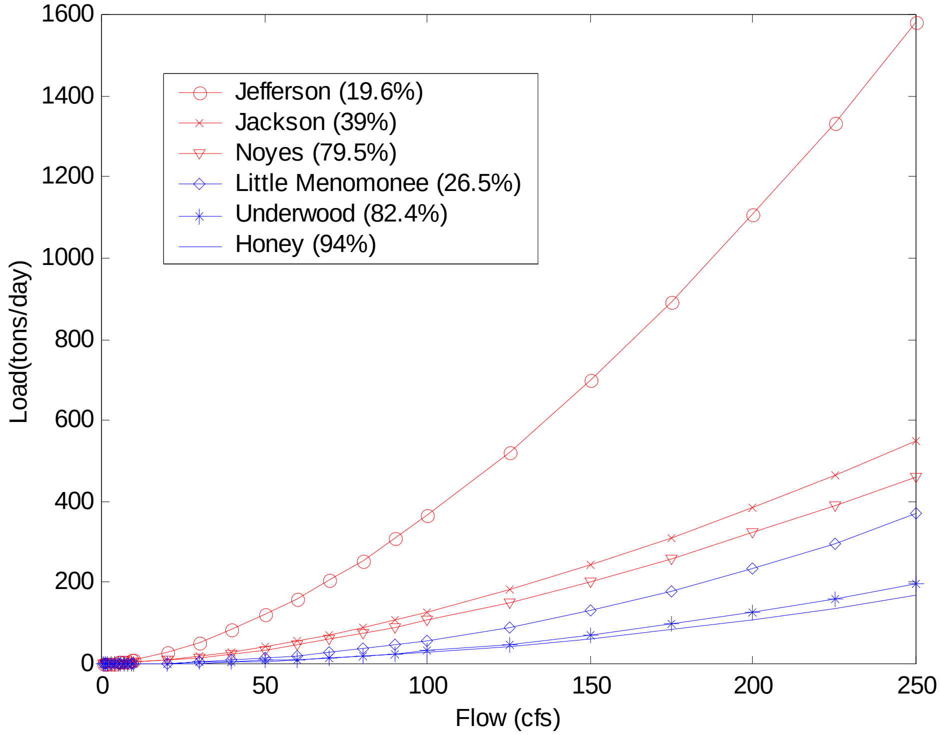


Figure 32. Sediment load rating curves for various gage stations (spring).

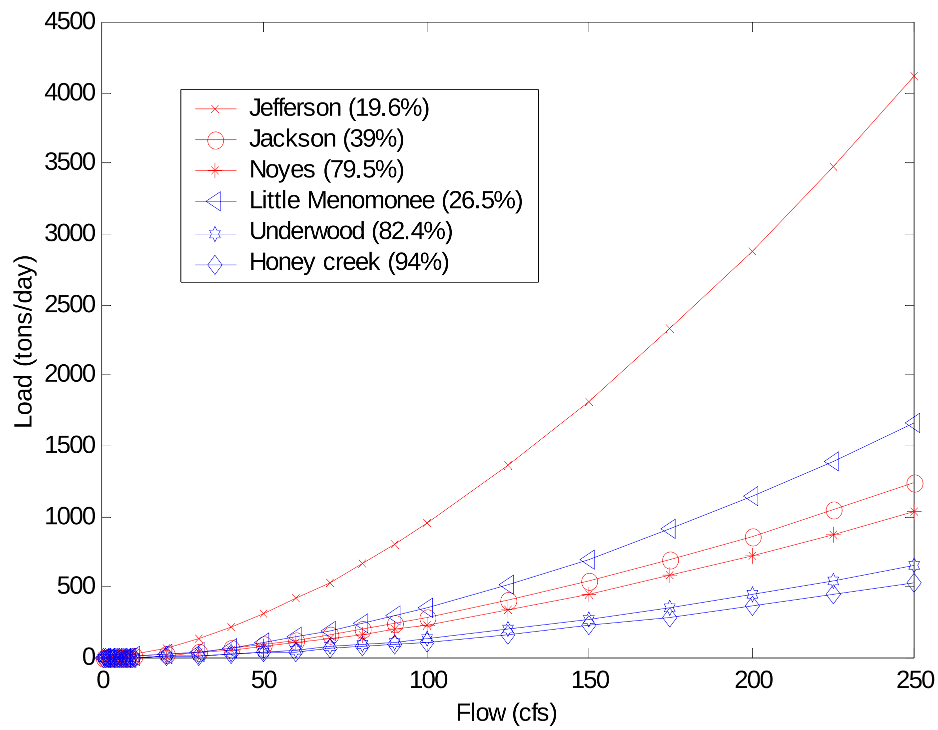


Figure 33. Sediment load rating curves for various gage stations (summer).

Sediment Delivery – Land Use Relationship

Change in land use is a factor that can significantly modify the runoff patterns and therefore affect the amount of soil erosion and sediment load. The sediment load generally decreases proportionally to the increase in urban coverage. This behavior can be observed from the series of plots shown in Figure 32 and 33, where higher loads are associated with lower urban-percentage basins.

Figure 34 shows data for different urban/agricultural land use percentages from the Menomonee River Watershed and their corresponding sediment load in tons per square mile (USGS, 1997). It can be observed that with increasing agricultural coverage the sediment load also increases.

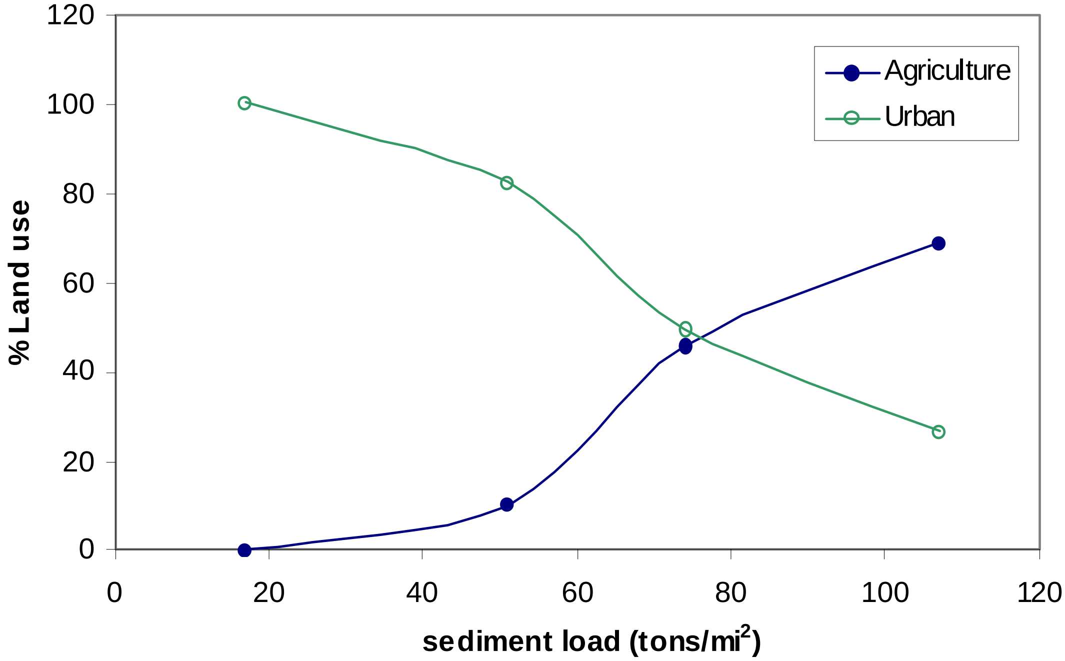


Figure 34. Sediment load for urban-agricultural portions

Since the Menomonee River Watershed is composed of wide varieties and densities of land use (Figure 35), it was very important to determine relationships between sediment load (independent of flow magnitude) and land use. To determine this relationship, coefficient *a* was plotted against the corresponding land use of the catchment basin and then a curve was fitted through each data set (i.e. *a* for spring-small, spring-large, summer-small and summer-large). It was found that the larger catchment basins had a linear trend and a very good fit was achieved (Figure 36), while smaller catchment basins had a negative exponential behavior (Figure 37).

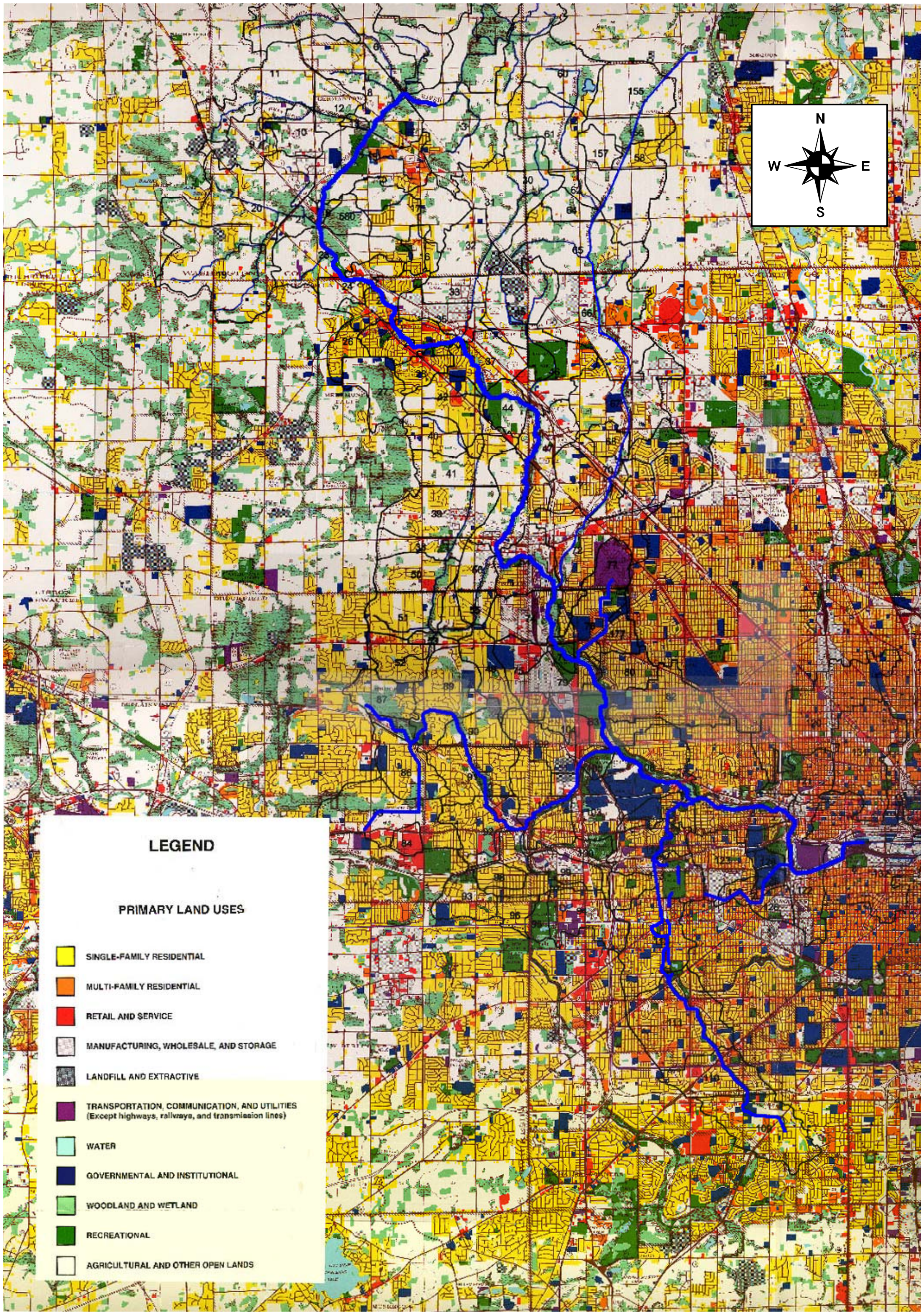


Figure 35. Land use from 1985.

Equations that represent these curves are listed below (Equations 1-4). Equations 3 and 4 have the same exponential value. This value was set this way for consistency.

$$a = 0.00004lu + 0.0061 \text{ (spring)}$$
(1)

$$a = 0.0014lu + 0.177 \quad \text{(summer)}$$
(2)

$$a = 3000lu^{-3.3} + 0.062 \text{ (spring)}$$
(3)

$$a = 8000lu^{-3.3} + 0.15 \quad \text{(summer)}$$
(4)

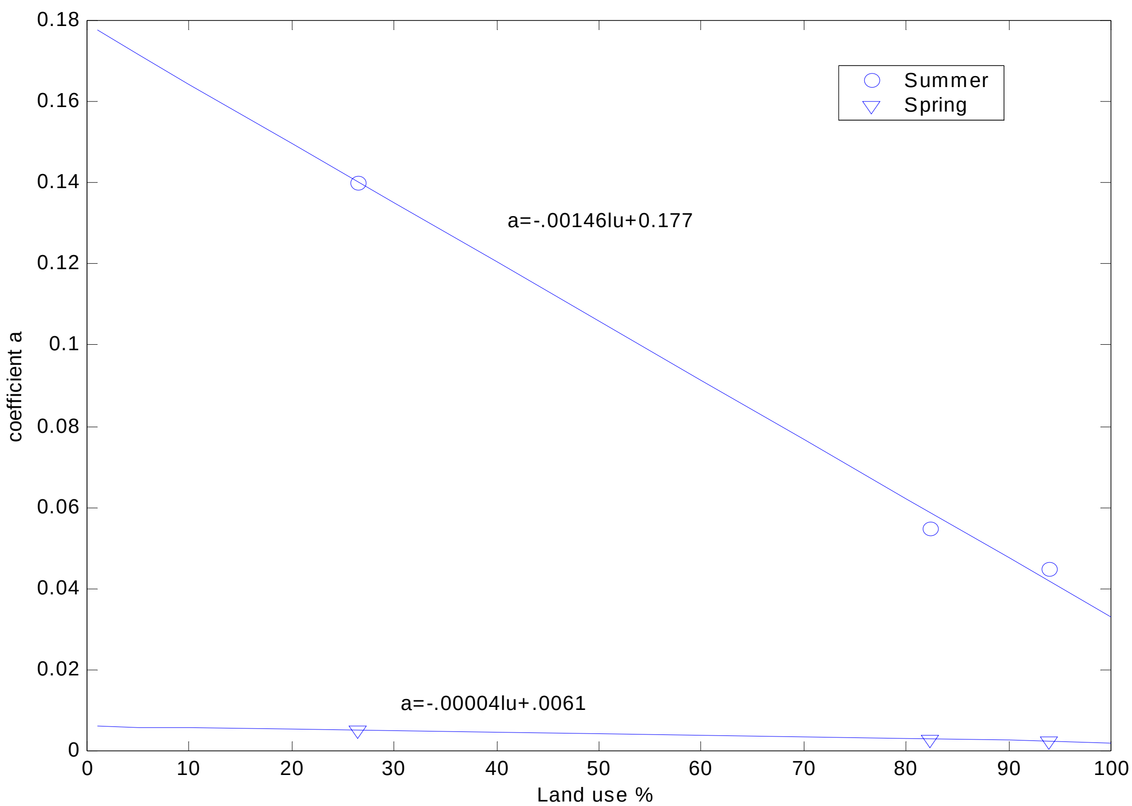


Figure 36. Land use percentage against coefficient *a* values for large drainage basins for spring and summer time periods.

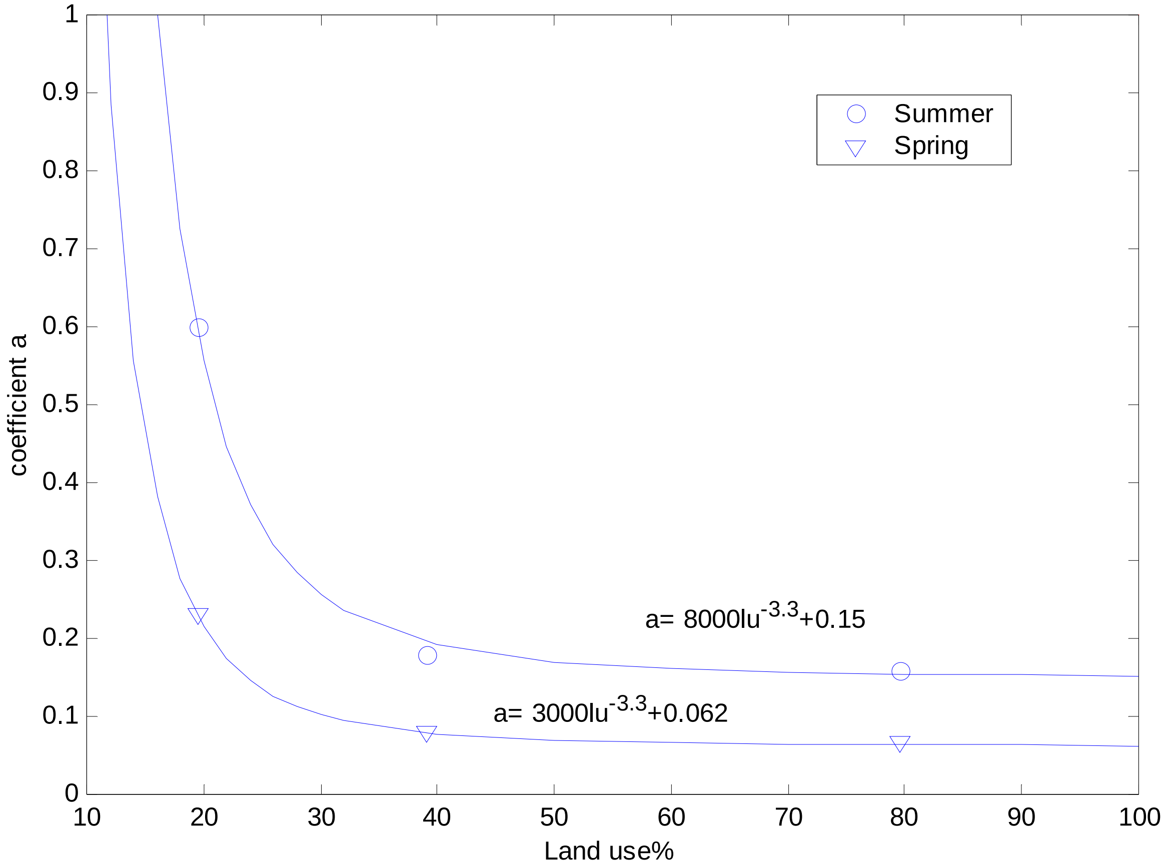


Figure 37. Land use percentage against coefficient *a* values for small drainage basins for spring and summer time periods.

The drainage basin area for each of the input flow points (Figure 38), and the percentage of urban coverage were determined (Table 9). By using these percentages, the basin area and Equations 1 and 3, it was possible to determine the corresponding rating curves for the model input file.

Table 9. Catchment basin areas and 1985 percent urban areas.

Stream	River Mile	Input point	Area (mi^2)	1985 Land Use (% urban)
MM BC		1	4.45	10
Menomonee River	4.239	2	6.83	95
Menomonee River	11.38	3	1.46	90
Menomonee River	14.45	4	5.67	80
Menomonee River	16.56	5	1.06	60
Menomonee River	17.86	6	3.92	25
Menomonee River	18.92	7	5.69	50
Menomonee River	20.26	8	4.66	25
Menomonee River	21.47	9	8.12	40
WC BC		10	1.08	95
Woods Creek	0.51	11	0.42	90
HC BC		12	1.91	80
Honey Creek	0.91	13	1.77	95
Honey Creek	1.95	14	1.20	50
Honey Creek	3.1	15	1.98	90
Honey Creek	4.53	16	2.56	90
Honey Creek	6.44	17	1.29	80
UW BC		18	4.77	50
Underwood Creek	0	19	0.16	50
Underwood Creek	0.22	20	0.79	80
Underwood Creek	0.8	21	1.22	70
Underwood Creek	1.49	22	0.94	90
Underwood Creek	2.56	23	2.49	70
Underwood Creek	3.43	24	1.48	85
Underwood Creek	4.82	25	0.77	70
Underwood Creek	5.41	26	1.81	60
GC BC		27	0.31	95
Grantosa Creek	0.22	28	0.22	95
Grantosa Creek	0.795	29	0.51	95
Grantosa Creek	1.511	30	0.67	90
LM BC		31	3.32	25
Little Menomonee River	2.25	32	3.22	70
Little Menomonee River	3.1	33	0.41	60
Little Menomonee River	3.4	34	4.83	50
Little Menomonee River	5.5	35	2.85	25

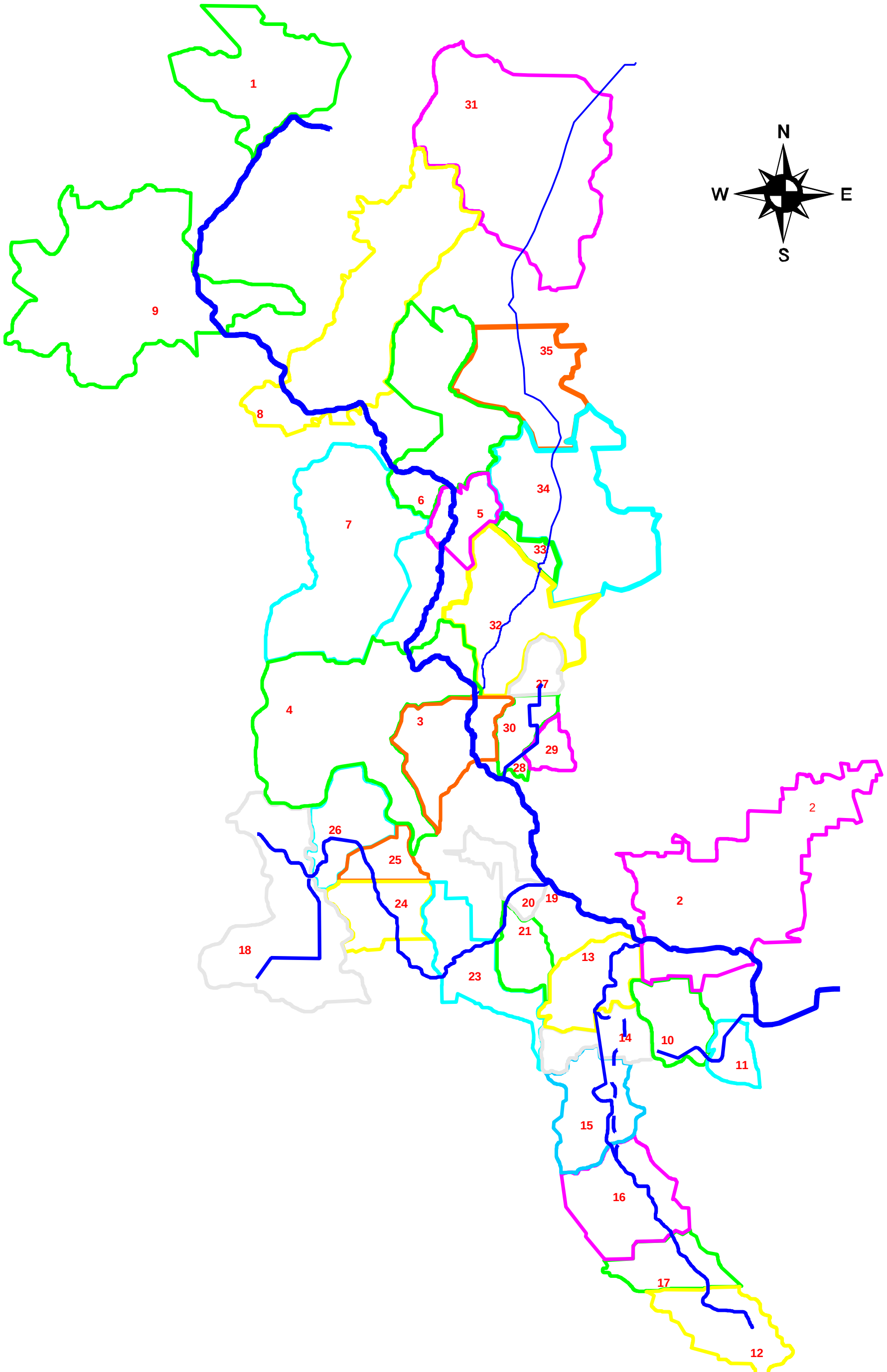


Figure 38. Catchment basins and input point ID numbers for the model domain.

SEDIMENT MODEL SYSTEM SETUP

Model System Setup Goals

When developing the Menomonee River Watershed sediment modeling system, the focus was on the following points with the intention of making the system cohesive and streamlined as well as efficient and economic:

- **Linkages** - Since this system incorporates several data sources and platforms, as well as hydrologic and hydraulic models, it was desired to have linkages between the components that would facilitate the passing of data through the system with a minimum of detailed data processing. The linkages bring cohesion to the modeling system as well as making it streamlined.
- **User-Friendly -** For the same reasons, it was also desirable to develop a system that was user-friendly and intuitive. The primary use of this system is as a planning tool to assess various basin conditions with respect to sediment delivery and transport. This stresses the importance of having a system that can produce results with efficiency and a minimum of difficulty.
- **Publicly Available Software** - The software used in this project was selected on the basis of its public availability, thus making the system very economic. The models used include BASINS 3.0 and HSPF, which are available at no cost from the U.S. Environmental Protection Agency, and HEC-6, which is another no-cost product of the U.S. Army Corps of Engineers.

Component Selection

The above criteria was used to choose the components of the modeling system. In addition, the availablity of existing models was another factor that weighed considerably in the selection criteria**.** From previous studies both HSPF and HEC-RAS models had been developed and were readily available from the MMSD. Since the HEC-RAS model channel geometry could easily be converted to HEC-6 format, HEC-6 was chosen as the sediment transport model. To increase the functionality of the modeling system, a GIS component was added, ArcView 3.X, as well as a water quality component BASINS 3.0, which also served as an umbrella for much of the modeling system. Figure 39 is a schematic of the modeling system and the following is a list of the models and their purposes:

- **Hydrology – HSPF**
- **Hydraulics - HEC-RAS**
- **Sediment Transport – HEC-6**
- **GIS – ArcView 3.X**
- **Water Quality (Umbrella) – BASINS 3.0**
- **Output Viewers – SDA, Microsoft Excel, GenScn**

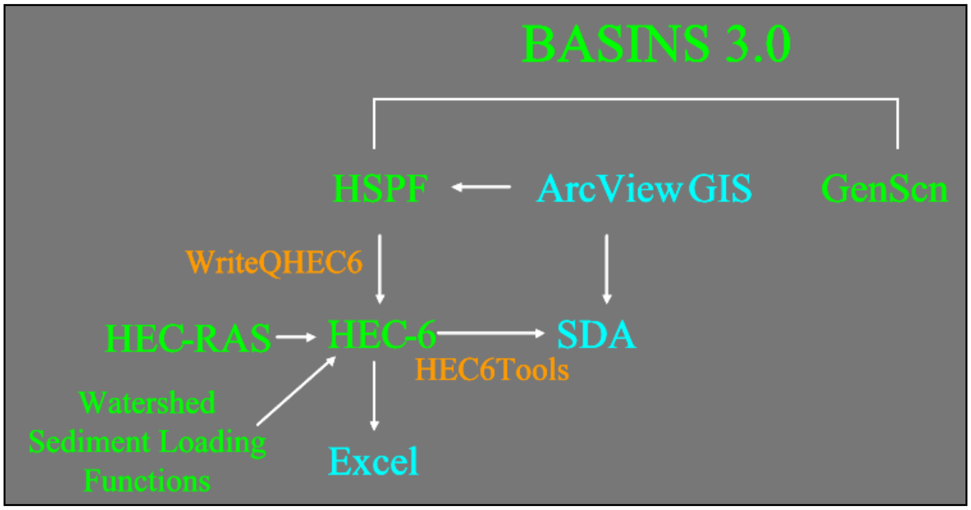


Figure 39. Modeling system schematic.

Component Details

HSPF – Hydrologic Simulation Program - Fortran

HSPF was chosen as the hydrologic component of the modeling system. An existing model had been developed during a previous study and was readily available for use. The model was received in pieces; a separate input file had been created for each subbasin. These individual subbasin files were combined into a larger watershed hydrologic model. Since the model had been calibrated for the previous study, this processes was not repeated, though model results were checked for validity.

Subbasin information is input into the HSPF model and includes area, land use and soil cover. Information regarding the tributaries and main stem reaches is also included for routing purposes. HSPF also requires meteorological data, which was obtained from measurements taken at Milwaukee's Mitchell Field and included 15-minute precipitation data, hourly solar radiation, evaporation, wind speed and temperature, and daily dew point temperatures. Additional information regarding the hydrologic calibration and inputs can be found in the Menomonee River Watercourse Study Report.

HEC-RAS

An existing HEC-RAS model was also available at the beginning of this project. The HEC-RAS model contained information about the channel and floodplain geometry. This HEC-RAS input data was converted to the format required for the HEC-6 sediment transport model.

HEC-6

Using the channel geometry from HEC-RAS, the HEC-6 model was developed. Additional data concerning channel and suspended sediment was also required for the HEC-6 model. A detailed description of the HEC-6 model follows in the next section of the report. The model was calibrated against measured data from 1975 and then run for different flow and land use scenarios.

ArcView 3.X

ArcView 3.2 was used to incorporate a GIS component into the modeling system. Existing GIS layers from previous studies were obtained from the MMSD and from CDM. Additional GIS data was developed and made available from a study done by Inter-Fluve for the MMSD in 2001. Baird has developed a customized routine within the GIS that allows the user to modify the land use layer. The routine then uses this new land use data to calculate the new parameters needed for the HSPF model.

BASINS 3.0

BASINS 3.0, which functions within the ArcView 3.X platform, was chosen to add additional functionality to the modeling system while, at the same time, providing an umbrella for several model components including HSPF, ArcView 3.X, and GenScn. The BASINS 3.0 datasets are available for download from the EPA's website and include significant amounts of water quality data which can be readily viewed and probed. While a water quality component was not required for this project, BASINS 3.0 provides some useful additional data with a minimal amount of additional development time.

SDA - Spatial Data Analyzer

SDA is a GIS-based model data viewer developed by Baird. A special browser was developed for distribution with the Menomonee model system. The SDA browser allows the user to view and navigate HEC-6 model output data. Included in this functionality is the ability to view model output data over time. The browser does not include the functionally to add new data to the project. To have the complete functionality of SDA, the full SDA package would have to be purchased from Baird Software. Figure 40 shows some of the capabilities of SDA including frame-in-frame viewing, legend, GIS layers, and concurrent viewing of model output data in plan view and multiple data plots for a specific point within the system.

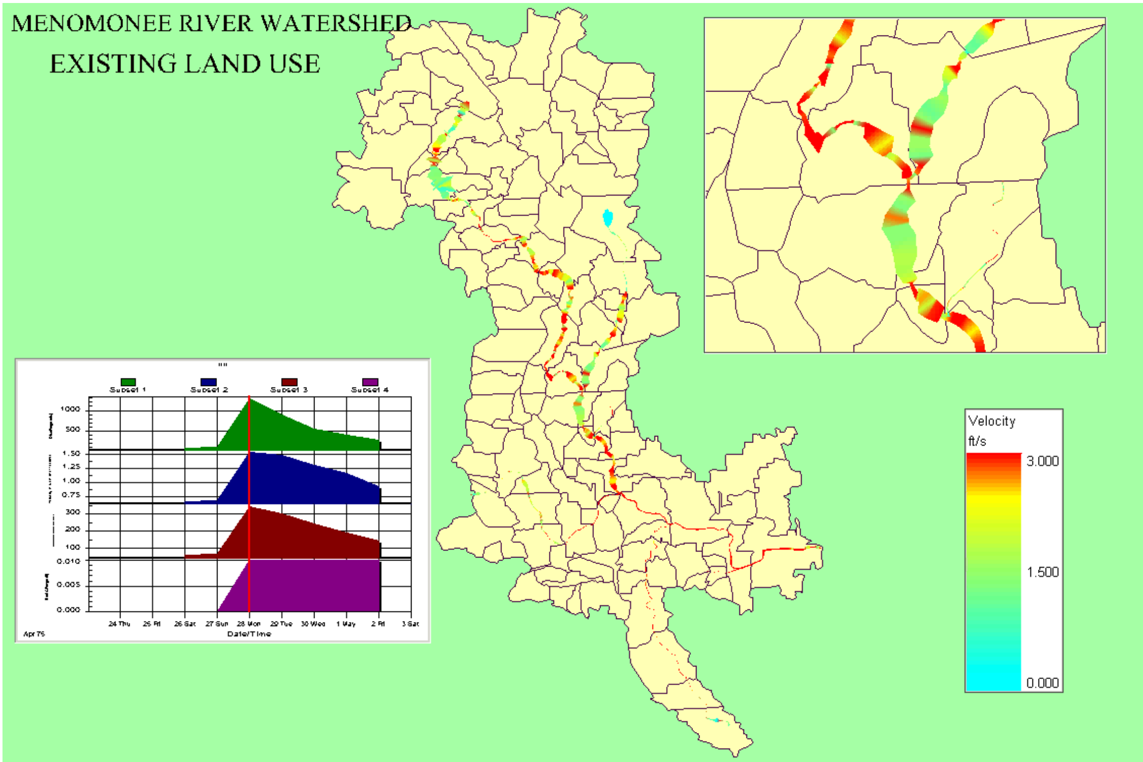


Figure 40. SDA sample output.

SEDIMENT MODEL (HEC-6)

For this study, a one-dimensional model was used for the prediction of sediment transport. This decision was based on the simplicity of the system and its relative small cross-sectional area along the river. The applied model for this study was HEC-6.

HEC-6 is a one-dimensional model with movable bed (i.e. allows change in bed elevation due to erosion-deposition processes) and steady-state flow (flow is specified constant over a period of time).

The model operates in an iterative form where a water surface profile is calculated for a specific flow. In the course of computing the water surface profiles, the model computes an energy slope, velocity and depth for every cross section within the domain. The model computes the amount of erosion and deposition that takes place at each cross section as a function of the flow magnitude and the duration of the model time step. The volumetric quantity of erosion or deposition is then transferred to the original geometry and the cross section is readjusted to the new bed elevation.

The model input consists of three basic sections related to morphology of the system, sediment characteristics and flow specification. For each of the model sections a data set is required. The accuracy of the model prediction is directly related to the quality of the input data, thus, it is very important to obtain accurate data and use caution while processing and recording the information.

Geometric data: In this section, the user specifies the morphology of each cross section, which include the following input:

- Cross section coordinate points (elevation vs. station);
- Length between each cross section;
- Friction coefficient (Manning's *n*);
- Boundaries between left bank, channel and right bank;
- Number and location of tributaries of the river system, including flow;
- Local inflows/outflows for each stream.

The following is an example of the data structure:

```
T1      MENOMONEE RIVER MAIN BRANCH
T2      Menomonee River: 1995 LAND USE: 2-YEAR FLOOD
T3      HEC-6 WITH USGS BED MATERIAL DATA FROM IJC STUDY 1975-77
NC  0.16   0.16   0.018     0.3     0.5
X1  1.86     28     900    1100     575     420     475
X3                        900.1     610  1099.9   589.5
GR 589.5      0   589.3     100   589.3     200     589     300   588.6     400
GR 588.4    500   588.4     700   588.7     800   588.7     900   582.4   902.2
GR 581.7    910   579.5     920     574     937     574    1049   577.7    1060
GR   578   1070     578    1080   579.2    1087   584.2    1098   588.5    1100
GR 588.3   1200   587.7    1300   587.3    1400   586.7    1500   586.3    1600
GR   586   1700   585.7    1800   585.7    2000
HD  1.86      0
```

The data input for the HEC-6 model is generally described as a card format, where each data line, or card, contains a specific type of input. The T1-T3 cards are comment fields for stream specifications. The NC cards contain the Manning *n* fields, the X1 card defines the location of the cross section relative to the upstream and downstream cross sections, and the boundaries between the banks and the main channel, as well as the number of coordinate points and datum. The X3 card is an optional parameter used to set the encroachments on the cross section, which is a means of precluding ineffective flow sections from the hydraulic computations. The GR cards contain the coordinate points, and the HD card contains the movable bed limits.

Sediment data: This section specifies sediment characteristics such as settling velocity, erosion deposition parameters, sediment classes, grain size distribution by percentages and depth of the erodible layer (i.e. the thickness of the sediment available for initial erosion). Part of this section includes a rating curve that relates flow magnitude to sediment load. This part is very important for the modeling effort because it defines the amount and grain size distribution of suspended load that enters the system in relation to the incoming flow.

The following is an example of the sediment input data structure:

```
T4      MENOMONEE RIVER MAIN BRANCH
T5      SEDIMENT DATA
T6      BED SEDIMENT DATA FROM USGS WATER RESOURCES DATA FOR WISCONSIN
T7      USING BED DATA AVERAGED FROM 1975-1977
T8      NO INFLOW SEDIMENT LOAD
I1           20       0                               2       1
I3  SILT      1       3       4       0       0       0       0       0
I4  SAND     14       1      10       0       0       0       0     110
LQ     Q      1     2.5      5.     10.     25.     50.    100.    250.    500.
LT TOTAL      0       0       0       0       0       0       0       0       0
LF SILT3      0       0       0       0       0       0       0       0       0
LF SILT4      0       0       0       0       0       0       0       0       0
LF   VFS      0       0       0       0       0       0       0       0       0
LF    FS      0       0       0       0       0       0       0       0       0
LF    MS      0       0       0       0       0       0       0       0       0
LF    CS      0       0       0       0       0       0       0       0       0
LF   VCS      0       0       0       0       0       0       0       0       0
LF   VFG      0       0       0       0       0       0       0       0       0
LF    FG      0       0       0       0       0       0       0       0       0
LF    MG      0       0       0       0       0       0       0       0       0
LF    CG      0       0       0       0       0       0       0       0       0
LF   VCG      0       0       0       0       0       0       0       0       0
PF  1.00  0.010       1 128.000 104.751  95.000  85.226  90.000  76.874  85.000
PFC 69.3 80.000  57.148  70.000  48.329  60.000  36.866  50.000  28.857  40.000
PFC 24.0 30.000  18.616  20.000  15.743  15.000   6.723  10.000   1.692   5.000
```

The T4-T8 cards are comment fields for stream specifications. The I1- I4 cards are sediment property fields (e.g. settling velocity, erodibility) for sand, silt and clay. The LQ card is the flow field for the rating curve and LT and LF fields are the total sediment and fraction of sediment classes that correspond to a specified discharge. The PF and PFC cards describe the grain size distribution of bed sediment at a particular cross section.

Flow data: This section specifies the water discharge that leaves or enters the system at each tributary. Each tributary and the main stem can contain local inflow/outflow points for which a discharge must be specified. In order to specify the flow, a continuous time series must be obtained and partitioned in small intervals of a constant magnitude. The time interval can be in the order of minutes, hours or days depending on the complexity and variability of the flow. This section also includes a water surface elevation vs. flow rating curve (RC record) used as a boundary condition for the backwater calculation. Most of the model runs in this study used a time step of one day, so the flow values for each stream section were daily average flows for each stream segment.

Data structure:

```
RC          5.0       6                  558.70   558.9   559.1   559.3   559.5
*    B  4/26/75    0:00
Q  54.60   3.80    3.05    2.81    1.66    0.27    3.05    4.66    9.96    1.00
Q   0.65   2.68    0.29    0.46    0.63    0.32    0.46    6.73    0.24    0.44
Q   0.31   2.73    0.48    0.89    1.17    0.31    0.51    0.13    0.10    0.16
Q   8.28   0.75    0.10    2.89    1.75
T  65.00  65.00   65.00   65.00   65.00   65.00   65.00   65.00   65.00   65.00
T  65.00  65.00   65.00   65.00   65.00   65.00   65.00   65.00   65.00   65.00
T  65.00  65.00   65.00   65.00   65.00   65.00   65.00   65.00   65.00   65.00
T  65.00  65.00   65.00   65.00   65.00
W   1.00
```

Where * defines the output format, Q is the discharge at each source/sink location, T is the water temperature and W is the time step in days.

Available Data

The model domain encompasses the Menomonee River, from the confluence with the Milwaukee River up to mile 27.12 (which corresponds to Freistadt Rd), and tributaries Woods Creek, Honey Creek, Underwood Creek, Grantosa Creek and Little Menomonee River (Figure 4).

The sediment and flow data used in the calibration of the model were measured in water years 1975 to 1977. This data set was chosen because of the availability of suspended sediment measurements taken by USGS during this period.

Geometric data: Most of the geometric data was already available from previous hydrodynamic modeling efforts with HEC-RAS, which has a very similar input structure to HEC-6 thus only minor modifications were required. Due to the extent of the domain, its complexity and large amount of cross sections and inflow points, the source code had to be modified to allow for such dimensions. The geometric data includes 1250 cross sections, five tributaries and 35 flow fields.

In 1975, the Southeastern Wisconsin Regional Planning Commission (SWRPC, 1975) developed a management plan for the Menomonee River Watershed, which included modeling computations of the bed elevation profiles for Menomonee River, Little Menomonee River, Butler Ditch, Dousman Ditch and Honey Creek. Inter-Fluve Inc. performed a similar study in 2000, which focused on sediment transport within the system. The latter included a field survey from which 240 river cross sections of the main stem and tributaries were obtained.

Sediment data: Sediment size distribution data was obtained from a Geographic Information System (GIS) project developed by Inter-Fluve in 2001. The data included scattered samples along the system. Many of the samples were pebble count samples thus the finer fractions of the sediment were not measured. There were no samples available for Little Menomonee. A sediment sampling effort was carried out in

September 2001 to compare and complement the Inter-Fluve data (Table 10). Sediment thickness was also determined along the Menomonee and Little Menomonee Rivers. A bed thickness profile was developed by interpolating the measured data at the model cross sections.

Table 10. Sediment sampling sites and grain size distribution.

Site#	Location	Gravel	Sand	Silt	Clay	D85	D50	D30
LM1	Calumet Rd	0	19.1	69.2	11.7	0.086	0.041	0.020
LM2	County Ln	0	18.9	69.9	11.2	0.124	0.043	0.009
M1	Mequon Bridge	0	93.4	6.6		0.57	0.30	0.221
M1-a	Mequon Bridge	19.8	76	4.2		6.16	0.88	0.44
M2	Lilac Ln	45.7	51.7	2.6		16.03	3.72	0.57
M3	River bend	0.3	90.4	5.8	3.5	0.68	0.29	0.231
M4	County Ln (upstream)	0.3	82.5	10.7	6.5	0.42	0.24	0.151
M5	County Ln (downstream)	0	68.5	20.6	10.9	0.37	0.19	0.069
M7	Arthur Ave	16.7	82.7	0.6		5.05	1.90	1.134
M9	Fond du lac Park	45.2	54.4	0.4		8.51	4.27	2.213
M10	Fond du Lac construction	35.3	63.5	1.2		13.49	2.29	0.976
M12	Silver Spring Drive Bridge	44.7	52.9	2.4		14.96	3.75	1.257
M14	Congress	0	22.4	51.2	26.4	0.155	0.02	0.007
M15	Golf course	53.9	44.9	1.2		17.38	5.35	1.963
M16	Junction Grantosa and Menomonee	74.9	24.9	0.2		34.51	18.51	7.203

Additional sediment size distribution information was obtained from dredging records from the Corps. This data corresponds to an area at the lower Menomonee River just before the confluence with Milwaukee River (

Figure 41). Historically the USACE has dredged this site substantially. Bathymetric data was also provided which helped to determine the annual deposition volume for the site.

The Inter-Fluve GIS also provided relevant bed characteristic information, which helped to determine the sections where there was no erosion (i.e. bed rock, concrete) (Figure 42). This information was then specified at the corresponding model cross sections.

There was data related to bank stability. Inter-Fluve determined areas of bank stability based on a visual assessment and assigned values from –4 to 4 where negative numbers represent erosion and positive represent accretion and 0 represents a stable bank. This data was then incorporated into the Inter-Fluve GIS (Figure 43), where consistent areas of erosion can be observed at Little Menomonee and the Lower Menomonee and some accretion areas at Honey Creek, Underwood Creek, Little Menomonee and Menomonee River.

Suspended sediment concentration and sediment load was obtained from the USGS gages shown in Figure 42.

Figure 41. Dredging area used for deposition volume and grain size distribution.

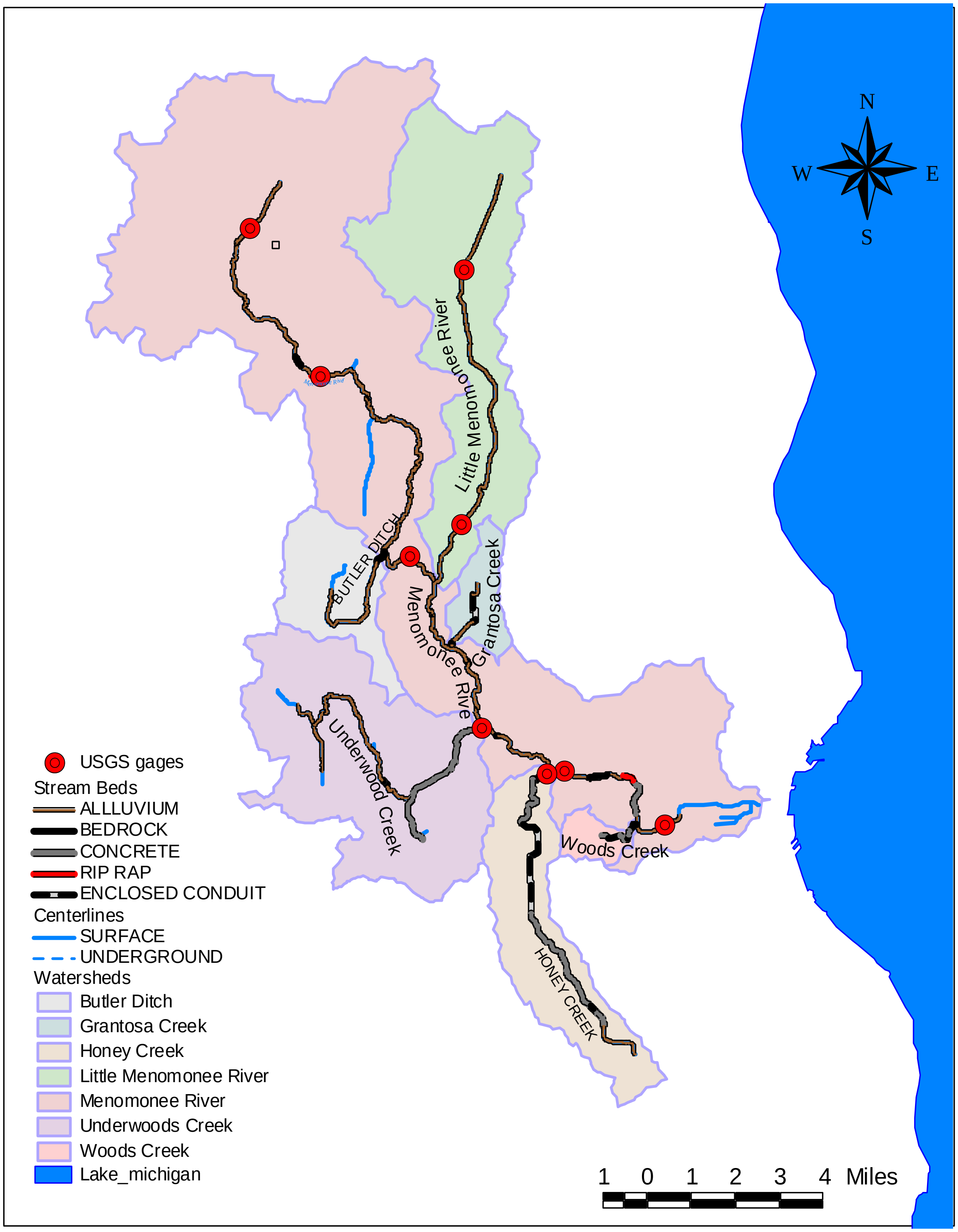


Figure 42. Bed type and USGS gage locations.

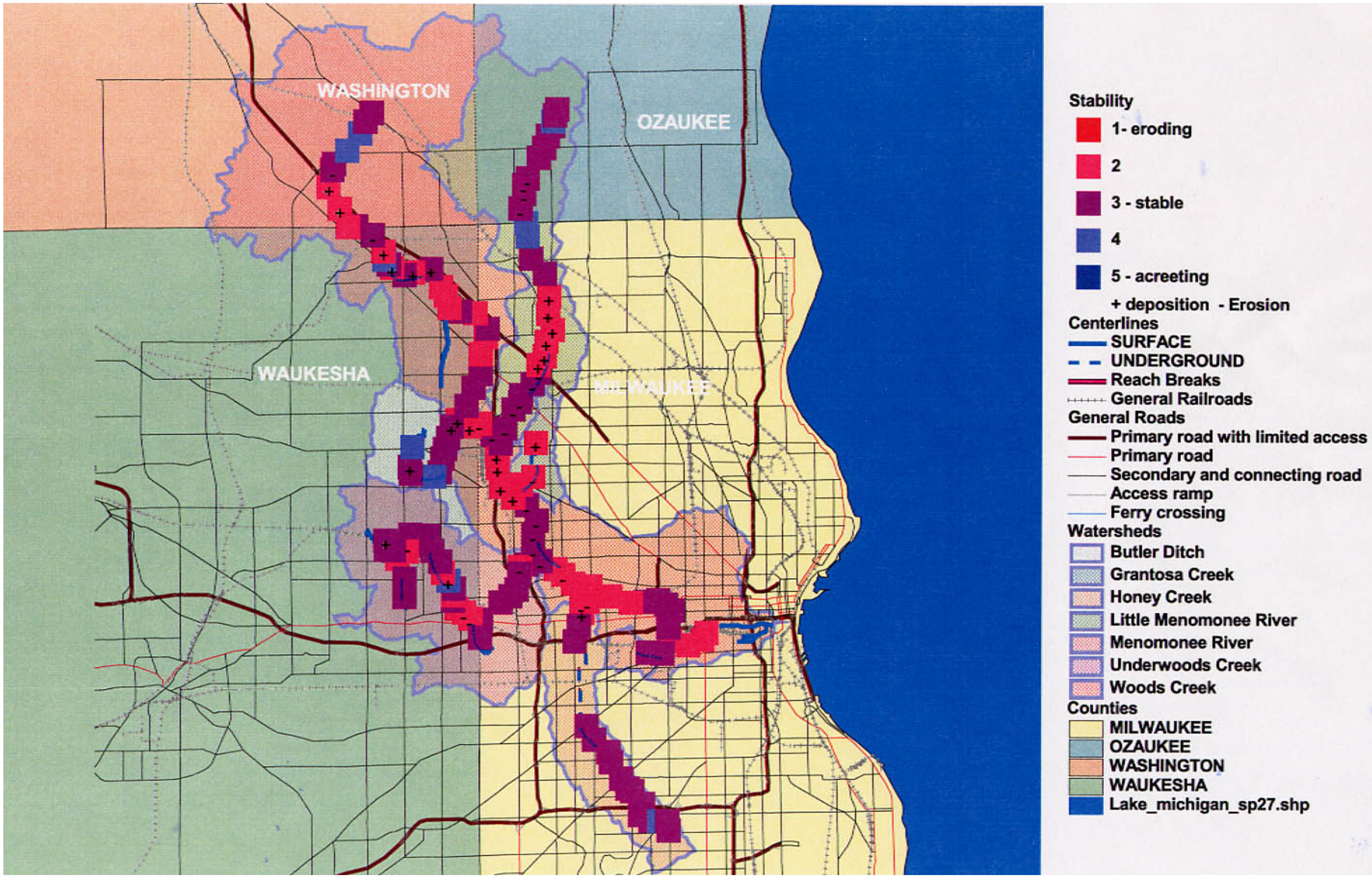


Figure 43. Bank stability.

Model Calibration

Flow data from March 1, 1975 to September 30, 1977 was obtained from USGS gage stations, (Figure 42) which include 5 gages from Menomonee River, two from Little Menomonee River, one from Honey Creek and one from Underwood Creek. The following is a brief description of the procedure used to estimate the nodal hydrographs.

An estimate of the flow at the mouth of each of the tributaries was derived by scaling the measured hydrograph by a factor of the drainage area at the mouth divided by the drainage area at the gage. This adjustment was minor for most of the tributaries since their gages were located near the confluence with the Menomonee River. One example of this is Honey Creek, which has a total drainage area of 10.7 square miles, and the drainage area at the gage is 10.3 square miles. In this case, the total flow contribution of Honey Creek was estimated as the measured flow data multiplied by the factor of 10.7/10.3, or about 1.04.

The flow estimates for the tributaries at locations upstream of the mouth were computed by multiplying the measured flow by the ratio of the drainage area at the model node to the drainage area at the gage.

The flow estimates for the ungaged tributaries were derived by a ratio of the nearest hydrologically similar gaged drainage basin.

After an estimation of the total flow contributions for each of the tributaries was completed, the flow at model nodes on the Menomonee River itself was computed by factoring the nearest upstream and downstream gage records along with subtraction of the intervening tributary flows. In general, the flow at nodes between gage locations on the Menomonee River was estimated by taking the flow at the downstream gage, subtracting the estimated flows for tributaries between the bounding gages, and interpolating the flow at the node by the ratio of the drainage area.

Among the main objectives of the project was to understand the system behavior and the influence of land use changes and management practices on sediment yield, delivery and transport, thus a single storm event flow was enough for the model calibration effort. An event was chosen from the 3-year hydrograph based on the magnitude of the event and the significance in comparison with other events. This approach simplifies the input file and reduces considerably the computational time. The use of a single storm event is a reasonable and appropriate approach since erosion primarily occurs during extreme flow events.

Results

The model output gives information related to bed change (erosion and deposition), sediment load and flow magnitude at each cross section, so a vast amount of information is generated for each model run.

The most reliable information available for validation of the model was flow and sediment load. The following are gage measurements from several stations within the Menomonee watershed, which were used to compare against the model results (Table 11).

Table 11. USGS gages (and location) used for validation of the sediment transport model.

Gage Number	Location	River Mile
4087018	Menomonee River At Germantown,	25.9
4087030	Menomonee River At Menomonee Falls,	21.1
4087040	Menomonee River At Butler,	13.5
4087120	Menomonee River At Wauwatosa,	6.2
4087140	Menomonee River At Falk Corp At Milwaukee,	2.4
4087050	Little Menomonee River Near Freistadt,	8.04
4087070	Little Menomonee River At Milwaukee,	1.55
4087119	Honey Creek At Wauwatosa,	0.04
4087088	Underwood Creek At Wauwatosa,	0.1

Gage measurements reflect the total flow at the point of measurement while for HEC-6 the incremental flow magnitudes must be specified. In order to calculate the input flows one must subtract the nearest upstream flow quantity from the desired point of inflow. The uppermost inflow (boundary condition) is determined by subtracting all the input flows from the total flow at the mouth of the river.

Honey Creek and Underwood Creek

There was one gage station near the mouth of each tributary (Table 11) where sediment data and flow magnitude were acquired. It can be observed in Figure 44 and 45 that the simulated flow field shows a good agreement with the gage data. Both Honey Creek and Underwood Creek show a similar discharge magnitude. However, the drainage area of Underwood Creek is almost twice the size of Honey Creek (Table 6), thus one would expect to have a higher discharge at Underwood Creek. If we observe the land use coverage for both areas (Table 7), the urban % for Honey Creek is higher than for Underwood Creek, and there are more multi-family land use areas at Honey Creek, (Figure 38) which feature less permeable surfaces. These two factors decrease the amount of water infiltration, which leads to higher runoff volumes.

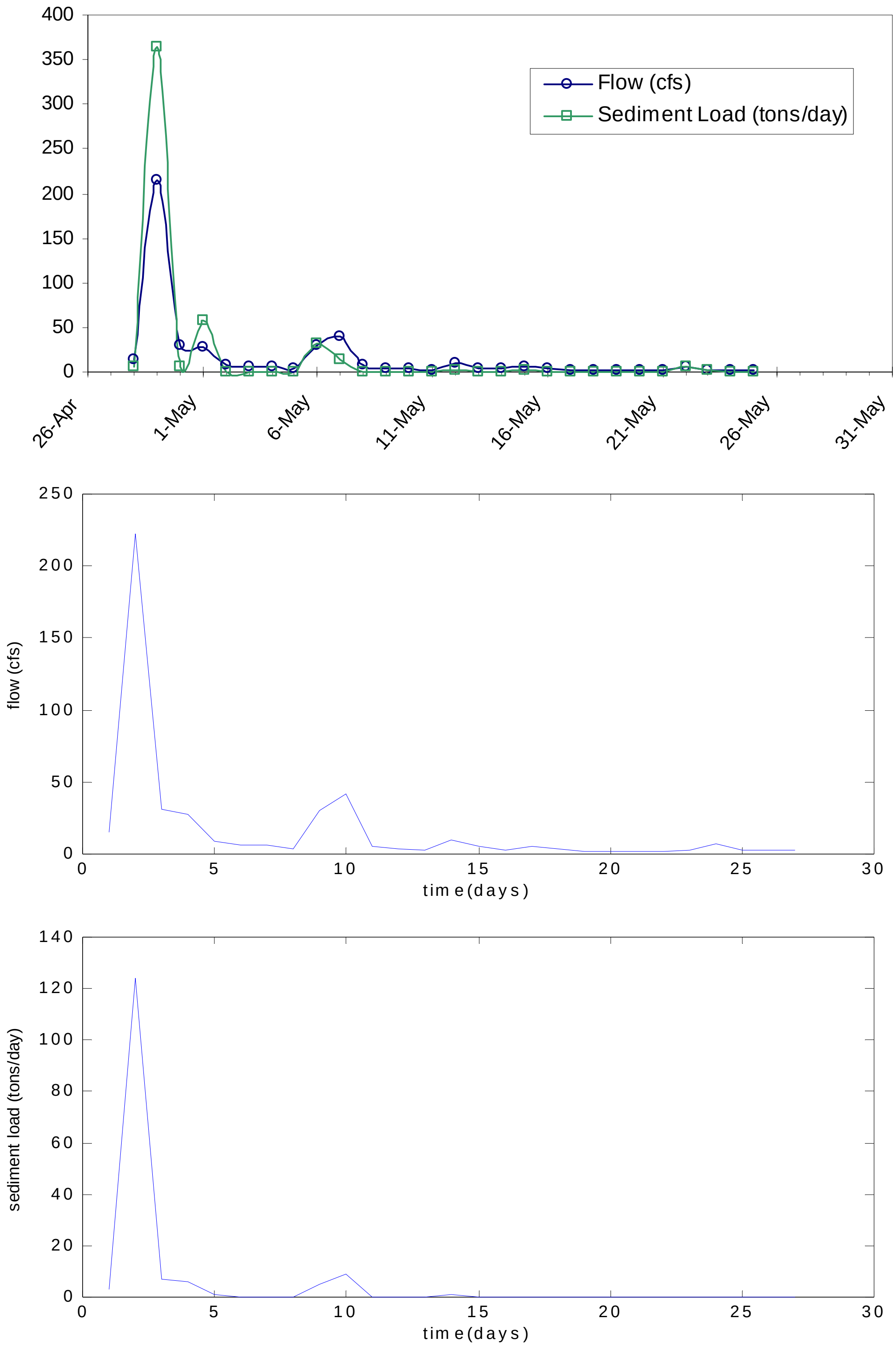


Figure 44. Measured discharge and sediment load (top) and simulated discharge (middle) and sediment load (bottom) for Honey Creek.

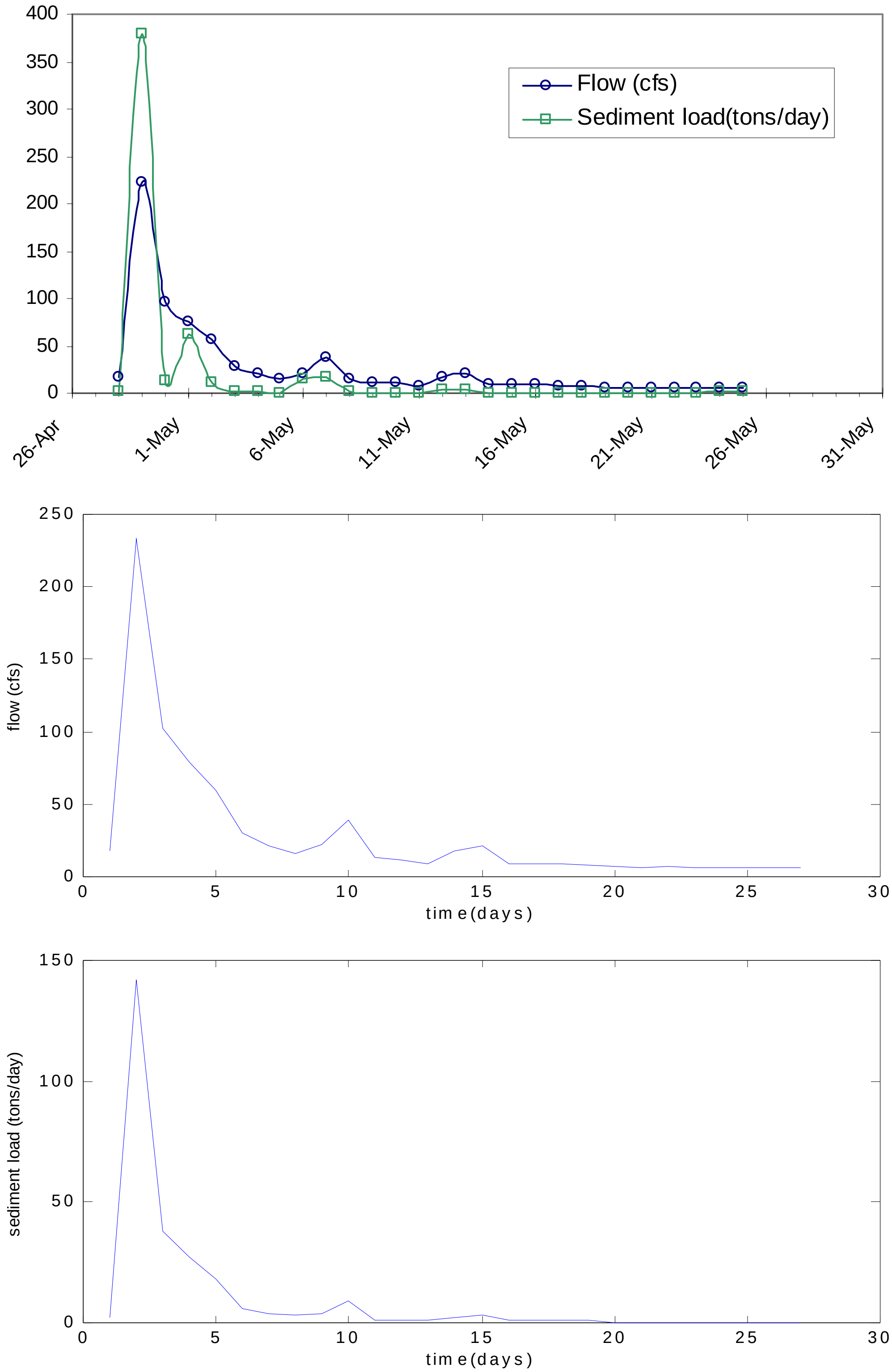


Figure 45. Measured discharge and sediment load (top) and simulated discharge (middle) and sediment load (bottom) for Underwood Creek.

Figure 46 shows different precipitation events for these two gages, and a higher flow magnitude can be observed at Honey Creek compared to Underwood Creek.

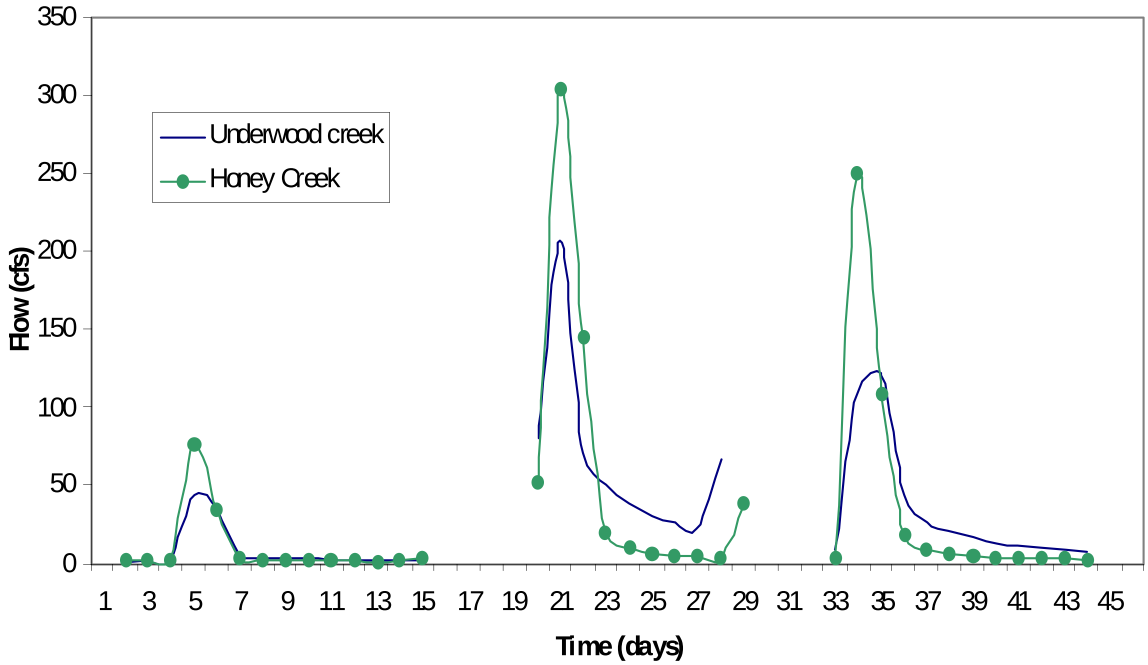


Figure 46. Flow magnitude for Underwood Creek and Honey Creek for several storm events.

The measured sediment load for the simulated event is higher for Underwood Creek than for Honey Creek, which correlates to the rating curves from Figure 32 and 33. The simulated sediment load for both Honey Creek and Underwood Creek (Figure 44 and 45) seem to be significantly underestimated. However, the data plotted in Figure 22 through 29 demonstrates that the sediment load for the peak discharge (approximately 200 cfs) is very high in relation to other data points.

The USGS data are daily average values. The discharge is computed by a rating curve of stage versus discharge, where the stage is measured every 15, 30 or 60 minutes (depending on the gage station). Sediment load is computed by multiplying discharge (cfs) by suspended sediment concentration (mg/l) and a conversion coefficient of 0.0027 (units = liters * tons * sec * feet^{-3} * day^{-1} * mg^{-1}). Suspended sediment concentration is measured once a day and, on occasions of rapidly varying flow, the sampling frequency is increased to 1-hour intervals.

The flow magnitude varies more rapidly than the sediment load, thus, by using daily average values, there is the possibility of the peak flow being missed, which would cause the sediment load versus flow relation to have high point values (as shown in Figure 22 through 29). Figure 47 shows two storm events of similar magnitude and season for Honey Creek.

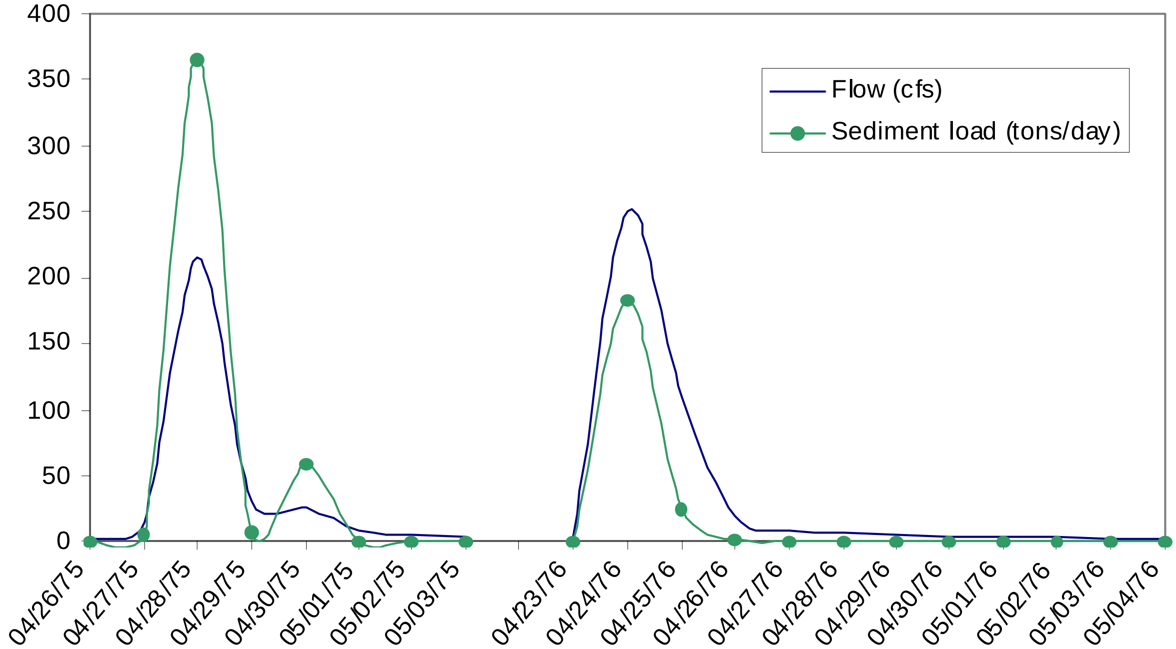


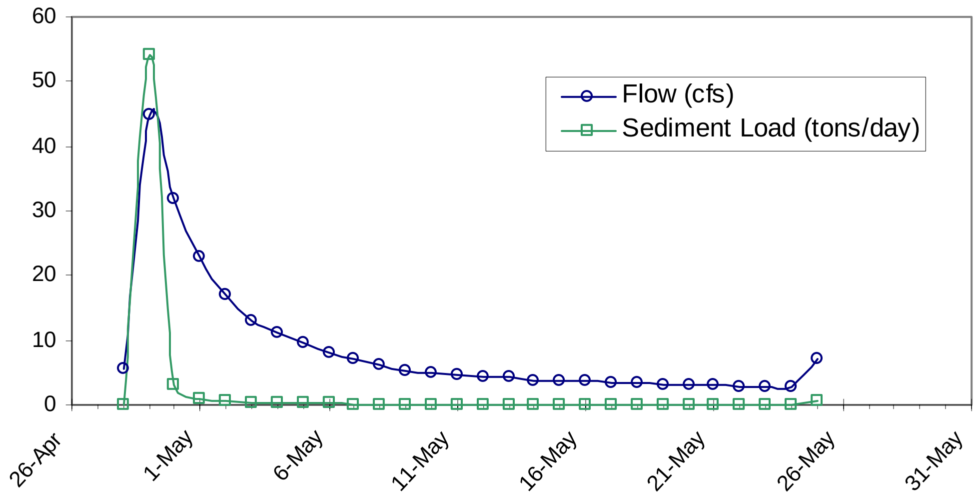
Figure 47. Discharge and sediment load for two storm events at Honey Creek.

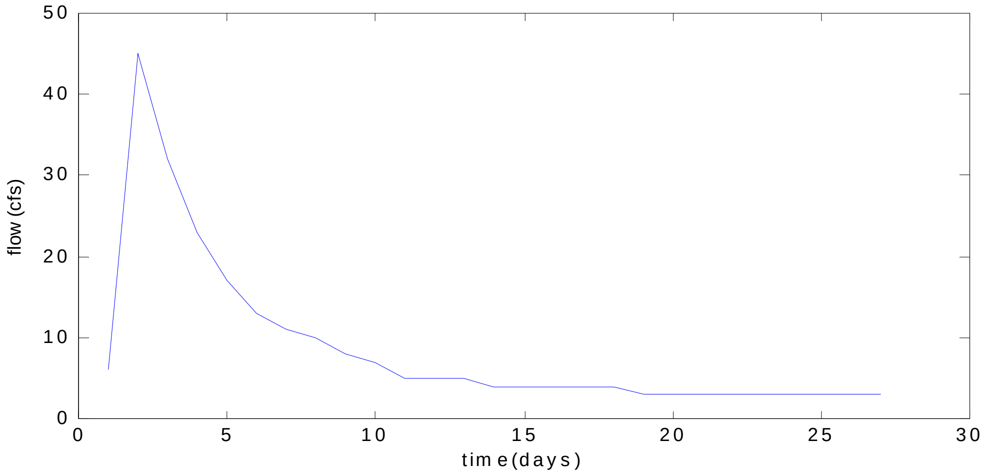
The sediment load for the 1975 event is much higher than the 1976 event. Also the 1975 event shows a sudden increase in sediment load (April 30, 1975) but there is no apparent increase in flow, which suggests that the flow is underestimated.

Due to the nature of the available data, it was determined that validation against any single event would not be appropriate for assessing the capability of the model. Instead, the data was compared against the rating curve used for calibration purposes (Figure 24 and 25). The peak discharge and flow results for Honey Creek (Figure 44) are 220 cfs and 116 tons/day, which are consistent with the rating curve. The same approach was applied for Underwood Creek. The results show a peak flow of 230 cfs and a sediment load of 128 tons/day (Figure 45), which is underestimated from the rating curve (Figure 22 and 24).

Little Menomonee

For the Little Menomonee there were two USGS gages located at miles 8.05 and 1.55 (Table 11). The Freistadt gage data was used to determine the upstream flow boundary conditions. The hydrographs in Figure 48 indicate that the simulated flow is very similar to the measured data while the sediment load is overestimated. However, the difference between measured and estimated load is minimal and can be attributed to the influx of sediment between the gage station (river mile 8.06) and the location of the boundary of the model (river mile 6.5). Ideally, the input location should match the boundary condition but no cross-sectional data was available beyond river mile 6.5.





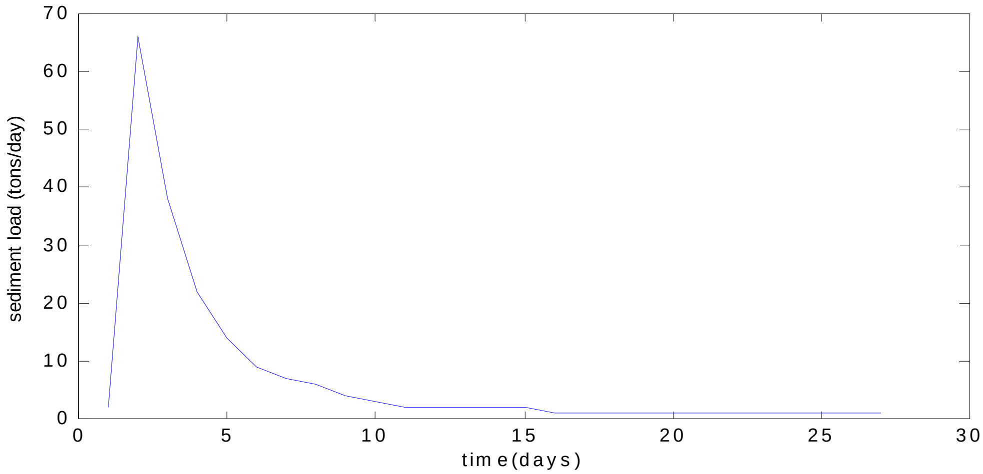


Figure 48. Measured discharge and sediment load (top) and simulated discharge (middle) and sediment load (bottom) for Little Menomonee at Freistadt.

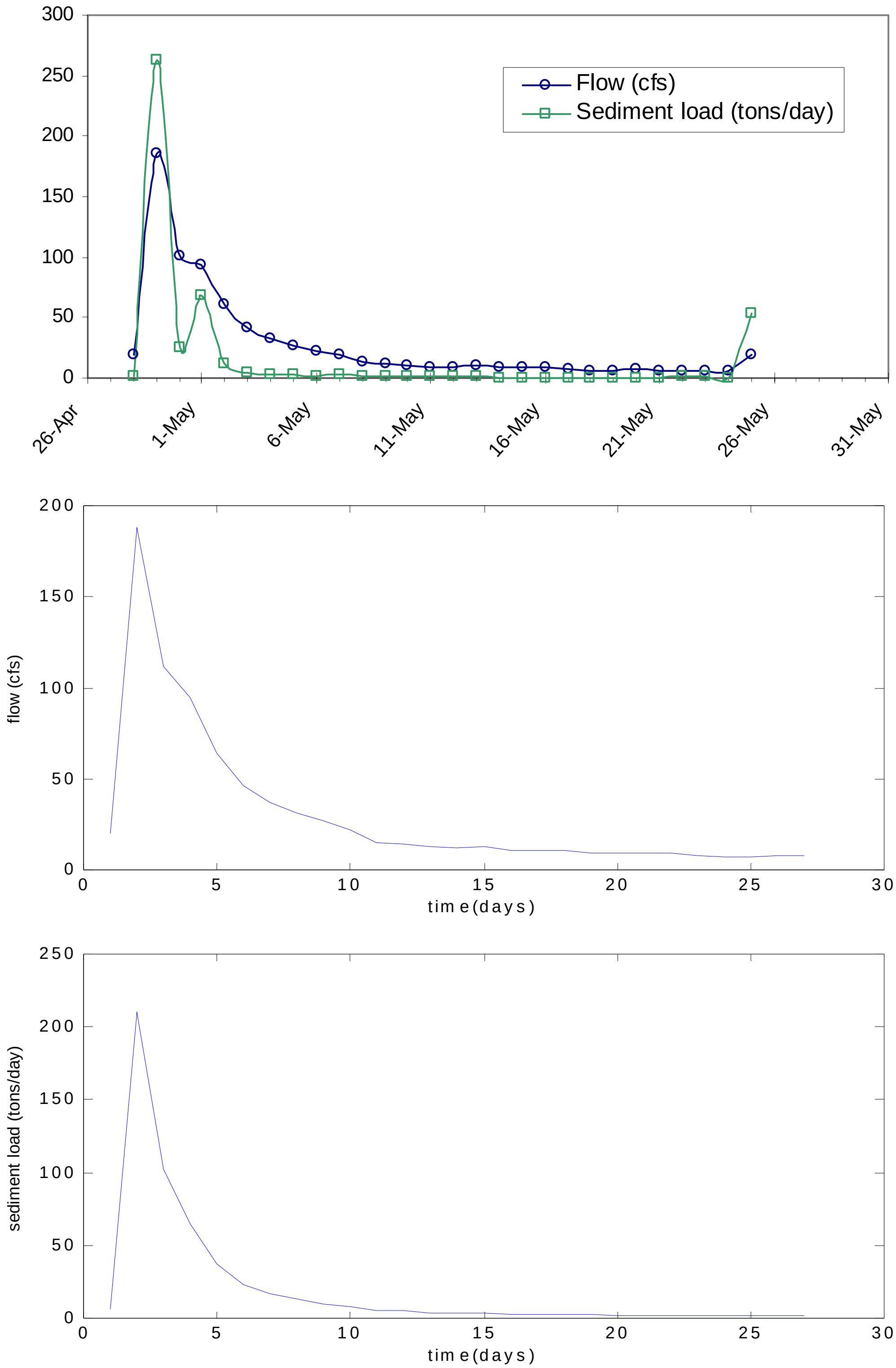


Figure 49. Measured discharge and sediment load (top) and simulated discharge (middle) and sediment load (bottom) for Little Menomonee at Milwaukee.

From Figure 48 it can also be noted that the measured data shows a rapid decrease in sediment load after the peak discharge, which is not shown at the downstream gage (Figure 49).

The downstream gage was used for validation purposes. Figure 49 shows the gage data for this location as well as the model output. It can be observed that the flow field is similar for both measured and simulated data while the sediment load is underestimated by the model. At this location, it can be observed that after the main peak flow there is a sudden increase in the sediment load, similar to the Honey Creek location, not captured by the flow gage, which shows inconsistency between the discharge and sediment data sets. For this reason it was decided to compare the simulated results against the rating curve used for the land use analysis (Figure 20 and 21) and a good agreement was observed for the peak simulated flow (188 cfs) and sediment load (210 tons/day).

Menomonee River

For the Menomonee River, there was data available from five gages. In general, the flow results show a consistent agreement with the measured data, although for some parts of the river the flow is underestimated by the model and at the Falk gage it is overestimated (Figure 50 through 54). This behavior could be due to the difficulty of representing attenuated river and tributary flows with the flow disaggregation methods necessary to compute model inflows.

Sediment load for Germantown (Figure 50) is overestimated. This same behavior is observed at the Friestadt gage, which suggests that the model results are not very reliable at the upper boundaries. Reviewing the model output downstream from the boundary, it can be observed that the simulation results are more in agreement with the measured data. The results at Menomonee Falls (Figure 51) show a very good match between the measured and simulated data. The results from Butler gage (Figure 52) similarly show a good agreement between both data sets. Up to this point there have not been any inflows related to the tributaries thus the sediment load present is directly related (model wise) to the main stem.

The sediment load for Wawatosa and Falk shown in Figure 53 and 54, respectively, do not match well with the gage data. By comparing the measured sediment load from Figure 53 and 54 it can be observed that the sediment load downstream (Falk) is actually lower than for Wawatosa even when the flow magnitude is larger in the downstream gage. Also, the Wawatosa gage station is located 0.15 miles downstream from the confluence with Honey Creek, which, according to the measured data, contributes to the main stem with a load of approximately 350 tons/day. This would mean that the incoming sediment from the main stem above Honey Creek would have to be about 100 tons/day in order to match the measured data or that a large amount of sediment settles within a distance of 800 feet. Due to the fine sediment, which would travel farther, this is not likely the case.

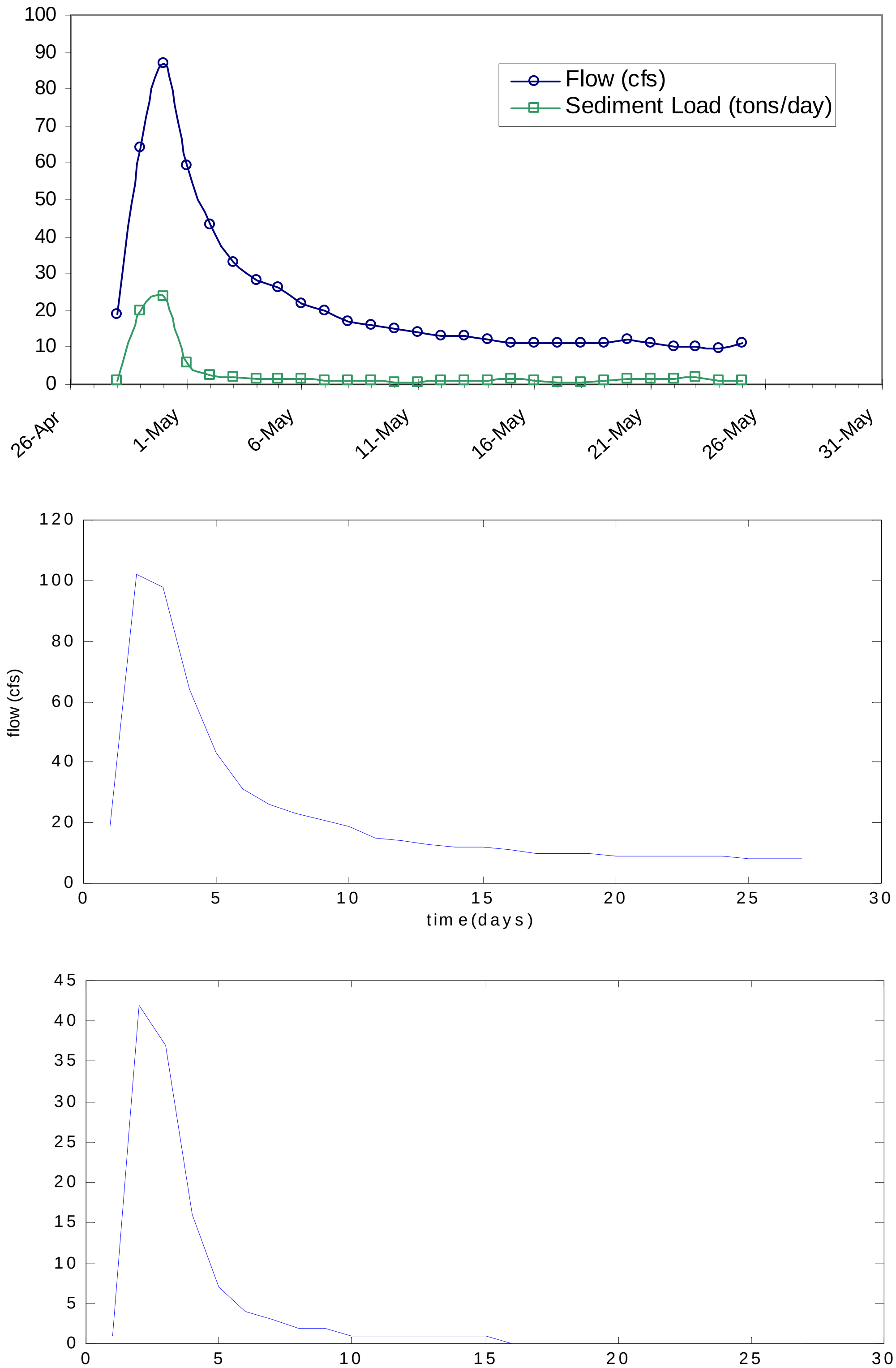


Figure 50. Measured discharge and sediment load (top) and simulated discharge (middle) and sediment load (bottom) for Menomonee River at Germantown.

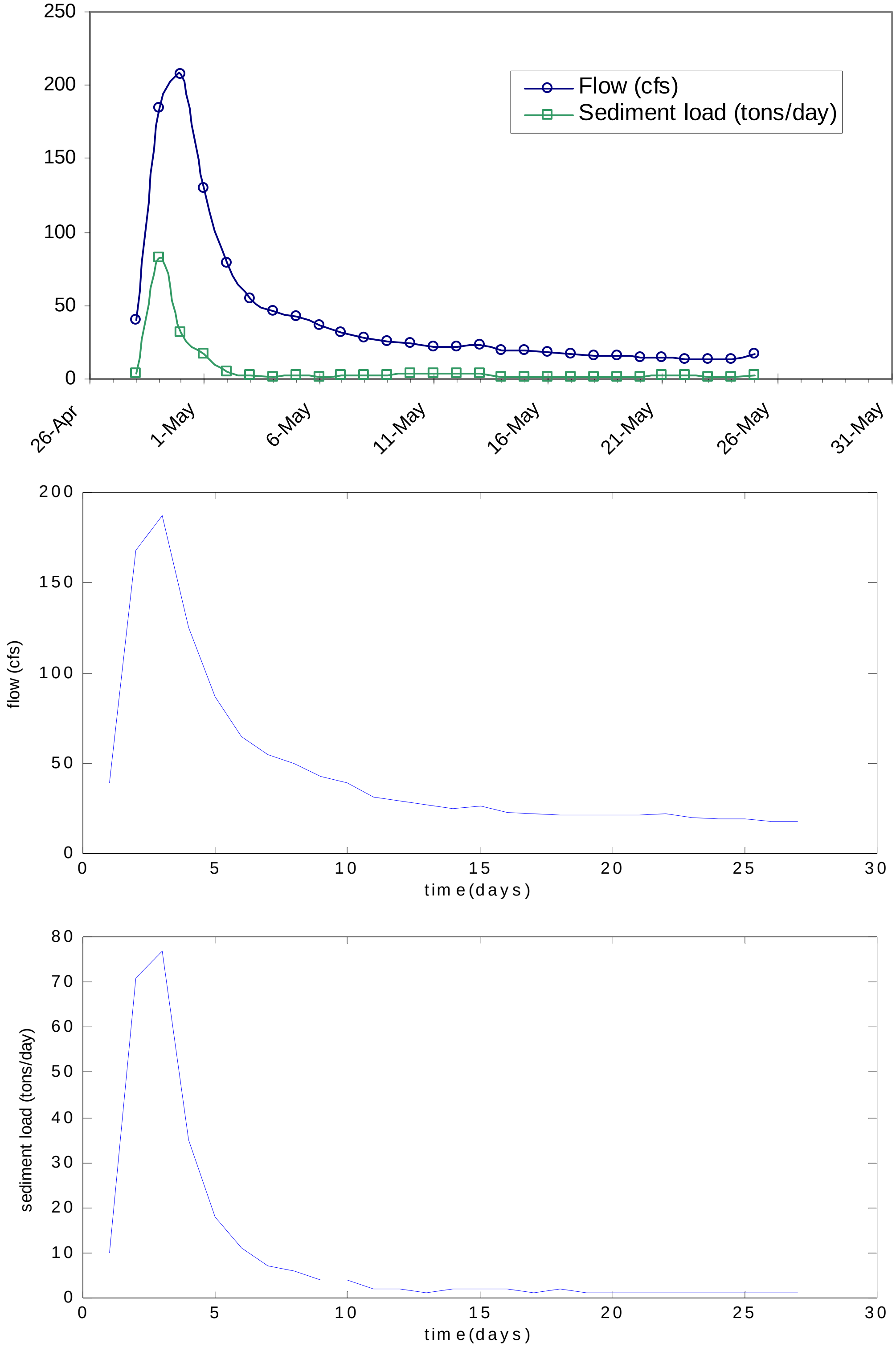


Figure 51. Measured discharge and sediment load (top) and simulated discharge (middle) and sediment load (bottom) for Menomonee River at Menomonee Falls.

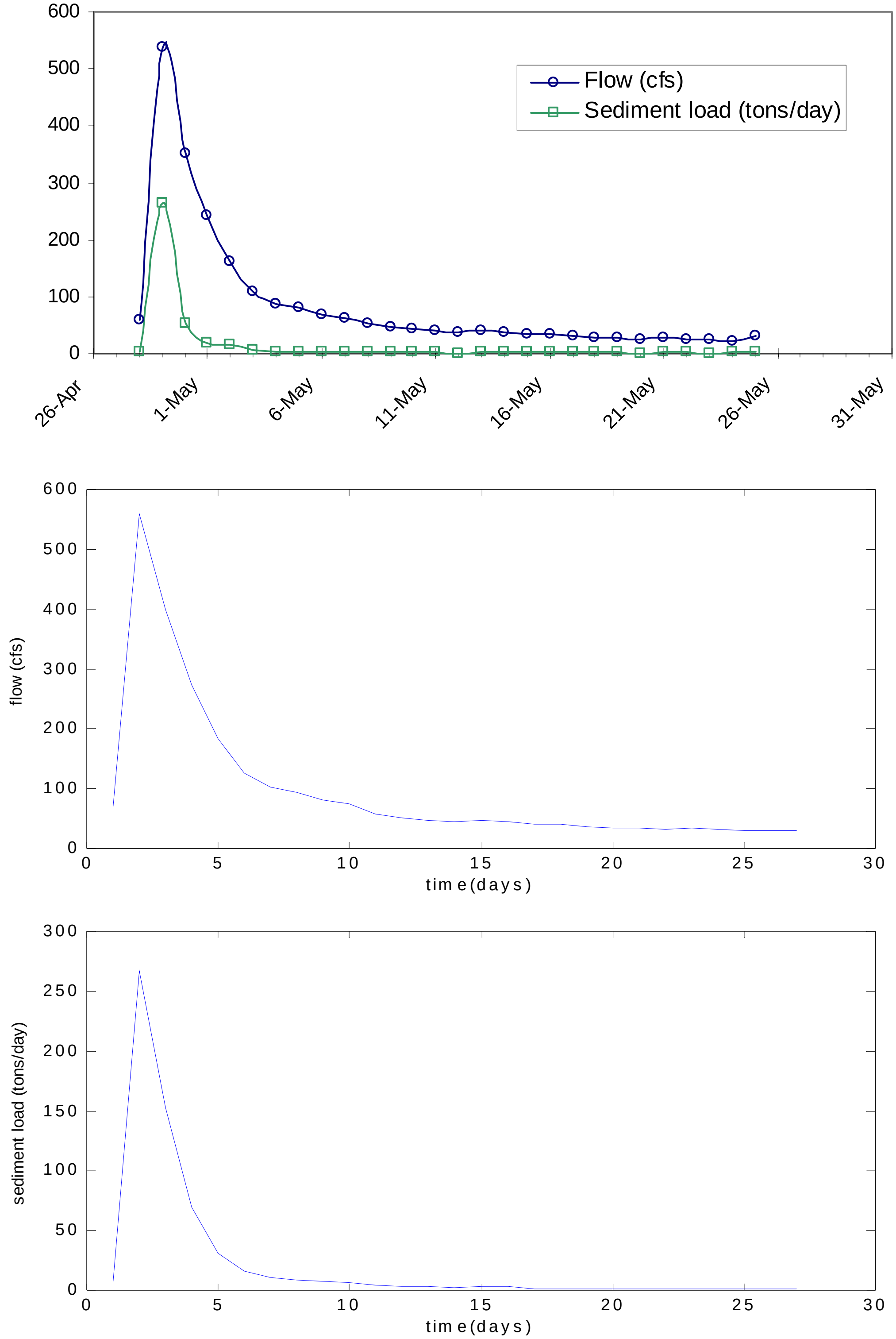


Figure 52. Measured discharge and sediment load (top) and simulated discharge (middle) and sediment load (bottom) for Menomonee River at Butler.

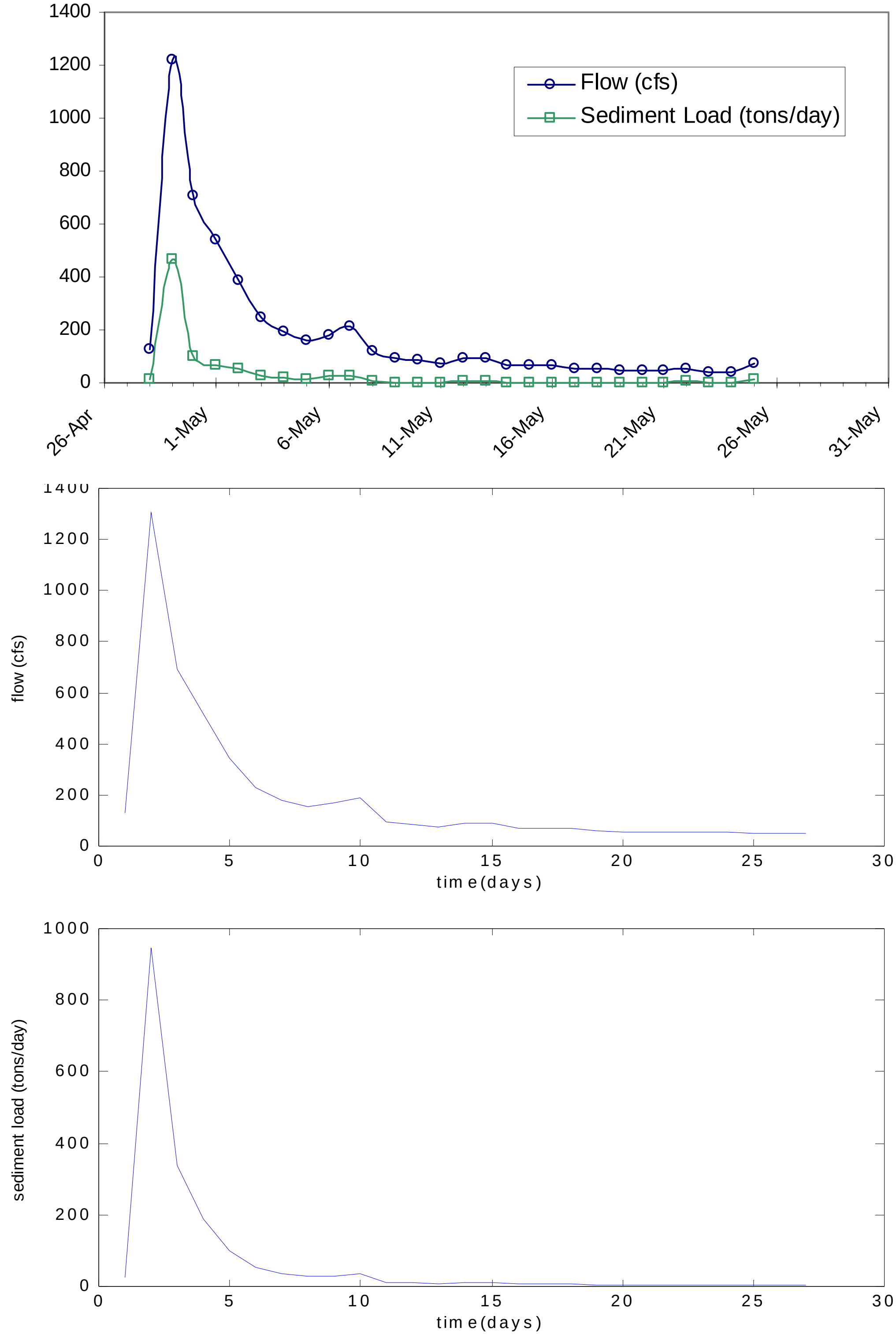


Figure 53. Measured discharge and sediment load (top) and simulated discharge (middle) and sediment load (bottom) for Menomonee River at Wawatosa.

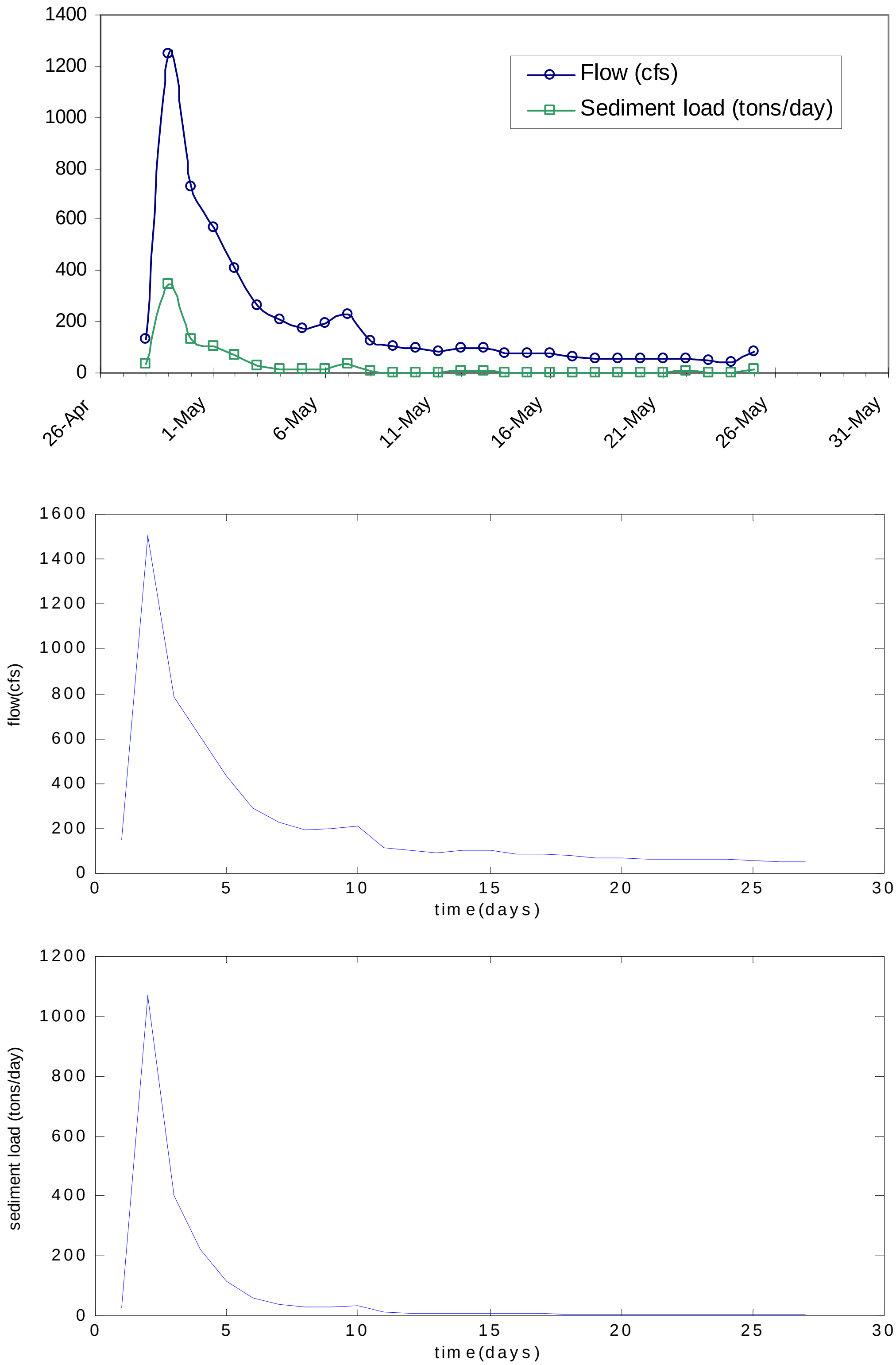


Figure 54. Measured discharge and sediment load (top) and simulated discharge (middle) and sediment load (bottom) for Menomonee River at Falk.

Taking these factors into account the Wawatosa model results were compared to similar events obtained from the gage station.

The events used for this purpose are shown in Figure 55. It can be noted that even for the March event (which could still have frozen soil and has a lower flow magnitude) the sediment load is higher than that estimated for the simulated event.

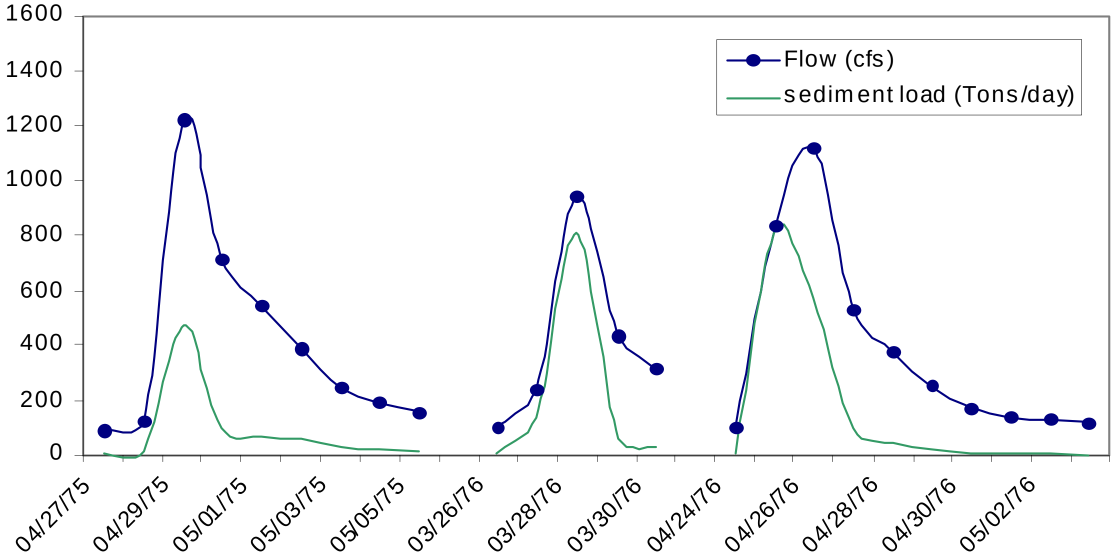


Figure 55. Storm events recorded at the Menomonee Wawatosa gage.

Another factor that was taken into account was the influence of the sand fraction on the sediment load. The sand-load river profile in Figure 56, which corresponds to April 29 and 30 (peak flow and receding limb), shows that the sand fraction contributes significantly to the total load of the Menomonee River from river mile 8 to the downstream boundary. The USGS sediment load data is calculated from suspended sediment concentration and Dong et al (1979) reports that for the lower Menomonee River the suspended sediment is composed of silts and clays so the sand load reported by the model must be transported as bed load and was subtracted from the total load in order to compare the results.

Figure 57 shows the data points from the gage station and the data points from the model. As it can be noted there is a wide variation of sediment load when the flow increases. The simulated data show a reasonably good fit with the trend line (which was automatically calculated by Excel) and the measured data.

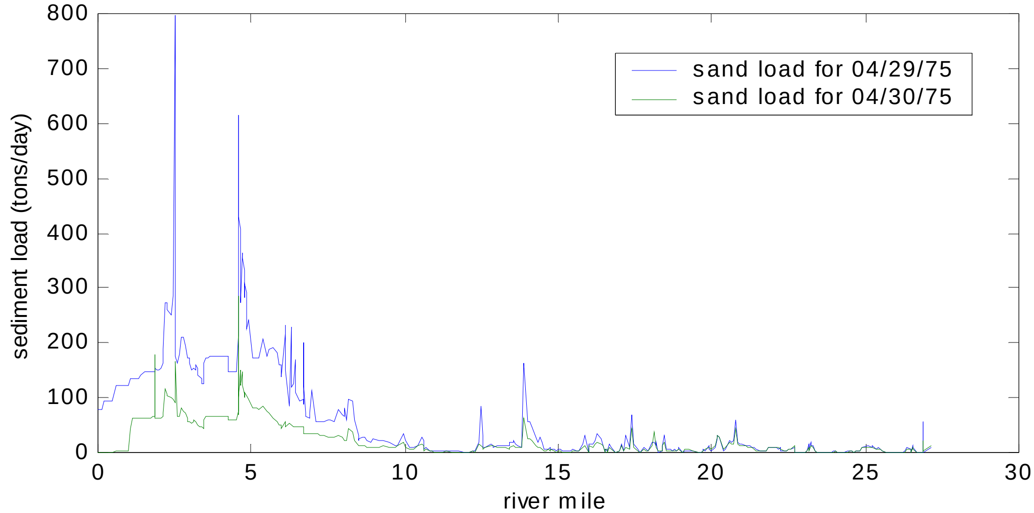


Figure 56. Sand fraction load profile for Menomonee River at 04/29/75 and 04/30/75.

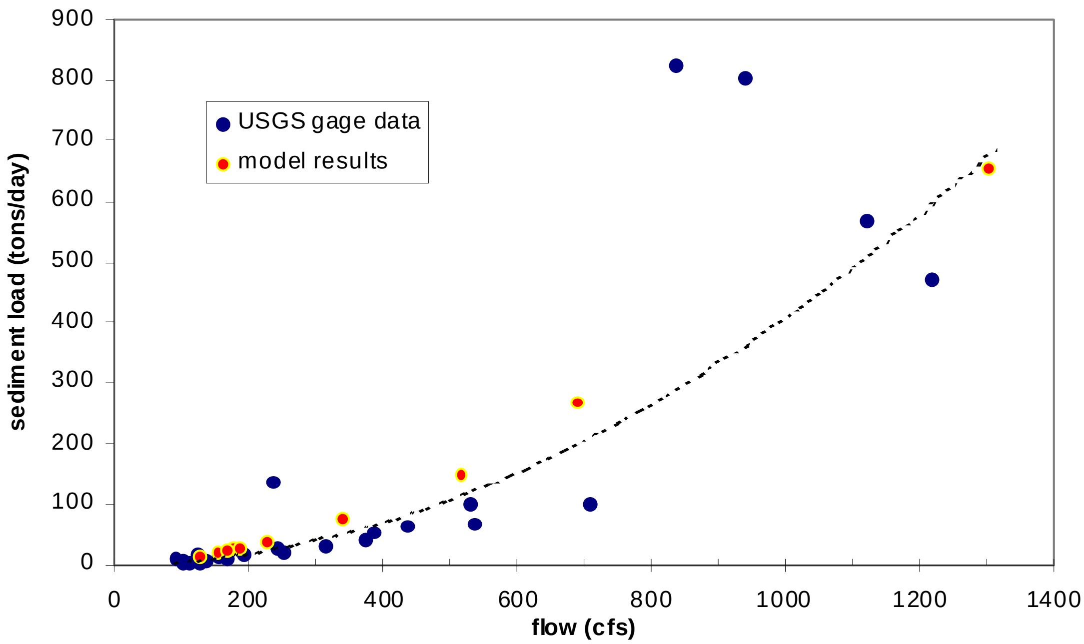


Figure 57. Measured and simulated data of flow vs. sediment load at Wawatosa gage in Menomonee River.

For the Falk gage a similar approach to the Wawatosa gage was taken, where the measured data from several storm events of similar seasons was used to compare against the model results.

Figure 58 shows data points of sediment load versus flow for four different events, where the yellow points show the peak discharge for each event. It can be noted that the simulated event has a low sediment load (344 tons/day) compared to the other events. The red points show the values obtained from the numerical model, which are relatively close to the trend line.

In general, the model results show a good agreement with the data. However, from the previous analysis it can be observed that the available data is not very reliable for the purpose of quantitative calibration. In order to have more confidence in the model results, hourly data for sediment load and flow would be required.

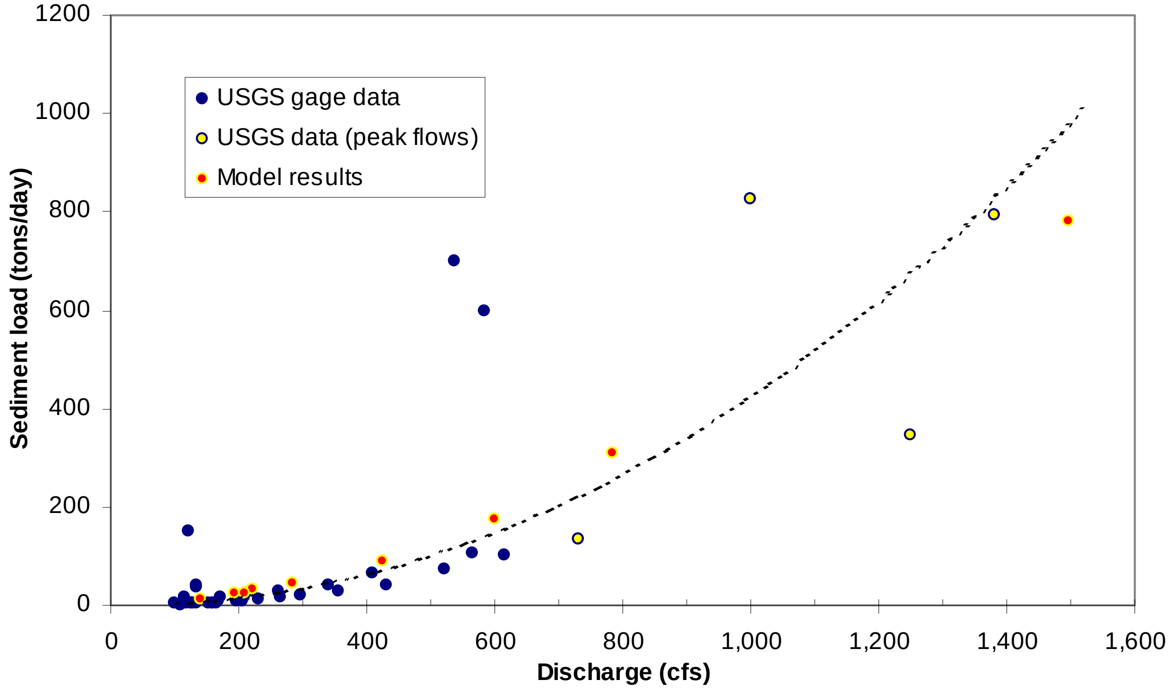


Figure 58. Measured and simulated data of flow versus sediment load at Falk gage in Menomonee River.

Another aspect to take into consideration about the rating curves used for the model input is that the sediment load and flow curves are not symmetric (i.e. rapid increase for increasing flow and lower decrease for decreasing flow, Figure 55). Therefore, by using an exponential form rating curve the sediment load will be under estimated for the rising limb and overestimated for the receding limb.

For planning and management tools, it is not very important to have accuracy on the exact volume of sediment transported by the river but to have a good simulation of the processes that influence the system. We are confident that this model represents the physical parameters related to the Menomonee River as well as the influence of land use changes and land management practices on the sediment dynamics of the region.

Following is a time series of sediment load (tons/day) output visulatization produced by the Spatial Data Analyzer (SDA) computer package developed by Baird & Associates. It can be noted that Little Menomonee has a major contribution of sediment load to the main stem.

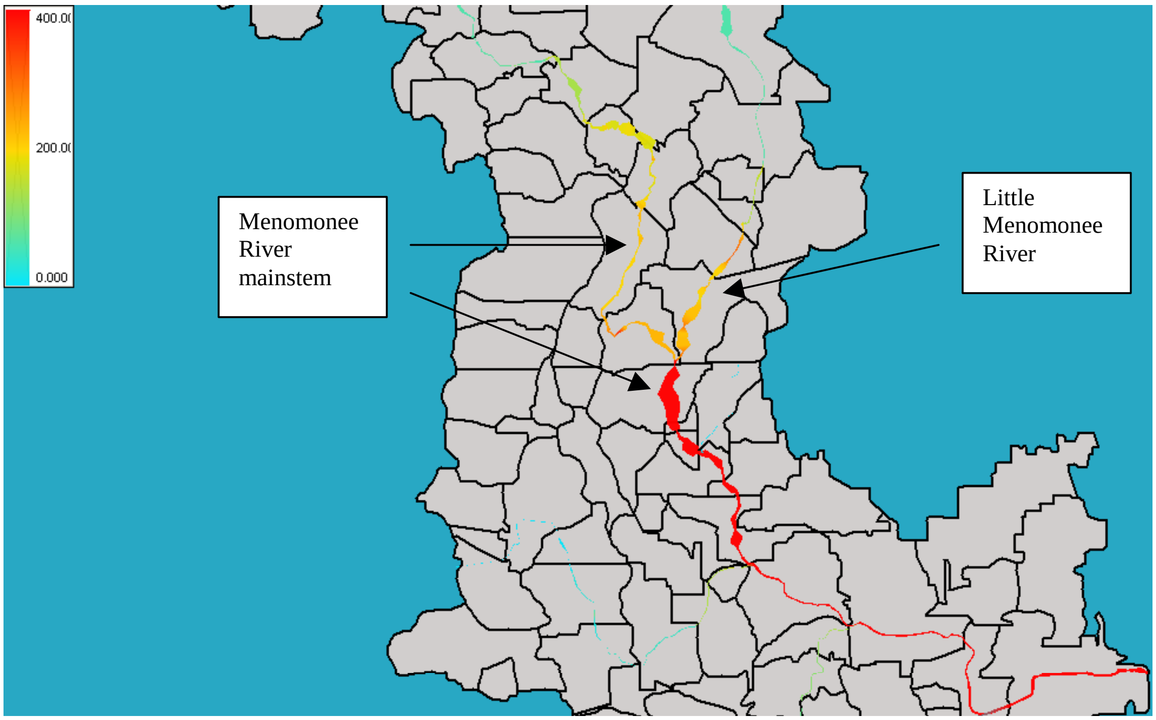


Figure 59. Sediment load (tons/day) output for April 28, 1975.

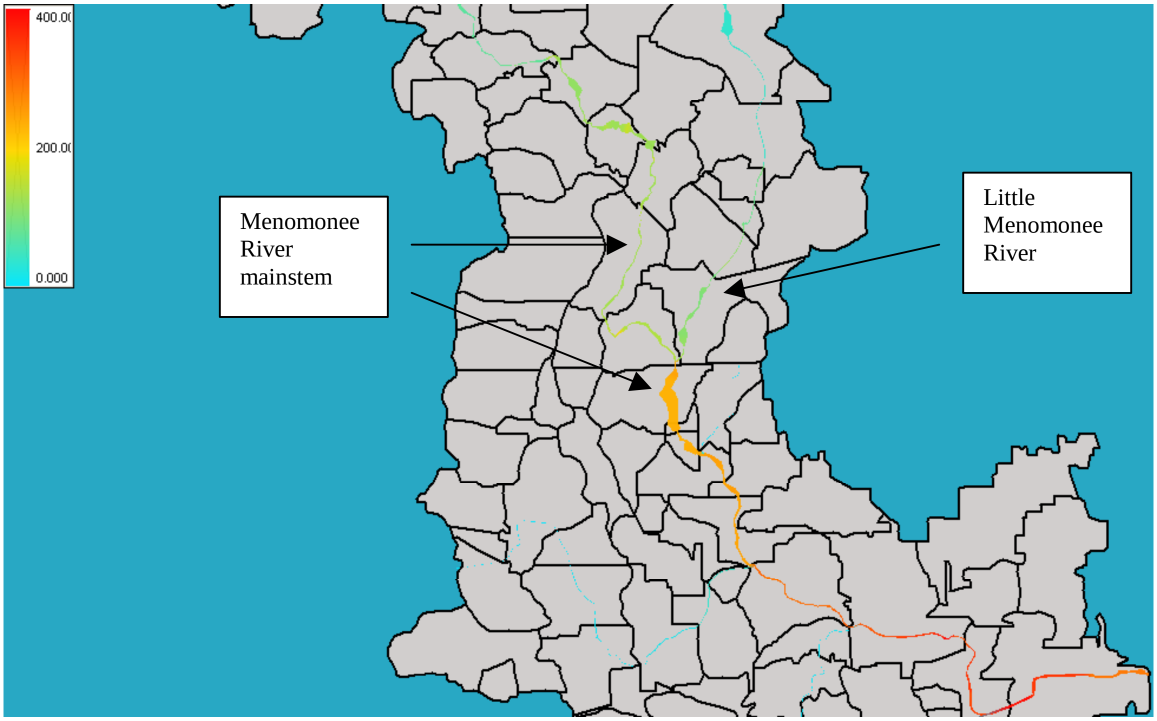


Figure 60. Sediment load (tons/day) output for April 29, 1975.

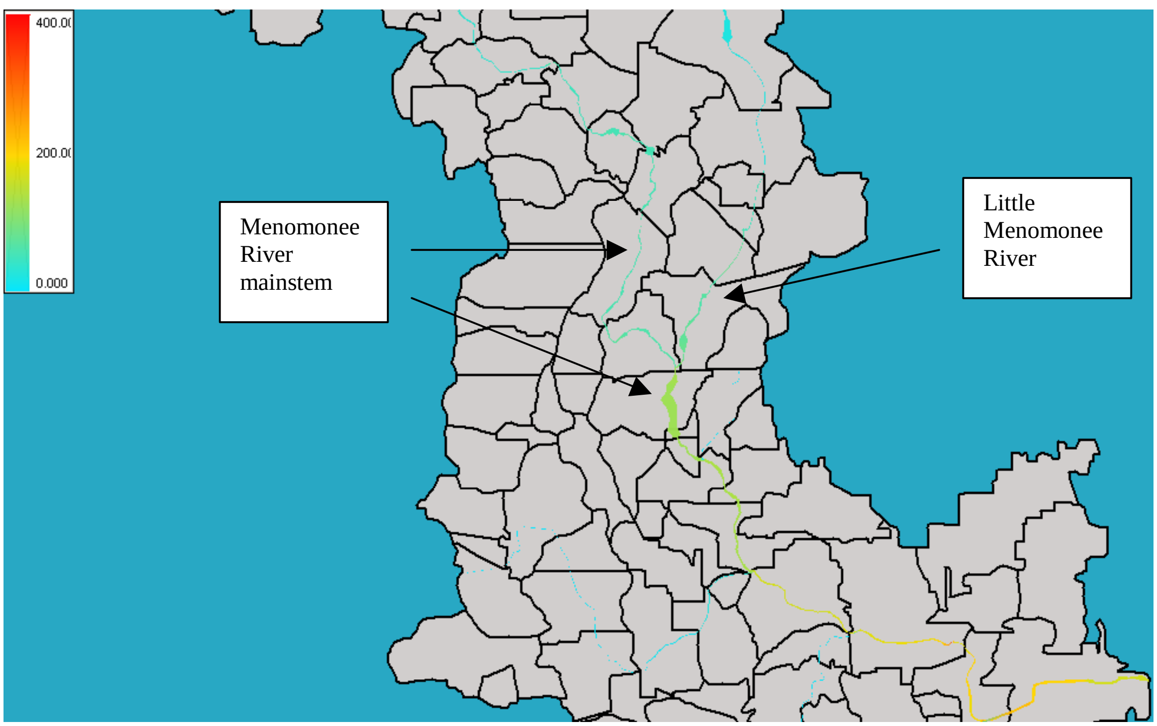


Figure 61. Sediment load (tons/day) output for April 30, 1975.

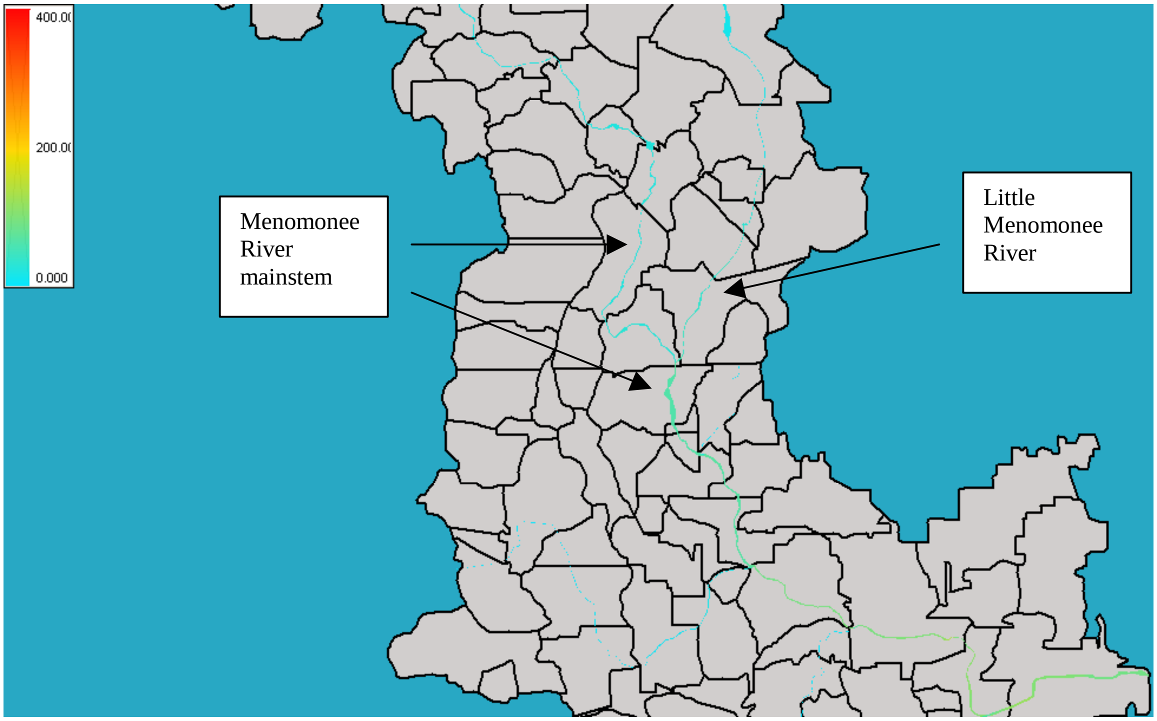


Figure 62. Sediment load (tons/day) output for May 1, 1975.

Another flow scenario was set up which corresponds to a large flood event from 1997. Figure 63 shows a hydrograph from June 1, 1997 to June 30, 1997 at approximately river mile 4.5.

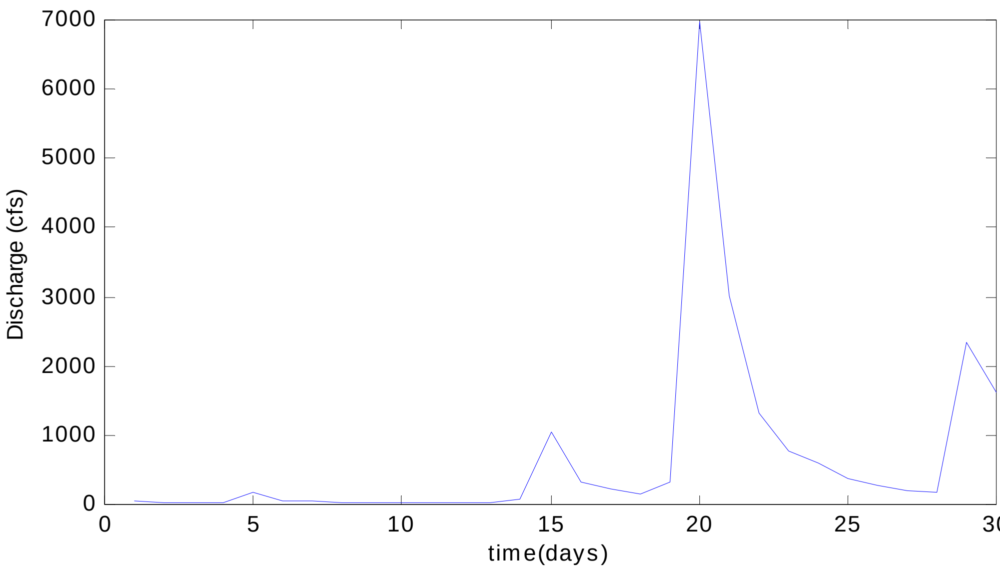


Figure 63. Discharge in cfs at river mile 4.5 of Menomonee River.

The river profile in Figure 64 below shows an area between river mile 4 and 4.5 of the Menomonee River (Valley Park). The brown line represents the initial bed elevation and the blue line shows bed change over time. It can be observed that there is no bed erosion between river miles 4 and 4.45 which is due to the concrete bottom and riprap. However, significant deposition can be observed between River miles 4.22 and 4.45.

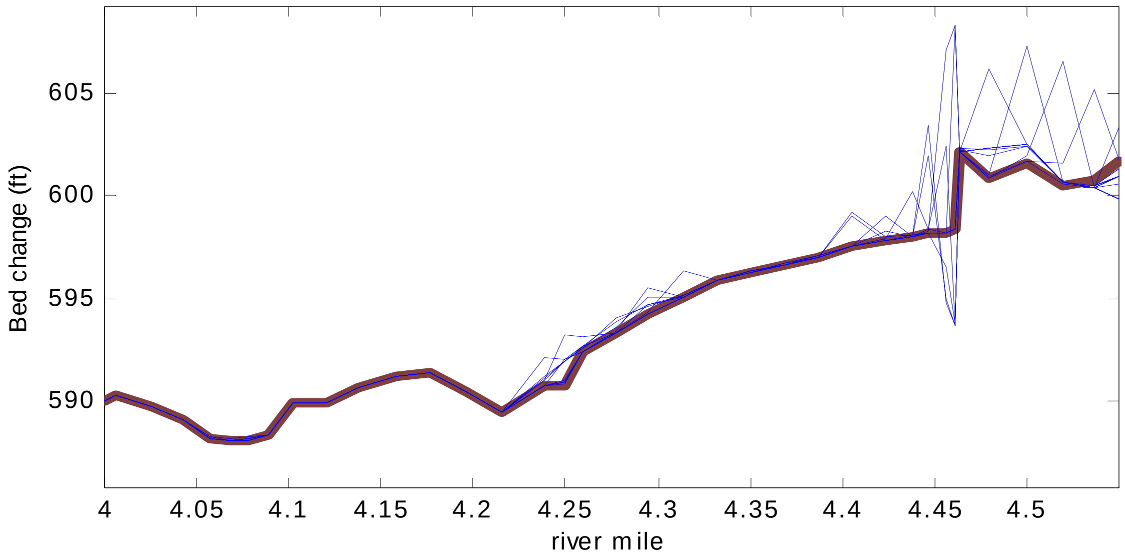


Figure 64. Bed change for Park Valley area.

Above river mile 4.45 there is an apparent oscillatory behavior in bed change. This data was further analyzed by plotting bed change over time at every one of the peaks and it was observed that the bed change corresponds to a sediment mass moving downstream through time (Figure 65).

The first plot of the series corresponds to river mile 4.56. As it can be observed the most prominent change in bed elevation matches with the peak discharge of the event which suggests that this sediment load was eroded from the bed and is transported downstream as bed load. From the first plot it can also be observed that once this sediment mass is transported downstream a significant decrease in bed elevation is established which denotes a significant amount of eroded material. As the sediment mass is transported downstream and the flow reduces its velocity it can be noted that there is increase in bed elevation Rm. 4.5 and 4.48.

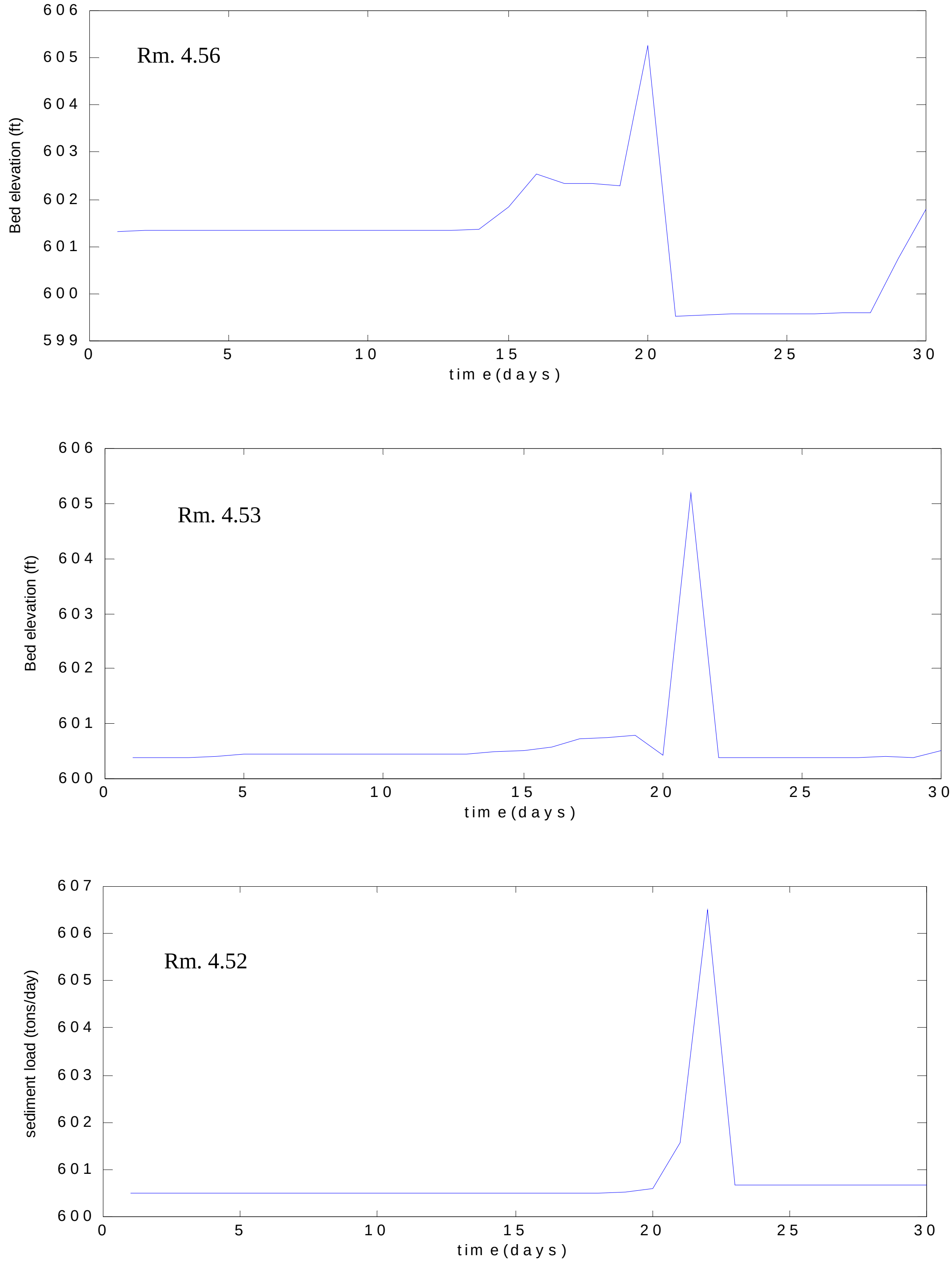
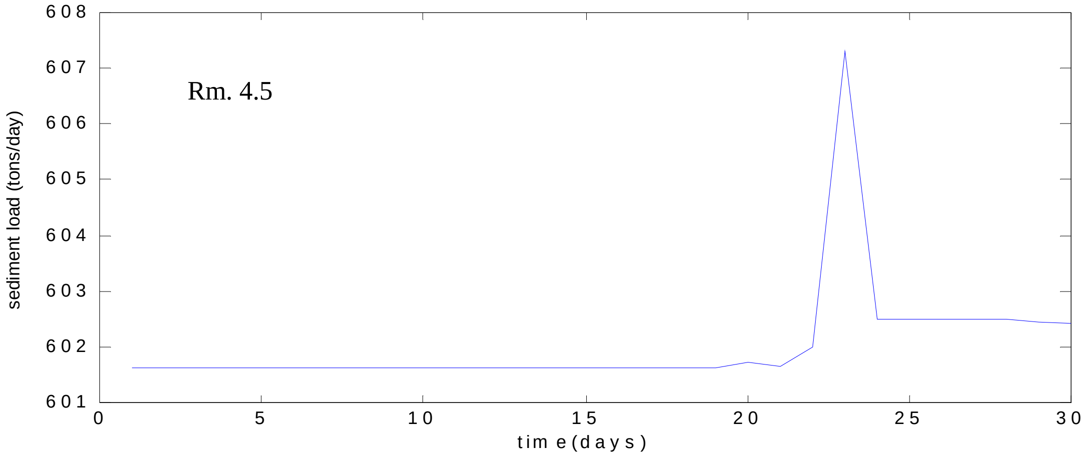
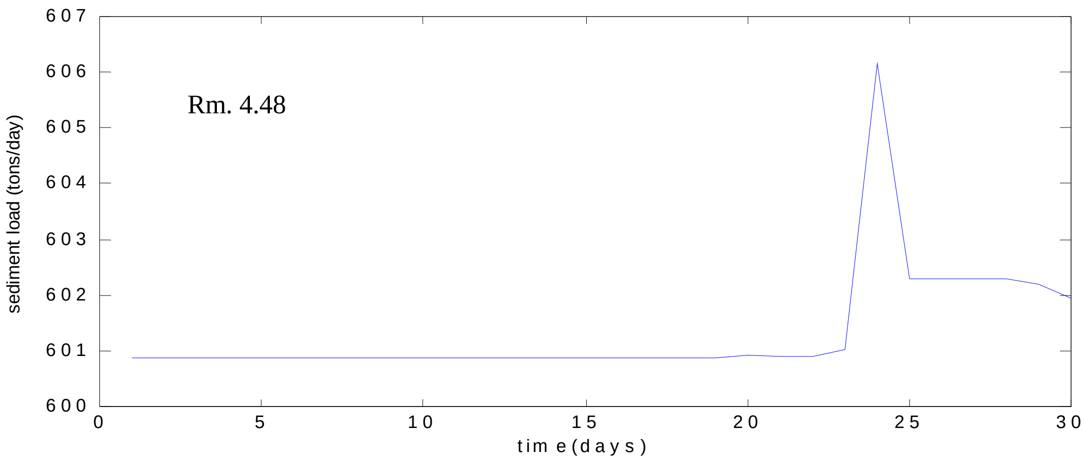


Figure 65a. Time progression of sediment load from river miles 4.56 to 4.46 of Menomonee River.





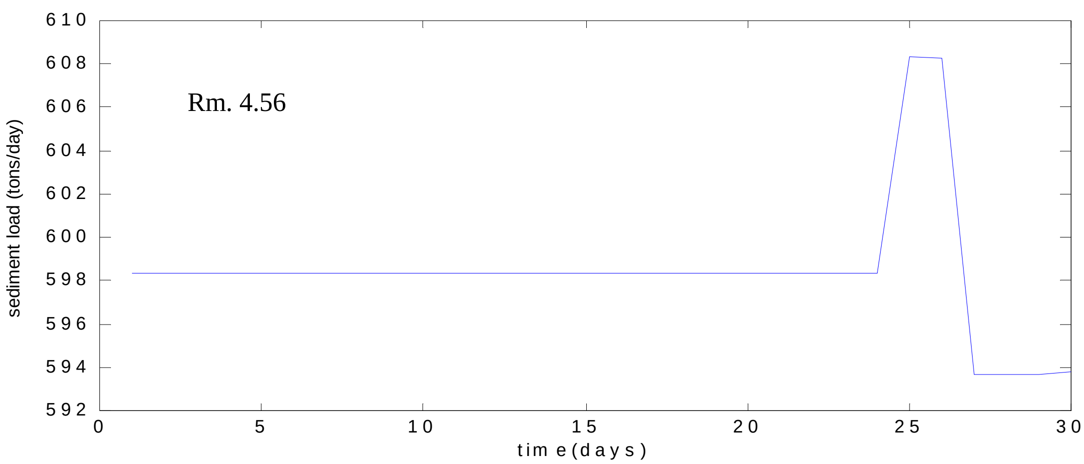


Figure 65b. Time progression of sediment load from river miles 4.56 to 4.46 of Menomonee River.

CONCLUSIONS

The key findings of the study include the following:

E*ach portion of the river system has a unique sediment delivery characteristic*. Several analyses were performed to develop generalized equations for sediment delivery that were used to generate input data for the sediment transport model. The sediment delivery characteristic for each subwatershed is a function of the land use and the size of the subwatershed. There is also a seasonal variation to the sediment delivery characteristic. It appears that during the winter season, the sediment delivery is independent of land use becoming a function of temperature (i.e. frozen soil).

Bank erosion as a sediment source is a minor contributor on this watershed and is not expected to increase significantly with the accompanying increased urbanization. It is possible that the frequency of larger flows may increase in the future, but these increased flows will not change the relative contribution of bank erosion to the overall sediment contribution. The increased flows may, however, be a concern regarding the bank stability.

Primary sources of sediment to the Menomonee River are first agricultural lands and second, urban non-point sources. The determination of the sources of sediment is a key factor in assessing the effectiveness of any cultural practice or land use control to reduce the sediment delivered to the river system and ultimately depositing in a downstream harbor or Lake Michigan.

One example use of this information could be an assessment of soil conservation measures on agricultural areas, such as those in the Little Menomonee Watershed. In one case, it was determined by regression that the agricultural portion of the Little Menomonee contributed 83% of the sediment, even though less than half of the watershed is considered agricultural land.

The following calculations illustrate the significance of this information:

The sediment delivered to the lower end of the Menomonee River could range in the magnitude of 10,000 to 20,000 tons per year. The results of the data analysis and modeling in this study indicate that Little Menomonee contributes approximately 27% of this total. Using15,000 tons (delivered to the lower Menomonee) as an example, the Little Menomonee contribution would be approximately 4,050 tons. Of this total, approximately 3,400 tons originated from agricultural lands. If conservation measures were undertaken that could reduce erosion by 30%, this would result in a reduction of approximately 1,000 tons of sediment. This reduction of 1,000 tons represents a nearly 7% reduction in sediment delivered to the lower Menomonee River.

The majority of the sediment delivered to the river system occurs during a relatively small number of rainfall/runoff events. In a one-year period during 1975 and 1976, over 75% of sediment delivered to the river occurred during the 73 days (20% of one year) of the highest flows. This is an important consideration when assessing the benefits of flood peak mitigation projects. There are several flood peak mitigation projects under consideration in the watershed, and in all cases, can produce a noticeable effect on the sediment dynamics through the Menomonee River System.

This modeling system has been developed and successfully tested to provide decision support on sediment load issues associated with the management of the watershed. The system and models described in this report provide the basis for a wide range of other investigations of the effects of flood peak mitigation structures, cultural practices and land use controls on the sediment dynamics of the Menomonee River Watershed.

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