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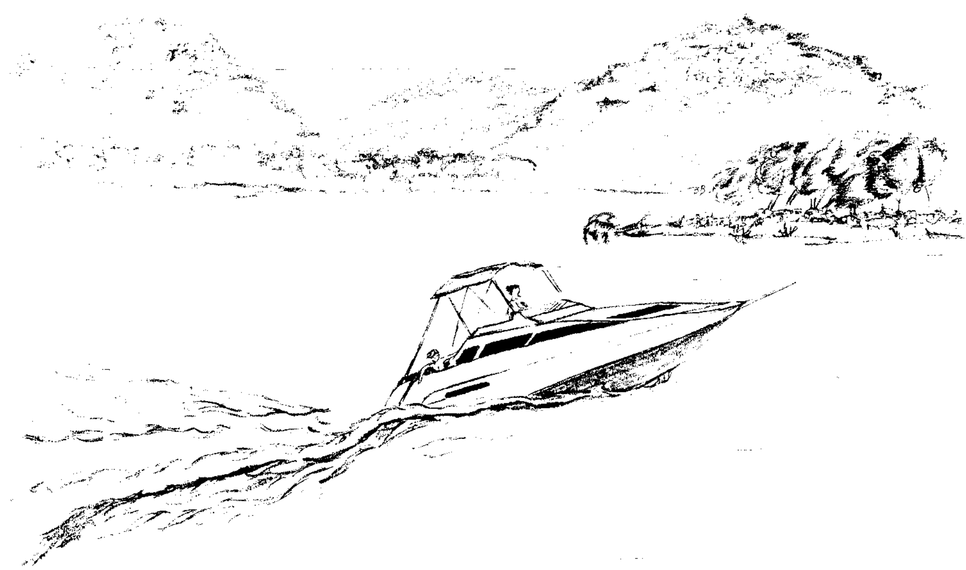
Recreational Boating Impact Investigations

Upper Mississippi River System, Pool 4
Red Wing, Minnesota



February 1994

Recreational Boating Impact Investigations
Upper Mississippi River System, Pool 4
Red Wing, Minnesota

by

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Cover graphic
by Brian Blair

Preface

This report is a product of the Long Term Resource Monitoring Program (LTRMP) for the Upper Mississippi River System (UMRS). The LTRMP was created in 1987 as a cooperative effort by the U.S. Army Corps of Engineers, the U.S. Fish and Wildlife Service, and resource management and research agencies of the cooperating states (Illinois, Iowa, Minnesota, Missouri, and Wisconsin). The overall mission of the LTRMP is to provide decision makers, resource managers, and resource users with information needed to maintain the UMRS as a viable multiple-use ecosystem. This mission is undertaken using a combination of long-term trend monitoring and focused research on identified problems.

The primary products of the LTRMP are data (recorded facts) and information (usable interpretation of data). A network of six field stations on the Upper Mississippi and Illinois Rivers collect data on water quality, vegetation, aquatic macroinvertebrates, and fish. The Environmental Management Technical Center (formerly a U.S. Fish and Wildlife Service facility and currently in the National Biological Survey), which is the operational center of this network, works closely with the six field stations to analyze, interpret, and report the LTRMP data. Informational products of these efforts include professional presentations, reports, and publications in the open and peer-reviewed scientific literature.

This document reports the results of a study conducted on recreational boating impacts in Pool 4 of the Upper Mississippi River near Red Wing, Minnesota. The report focuses on the resuspension and erosion effects of recreational boat traffic. It includes the interpretation and recommendations of the author. This study was conducted as part of Strategy 1.2.2, *Determine Effects of Navigation on Selected Components and Processes of the Upper Mississippi River System Ecosystem*, as specified in Goal 1, *Develop a Better Understanding of the Ecology of the Upper Mississippi River System,* of the Operating Plan for the LTRMP (USFWS 1992).

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Introduction

Over the past 170 years, the U.S. Federal Government authorized and funded a series of navigation improvement projects on the Upper Mississippi River System (UMRS). These river improvement projects were designed to make the UMRS a reliable navigation waterway for the commercial tow industry. Early proponents of the navigation system could not have foreseen the number of recreational boaters currently using the navigation system, which continues to grow while commercial navigation in Pools 1 through 4 remains essentially flat or on the decline (Figs. 1 and 2 adapted from Johnson 1990).

Longstanding environmental concerns have directed most scientific research toward the investigation of environmental impacts associated with commercial navigation. In a data base search of the literature, only a handful of recreational boating references were found to pertain specifically to the UMRS. The majority of the references identified the need for further study but provided little, if any, new scientific research information concerning recreational boating impacts.

Past Recreational Boating Studies on the Upper Mississippi River System

The River Studies Center (1981) conducted an investigation of recreational boating impacts on the UMRS during development of the Comprehensive Master Plan for the Management of the Upper Mississippi River System (UMRBC 1982). Although this inquiry was essentially an aside to a much larger commercial navigation investigation and looked only at individual recreational boat passages, the study found that a 24-ft cruiser in a side channel significantly increased total non-filterable residue and increased the average size of suspended solids. However, the investigators found no significant changes for total non-filterable residue, turbidity, sediment particle size, or nutrient concentrations associated with a single recreational boat passage in the Main Channel. Depth-integrated suspended sediment samplers were used to collect samples.

The Illinois State Water Survey and the Illinois Natural History Survey (1981) completed an informational summary regarding the physical, chemical, and biological effects of navigation on the UMRS for the Upper Mississippi River Basin Commission. Information was gleaned from the literature over the 10-year period from 1970 to 1980. The emphasis of the report was on commercial navigation, but the report did contain some references to recreational boating activity. Rasmussen (1983) summarized known navigation effects and prioritized data gaps for the biological effects of navigation on the UMRS.

The interagency Mississippi River Marina Cumulative Impacts Task Force's "Cumulative Impact Analysis of Proposed Recreational Marina Expansions for Pools 2, 3, and Upper Pool 4 of the Upper Mississippi River" (Johnson 1990) compiled and presented all available information concerning the status of marinas and recreational boating on this reach of the river. The Cumulative Impact Analysis discussed the status of the river's natural resources, restated the Federal and State agencies' multiple-use management goals, and listed numerous concerns regarding the growing number of recreational boats on the river. The study identified the need for scientific investigations into potential problems associated with recreational boating activities on the UMRS.

The first scientific investigation designed specifically to study recreational boating on the UMRS was conducted by the Illinois State Water Survey (Bhowmik et al. 1991) under contract with the U.S. Fish and Wildlife Service's Long Term Resource Monitoring Program (LTRMP). The Illinois State Water Survey measured wave characteristics associated with individual runs of different types of recreational boats, as well as cumulative wave characteristics associated with heavy recreational boating on the river in two locations: Red Wing, Minnesota, on the Mississippi River and near Havana, Illinois, on the Illinois River. The Illinois State Water Survey collected valuable baseline information concerning wave characteristics, recreational boating activity levels, and types of boats using the UMRS. The authors identified the need to study recreational boating effects on bank stability and bed sediment resuspension.

Study Objective

The objective of this investigation was to build on the knowledge gained by the Illinois State Water Survey and to document environmental impacts associated with recreational boating. This objective is consistent with the LTRMP's 1992 Operating Plan Strategy 1.2.2, *Determine Effects of Navigation on Selected Components and Processes of the Upper Mississippi River System Ecosystem* (USFWS 1992). A series of related field investigations examined potential physical and water quality changes associated with recreational boating on the UMRS. Investigations were designed to qualitatively and quantitatively measure and compare erosion rates along bank shorelines and document water quality changes associated with boating activities.

In addition, the findings of other researchers were reviewed in the literature to aid in placing recreational boating activity in the proper perspective for evaluating its potential for environmental impacts on the UMRS.

Background

The geomorphic processes responsible for the development of the UMRS natural floodplain features are directly linked to the Late Wisconsin Glacial Period. Meltwater from glaciers and glacial lakes drained through the Mississippi River Valley, entrenching the river deep into the sedimentary bedrock, leaving terraces along the valley sides. As the supply of glacial waters diminished, the Mississippi River no longer needed the deep valley to convey water and was unable to transport the sediment load from its tributaries. Over the last 9,200 years, the river valley has slowly filled with sediments, creating an alluvial floodplain river with interlacing branching channels (often referred to as anastomosing or island-braided channels) bound by natural levees, river terraces, and bedrock bluffs. Prior to European settlement, the river was a complex of bathymetric and structural diversity with sloughs, backwater lakes, and marshes amid the running channels within the floodplain. The sediment load from the Chippewa River was so great during the early post-glacial epoch that its delta dammed the Mississippi River and created Lake Pepin. Lake Pepin extended to St. Paul, Minnesota, and included what we now call Pools 2, 3, and most of 4. The head of Lake Pepin slowly aggraded with sediments and the reach of the river between Red Wing and St. Paul has once again returned to a riverine environment (Lively 1985).

Beginning with snag and riffle removal in 1824, through construction of wing dams and closing structures for the 4.5- and 6-ft channels, and culminating in the 9-ft channel lock and dam system, the UMRS has been dramatically changed from its natural state. The UMRS can now best be described as a series of slack water reservoirs for navigation (Merrit 1980). Some stretches of the river have retained riverine channel conditions, while other river reaches, especially those at the lower ends of each pool, now contain large inundated areas dominated by wind-swept open water. The hydrologic changes described above, coupled with land use practices in the uplands, have created a highly perturbed riverine system. As with all riverine systems, the UMRS is a dynamic system that continues to adjust gradient, channel position (within the constraints of the U.S. Army

Corps of Engineers' training structures), and geomorphic features in response to changing hydrologic conditions, sediment load, and energy inputs.

General Experimental Design

All investigations were conducted in Upper Pool 4 of the UMRS near Red Wing, Minnesota (Figs. 3 and 4). This study area was selected because of its high level of recreational boating activity attributable to its close proximity to the Twin Cities Metropolitan Area, the St. Croix River, and Lake Pepin. The Red Wing area was the study area used by the Illinois State Water Survey and, therefore, information reported in their investigation was directly applicable to the field studies. Also, field observations made in the area suggested recreational boating impacts could be measured and the nearby Wisconsin Channel would be an appropriate control channel. For this investigation, the term "erosion" is used in the broadest sense to include mass wasting of the bank as well as grain-by-grain removal of sediments by water.

Data Collection Techniques and Results

Qualitative Shoreline Erosion Assessment Investigation

As a first step in evaluating the Red Wing study area, a qualitative shoreline erosion assessment was conducted between river miles 790.7 (Highway 63 bridge) and 787.5 (downstream tip of Baldwin Island) on the Main Channel. The Wisconsin Channel was qualitatively assessed between river miles 792.5 and 786.5.

Numerous factors can contribute to shoreline erosion (Table 1). The Main Channel and the Wisconsin Channel evolved under similar geologic histories and anthropogenic influences. When contributing influences are compared between the two channels (Table 2) they are found to be quite similar, including advective flow velocities. It is important to note that throughout these investigations the Wisconsin Channel was used as a control for contributing influences. The working assumption is that if a difference in erosion rates is observed or measured it is due to the contributing influences that are different rather than those that are similar between the two channels.

The Main Channel and Wisconsin Channel shorelines were qualitatively evaluated and placed into four erosion rate classifications based on field observations. These field observations included the relative amount of unvegetated soils, riparian vegetation, exposed roots, dead trees, down trees, steep cut banks, or presence of riprap. High erosion rates included areas with steep cut banks, exposed tree root wads, and down and dying trees. Moderate erosion rates included gentler sloped banks, some exposed soil, and exposed roots. Areas classified as exhibiting low erosion rates were vegetated, with little or no evidence to suspect active erosion of the shoreline. Shorelines protected by rock were classified as riprapped. These classifications were marked on a map in the field, and the percent shoreline in each classification was measured using an electronic planimeter.

The qualitative assessment classified 66% of the Main Channel as experiencing a high erosion rate, 10% a medium erosion rate, 14% a low erosion rate, and 9% as riprapped (Fig. 5). In comparison, high erosion rates were observed along only 3% of the Wisconsin Channel shoreline in two locations subject to heavy foot traffic. The majority of the Wisconsin Channel (64%) was classified as experiencing low erosion rates. Medium erosion rates were measured along 32% of the shoreline and riprap along only 1%. This qualitative assessment suggests that the contributing influences to shoreline erosion are not the same for the two channels.

Contributing influences readily identified as being different include commercial navigation and a large number of recreational boats, many of which are deep draft boats found only in the Main Channel. The Wisconsin Channel contains sand bars and spits which limit recreational use to fishing boats and other shallow draft boats capable of navigating the channel during low control pool (LCP) water levels. A partial closing structure across the uppermost reach of the Wisconsin Channel is another restriction to navigation in the channel. Other differences in contributing influences include the presence of emergent, floating, and submergent aquatic plants as well as terrestrial plants along the Wisconsin Channel shore. Also, the surficial sediments along the Main Channel shoreline appear to contain a higher percentage of sand in many reaches, while the Wisconsin Channel shoreline materials primarily contain fine-grain cohesive materials.

The differences in vegetation and shoreline sediment can possibly be linked to commercial and deep draft recreational boat navigation in the Main Channel. Corps of Engineers channel maintenance sand has been disposed along the Main Channel shoreline and on top of the bank in the past. An examination of the sediments in the upper 2 ft of the Main Channel shoreline alluvium indicated that below the surface the shoreline sediments are fine-grain cohesive materials like in the Wisconsin Channel. Winnowing of the fine-grain particles by commercial and deep draft recreational boat waves and redeposition of channel maintenance sand may be responsible for the surficial sand layer along the Main Channel shoreline.

Wave action may also be responsible for the absence of near-shore vegetation. Bonham (1983) described a "succession" of bank phenology where vegetation was first lost due to boat wave action, with subsequent erosion of the shoreline. The qualitative shoreline erosion assessment suggested that commercial navigation and/or large numbers of deep draft recreational boats are responsible for the observed high erosion rates along the Main Channel.

Quantitative Shoreline Survey

Beginning in the spring of 1989, shoreline survey transects were established to measure changes in shoreline profiles due to erosion or deposition of alluvial materials (Fig. 6). The transects were established with permanent vertical and horizontal controls at five locations representing different river geomorphic reaches. Transects were set perpendicular to the shoreline and vertical elevations were measured using an automatic level and stadia rod at 2-ft horizontal intervals. Transects were surveyed approximately 15 times between 1989 and 1992.

Transects 1 through 3 were established on the Main Channel and Transects 4 and 5 on the Wisconsin Channel. Transect 1 represents a Main Channel straight river reach at river mile 788.4 on the right descending bank. Transect 2 represents an outside meander bend and Transect 3 is an inside meander bend, both located at river mile 789.8 on the Main Channel. In the control channel (Wisconsin Channel), Transect 4 represents an inside meander bend and Transect 5 an outside meander bend at river mile 788.8.

The results of surveys from May 1989 to September 1992 are found in Figures 7 through 11. Each figure illustrates the successive survey profiles and the changes that have occurred above LCP water levels between survey periods. Water levels shown on the graphs ($\underline{\nabla}$) are typical water levels during the survey period and are a bit above LCP water levels. A comparison of Main Channel profiles (Figs. 7, 8, and 9) to the Wisconsin Channel profiles (Figs. 10 and 11) clearly shows a greater recession of the shoreline along the Main Channel. Transect 2, which represents a Main Channel outside meander bend, documented 14 ft of shoreline recession.

Under normal flow conditions, the erosion of stream banks in a meandering channel is generally attributable to the thalweg (line of greatest flow velocity in the channel) impinging against the banks of the outside meander bends. The resultant shear stress erodes the bank and develops a steep cut bank and pool (Morisawa 1985; Leopold et al. 1964). When stream bank erosion is observed in areas other than outside meander bends, additional contributing influences are at work in the channel to promote bank erosion.

The shoreline surveys show that erosion of the Main Channel shoreline occurred at all transects regardless of geomorphic position. Measurement of the Wisconsin Channel transects revealed some erosion on the outside meander bend at Transect 5 (less than any of the Main Channel transects) and little change along the inside meander bend at Transect 4. The Main Channel transect results indicate that additional contributing influences to shoreline erosion are at work. The Wisconsin Channel transect measurements were consistent with expectations for a meandering stream.

Shoreline erosion rates were calculated for the three Main Channel transects. Due to the complex and cyclical nature of erosion, deposition, and changing water levels, the shoreline erosion rate calculations were restricted to clearly eroded materials between surveys above LCP water levels. An electronic planimeter was used to measure the area of bank material lost between each surveying event. An erosion rate in square feet per day was calculated by dividing this area by the number of days between transect surveys.

Relative erosion rates were calculated to make the comparison of erosion rates between survey intervals easier. The erosion rate between September 10, 1990, and April 17, 1991, was chosen as a baseline erosion rate because many contributing influences are minimized during the winter months and, therefore, it was assumed that erosion rates would be lowest during this time period. A relative erosion rate factor for all other survey intervals was calculated by dividing the individual survey interval erosion rate by the baseline erosion rate (Fig. 12).

Most erosion generally occurred during the recreational boating season, which typically runs from Memorial Day (late May) to Labor Day (early September). The one exception is the 1989 Transect 2 results, which show a slightly higher erosion rate in the non-boating season. This may be attributable to a high water event in March 1990 which occurred before the spring transect survey was completed. An inspection of 1991 erosion rates suggests that erosion was less once the recreational boating season was over and commercial tow traffic was the dominant form of navigation.

The Mississippi River experienced bank full conditions on numerous occasions but did not experience a major flood event during the survey period. (A major flood is often responsible for major erosion events in a riverine environment.) A visual comparison of the location of the channels and channel meander bends shown on 1895 Mississippi River Commission charts (Mississippi River Commission 1895), 1974 U.S. Geologic Survey 7-1/2-min quadrangles (USGS 1974), and a 1989 LTRMP GIS map (Olsen 1991, unpublished) indicated little change in channel location other than those attributable to Corps of Engineers' channel-straightening activities. Floods between 1895 and 1989 did not alter the location of the channels to any measurable degree during this time period. It is likely that wing dams, armoring of shorelines, and other training structures are partially responsible for the relative stability of channel locations.

A review of these results with respect to the discussion of contributing influences (presented previously in the *Qualitative Shoreline Erosion Assessment Investigation* section) suggests that commercial navigation and deep draft recreational boats are the contributing influences responsible for the accelerated erosion rates along the Main Channel. It is interesting to note that more erosion occurred during 1991 and 1992, when water levels were above LCP most of the boating season. The observed increase in erosion rates may be attributable to the fact that wave energy was not dissipated against a gently sloping shoreline but rather was fully expended against the steeper sloped portion of the shoreline. This observation suggests a greater potential for wave erosion when water levels are above LCP.

General Water Quality Assessment Investigation

Three water quality monitoring stations were sampled during five recreational boating events to assess water quality changes associated with recreational boating activity. The five recreational boating events took place on Memorial Day weekend, the June 23rd weekend, the Fourth of July weekend, the August 10th weekend, and Labor Day weekend in 1991. The three water quality monitoring stations were located in three different hydrologic settings: Site 1 represented the Wisconsin Channel at river mile 788.0, Site 2 represented the Main Channel at river mile 788.0, and Site 3 represented Lake Pepin at river mile 784.2 (Fig. 13). Each sampling event included a pre-weekend/holiday sample, an early morning weekend/holiday sample, and a peak boating weekend/holiday sample. Sampling protocols followed the Minnesota Pollution Control Agency Lake Pepin Phosphorus Study and U.S. Fish and Wildlife Service LTRMP standard techniques (USFWS 1992), which included integrated 2-m water column samples.

Water quality parameters included chlorophyll-*a*, nitrite/nitrate as N, kjeldahl nitrogen, total phosphorus, total solids, total dissolved solids, total suspended solids, suspended volatile solids, and fixed suspended solids. Field measurements included dissolved oxygen, temperature, Secchi, turbidity, wind magnitude, wind direction, flow magnitude, flow direction, specific conductivity, and depth. Water quality data are presented in Appendix A of this report.

The water quality investigation experimental design was not intended to attach statistical significance to the water quality data but instead to examine possible gross trends or obvious changes associated with recreational boating at minimum cost and effort. A review of the data indicated an increase in total suspended solids in the Main Channel during peak boating times (Fig. 14). It appeared that most of the change in total suspended solids is attributable to fixed suspended solids as opposed to volatile suspended solids. There appeared to be no discernible trend in nutrient or chlorophyll-*a* concentrations. This finding suggests that the suspended solids being resuspended or eroded into the water column either do not release nutrients or do not release nutrients in concentrations high enough to be detected using integrated 2-m water column samples. The use of 2-m integrated water column samples to characterize the possible changes associated with recreational boating events is questionable, since impacts are concentrated in a discrete zone within the water column (as shown in the following section of this document).

Turbidity Monitoring Investigation

Discrete water samplers and a turbidimeter were used to measure changes in turbidity associated with recreational boating activity. The water samplers were programmed to take composite samples at various time intervals before, during, and after peak recreational boating periods. Figures 15 and 16 from the Illinois State Water Survey Investigation (Bhowmik et al.

1991) illustrate the general boating patterns for the Red Wing area. Typically, weekends and holidays are much busier than weekdays and during these heavy boating periods the activity is generally concentrated in the late morning through the afternoon and into the early evening hours. The target "event" for the turbidity investigations was the general recreational boating activity level and not individual boat passages. Therefore, composite samples were used in the assessment to reduce the influence of any one individual boat passage. The turbidimeter was then used to measure turbidity for each composite sample. The sample intake tube was attached to a threaded rod driven into the bottom substrate, which facilitated sampling at various fixed distances from the river bottom at representative locations in both channels (Fig. 17).

Sample intake tubes from three water samplers were attached to the same threaded rod at different depths within the water column. This arrangement was designed to measure possible vertical stratification of turbidity in the Main Channel. The water samplers were programmed to take samples simultaneously at 4, 14, and 24 inches (10, 35, and 60 cm, respectively) from the channel bottom in approximately 3 ft (100 cm) of water 20 ft (6 m) from shore. The results indicate that from 4 to 10 a.m. all samplers were measuring an unstratified background turbidity level of $<$50 NTUs (Fig. 18). Beginning at about 10 a.m. and corresponding to an increase in recreational boat traffic, turbidity levels increased in all samples. The increase in turbidity levels was markedly higher in the samples taken 4 inches from the channel bottom ($>$300 NTUs) compared to samples taken at the same time but at a greater distance from the channel bottom. These results suggest an increase in turbidity associated with an increase in recreational boating activity and that higher turbidity levels are concentrated near the channel bottom.

In a subsequent monitoring event, sample intakes were set 4 inches from the channel bottom at both 10 and 20 ft from shore, and samplers were programmed to take simultaneous samples over a Sunday with heavy boating activity. Data from this monitoring event suggest that turbidity levels associated with peak recreational boating activity do not diminish with increasing distance from shore (Fig. 19).

Monitoring results with sample intakes at 20 and 30 ft from shore over a 5-day period confirmed that turbidity levels do not diminish with increasing distance from shore (Fig. 20). The results also suggest that turbidity levels are higher on weekends compared to weekdays and that turbidity levels peak during peak recreational boating times. Results from this monitoring event indicated that a 4-h composite sample made of four individual hourly samples was adequate to capture the temporal changes in turbidity.

A review of Figures 19 and 20 suggests that the near-bottom turbidity increases are laterally extensive and may act as a turbidity plume or density current along the entire littoral zone of the river. The film *Sedimentation Due to Waves and Density Flows*, University of Minnesota, St. Anthony Falls Hydraulics Lab, depicts experimental confirmation of the development of a density current as a result of wave action on a fine-grain beach (University of Minnesota 1961).

In a subsequent monitoring event, water column turbidity profiles were measured to document turbidity changes throughout the entire littoral zone. Samples were taken at 3-h intervals at distances of 10, 25, 50, 100, and 200 ft from shore using a portable pump and a winch to lower the sampling intake tube. Samples were taken at the bottom (6 inches), at 1 ft, and, depending on the total depth, at 4, 7, 11, 14, and 17 ft, and then at the surface. Profiles were taken at 7 and 10 a.m., representing pre-peak turbidity levels, and then at 1 and 4 p.m., representing peak boating turbidity levels (Table 3). The profiles verified that the change in turbidity is laterally extensive and is associated with recreational boating activity levels, and suggests that the entire bottom of the littoral zone of the river is affected by increased turbidity levels. In the transition zone between the shallow littoral zone and the deeper navigation channel, the turbidity plume moved down slope toward the bottom of the channel and was soon diluted by the increased flow velocity and volume of water (Figs. 21-24). The contour plots of turbidity concentrations in Figures 21 through 24 were made using a 40-NTU minimum contour line and a 10-NTU contour interval.

Adams and Delisio (1991) found a similar spatial distribution of suspended sediment associated with the passage of a single commercial tow in the Illinois River. The Red Wing study area investigations were designed to monitor recreational "events" and did not detect changes in turbidity associated with individual commercial tow passages. If the Illinois River data provide an accurate indication of what would be measured with barge traffic on the Mississippi River, some generalizations can be made to place the recreational boating turbidity plume in perspective. For commercial navigation to create a turbidity plume similar in duration and concentration to the plume associated with recreational boating in the Red Wing area, a tow would need to pass the sampling location approximately every 20 min. On average, a commercial tow passes through the study area once every 2.4 h.

Turbidity values were compared to total suspended solid concentrations to determine if the resuspension/erosion of sediments was the cause of the increase in turbidity (Fig. 25 and Appendix B). The graph clearly shows a strong relationship between turbidity values and total suspended solids. The R^2 value for the linear regression line is 0.95. These results, in conjunction with the water quality investigation findings, suggest that the increase in turbidity was a result of the resuspension/erosion of sediments and was not related to algae growth. The results also show that turbidity was an appropriate surrogate measurement for total suspended solids in the study area.

Dissolved oxygen concentrations were also spot-checked during the collection of turbidity profiles and no changes were detected, suggesting that the sediments resuspended or eroded in the study area were not oxygen-demanding sediments. A laboratory particle size analysis was not completed on the turbidity samples, but a visual inspection of the samples suggested that the majority of the suspended solids associated with the increased turbidity values are silt and clay-size particles.

The next monitoring event was designed to compare changes in turbidity in the Main Channel with changes in the Wisconsin Channel over the same time period. The Wisconsin Channel was used as a control for a number of reasons, including, as noted earlier, the fact that recreational boats traveling the Wisconsin Channel are smaller in size and fewer in number in comparison to those in the Main Channel. The monitoring run found an increase in turbidity during peak recreational boating times in the Main Channel compared to in the Wisconsin Channel (Fig. 26). It should be noted that an increase in turbidity was also detected during peak boating times on Saturday in the Wisconsin Channel, probably due to a fishing tournament, but to a much lesser degree than in the Main Channel. It appears that fishing boats and other shallow draft boats can affect turbidity levels if enough of them are using the channel at a given time. Efforts to quantify recreational boat traffic on the Wisconsin Channel were unsuccessful.

The longest monitoring event was completed using three water samplers over a 9-day period. One sampler was placed on a natural Main Channel shoreline in the Red Wing No-Wake Zone, while the other two were placed in the same locations in the Main Channel and in the Wisconsin Channel as previous monitoring events. The Main Channel results clearly show an increase in turbidity during peak recreational boating times (Fig. 27). The Wisconsin Channel showed much less of an increase in turbidity during peak boating times compared to the Main Channel. Due to a battery failure, the No-Wake Zone sampler did not sample the entire time period; however, the sampler did provide useful samples on Labor Day and the results show no increase in turbidity during peak boating times in the Main Channel No-Wake Zone.

The results of the No-Wake Zone monitoring event were later verified by a monitoring event in the summer of 1992. Water samplers were placed both in the Red Wing Main Channel No-Wake Zone and along the Main Channel where boats were unrestricted and free to create waves. Turbidity levels basically remained unchanged in the No-Wake Zone, while turbidity levels near the bottom of the Main Channel increased to levels approximately five times the No-Wake Zone turbidity values (Fig. 28).

Wind speed, wave height, and turbidity were measured within the Red Wing Study area 155 times between 1989 and 1991 by the Pool 4 LTRMP Field Station and the Minnesota Department of Natural Resources (Fig. 29). In Figure 29, wind speed was the independent variable on the x axis, with turbidity and wave height graphed as dependent variables on separate y axis scales. No readily discernable trend was observed for turbidity in relation to wind speed, and turbidity values were all below 80 NTUs. The results of this analysis suggest that the elevated turbidity values measured during peak boating times were likely due to boat wave resuspension and not related to wind wave resuspension.

Discussion

Gatto and Doe (1987) and Mason et al. (1983) found that boat waves alone or in combination with other contributing influences may be responsible for river shoreline erosion. Gatto and Doe stated that while the processes involved in bank erosion appear to be generally known, there is little known about the amount of erosion attributable to a given process. Ouellet and Baird (1978) believed that it might be impossible to quantify the amount of erosion that any one process contributes to total bank erosion because there are so many interdependent contributing processes. These statements convey how difficult it is to sort out the relative contribution of each contributing influence and emphasize the usefulness of the Wisconsin Channel as a control in qualitative and quantitative erosion studies. Qualitative and quantitative study of shoreline erosion in the Red Wing study area strongly suggests that commercial navigation and passage of many large, deep draft recreational boats are the major contributing influences responsible for the shoreline erosion prevalent along the Main Channel.

The Illinois State Water Survey Investigation (Bhowmik et al. 1991) confirmed what river managers had long contended based on observation and professional judgment. Simply stated, the larger the recreational boat, the greater the capacity to generate large waves. The larger the wave, the more energy contained in the wave, and the more energy needed to be dissipated by the shoreline. The relationship between wave height and energy is represented in Equation 1 for simple harmonic motion (Ippen 1966).

Equation 1. $E = KE + PE = ya^2/2$

Where E = total energy
KE = kinetic energy
PE = potential energy
y = unit weight of water
a = wave amplitude (one-half the wave height)

A further analysis of Figure 29 shows that wave height increased with increasing wind speed but waves were generally < 4 inches in height and were never > 8 inches. Average recreational boat wave heights were determined by the Illinois State Water Survey to be 10 inches and maximum wave heights 25 inches (Bhowmik et al. 1991). Recreational boating activity, therefore, created waves of greater potential for causing erosion than wind waves. Bhowmik calculated that, given the wind fetch in the study area, wind 45 and 58 mph would be necessary to generate waves 12 (0.3 m) and 16 inches (0.4 m) high, respectively. Recreational boats commonly produced waves 12 to 16 inches high, but $\geq$45-mph winds are rare in the study area (Baker 1983; Lemmerman 1991, unpublished).

A comparison of recreational boating and commercial tow physical forces places the relative potential for environmental impacts for each mode of navigation in perspective (Table 4). Note that these values are for the most part median values for comparison purposes and may not be representative in all circumstances. For example, many recreational boats throw little, if any, wave when up on plane or traveling at very slow speeds. On the other hand, recreational boats unable to come out of the water with increasing velocity continue to displace greater volumes of water, resulting in larger waves. Likewise, tows traveling at speeds greater than optimum for fuel economy may create larger surface waves than those presented in Table 4.

Recreational boats typically produce more waves in the wave train than commercial tows, although the duration of the wave train is similar. Compared to wave heights generated by commercial navigation, average and maximum wave heights are larger for recreational boats. Therefore, an average recreational boat in the Red Wing study area is capable of delivering more surface waves of larger amplitude when compared to the typical commercial tow. Recreational boats far outnumber commercial tows, which translates into a much greater cumulative potential for shoreline erosion due to surface waves generated. In their report, Bhowmik et al. (1991) also illustrated that wave heights are additive, and that the more boats on the river at one time the higher the significant wave height.

Wave velocity (celerity) is directly related to the shear stress induced on the channel bottom and shoreline by waves. The greater the velocity, the greater the shear stress and, therefore, the greater the erosion potential. The Corps of Engineers used combined ambient and tow-induced wave velocities to calculate shear stress in their Navigation Predictive Analytical Technique (NAVPAT) model to predict depth of substrate disruption (Siemsen, in review). Comparison of advective flow velocities measured by Burdis (1991, unpublished) to the recreational boat wave velocities measured in the Red Wing study area for this investigation shows that recreational boat waves travel at velocities greater than the river's advective flow during normal to bank-full conditions. Recreational boat-generated surface waves in the Red Wing study area typically move at greater velocities than commercial tow-generated surface waves. From a surface wave physical force perspective, recreational boating in the Red Wing study area has a greater potential for contributing to shoreline erosion than commercial tows or advective flow under normal to bank-full flow conditions.

Erosion of the shoreline and resuspension of bottom materials will add to the sediment load in the river. Sedimentation is widely considered to be the most severe environmental problem on the river (USFWS 1991). Sedimentation is responsible for the loss of bathymetric diversity, loss of water depth, and the development of a loose, flocculent bottom substrate in many backwater lakes.

The contribution of commercial tow prop wash to the shoreline erosion observed in the study area has not been quantified. Since prop wash effects are usually associated with tow maneuvers at meander bends and shoreline erosion is occurring at a high rate along most of the

Main Channel in the study area, recreational boat-generated surface waves must be considered a more pervasive contributing influence to shoreline erosion.

Recreational boat waves are potentially more harmful to shorelines in narrow and unvegetated river reaches. Hurst and Brebner (1969) found that in reaches of the St. Lawrence River with widths $<2{,}000$ ft navigation was a major contributing influence ($>50\%$ responsible) to erosion of the shoreline.

Based on the investigation results and the discussion concerning physical forces in the study area, it is reasonable to conclude that recreational boating is the major contributing influence to the erosion observed in the study area. As the river adapts to this relatively new energy input into an already disturbed system, the river channel will continue to become more shallow and wider as the shoreline develops the gentle slope necessary to dissipate recreational boat wave energy.

A fringe of aquatic vegetation can dissipate wave energy and slow advective channel flow near shore (Bonham 1983; Thornes 1990). Advective flow velocities measured near shore in the Wisconsin Channel were reduced for a greater distance from shore in comparison to those in the Main Channel due to the greater frictional resistance at the water/shoreline boundary associated with shoreline vegetation. Bonham also reported that boat waves on the Thames River were responsible for disturbing emergent aquatic plant stems and rhizomes, leading to greater vulnerability of the shoreline to erosion from both waves and increased advective flow. Liddle and Scorgie (1980) discussed the vulnerability of some plants for disturbance by wave action based on physical characteristics of the plants.

Garrad and Hey (1987) concluded that passage of a single boat could resuspend sediments and that diurnal changes in boat traffic could affect the pattern of suspended solids and turbidity in the Norfolk Broad River. While the Red Wing study area investigations looked at cumulative recreational boating effects, observations near shore on weekdays suggest that one large boat on the UMRS can raise turbidity values in a limited near-shore area. Also, as stated earlier, the field investigations detected a diurnal change in turbidity values associated with recreational boating activity.

The Norfolk River study (Garrad and Hey 1987) suggested that increased turbidity values associated with recreational boating may be partially responsible for the decline in aquatic macrophytes in the river. The authors also reference other studies that suspect high levels of turbidity as a major factor responsible for declining submergent macrophyte populations in England in the last few decades. Murphy and Eaton (1983) reported an inverse relationship between recreational boating activity levels and aquatic macrophyte abundance in canals in England. The authors concluded that heavy boat traffic is probably the principal factor involved in suppressing aquatic macrophyte growth to such an extent that its value for fish management, conservation, and the visual attraction of a vegetative fringe along the channels is lost. In the report, the authors propose an ecologically defined recreational boating capacity for the canals.

In a study to investigate the loss of submergent aquatic plants in Chesapeake Bay, the Environmental Protection Agency concluded that no single factor could be identified (Gucinski 1982). The study found that the depths to which boating affects sediment resuspension coincided with depths where submerged aquatic plants were limited. It was observed that the areas exhibiting the slowest recovery of submergent vegetation corresponded to the areas with the greatest boating activity. The authors recommended that ecologically sensitive areas with fine-grain sediments be protected from excessive traffic, particularly deep draft high-power craft.

Yousef (1974) and Yousef et al. (1980) completed water quality studies in a number of shallow lakes in Florida. This work suggested that recreational boating activity may be capable of affecting turbidity, dissolved organic carbon, total phosphorus, and chlorophyll-*a*. Mississippi River recreational boating turbidity and water quality investigations detected an increase in turbidity and total suspended solids associated with recreational boating activity. The water quality investigation did not detect discernible trends in the other water quality parameters in the three locations sampled. As noted earlier, the integrated 2-m water column samples may not be appropriate for detecting the changes associated with recreational boating because the measurable effects may be restricted to an area near the bottom of the littoral zone.

Wetzel (1990) described the importance of the land/water interface to the productivity and stability of aquatic ecosystems. The series of field studies completed for this investigation indicate that recreational boating impacts are concentrated near the land/water interface. Potential biological impacts suggested by the results of the recreational boating investigations, review of the literature, and professional opinions include:

1. Reduction in light penetration which may limit or eliminate macrophyte plant growth and reduce primary production by phytoplankton.

2. Physical disturbance, burial, or development of unsuitable bottom substrate for rooted aquatic plants.

3. Loss of terrestrial vegetation due to the erosion of basal support and the undermining of roots.

4. Dislodgement and physical disturbance of benthic organisms.

5. Loss of spawning habitat, inhibition of reproduction, deserting of nests, gill damage, loss of fish nurseries, modified schooling behavior, skin irritation, interference with disease protection, and hindrance to site feeding.

6. Reduced reproductive success and survival of burrowing mammals due to den site collapse.

7. Disturbance of turtle nesting and basking sites.

8. Destabilization and abrasion of snag habitat and associated loss of food production and cover.

9. Disturbance and hazing of waterfowl, shorebirds, and other birds that use the river.

Conclusions

From the results of the field investigations, it can be concluded that recreational boating on the Mississippi River Main Channel is the contributing influence most responsible for the documented high rate of shoreline erosion. Recreational boating is also directly responsible for elevated turbidity levels in the littoral zone during peak boating times. The physical and chemical changes measured in the investigations have far-reaching biological implications for the river. The investigation findings may be applicable to Pools 2 and 3 and Upper Pool 4 of the UMRS since they have similar geologic histories and anthropogenic influences.

Additional field investigations can be designed to further quantify the physical impacts in the study area, test the applicability of the investigation findings to other reaches of the river, determine thresholds or carrying capacity for boating activities, and quantify biological impacts. However, protection of the Mississippi River from the documented impacts and potential impacts identified in this report should not be contingent on the completion of these additional tasks. This report documents an existing threat to the health of the Mississippi River's ecosystem. Federal, state, and local government agencies responsible for managing activities on the UMRS should consider the implications of these findings and act appropriately to protect the Mississippi River ecosystem.

Acknowledgments

Support for the recreational boating impacts field investigations was provided by the Minnesota Department of Natural Resources' Division of Waters and Ecological Services Section. The Long Term Resource Monitoring Program provided partial funding and technical support. Gary Rott from the Minnesota Pollution Control Agency arranged for the use of the water samplers. Special thanks to Ceil Strauss, Mike Davis, and Jack Enblom for their vision, initiative, and guidance. Thanks to Beth Knudsen, Zach Boudreau, Joyce Kassen, Jeff Wangen, Steve DeLain, and Aimee Martinek for their field and office assistance. Jim Zicopula provided assistance with the graphics. Thanks to Nani Bhowmik and his associates at the Illinois State Water Survey for pioneering the study of recreational boat waves.

References

Adams, J. R., and E. Delisio. 1991. Temporal and lateral distributions of resuspended sediment following barge tow passage on the Illinois River. Hydraulic Engineering, Vol. 2: Proceedings of the 1990 National Conference, San Diego, July 30-August 3, 1990. American Society of Civil Engineers, New York.

Baker, D. G. 1983. Climate of Minnesota: Part XIV - Wind climatology and wind power. Technical Bulletin, Agricultural Experiment Station, University of Minnesota.

Bhowmik, N. G., T. W. Soong, W. F. Reichelt, and N. M. L. Seddick. 1991. Waves generated by recreational traffic on the Upper Mississippi River System. Illinois State Water Survey Research Report 117.

Bonham, A. J. 1983. The management of wave-spending vegetation as bank protection against boat wash. Landscape Planning 10:15-30.

Garrad, P. N., and R. D. Hey. 1987. Boat traffic, sediment resuspension and turbidity in a broadland river. Journal of Hydrology 95:287-297.

Gatto, L. W., and W. W. Doe III. 1987. Bank conditions and erosion along selected reservoirs. Environmental Geology and Water Sciences 9(3):143-154.

Gucinski, H. 1982. Sediment suspension and resuspension from small craft induced turbulence: Project summary. EPA-600/S3-82-084.

Hurst, C. K., and A. Brebner. 1969. Shore erosion and protection, St. Lawrence River - Canada. XXII International Navigation Congress, Sec.1, Subj. 6, pp. 45-56.

Illinois State Water Survey and Illinois Natural History Survey. 1981. Information summary of the physical, chemical, and biological effects of navigation. Submitted to the Upper Mississippi River Basin Commission.

Ippen, A. T. 1966. Estuary and coastline hydrodynamics. Engineering Societies Monographs. McGraw-Hill.

Johnson, S. P., editor. 1990. Summary: Cumulative impact analysis of proposed recreational marina expansions for Pools 2, 3, and Upper 4 of the Mississippi River. U.S. Army Corps of Engineers, Minnesota Department of Natural Resources, Wisconsin Department of Natural Resources, and Minnesota-Wisconsin Boundary Area Commission.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman and Company.

Liddle, M. J., and H. R. A. Scorgie. 1980. The effects of recreation on freshwater plants and animals: A review. Biological Conservation 17:183-206.

Lively, R. S., editor. 1985. Pleistocene geology and evolution of the Upper Mississippi River. Minnesota Geologic Survey.

Mason, C., W. Grogg, and S. Wheeler. 1983. Shoreline erosion study Pleasure Island, Texas. U.S. Army Corps of Engineers, Galveston, Texas, A138653.

Merrit, R. H. 1980. Creativity, conflict, and controversy: A history of the St. Paul District, U.S. Army Corps of Engineers. U.S. Governmental Publishing Office.

Mississippi River Commission. 1895. Survey of the Mississippi River, 1:20,000-scale maps.

Morisawa, M. 1985. Rivers: Form and process. Longman Group Limited.

Murphy, K. J., and J. W. Eaton. 1983. The effects of pleasure boat traffic on macrophyte growth in canals. Journal of Applied Ecology 20:713-729.

Ouellet, Y., and W. Baird. 1978. L'erosion des rives dans le Saint-Laurent. Canadian Journal of Civil Engineering 5:311-323.

Rasmussen, J. L. 1983. A summary of known navigation effects and a priority list of data gaps for the biological effects of navigation on the Upper Mississippi River. U.S. Fish and Wildlife Service. Submitted to U.S. Army Corps of Engineers.

River Studies Center - University of Wisconsin La Crosse. 1981. The effects of commercial and recreational navigation on selected physical and chemical variables in Navigation Pool No. 9 Upper Mississippi River. Submitted to Upper Mississippi River Basin Commission.

Siemsen, T. Environmental effects of commercial navigation traffic: A pilot application of the navigation predictive analysis technique (NAVPAT) for Pool 13, Upper Mississippi. Report by the U.S. Army Corps of Engineers-Louisville, Kentucky. Submitted to U.S. Fish and Wildlife Service, Environmental Management Technical Center, Onalaska, Wisconsin. (in review)

Thornes, J. B., editor. 1990. Chapter 10. Vegetation and erosion: Processes and environments. Wiley and Sons, Cobin R. Thorne.

U.S. Fish and Wildlife Service (USFWS). 1991. Environmental Management Program Long Term Resource Monitoring Program Upper Mississippi River System: Final Draft Operating Plan.

USFWS. 1992. Operating Plan for the Upper Mississippi River System Long Term Resource Monitoring Program. Environmental Management Technical Center, Onalaska, Wisconsin, August 1992. EMTC 91-P002. 183 pp.

U.S. Geological Survey (USGS). 1974. Red Wing, Minnesota, 7-1/2-minute quadrangle map.

University of Minnesota, St. Anthony Falls Hydraulic Laboratory. 1961. Sedimentation due to waves and density flows. One 339-ft reel, 10 min, Kodachrome, silent.

Upper Mississippi River Basin Commission (UMRBC). 1982. Comprehensive Master Plan for the Management of the Upper Mississippi River System.

Wetzel, J. 1990. Minnesota Lake Management Conference: Program notes. Broader perspective on Lake Management, Brainerd, Minnesota October 7-9.

Yousef, A. Y. 1974. Assessing effects on water quality by boating activity. EPA 670/2-74-072.

Yousef, A. Y., W. M. Mclellon, and H. H. Zebuth. 1980. Changes in phosphorus concentrations due to mixing by motorboats in shallow lakes. Water Research 14:841-852.

Table 1. A partial listing of possible contributing influences to stream shorebank erosion and failures

Recreational boat waves	Weather cycles
Commercial navigation	River stage and discharge
Wind-generated waves	Water level manipulation
Bank materials Particle size Sorting Stratificiation Cohesiveness	Sediment load Stream gradient Stream morphology
Internal erosion	Pore pressure/saturation
Rain splash	Groundwater discharge
Rain wash	Continental uplift
Ice heave	Freeze/thaw action

Table 2. A comparison of geologic, geomorphic, and hydrologic conditions in the Main Channel and Wisconsin Channel (river miles 787-790)

Attributes	Comparisons
Flow velocity	Similar
Energy gradient	Similar
Width	Similar
Channel sinuosity	Similar
Alluvial materials	Similar
Geologic origins	Similar
Weather conditions	Similar
Stage	Similar
Ice conditions	Similar
Sediment load	Similar
Wind orientation	Similar
Depth	Similar
Flow volume	Similar
Vegetation cover	Wisconsin Channel greater
Commercial navigation	Main Channel only
Recreational boating	Wisconsin Channel fewer/smaller
Surface sediments	Main Channel sandier

Table 3. Turbidity values for all locations, depths, and sampling runs on Saturday, August 1, 1992

Distance from shore (feet)	Distance from river bottom (feet)	Run #1 pre-boating 7:00 a.m.	Run #2 light boating 10:00 a.m.	Run #3 heavy boating 1:00 p.m.	Run #4 heavy boating 4:00 p.m.
10	0.5	37	82	250	230
25	0.5	42	54	125	185
25	1.5	39	57	122	138
50	0.5	29	40	125	93
50	1.0	32	39	145	96
50	2.5	27	34	145	54
100	0.5	53*	35	40	46
100	1.0	30	32	38	40
100	4	22	30	34	37
100	7	24	31	35	36
100	10	21	30	36	34
100	13	24	30	35	35
100	14	30	28	30	34
200	0.5	32	35	33	35
200	1.0	32	34	32	34
200	4	33	32	31	35
200	7	33	32	31	34
200	10	32	33	31	34
200	13	35	33	31	32
200	16	31	30	31	32
200	17	29	30	31	30

*Bottom disturbed while taking sample

Table 4. A comparison of commercial navigation and recreational boating contributing influences

Surface waves	Commerical	Recreational
Number per boat passage	10[1]	12-15, 30 max[2]
Wave train duration	40 sec[1]	20-26 sec., 50 max[2]
Average wave height	< 10 inches[4]	10 inches[2]
Maximum wave height	12 inches[3]	25 inches[2]
Speed of wave	5 FPS[1]	≈ 8 FPS[4]
Ratio peak 10 hours	1[5]	140-170[5]
Average number per week	70[5]	1,500-2,000[5]

Sources:

1. U.S. Army Corps of Engineers (1991, unpublished)
2. Bhowmik et al. (1991)
3. Illinois State Water Survey (1981)
4. DNR field observation
5. Bhowmik et al. (1991); Lemmerman (1991, unpublished)

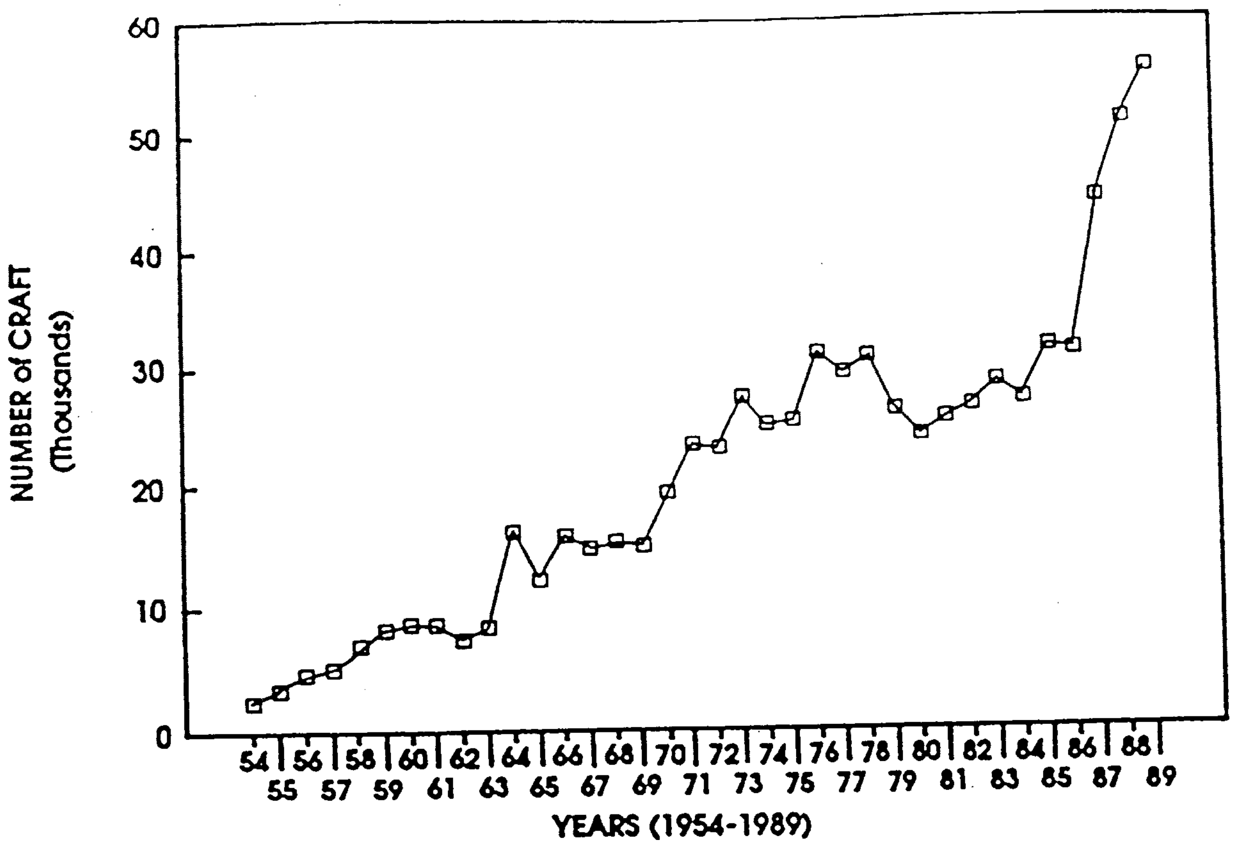


Figure 1. Combined recreational water traffic yearly totals at Lock and Dams 1 through 4

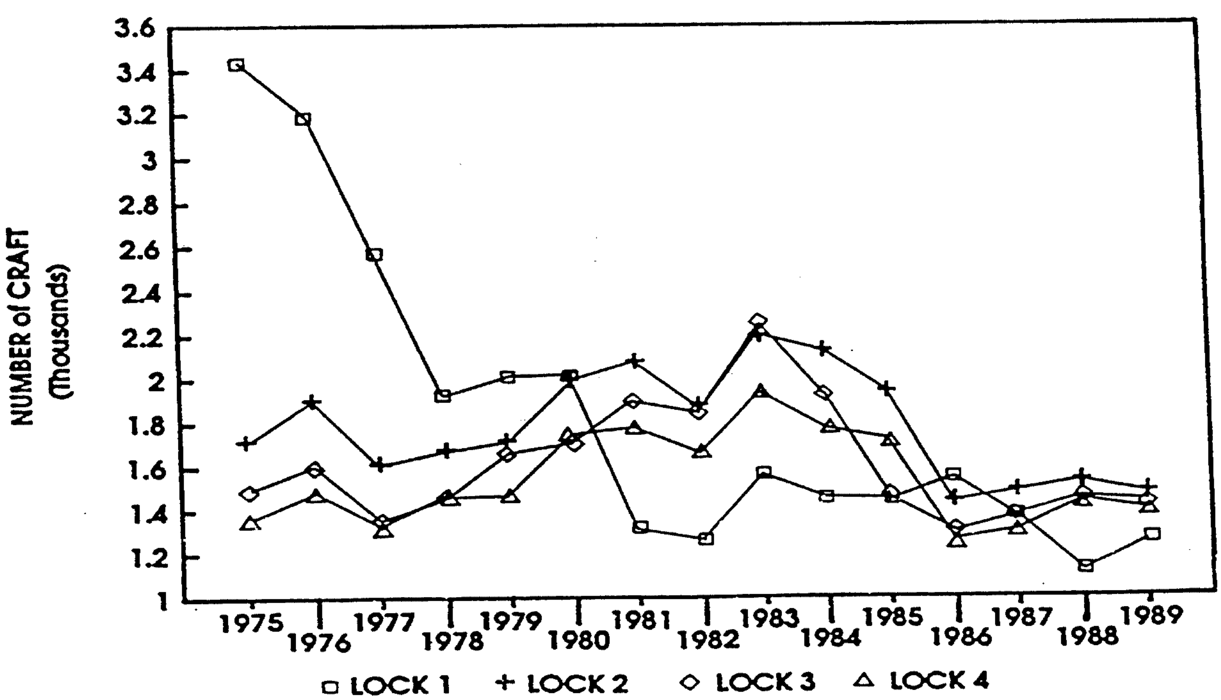


Figure 2. Commercial traffic at Lock and Dams 1 through 4

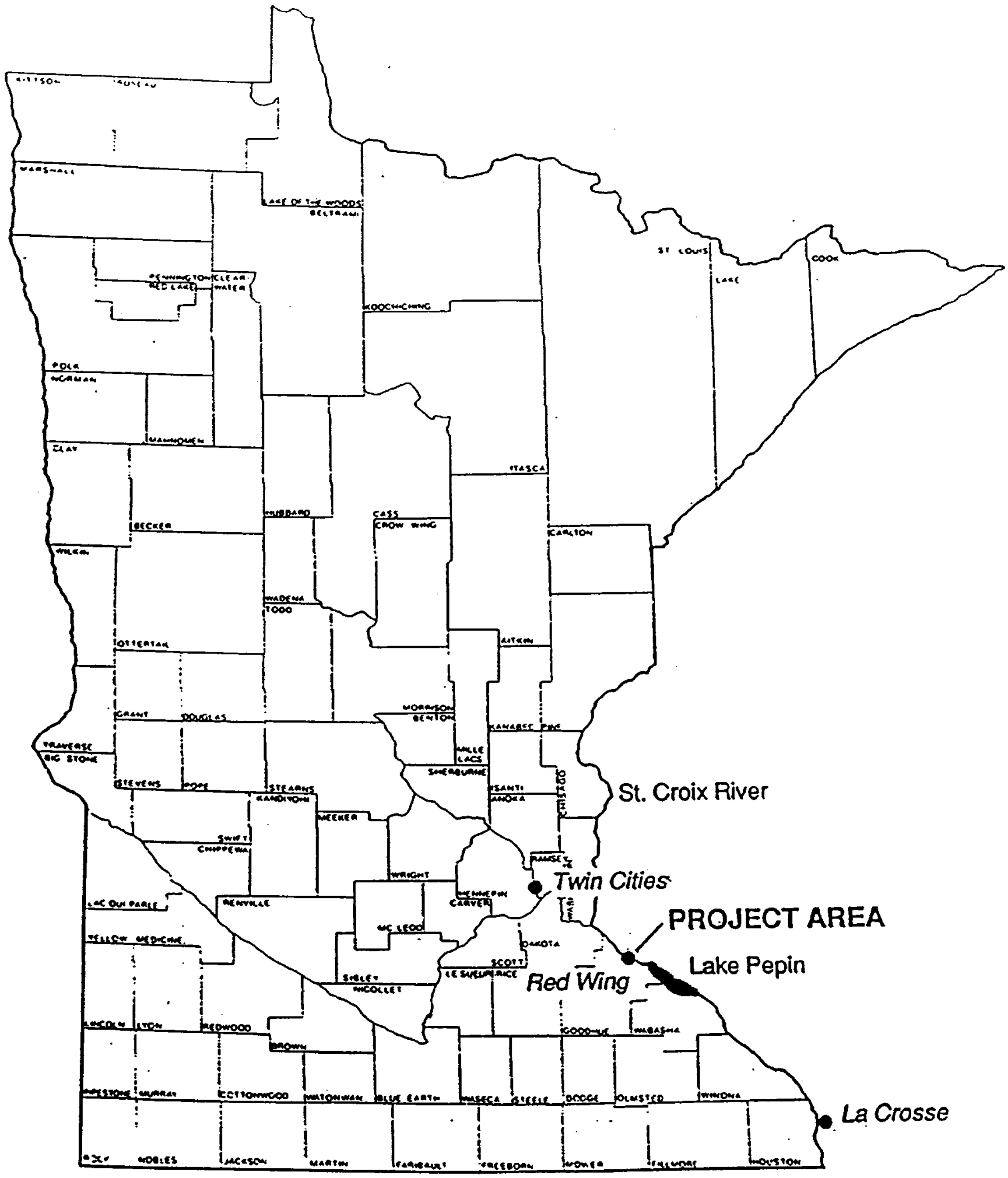


Figure 3. Study area location map

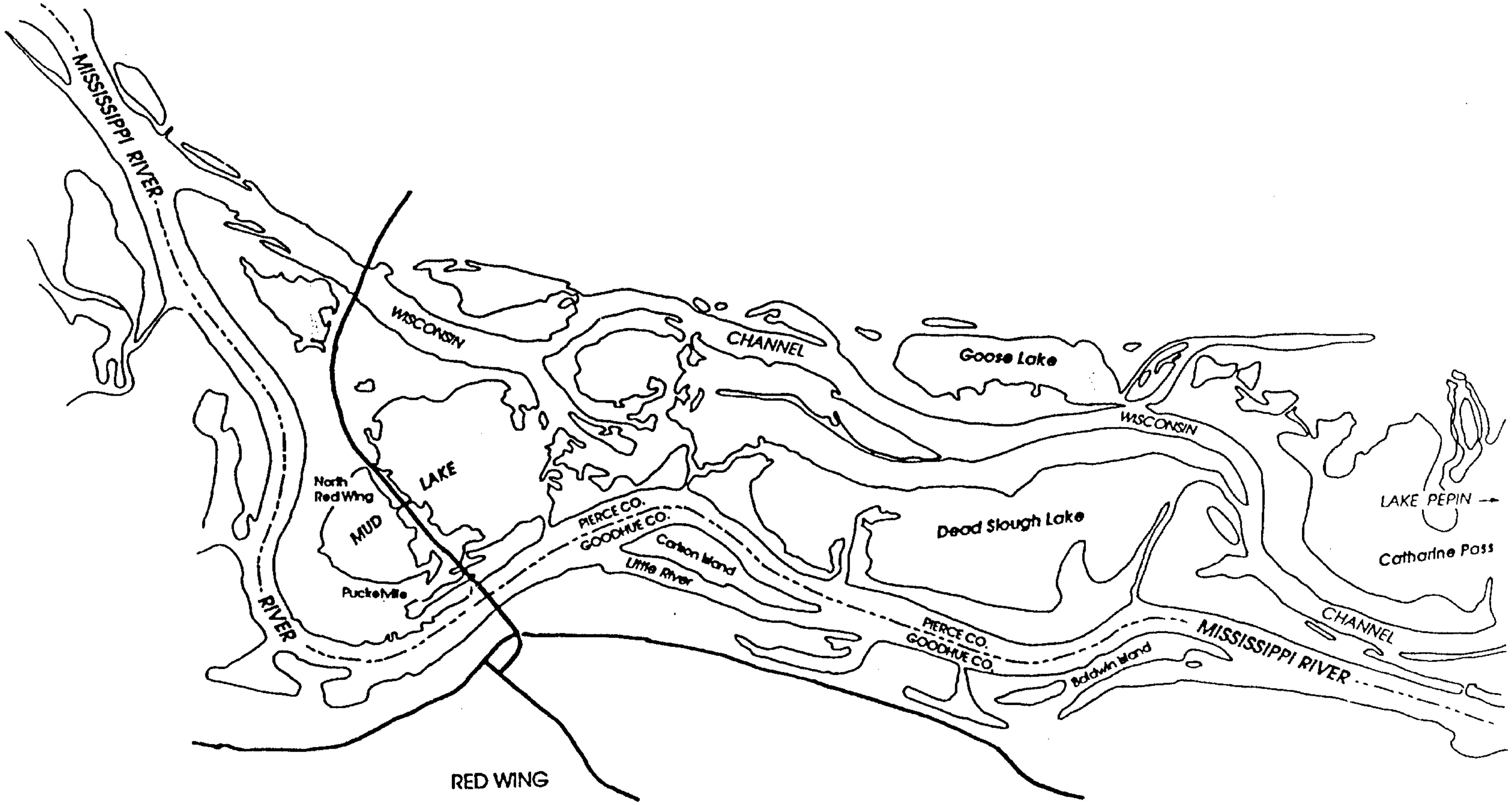


Figure 4. Red Wing study area

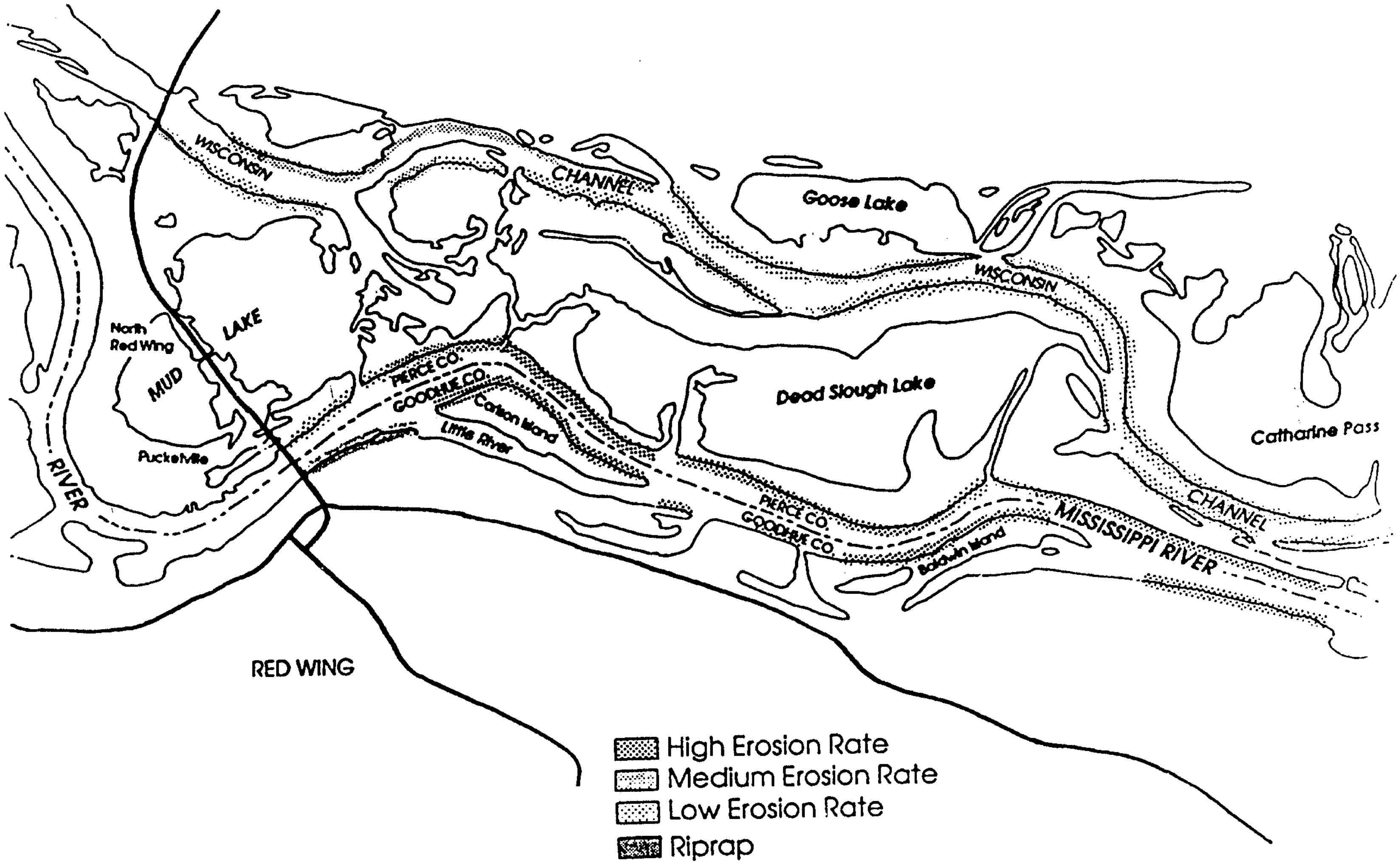


Figure 5. Qualitative erosion assessment results

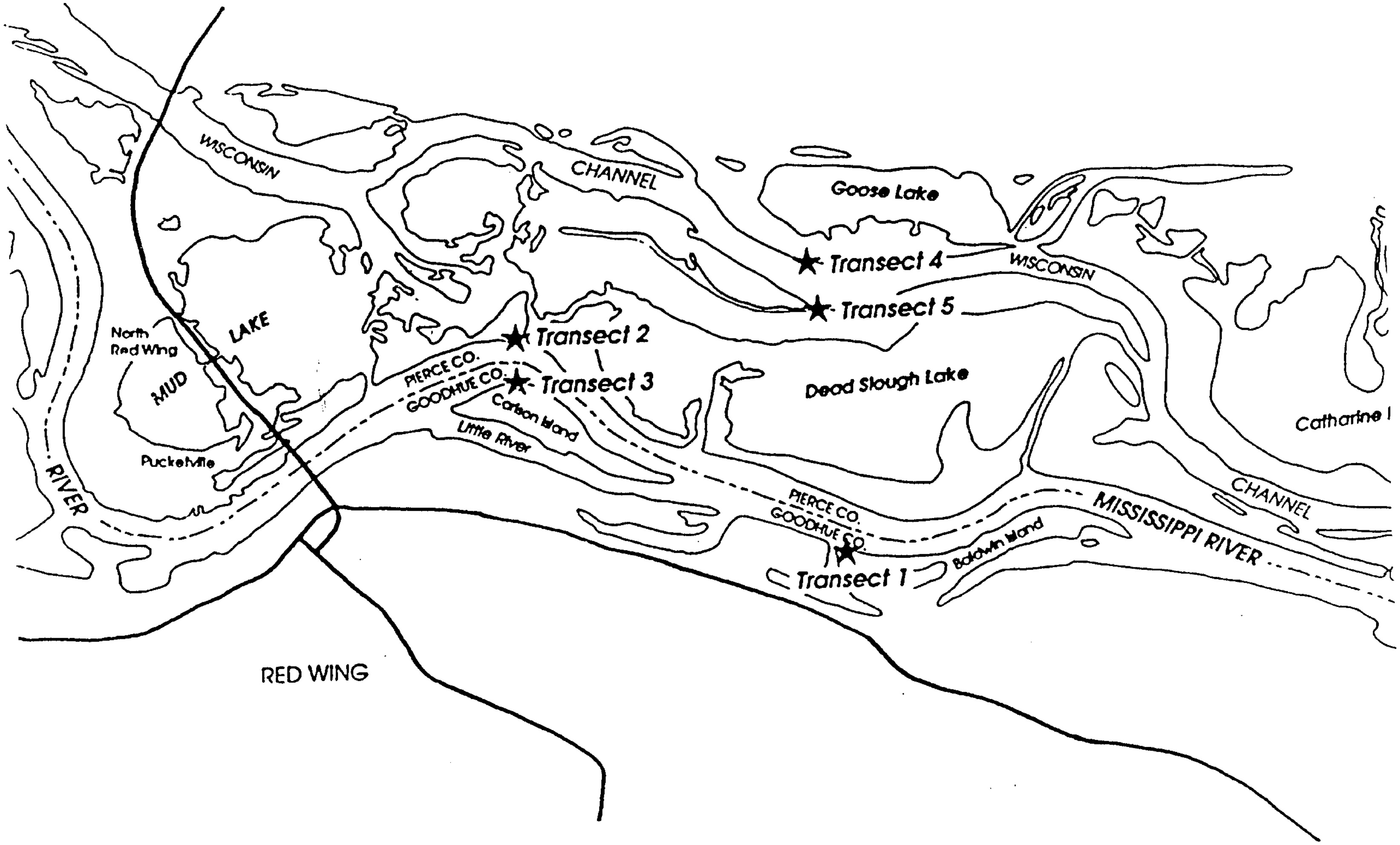


Figure 6. Quantitative shoreline survey transect locations

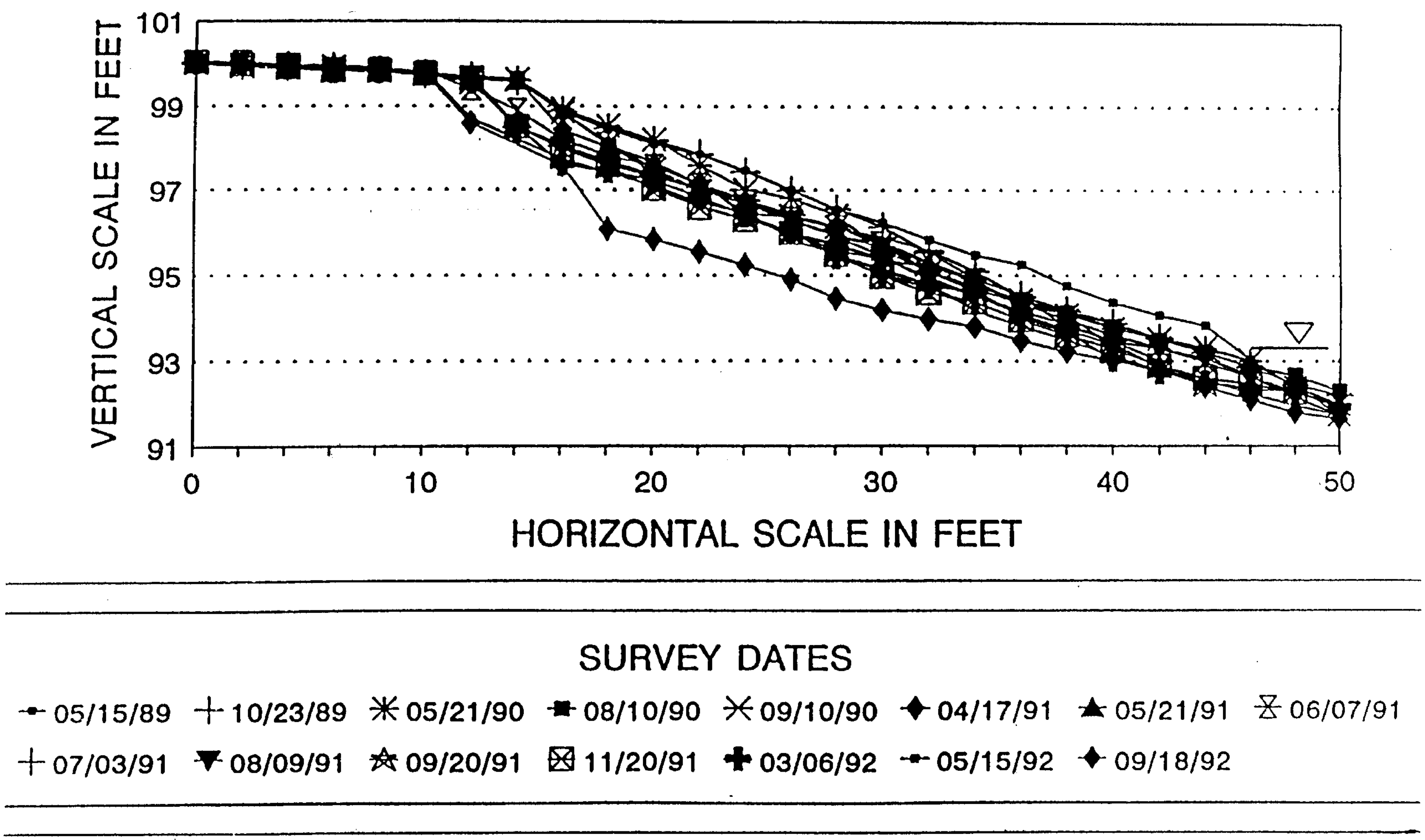


Figure 7. Transect 1, river mile 788.4 - Main Channel straight reach

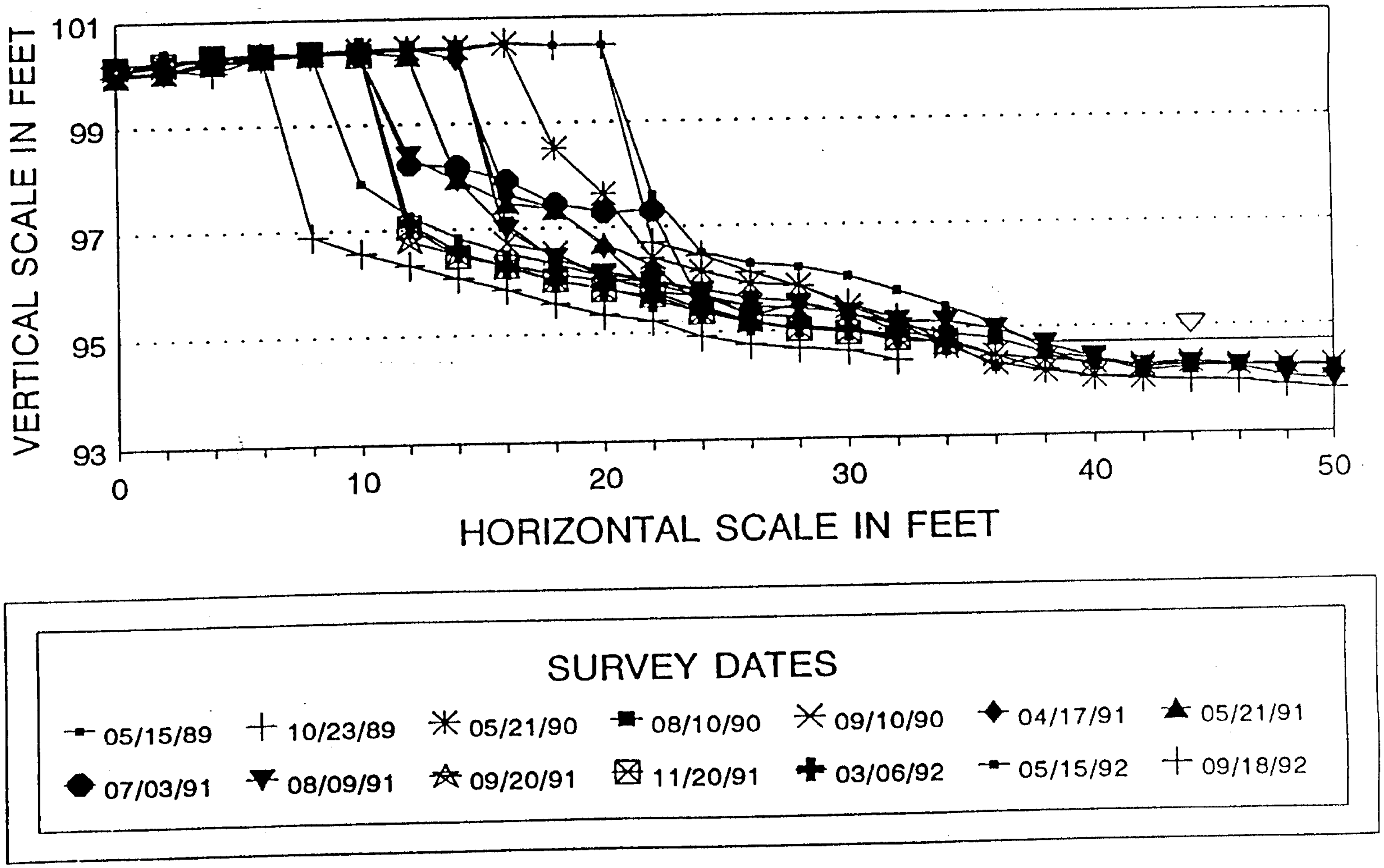


Figure 8. Transect 2, river mile 789.8 - Main Channel outside meander bend

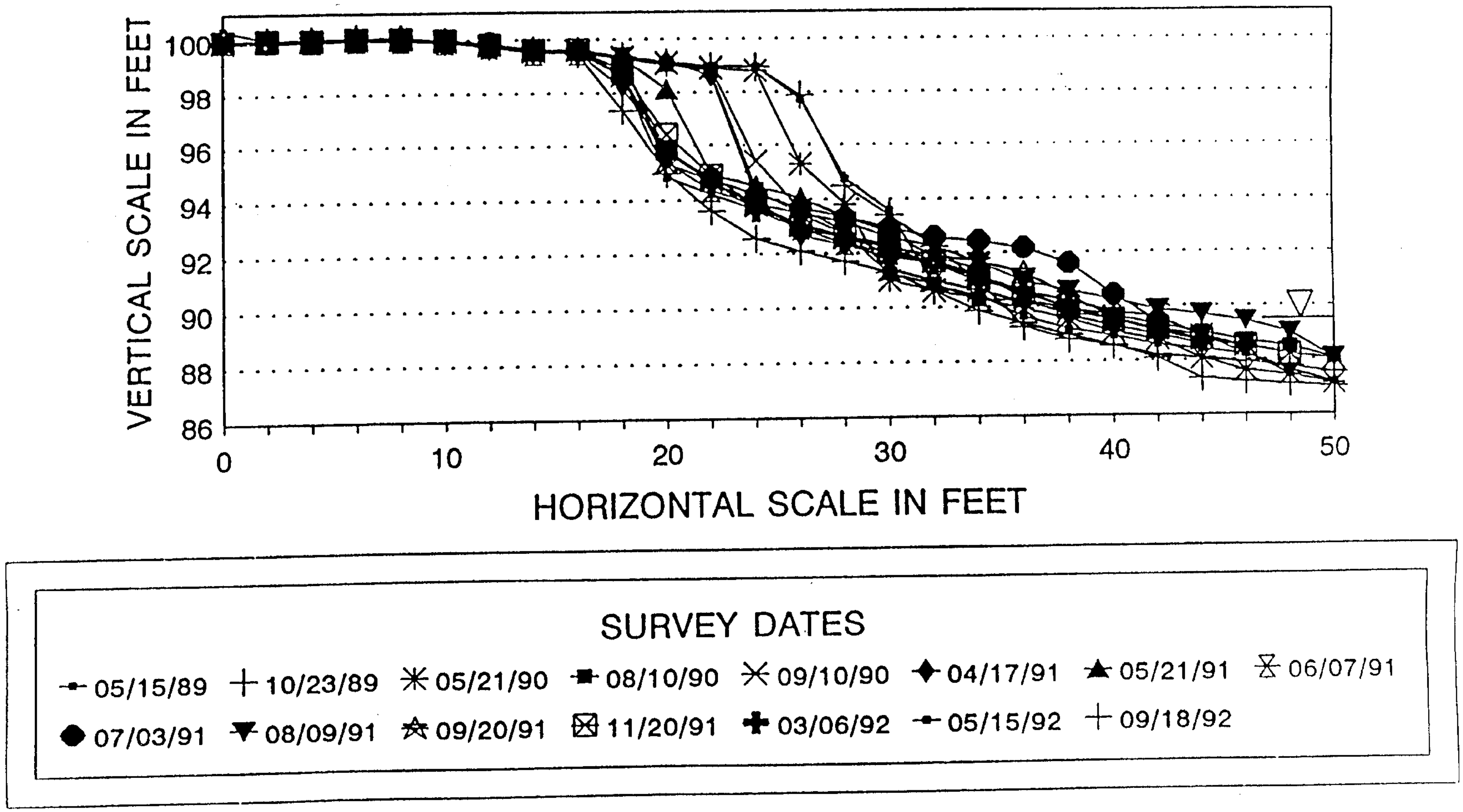


Figure 9. Transect 3, river mile 789.8 - Main Channel inside meander bend

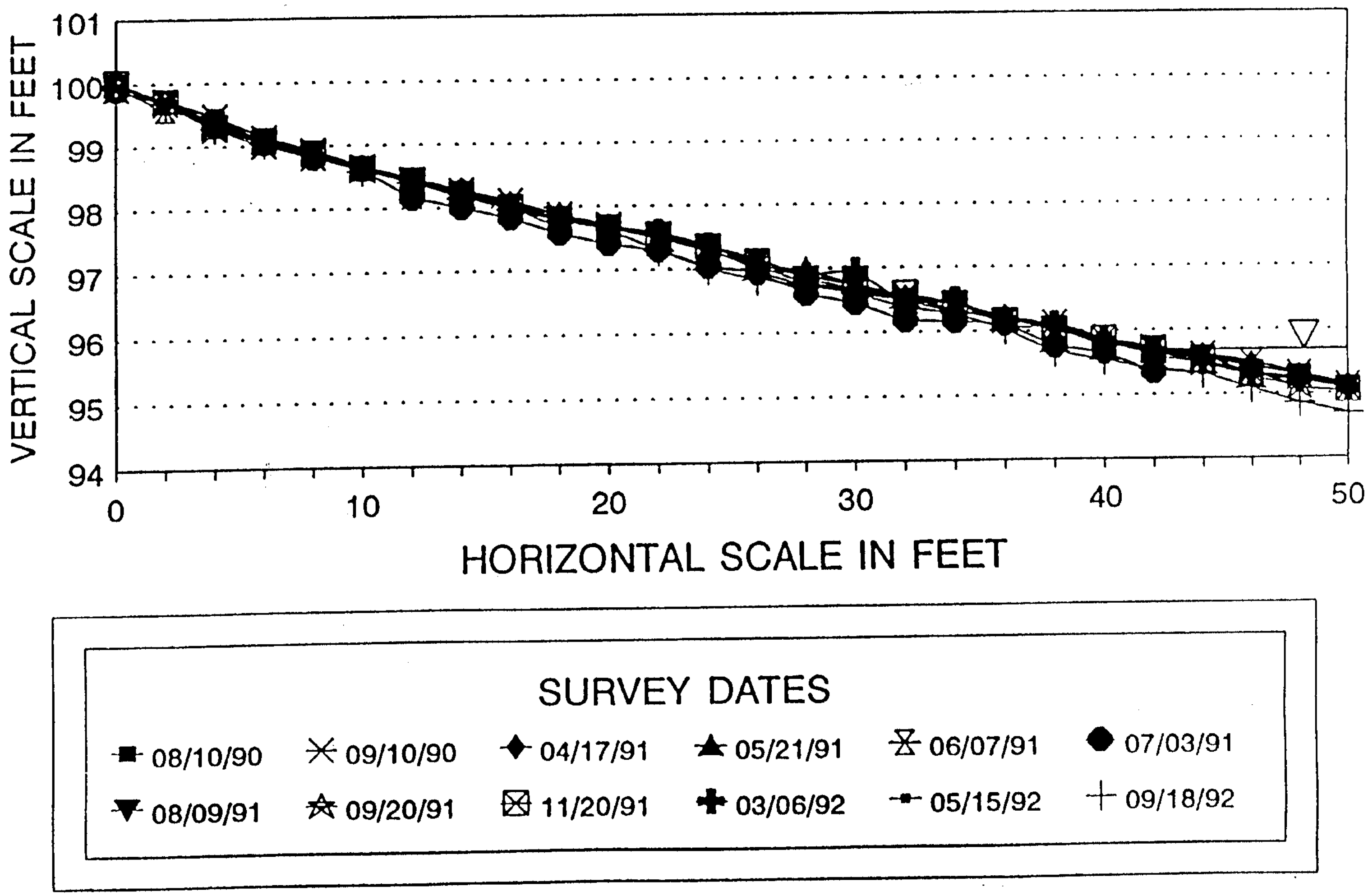


Figure 10. Transect 4, river mile 788.8 - Wisconsin Channel inside meander bend

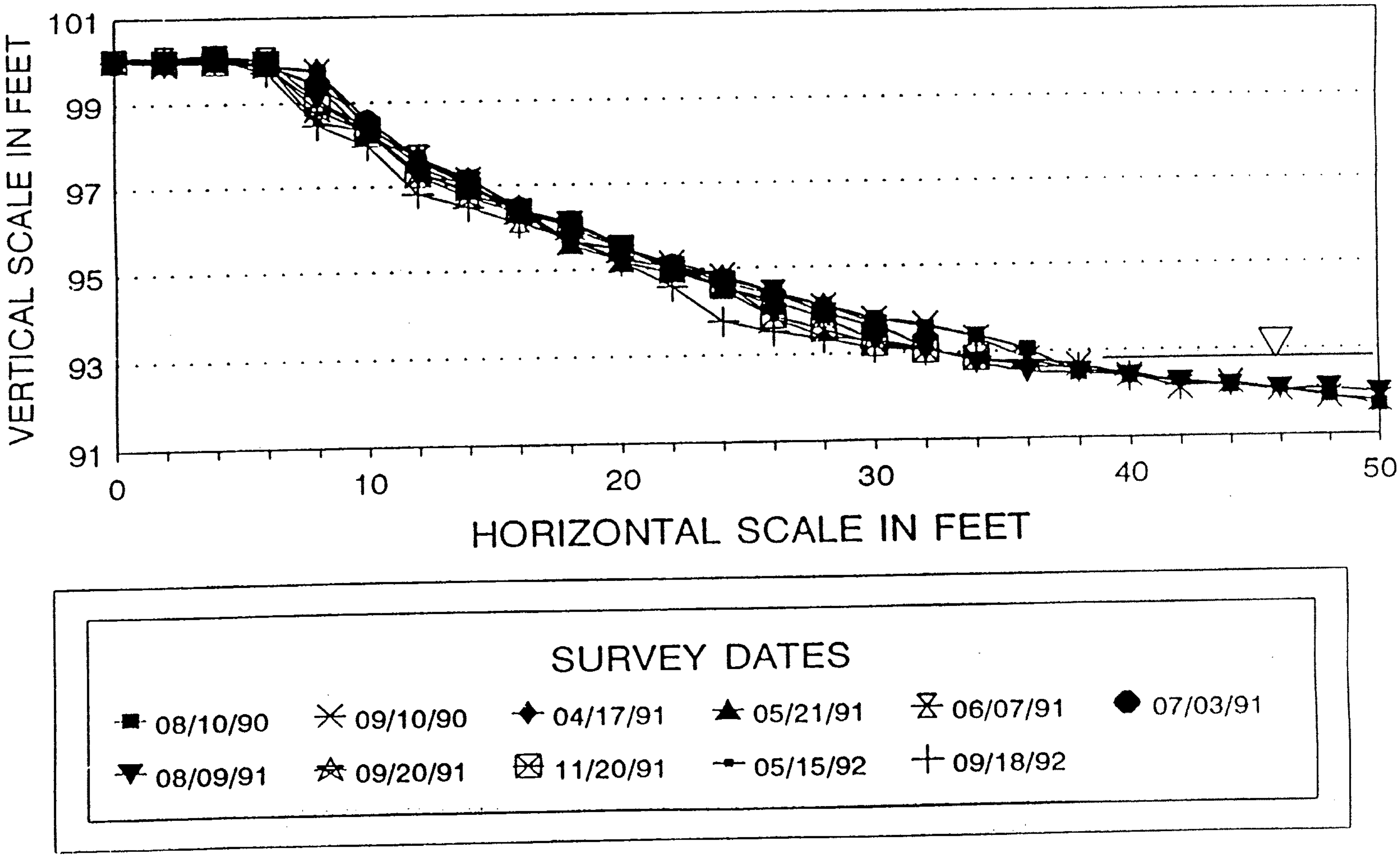


Figure 11. Transect 5, river mile 788.8 - Wisconsin Channel outside meander bend

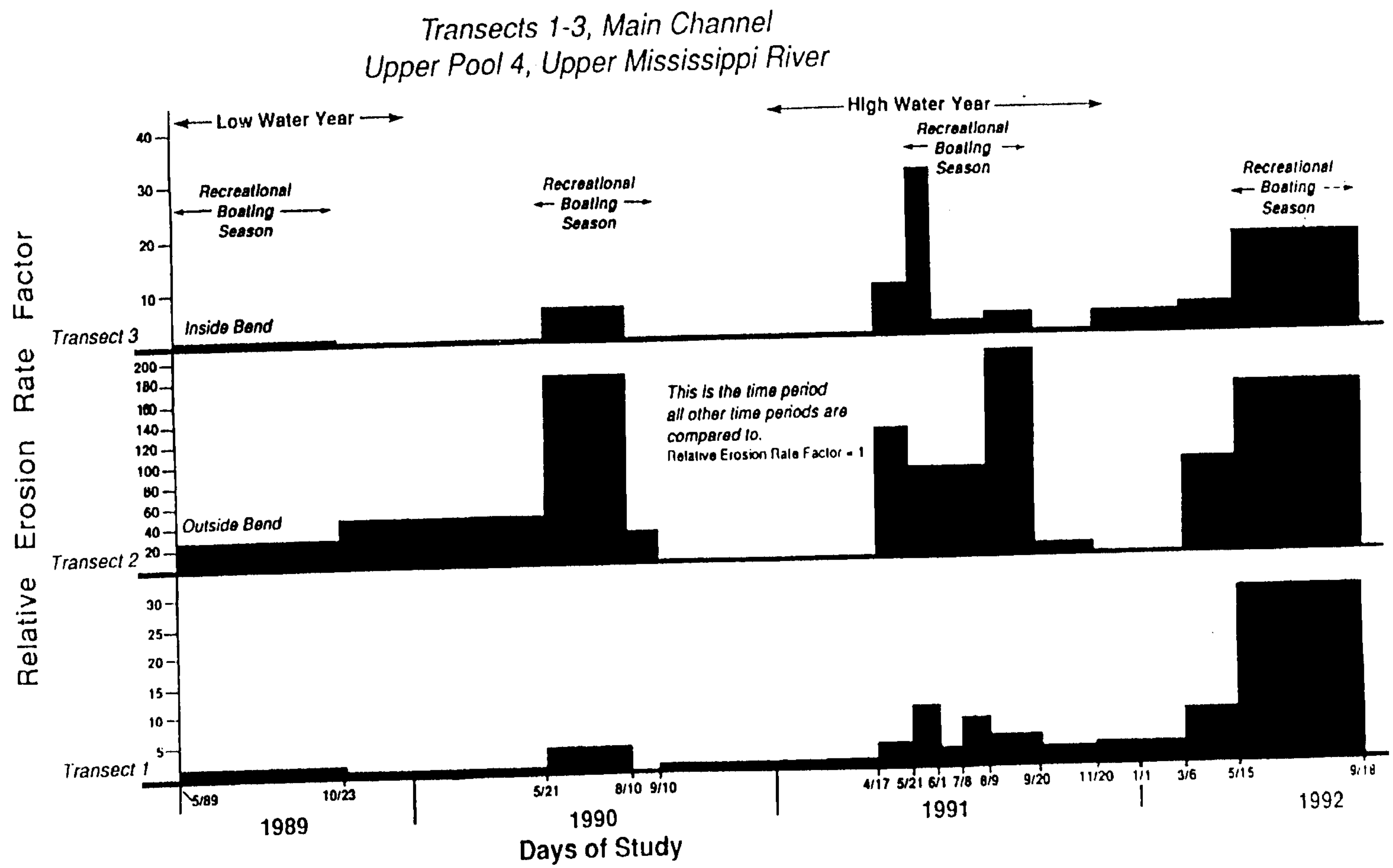


Figure 12. River shoreline relative erosion rates

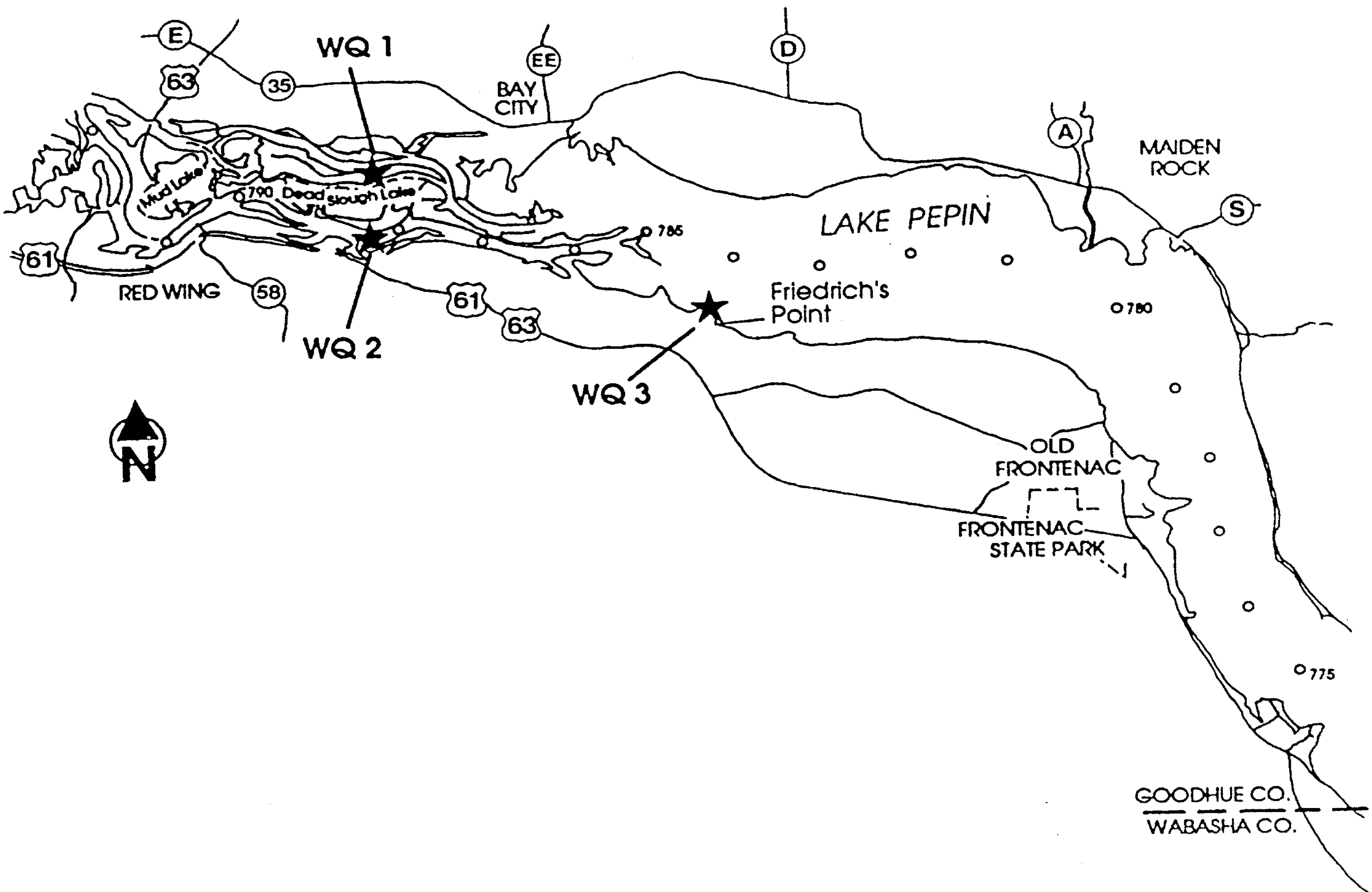


Figure 13. Water quality sampling locations for 2-m integrated samples

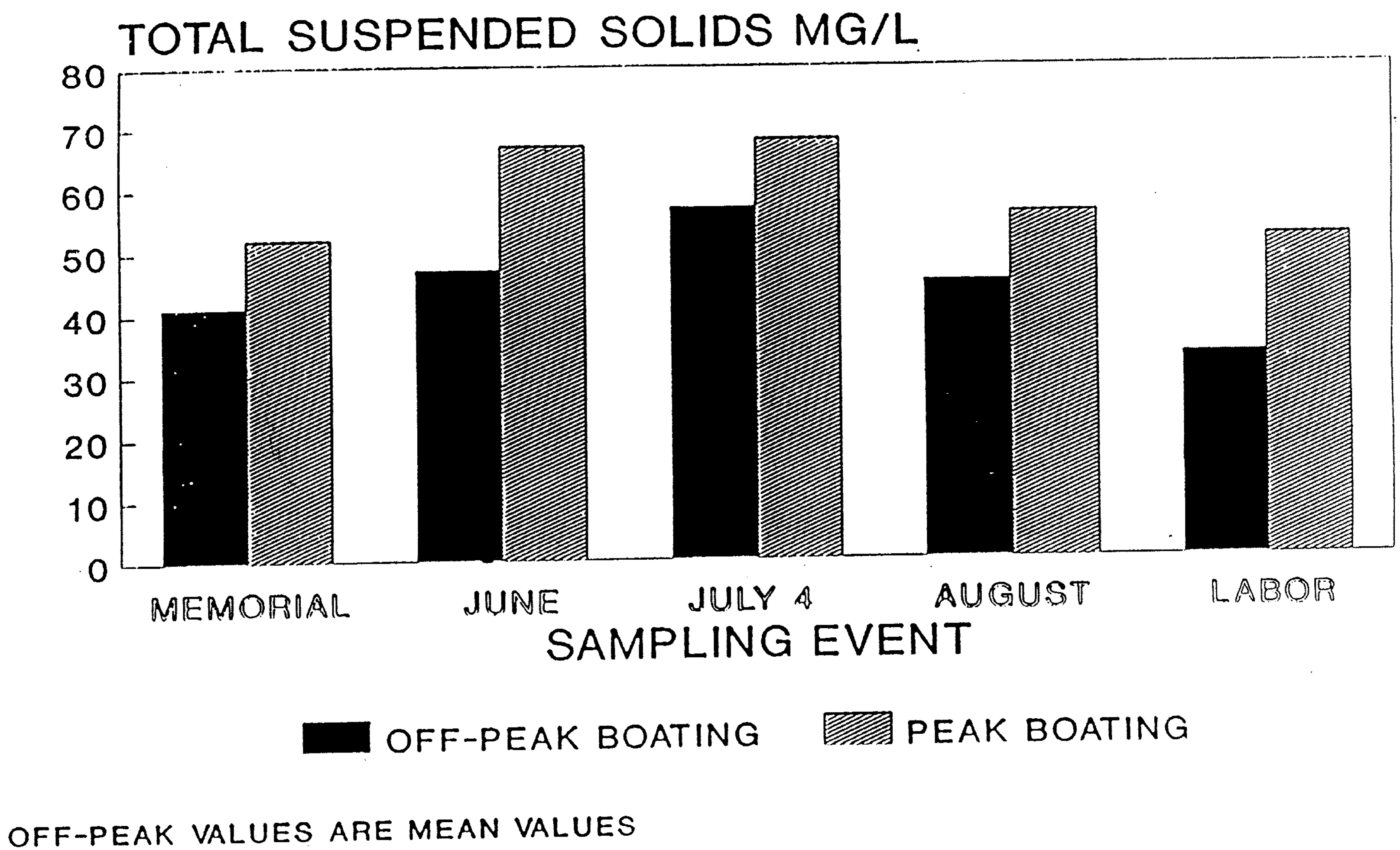


Figure 14. Main Channel total suspended solids - peak versus off-peak boating times

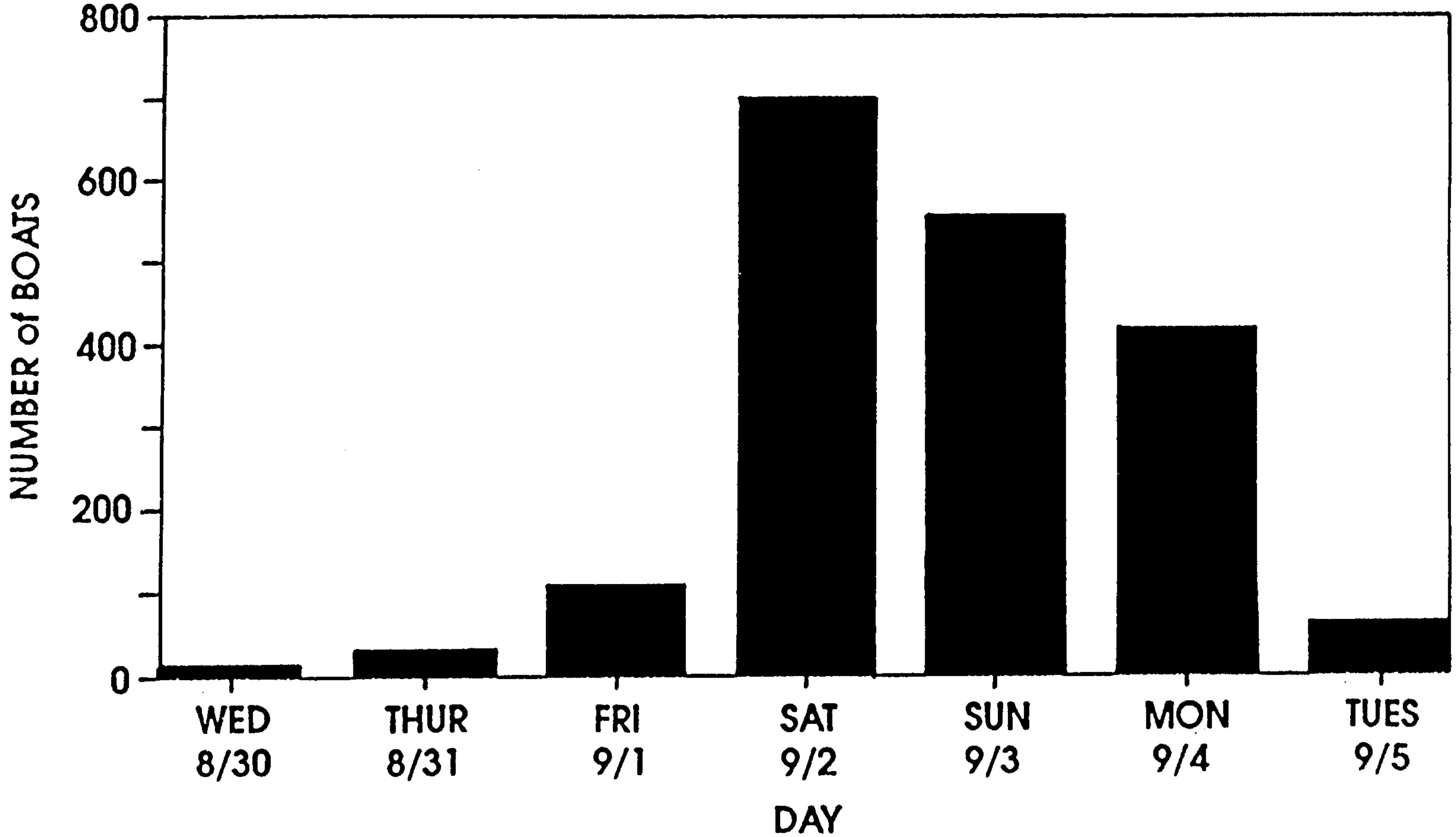


Figure 15. Typical holiday/weekend recreational boating activity levels

Frequency analysis of boat passages, August 30, 1989, through September 5, 1989, Red Wing site (adapted from Bhowmik et al. 1991)

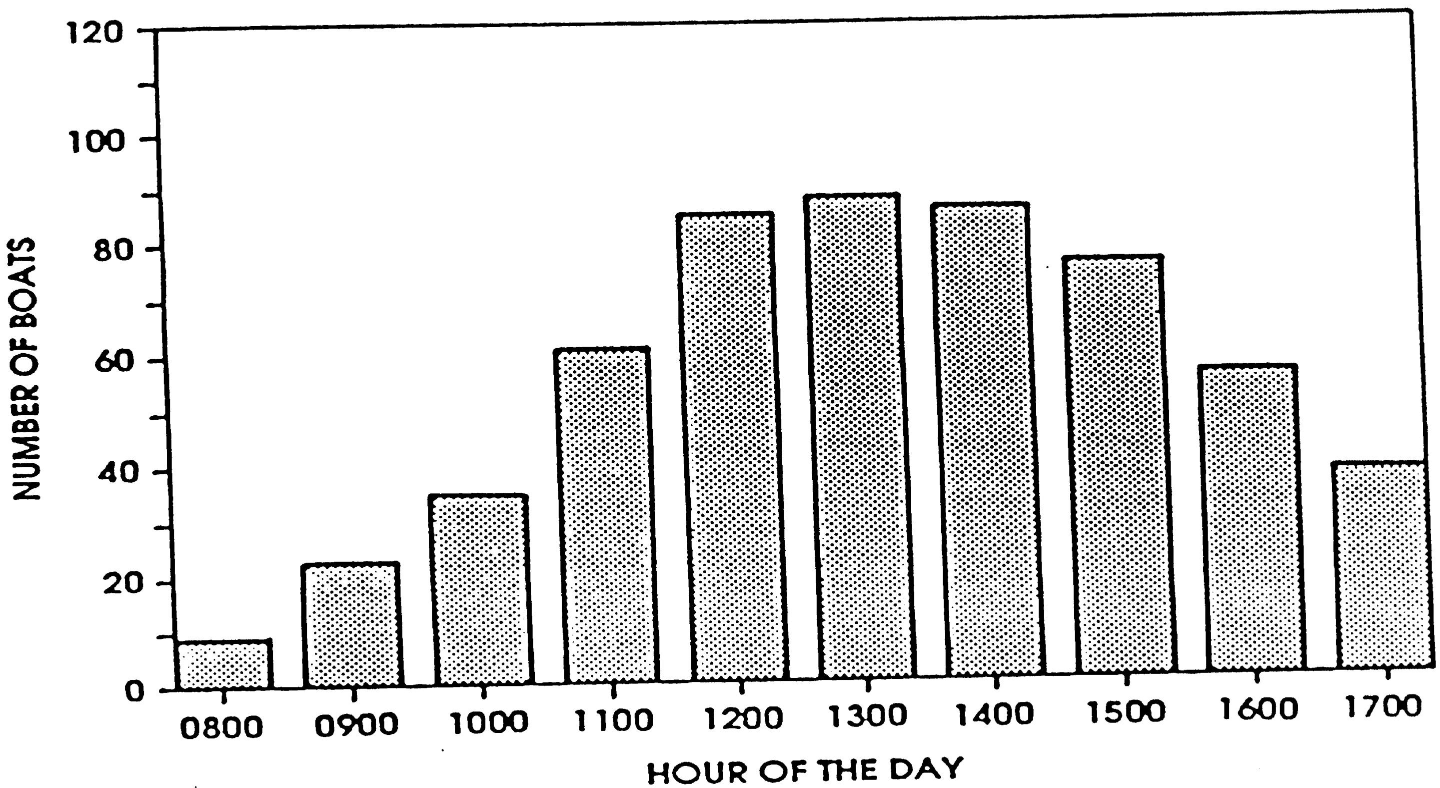


Figure 16. Typical holiday weekend daily distribution of boat passages (adapted from Bhowmik et al. 1991)

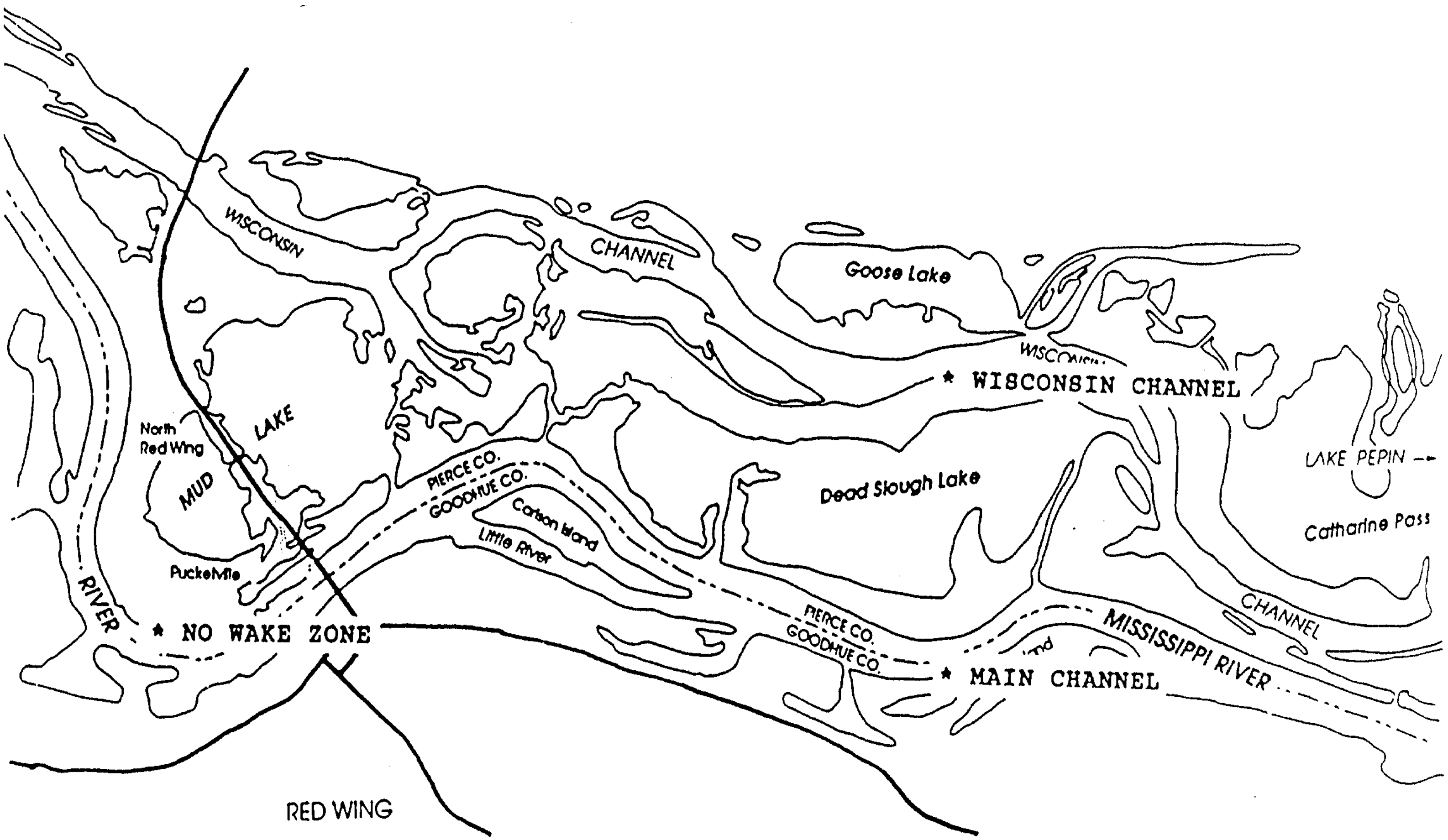


Figure 17. Location of discrete water samplers

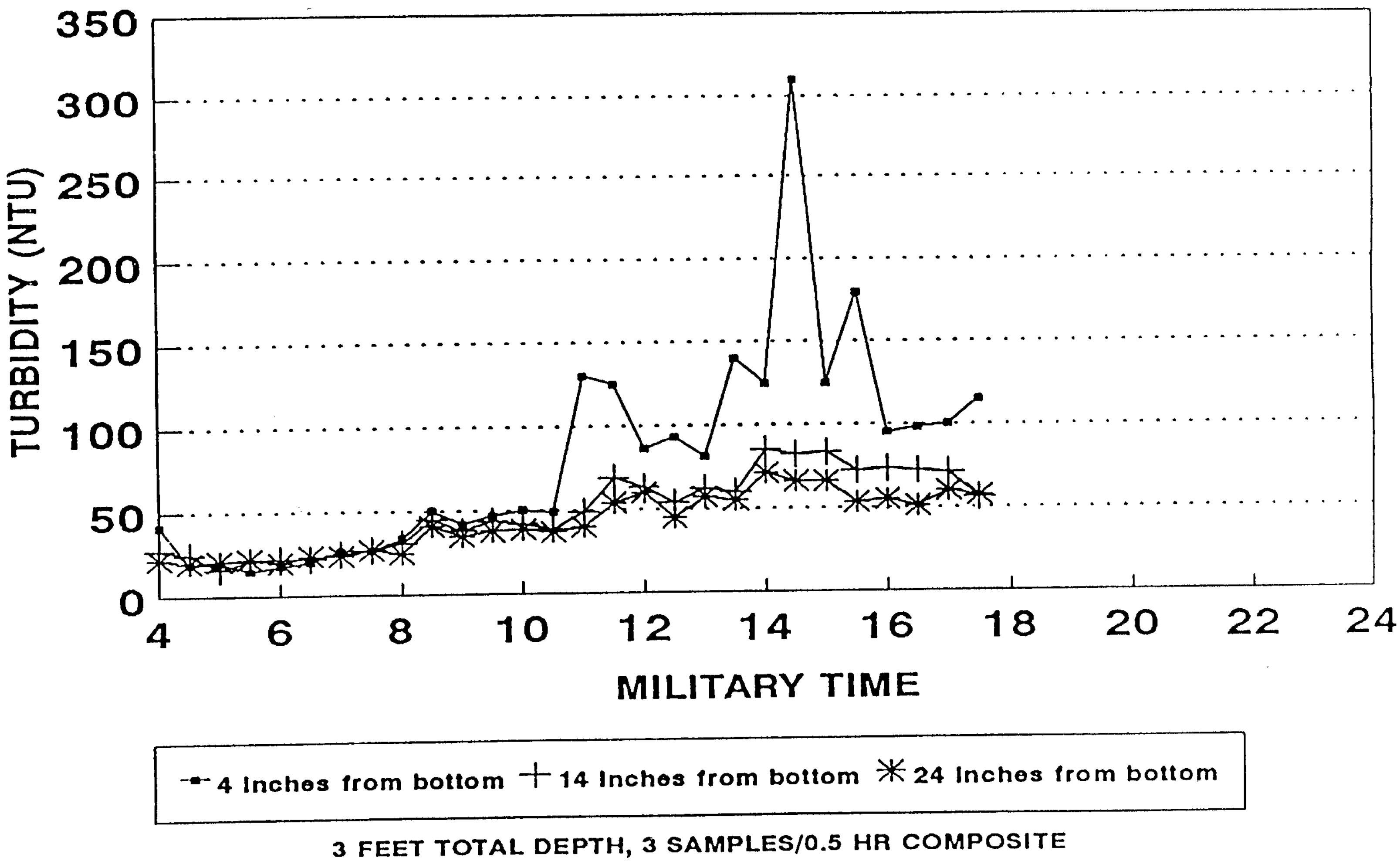


Figure 18. Main Channel water column turbidity at three different depths on Saturday, July 17, 1991

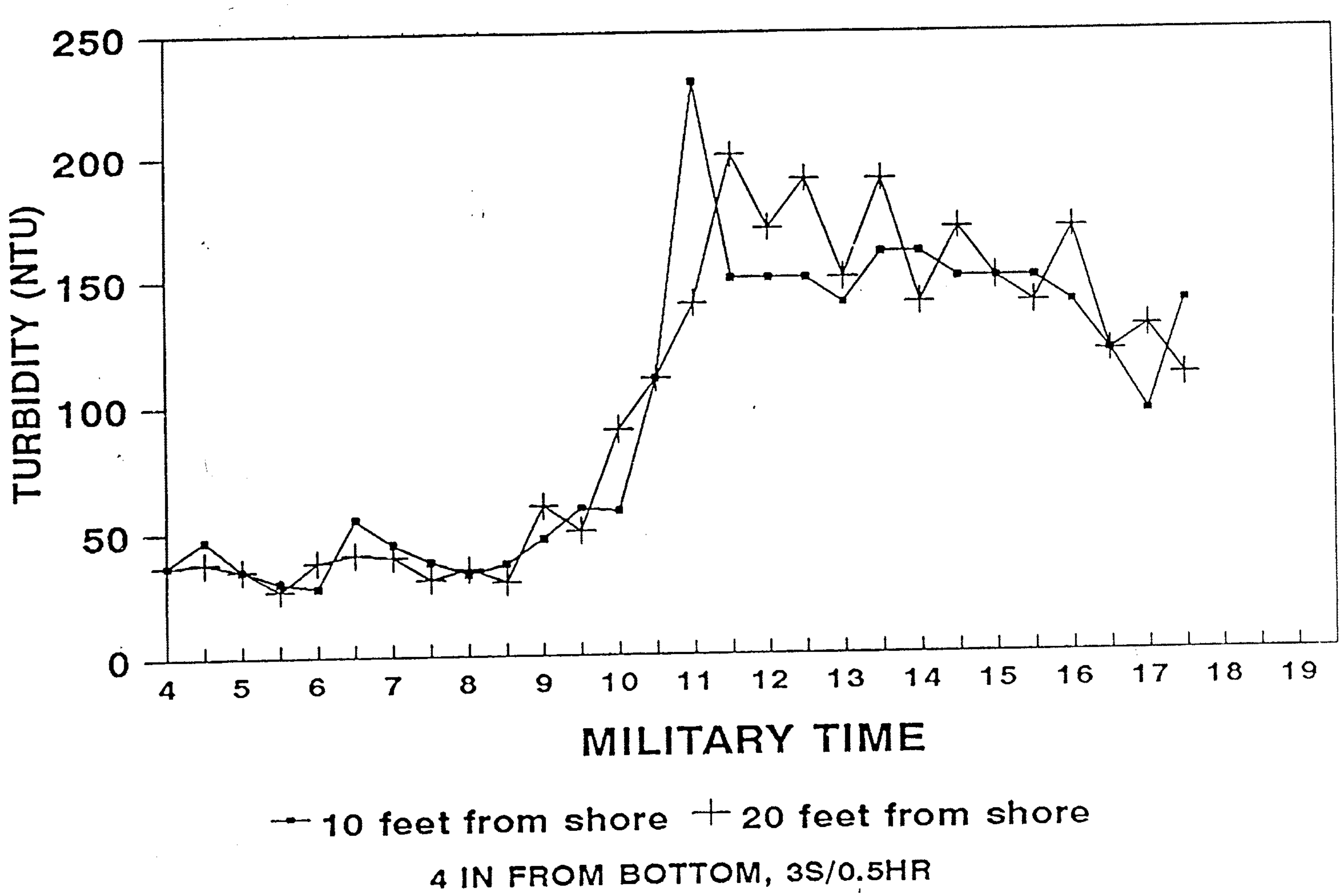


Figure 19. Main Channel turbidity at 10 and 20 feet from shore on Sunday, August 4, 1991

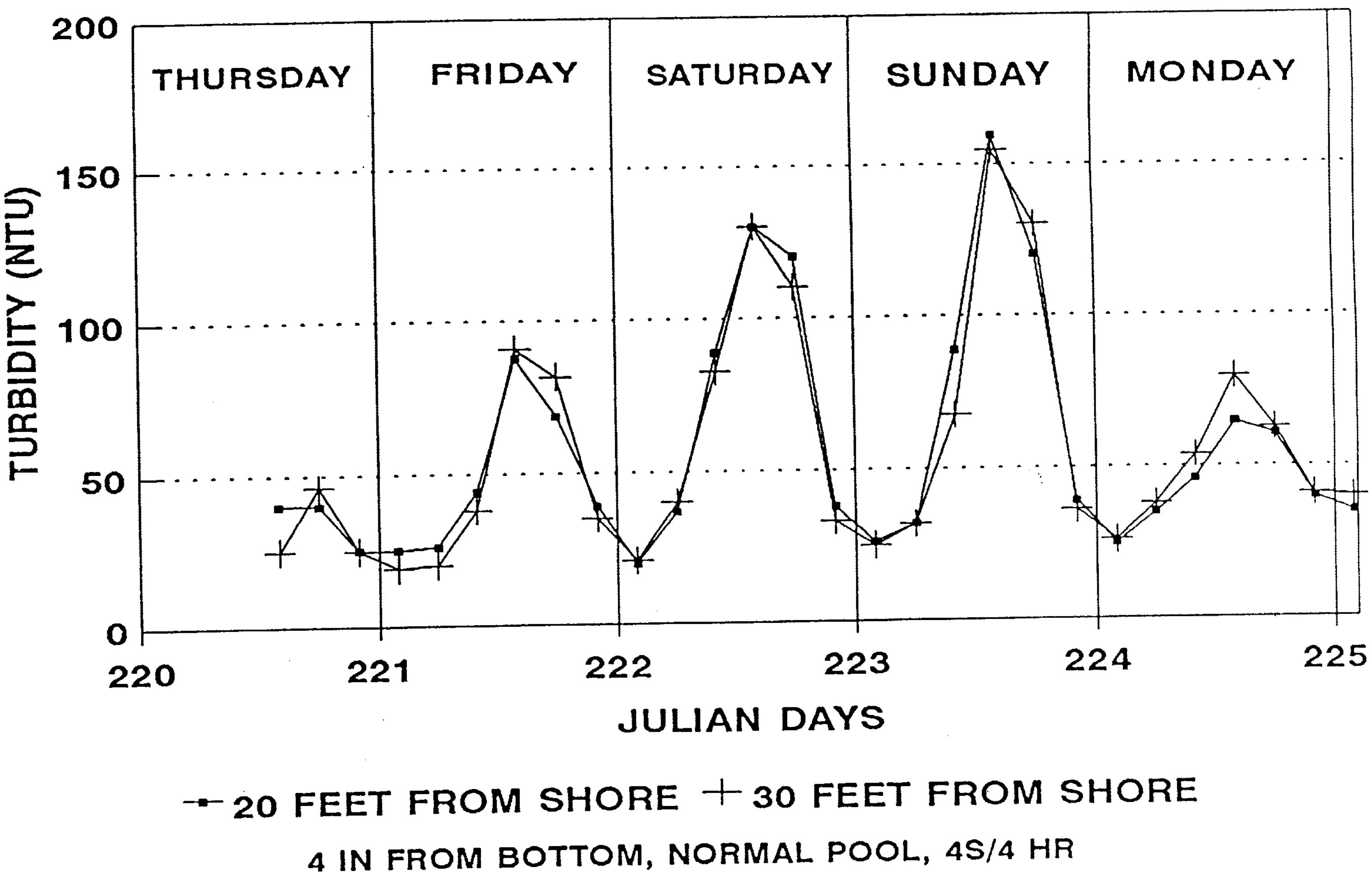


Figure 20. Main Channel turbidity at 20 and 30 feet from shore Thursday, August 8, to Monday, August 13, 1991

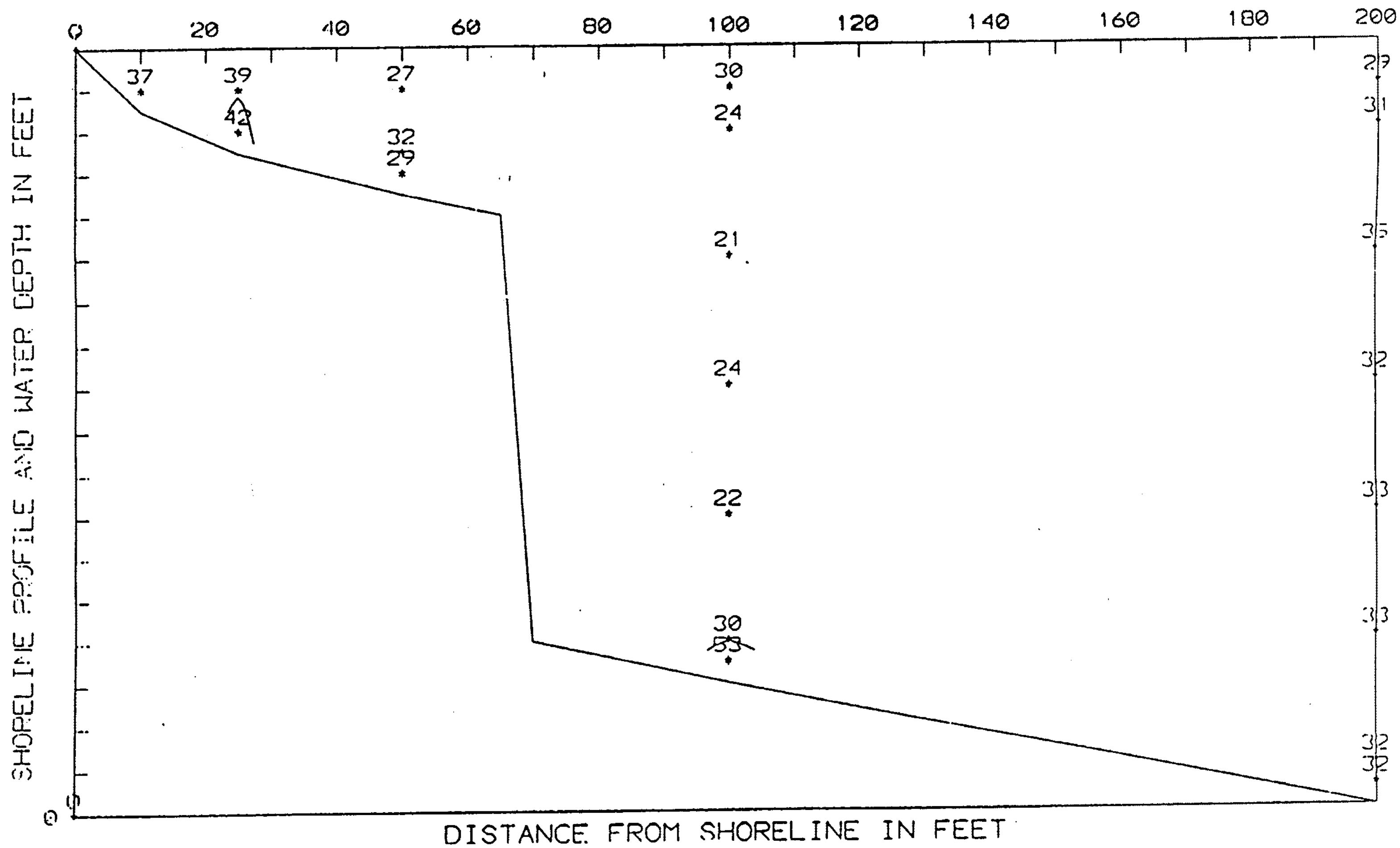


Figure 21. Run 1, 7 a.m., Saturday, August 1, 1992; contour plot of turbidity values

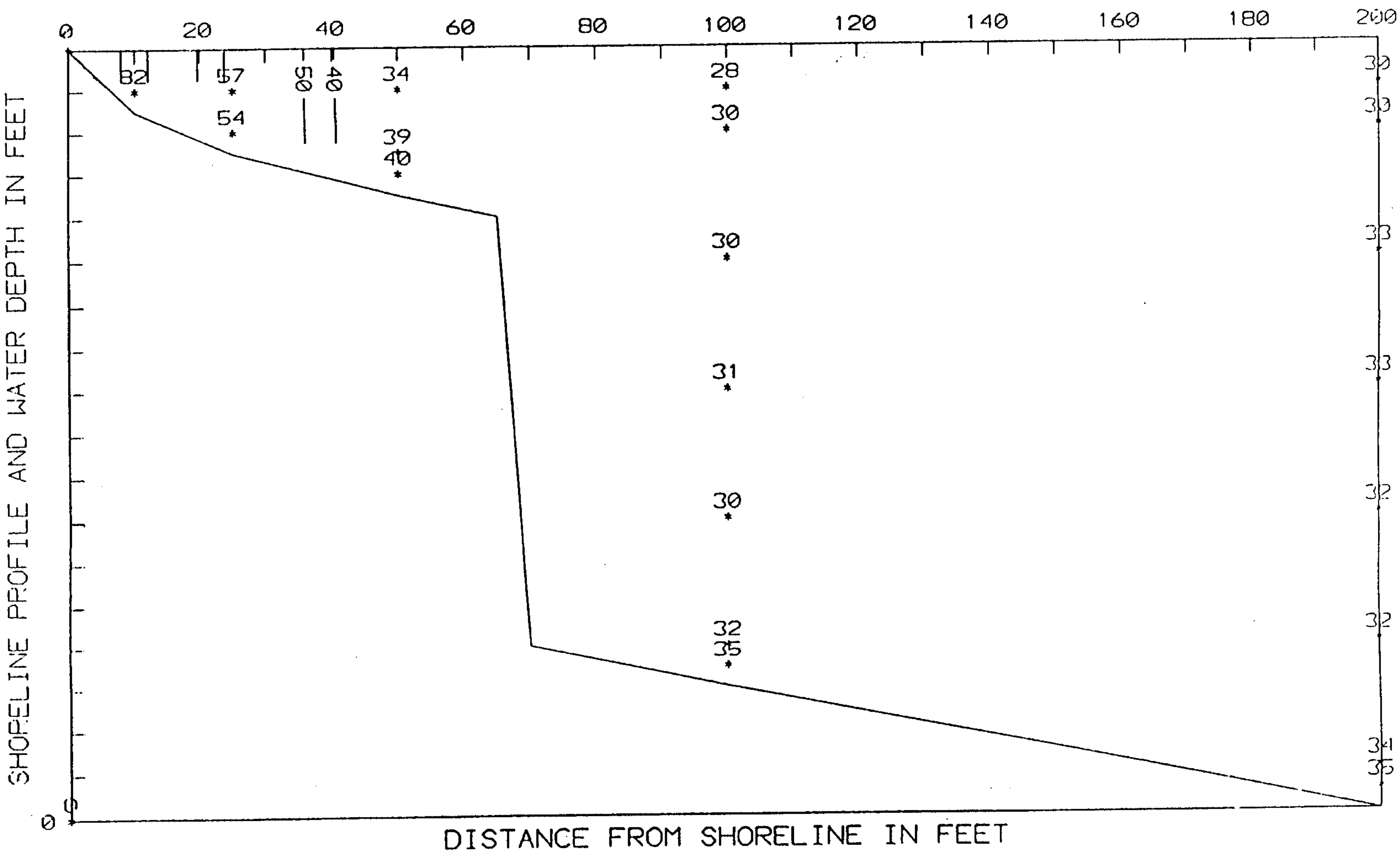


Figure 22. Run 2, 10 a.m., Saturday, August 1, 1992; contour plot of turbidity values

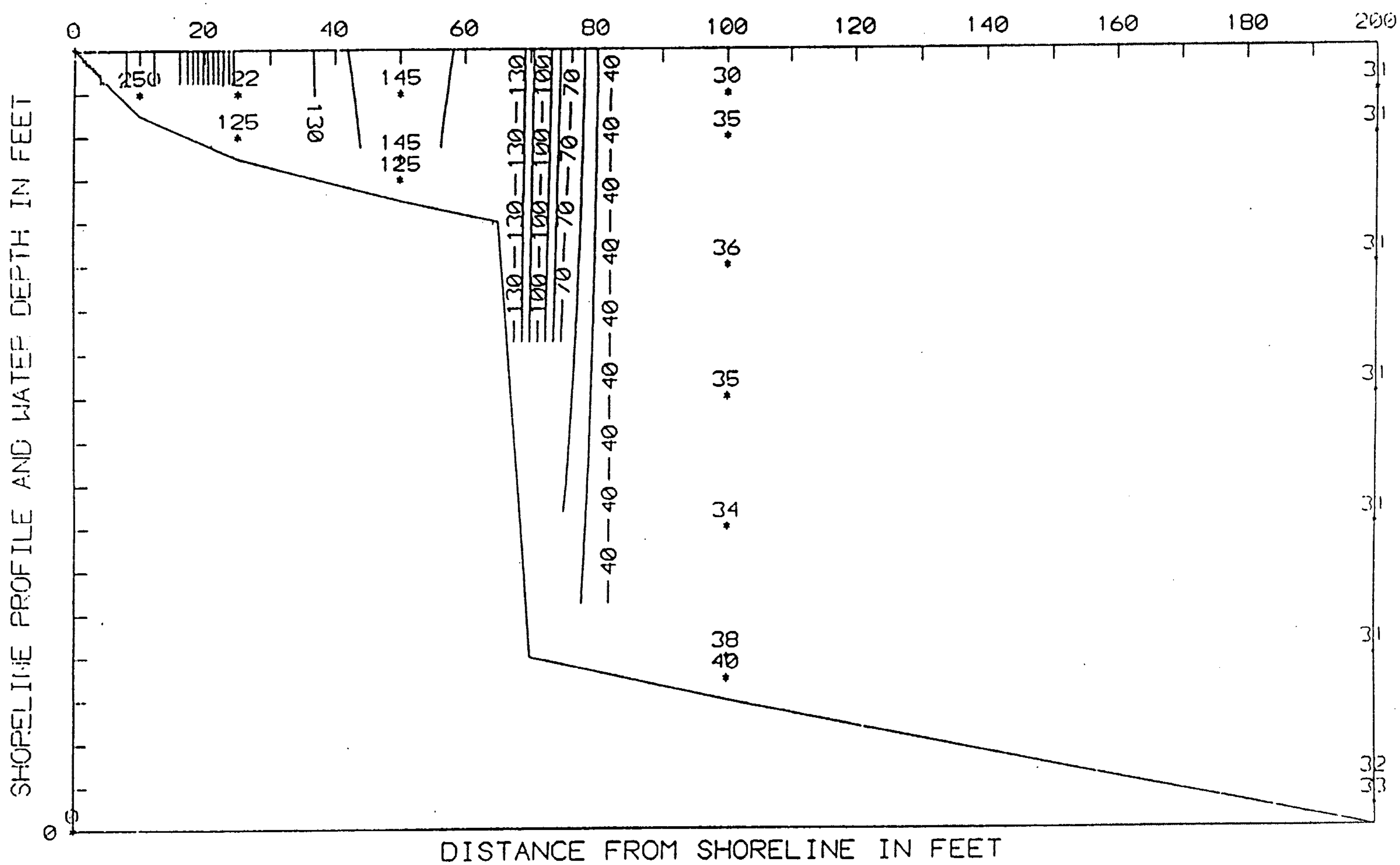


Figure 23. Run 3, 1 p.m., Saturday, August 1, 1992; contour plot of turbidity values

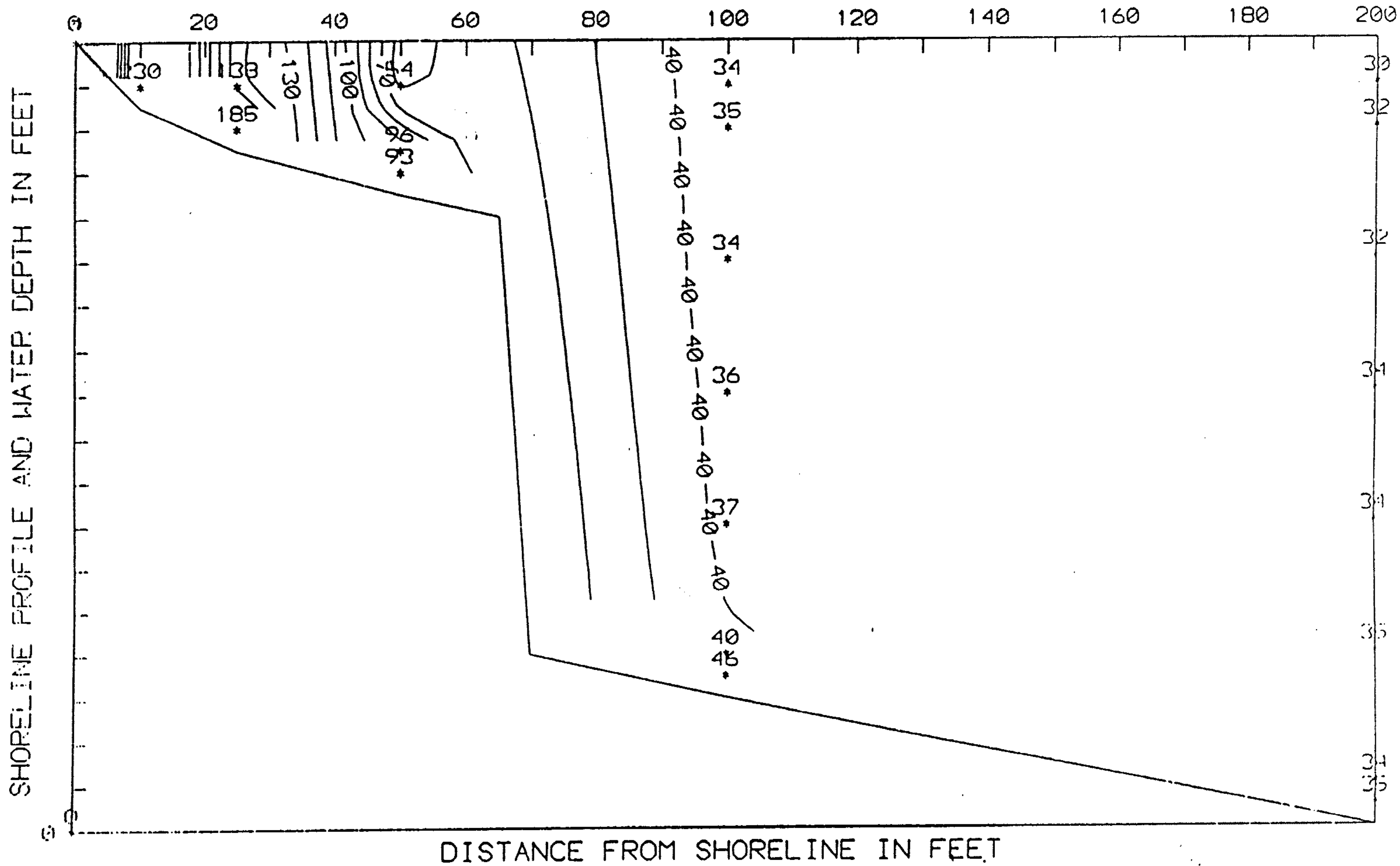


Figure 24. Run 4, 4 p.m., Saturday, August 1, 1992; contour plot of turbidity values

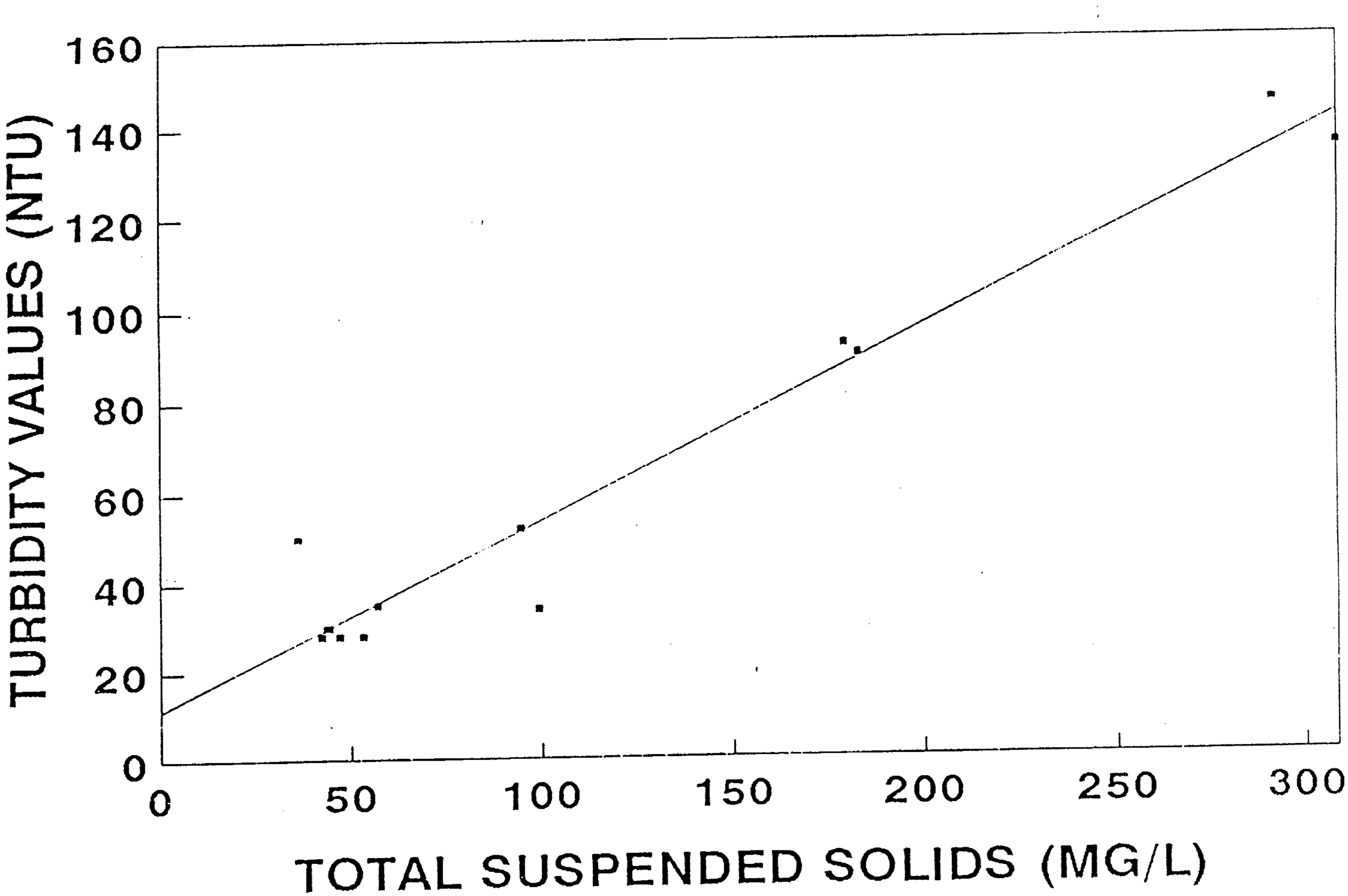


Figure 25. Main Channel turbidity and total suspended solids trend analysis

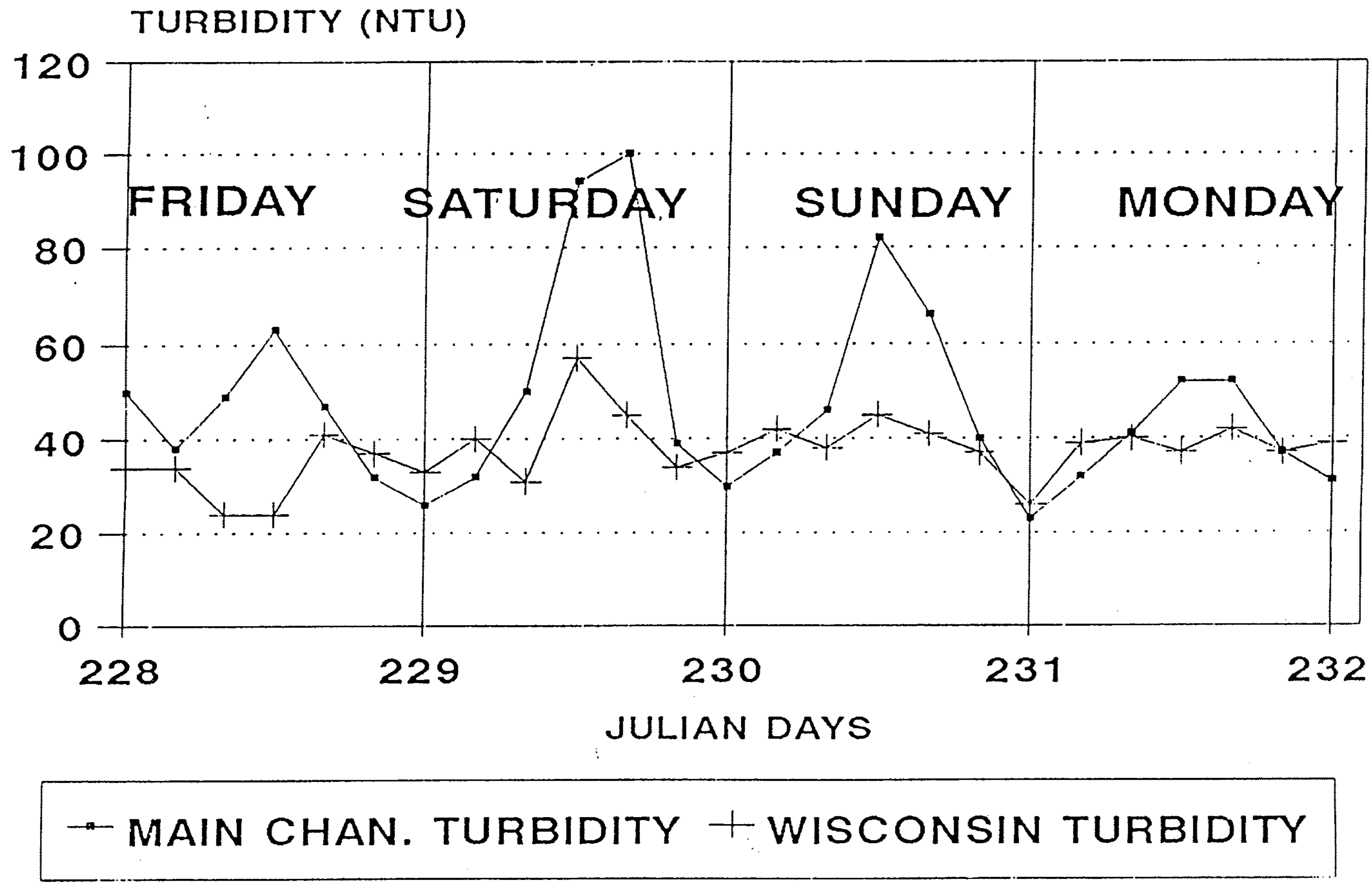


Figure 26. Main Channel and Wisconsin Channel turbidity values August 15-19, 1991

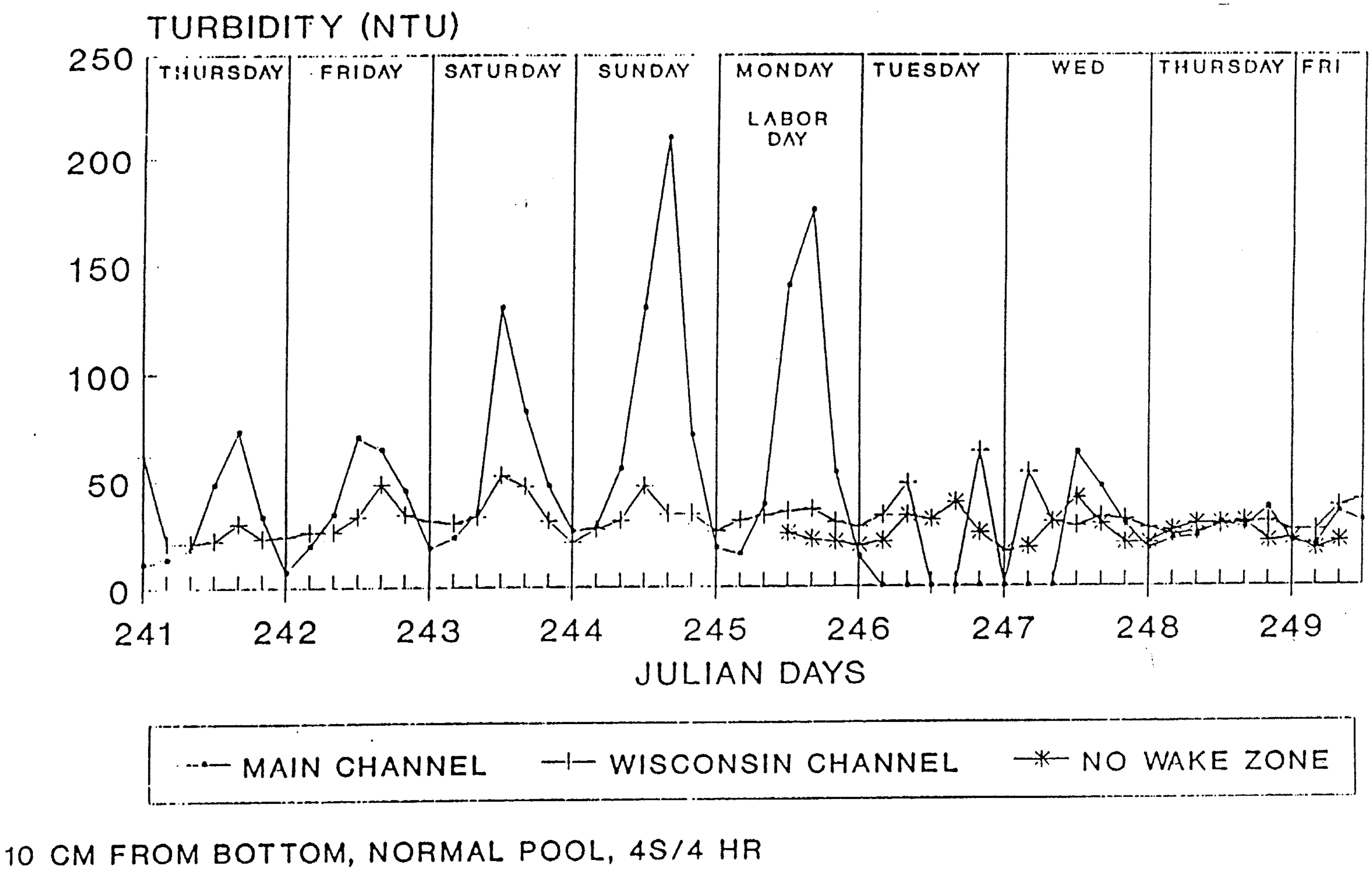
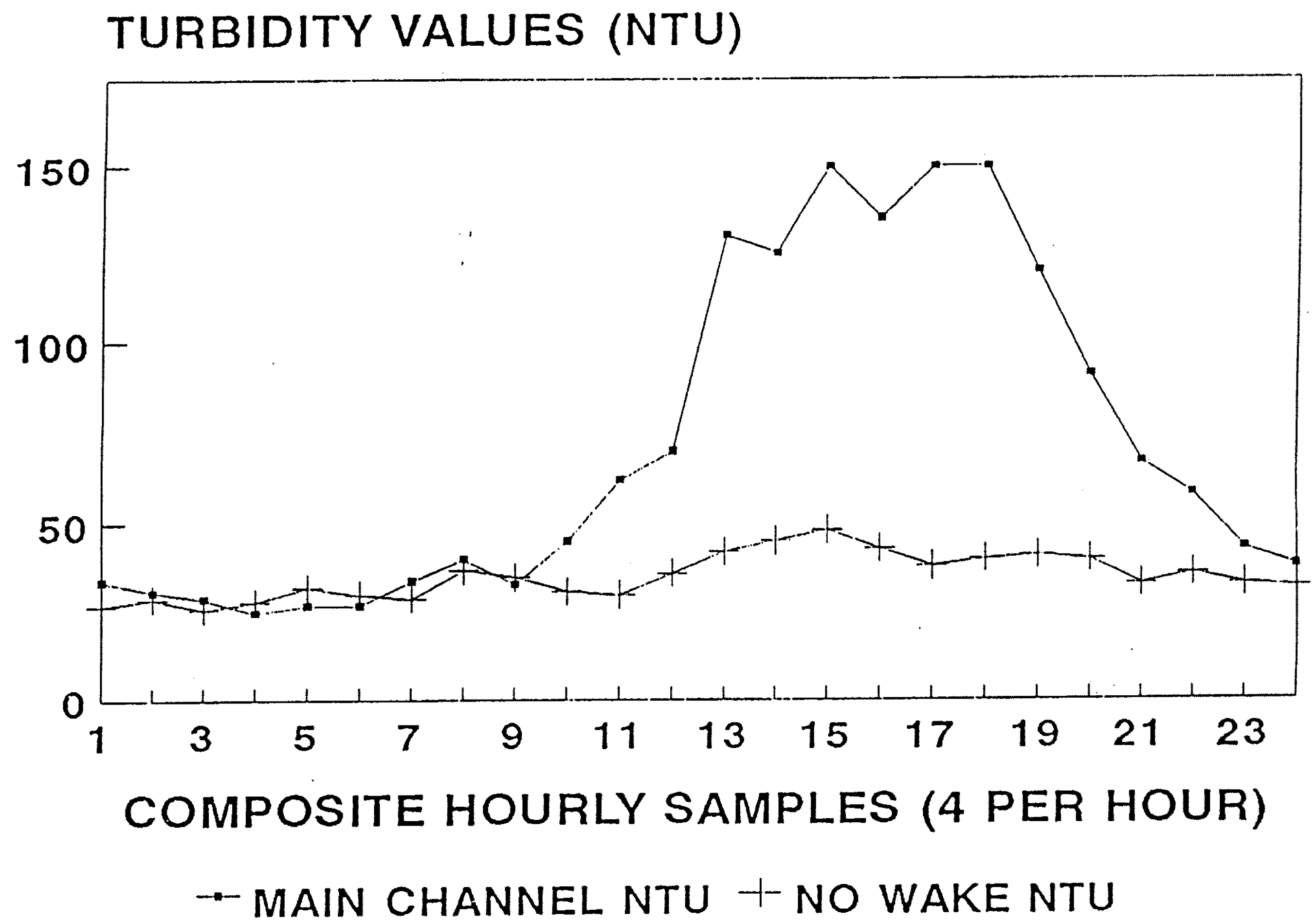


Figure 27. Turbidity value comparisons over the Labor Day Holiday Weekend, August 28-September 6, 1991



X AXIS IS IN MILITARY TIME

Figure 28. No-wake zone versus Main Channel turbidity values on Saturday, August 1, 1992

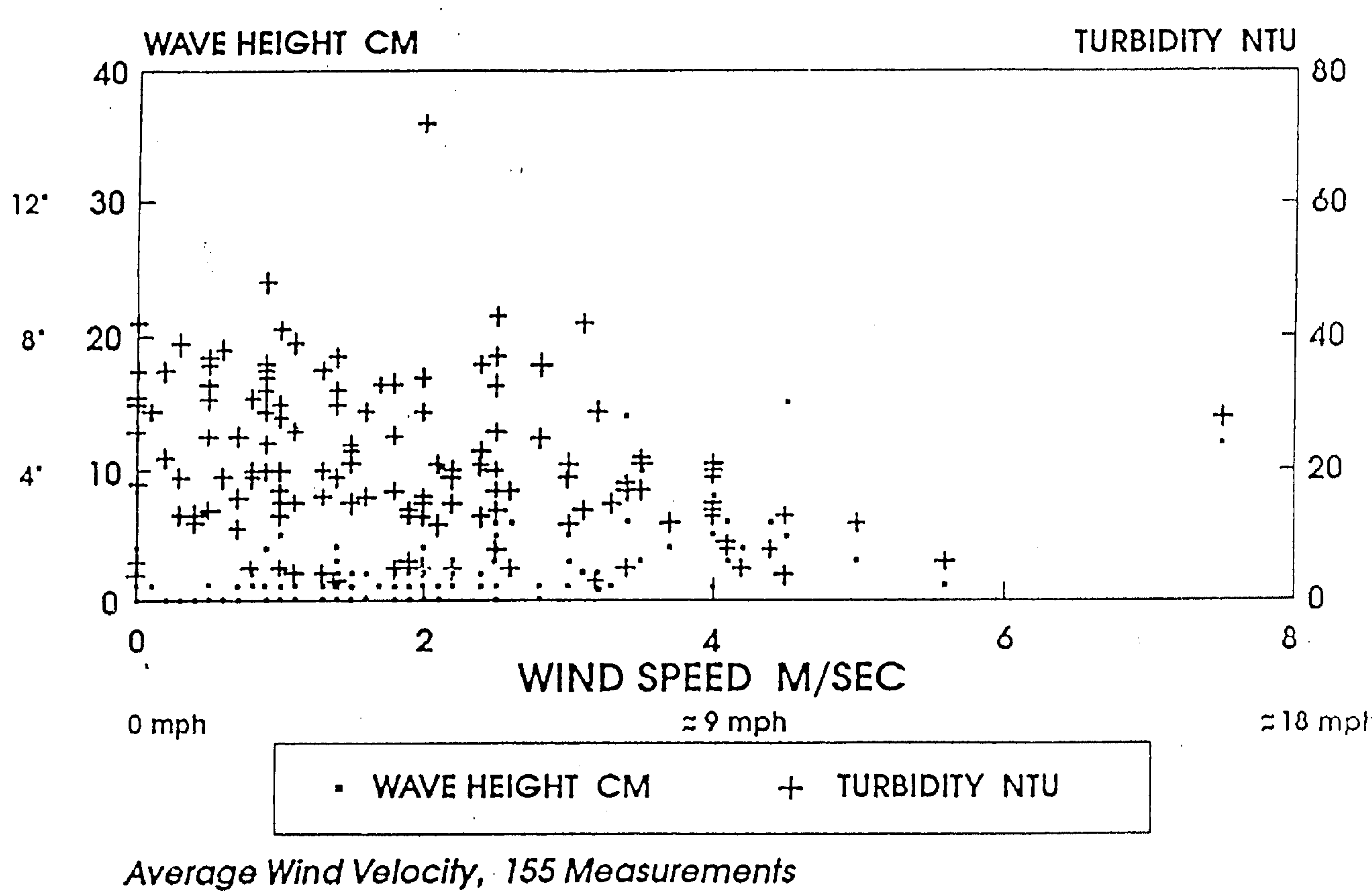


Figure 29. Wave height and turbidity compared to wind speed river channel data 1990-1991

Appendix A

Water Quality Assessment Data Sheet

WISCONSIN CHANNEL DATA (ALL IN MG/L UNLESS NOTED)

DATE	TIME	TOTAL SOLIDS	SUSPENDED SOLIDS	TOTAL DISSOLVED SOLIDS	TOTAL VOLATILE SOLIDS	SUSPENDED VOLATILE SOLIDS	FIXED SUSPENDED SOLIDS	TOTAL PHOSPHOROUS	KJELDAHL NITROGEN	NITRITE/ NITRATE	CHLOR A (ug/L)	WIND SPEED (M/S)	WIND DIRECTION (DEGREES)	WATER DEPTH (METERS)	WAVE HEIGHT (METERS)	FLOW VELOCITY (M/S)	WATER TEMP (CELCIUS)	DO (PPM)	TURB (NTU)	SPECIFIC COND (umhos/cm)	SECCHI DISK (cm)
5/22/91	13:00	330	31	290	110	5.2	25.8	0.139	1.60	4.1	30.4	0	NA	1.73	0.00	0.19	19.2	7.9	18	433	50
5/27/91	10:00	400	47	340	130	6.8	40.2	0.160	1.56	5.9	24.0	0	352	2.55	0.02	0.36	20.3	7.5	26	499	48
5/27/91	15:55	410	56	340	130	7.6	46.4	0.163	1.61	5.7	22.4	0−3.2	76	1.8	0.02	0.36	21.9	6.9	29	494	41
6/12/91	11:20										16.8	.5−1.3	66	1.85	0.00	0.33	24.5	5.3	48	523	25
6/20/91	11:00	500	49	340	180	7.0	42.0	0.251	1.63	5.0	20.8	1.2−3.4	64	2.15	0.02	0.40	24.9	5.8	36	565	39
6/23/91	8:57	520	58	340	180	8.0	50.0	0.241	1.99	5.3	12.0	0−1.8	62	1.71	0.04	0.42	22.2	6.5	36	567	36
6/23/91	15:50	500	48	440	180	7.2	40.8	0.198	1.81	5.3	16.8	.3−1.4	53	1.8	0.01	0.28	23.2	6.0	35	NA	40
7/3/91	11:30	480	57	360	180	7.4	49.6	0.261	1.70	4.0	22.4	1.0−1.7	240	2.1	0.03	0.40	24.9	6.3	37	565	36
7/4/91	9:15	460	56	360	170	7.8	48.2	0.241	1.64	3.8	19.2	2.1−3.4	256	1.68	0.01	1.53	24.1	6.3	36	515	36
7/4/91	15:45	460	52	350	170	9.0	43.0	0.288	1.60	3.7	20.8	.9−2.4	NA	1.73	0.01	NA	25.0	6.7	33	512	31
8/9/91	12:50	480	45	410	150	8.8	36.2	0.206	1.33	2.9	31.2	1.1−1.7	248	1.98	0.00	NA	22.0	7.6	32	586	33
8/10/91	9:15	460	40	390	140	8.0	32.0	0.221	1.40	2.9	35.2	0	NA	2.13	0.00	NA	21.7	7.2	30	575	29
8/10/91	14:05	450	47	390	130	8.0	39.0	0.231	1.48	2.9	42.4	.7−1.0	266	2.1	0.00	NA	23.1	8.6	32	580	30
8/29/91	14:35	490	41	410	160	8.2	32.8	0.187	1.52	2.0	41.6	0−.5	58	2.2	0.00	0.15	27.1	7.4	39	598	29
9/2/91	8:46	480	38	400	150	7.8	30.2	0.232	1.49	1.5	39.2	0	NA	1.95	0.04	0.18	23.6	6.3	35	571	34
9/2/91	14:46	490	38	410	150	7.8	30.2	0.239	1.33	1.5	39.5	0−1.0	52	2	0.00	0.09	25.0	7.1	33	571	28

MINNESOTA CHANNEL DATA (ALL IN MG/L UNLESS NOTED)

DATE	TIME	TOTAL SOLIDS	SUSPENDED SOLIDS	TOTAL DISSOLVED SOLIDS	TOTAL VOLATILE SOLIDS	SUSPENDED VOLATILE SOLIDS	FIXED SUSPENDED SOLIDS	TOTAL PHOSPHOROUS	KJELDAHL NITROGEN	NITRITE/ NITRATE AS N	CHLOR A (ug/L)	WIND SPEED (M/S)	WIND DIRECTION (DEGREES)	WATER DEPTH (M/S)	WAVE HEIGHT (M/S)	FLOW VELOCITY (M/S)	WATER TEMP (CELCIUS)	DO (PPM)	TURB (NTU)	SPEC COND (umhos/cm)	SECCHI DISK (cm)
5/22/91	13:35	390	36	340	130	5.6	30.4	0.154	1.56	5.3	32.0	1.7−2.2	162	1.92	0.02	1.60	19.3	8.0	72	505	58
5/27/91	8:12	440	46	370	140	6.4	39.6	0.199	1.81	6.4	24.0	CALM	45	2	0.02	0.35	20.1	7.2	30	534	50
5/27/91	16:47	430	52	360	130	7.6	44.4	0.211	1.76	6.3	27.2	1.2−1.6	57	1.6	0.04	0.33	23.0	6.6	30	548	42
6/12/91	12:00										14.4	1.9−2.9	69	1.95	0.01	0.22	24.5	5.5	NA	550	28
6/20/91	12:15	510	49	360	170	7.0	42.0	0.267	1.93	5.6	21.6	.9−1.6	54	1.9	0.00	0.31	25.0	5.8	35	605	NA
6/23/91	8:15	560	75	360	180	11.0	64.0	0.310	1.78	5.5	12.6	1.7−4.4	72	1.66	0.02	0.13	22.0	6.1	42	606	30
6/23/91	15:15	520	67	360	170	10.0	57.0	0.271	1.96	5.6	12.8	.4−1.5	46	1.8		1.10	23.0	6.1	41		30
7/3/91	12:50	520	58	390	190	7.8	50.2	0.307	1.68	4.6	23.2	0−.10	270	1.75	0.01	0.25	25.1	6.3	31	565	37
7/4/91	8:15	520	60	390	180	10.0	50.0	0.255	1.67	4.3	20.0	0−.4	298	1.75	0.00	0.28	24.1	6.3	35	566	36
7/4/91	16:00	520	68	380	190	10.0	58.0	0.459	2.63	4.2	22.4								42	556	NA
8/9/91	13:50	460	44	390	140	8.0	36.0	0.243	1.19	3.0	28.8	2.2−2.8	266	1.7	0.00	NA	22.0	7.3	33	590	36
8/10/91	8:00	470	43	390	140	8.0	35.0	0.218	1.43	3.2	29.6	0	NA	1.9	0.00	NA	22.0	7.1	31	570	39
8/10/91	14:30	500	56	390	150	9.6	46.4	0.267	1.48	3.2	33.1	.4−.7	300	2	0.00	NA	23.1	7.4	38	575	38
8/29/91	13:55	490	40	390	160	7.8	32.2	0.205	1.51	2.1	37.6	0	NA	2.1	0.00	0.13	27.4	7.2	35	602	25
9/2/91	7:51	460	25	400	150	5.8	19.2	0.286	1.47	1.6	34.4	0−.9	62	2	0.01	0.14	24.1	6.5	25	580	41
9/2/91	13:55	500	52	400	150	9.4	42.6	0.303	1.69	1.6	38.4	.8−1.3	206	2	0.02	0.10	26.5	7.3	39	581	25

LAKE PEPIN SITE 3 DATA (ALL IN MG/L UNLESS NOTED)

DATE	TIME	TOTAL SOLIDS	SUSPENDED SOLIDS	TOTAL DISSOLVED SOLIDS	TOTAL VOLATILE SOLIDS	SUSPENDED VOLATILE SOLIDS	FIXED SUSPENDED SOLIDS	TOTAL PHOSPHOROUS	KJELDAHL NITROGEN	NITRITE/ NITRATE AS N	CHLOR A (ug/L)	WIND SPEED (M/S)	WIND DIRECTION (DEGREES)	WATER DEPTH (METERS)	WAVE HEIGHT (meters)	FLOW VELOCITY (M/S)	WATER TEMP (CELCIUS)	DO (PPM)	TURB (NTU)	SPEC COND (umohs/cm)	SECCHI DISC (cm)
5/22/91																					
5/27/91	10:40	430	35	360	130	5.2	29.8	0.153	1.82	6.4	22.4	light	51	3	0.2−0.3	0.33	20.7	7.6	22	535	70
5/27/91	15:18	430	58	370	130	8.4	49.6	0.183	1.76	6.5	27.2	0.28−0.3	150	3	0.04	NA	23.8	6.8	25	516	60
6/12/91																					
6/20/91	10:00	490	39	450	160	6.6	32.4	0.234	1.84	5.4	22.4	3.0−3.4	80	1.5	0.20	0.52	25.0	5.7	30	610	40
6/23/91	9:40	480	26	400	170	5.4	22.6	0.202	1.76	5.5	14.4	3.6−4.4	95	2.08	0.43	NA	22.2	6.2	24	596	34
6/23/91	16:25	490	26	350	170	6.0	22.0	0.217	1.94	5.5	16.0	3.0−3.6	70	1.5	0.12	NA	23.8	6.8	26	586	41
7/3/91	12:25	500	32	390	190	5.4	26.6	0.217	1.84	4.6	26.8	3.2−5.4	275	1.97	0.04	0.05	25.0	6.7	27	573	37
7/4/91	8:45	490	34	390	190	5.4	26.6	0.226	1.79	4.3	21.6	3.4−4.1	263	1.77	0.02	NA	24.1	6.3	26	570	38
7/4/91	15:15	490	38	360	180	7.4	30.6	0.226	1.13	4.2	24.8	.28−.48	304	1.7	0.07	NA	25.0	6.7	27	557	37
8/9/91	13:30	420	31	350	130	6.4	24.6	0.207	1.32	2.9	28.8	.4−.8	302	1.8	NA	NA	22.7	7.5	27	587	40
8/10/91	8:50	460	47	390	140	8.8	38.2	0.283	0.92	3.0	30.4	0	NA	2	0.00	NA	21.8	6.9	34	540	29
8/10/91	13:30	450	33	400	140	8.4	24.6	0.256	1.12	3.0	45.2	.4−.6	353	1.9	NA	NA	24.0	9.2	26	544	NA
8/29/91	15:05	650	58	400	170	9.8	48.2	0.256	1.63	2.1	36.3	1.4−3.2	158	2.1	0.06	NA	27.2	7.3	44	605	NA
9/2/91	8:21	470	46	420	150	9.4	36.6	0.285	1.34	1.5	37.4	1.3−2.0	98	2	0.12	NA	23.9	6.3	45	582	27
9/2/91	14:24	470	43	400	150	9.0	34.0	0.262	1.63	1.5	38.4	2.0−2.5	110	2.05	0.11	NA	25.2	7.5	36	575	30

Appendix B

Recreational Boating Investigations
River Mile 788 Near Red Wing, MN

DATA SHEET

Run	Station	Time	Distance from Bottom	Lab Tare	Dry Wt.	ml filtered	TSS mg/l	Lab Turbidity NTU
1	100	7:50	1 ft	.12269	13602	250	53.3	28
1	200	8:17	4 ft	.12419	13476	250	42.3	28
1	200	8:17	7 ft	.12142	13235	250	43.7	30
2	25	10:05	bottom	.12128	14488	250	94.4	52
2	50	10:45	surface	.12404	13513	250	44.4	30
2	100	10:54	7 ft	.12409	13509	250	44.0	30
2	200	11:05	13 ft	.12121	13299	250	47.1	28
3	25	1:34	bottom	.12449	15364	*100	291.5	145
3	50	1:26	bottom	.12238	19942	250	308.2	135
3	100	1:13	bottom	.12170	13595	250	57.0	35
3	200	1:00	bottom	.12162	13274	250	44.5	30
4	50	4:17	bottom	.12424	16997	250	182.9	90
4	50	4:17	1 ft	.12430	16913	250	179.3	92
4	50	4:17	surface	.12494	13399	250	36.2	50
4	100	4:08	4 ft	.12122	14599	250	99.1	34

VALUES VS TOTAL SUSPENDED SOILDS
LAB AND FIELD MEASUREMENTS

TSS	**NTU**	Regression Output:	
36.2	50	Constant	
42.3	28		11.47700
43.7	30	Std Err of Y est	9.363277
44	30	R Squared	
44.4	30		0.949673
44.5	30	No. of Observations	15
47.1	28	Degrees of Freedom	13
53.3	28		
57	35	X Coefficient(s)	0.424035
94.4	52	Std Err of Coef.	0.27073
99.1	34		
179.3	92		
182.9	90		
291.5	145	TSS = X	
308.2	135	NTU = Y	

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Field investigations were undertaken to document physical and water quality impacts associated with recreational boating activities in upper Pool 4 of the Upper Mississippi River System. The study documented high erosion rates irrespective of geomorphic position in the Main Channel and development of a diurnal turbidity plume in the littoral zone. A comparison of commercial tow, wind, and recreational boat surface wave characteristics, along with other observations and the use of a control channel provided the perspective necessary to determine relative responsibility for the observed impacts. Recreational boating was found to be the contributing influence most responsible for the high shoreline erosion rates documented along the Main Channel and was found to be directly responsible for the development of the diurnal turbidity plume in the Main Channel's littoral zone on weekends and holidays. Other applicable literature findings were reviewed and potential impacts to the river habitat and biota associated with recreational boating activity were identified. Federal, State, and local government agencies responsible for managing the Upper Mississippi River System should respond to the findings of this report by implementing programs to protect the river from recreational boating impacts.

The Long Term Resource Monitoring Program (LTRMP) for the Upper Mississippi River System was authorized under the Water Resources Development Act of 1986 as an element of the Environmental Management Program. The mission of the LTRMP is to provide river managers with information to maintain the Upper Mississippi River System as a viable large river ecosystem given its multiple-use character. The LTRMP is a cooperative effort by the U.S. Fish and Wildlife Service, the U.S. Army Corps of Engineers, and the states of Illinois, Iowa, Minnesota, Missouri, and Wisconsin.