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**Characterization of Wake-Sport Wakes and  
Their Potential Impact on Shorelines**

by

**C.A. Goudey  
& Associates**

C.A. Goudey & Associates  
21 Marlboro Street  
Newburyport, MA 01950

24 November 2015

## Executive Summary

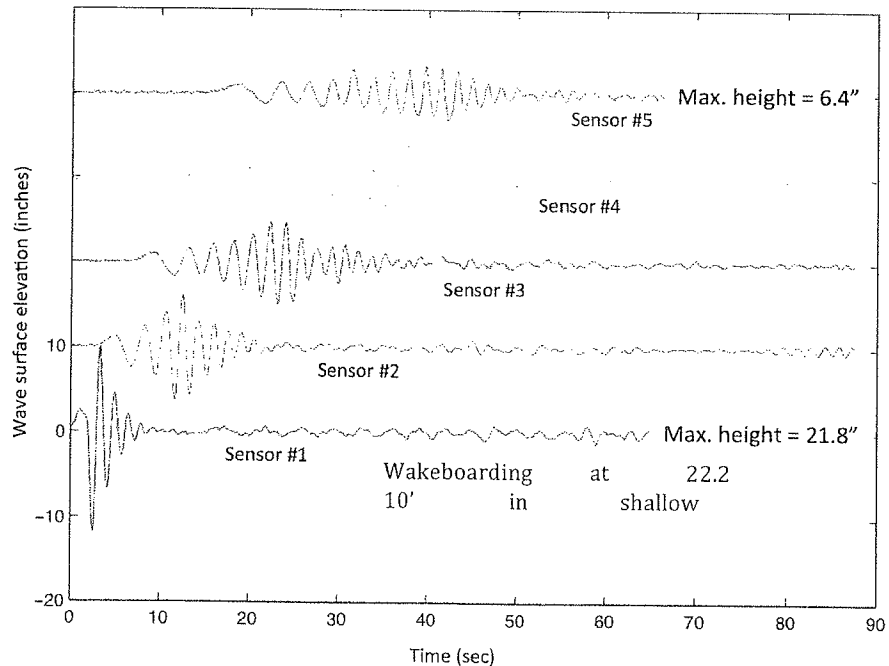
The effect of boat wakes on a shoreline varies depending on boat size, speed, water depth, and distance from shore. With the growing popularity of wake sports there has been a rise in concern over the potential effect of the associated wakes on shorelines. A study has been completed and reported here aimed at building an understanding of wake-sport wakes and how they fit into the spectrum of boat wakes in general as well as how those wakes compare to wind-driven waves.

A shallow and a deep-water test venue were used within the Conway Lake chain in Orlando, Florida. Both locations had sandy beaches and were surveyed for their depth profile to determine locations for wave-height probes within an array running perpendicular to the shore. At the four stations closest to shore, capacitance-wire wave probes were used. Due to the close passage of the boat to the outer probe, a submerged pressure probe was used. Each sensor was connected by underwater cable to a PC-based data acquisition system where the data was displayed and logged for post processing.

The vessel used for the tests was a Nautique G-23 wake-sport boat with an overall length of 23', a maximum beam of 102", and a light displacement of 5,900 lbs. This is considered typical of the fleet of wake-sport boats available from various manufacturers. The boat has factory installed ballast tanks that were filled to capacity with 2,850 pounds of water for the wakeboarding tests. For the wakesurfing runs, an additional 1,400 pounds of water was added, yielding a total displacement of 10,150 pounds.

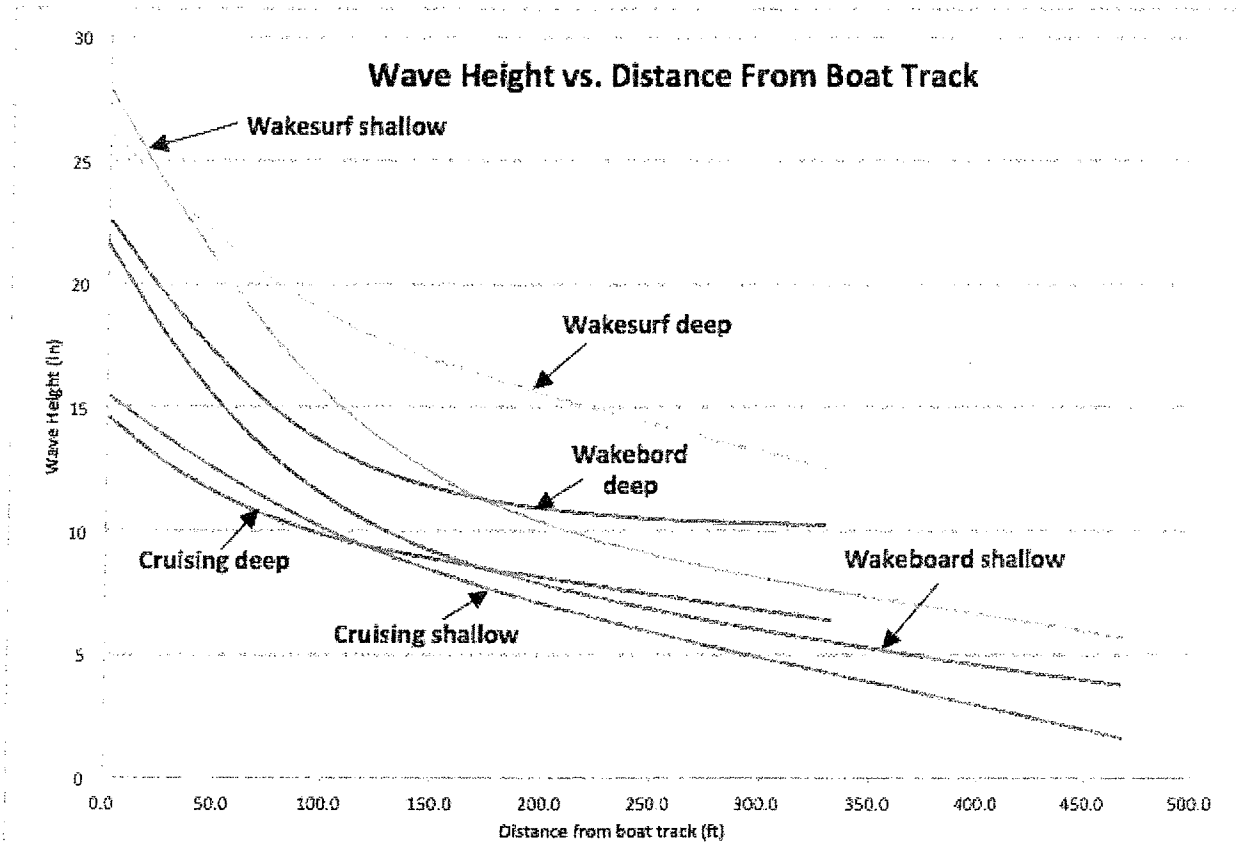
Test runs were conducted at cruising speeds (20, 25, 30 mph), wakeboarding speeds (21.2, 22.2, 23.2 mph), and wakesurfing speeds (10, 11, 11.5, 12 mph). These runs were done at three distances from the outer wave probe (10', 110', 210') with the closest track resulting in a wave measurement being taken very close to the boat. A total of 94 tests runs were made at the shallow and deep sites. Logged data from each run were then processed to yield plots of wave profiles vs. time and to determine wave heights and wave counts at each sensor station. Wave profiles from all five probes were plotted for each run to enable quality control as shown below.

Note that the wave heights are given in terms of the total height of the wave from its trough to its crest. It is worth noting that very close to the boat the trough is deeper than the height of the crest. Specifically, at sensor #1 a trough 11.8" deep precedes a 10" crest for a total wave height of 21.8".



Wakes dissipate in three ways. First, and as can be seen in the above figure, the small number of waves seen at sensor #1 grows to more numerous waves as the wake progresses away from the boat's track. The three initial waves become 14 distinct but much smaller waves by the time the wake has reached sensor #5, which is 270 feet away. A second cause of wake dissipation is the friction of the wave's motion on the lake bottom and is much more significant in shallow water. A third cause of wake dissipation is through breaking. This form of energy loss happens quickly behind a wake-sport boat that is generating a large wave.

Comparisons among runs are shown in the figure below and are based on the speed of each operational mode that produced the highest waves. For those "optimal" speeds the maximum wave height at each station is shown.



The higher waves associated with wakeboarding and wakesurfing dissipate more rapidly than those generated under the cruising condition, more typical of a conventional craft on a full plane. We can also see in this figure that the maximum wave heights associated with wakeboarding and wakesurfing dropped precipitously in the first 100 to 150' of their travel from the boat's track. By contrast, the waves heights associated with cruising speeds dissipate more slowly and lack the initial drop seen with the other two modes of operation. This difference is because these smaller waves tend not to break and therefore propagate with less energy loss.

These results demonstrate the importance of standoff distance from the shoreline and from the data wave height can be predicted for various standoff distances. As shown in the table below, with the exception of wake surfing in deep water, the wake sport waves from a track 200' from shore fall below heights that could be viewed as exceptional.

Distance from track (FT)		Maximum wave height (in)			
		0	100	200	300
Cruising	Shallow	15.42	10.16	8.83	5.09
Cruising	Deep	14.54	9.95	7.19	6.32
Wakeboard	Shallow	21.82	11.18	9.13	6.93
Wakeboard	Deep	22.46	13.63	10.10	9.87
Wakesurf	Shallow	27.83	11.75	9.63	5.91
Wakesurf	Deep	26.14	19.88	15.89	12.92

Wake surfing in deep water is the exception and it takes 300 feet for the wave height to drop by half of its original 26" height.

In understanding the significance of boat-wake effects on shorelines, it is necessary to compare them to naturally occurring processes. Wind waves are particularly important due to their persistent nature. Waves resulting from wind over a stretch of water are well studied and predictable based on wind speed and fetch. Predictions were made of the significant wave height and dominant wave period of typical combinations of wind speed and fetch distance. These values were turned into energy levels to allow comparison with boat-wake energy levels derived from our tests. Through this comparison we were able to determine how often a boat wake would need to occur in order to equal the energy associated with wind waves.

Our analysis shows that a cruising boat would need to pass 110 feet from a shoreline every 101 seconds in order to equal the energy coming from waves associated with 10 mph winds and one mile of fetch. A wakesurfing boat would only need to pass every 270 seconds to equal the same wind-wave effects. At higher wind speeds and longer fetch distances, wind waves become more energetic. For example, a 20 mph wind blowing over 4 miles of fetch yields wave conditions equivalent to a cruising boat passing 110 feet offshore every 9 seconds. Those same wind waves are equivalent to a wakesurfing passing every 23 seconds 110 feet from a shoreline. These sorts of repetition rates are not representative of the sport.

A 10 mph wind blowing over a mile of open water is a common occurrence and our results suggest boat wakes are not likely to be the most significant source of energy along the shores of all but the smallest bodies of water. The persistence of wind waves can belie their importance. While a boat wake coming ashore can seem like a significant event, in the larger scheme of things it can be of little consequence if that shore also experiences wind-driven waves. In all but the most protected of shorelines, it would be difficult for boating to match the role of wind waves and natural currents on shaping shorelines.



With a goal to scientifically measure the energy produced by towboat wakes and waves, the first-ever Towed Water Sports Wave Energy Study was conducted in the Spring of 2015 in Orlando, Florida.

Clifford Goudey, ocean engineer and naval architect, is one of the most distinguished experts on wave science in the field today. Mr. Goudey commissioned the assistance of Lewis Girod, PhD, who is an accomplished software and sensing engineer. On March 23-27, 2015, the pair conducted an extensive study on the Conway Chain of Lakes at two different sites to measure energy at a shallow-water profile and deep-water profile, while also monitoring the effects of wind-driven waves.

A 2015 Nautique G23 was used for testing with 2,850 pounds of factory ballast with an additional four sacks weighing 350 pounds each for a total of 4,250 pounds of ballast and a total vessel weight of 10,150 pounds.

What did WSIA learn from the scientific conclusions that emerged from the wave energy study?

1. Wakeboard and wakesurf wakes/waves, when operated at least 200 feet or more from shore, do not carry enough energy to have a significant impact on most shorelines or on properly maintained docks and other man-made structures.
2. The maximum wake/wave height associated with wakeboarding and wakesurfing drops 27 to 56 percent in the first 100-150 feet of its travel from the boat path.
3. Boat wakes/waves from cruising boats, recreational boats included, dissipate more slowly and lack the initial drop in size associated with wakeboard and wakesurf wakes/waves.
4. A Wakesurfing boat passing a section of shoreline every nine minutes is less damaging than naturally occurring waves from a 10 mph wind with one mile of fetch.
5. A wave loses the most significant amount of energy upon its initial break. This happens very quickly in wakeboarding and wakesurfing due to the wakes steepness, while a wave created by a boat at cruising speed with less displacement can fail to break while moving towards the shore, preserving its energy.



While the study has demonstrated that, in most conditions, wakesurfing and wakeboarding are far less destructive than naturally occurring waves, the WSIA still strongly recommends the following:

1. Always try to wakeboard or wakesurf in the center of any given body of water, and avoid narrow channels or thoroughfares, if possible.
2. Always try to stay at least 200 feet away from any shoreline, dock, or fixed objects.
3. Maintain a reasonable sound level on your stereo.
4. Always respect the shoreline you are using and if the property owner asks that you leave, do so immediately, and always be gracious with the property owner.
5. Repetitive passes result in an accumulation of energy reaching the shoreline. Repetition is never a good idea and can lead to risk of waterway conflicts.
6. The non-surfing side of a wakesurfing boat creates waves that are 10% to 23% smaller with 23% to 33% percent less energy than the surfing side. When possible, present the non-surfing side of the boat to the closest shoreline.
7. Waves tend to increase in height on the inside of a gradual turn. Avoid such maneuvers close to shore.
8. Glass calm water is not a requirement for wake surfing, be respectful and operate as far from shore as you can.





Long Term Resource Monitoring Program



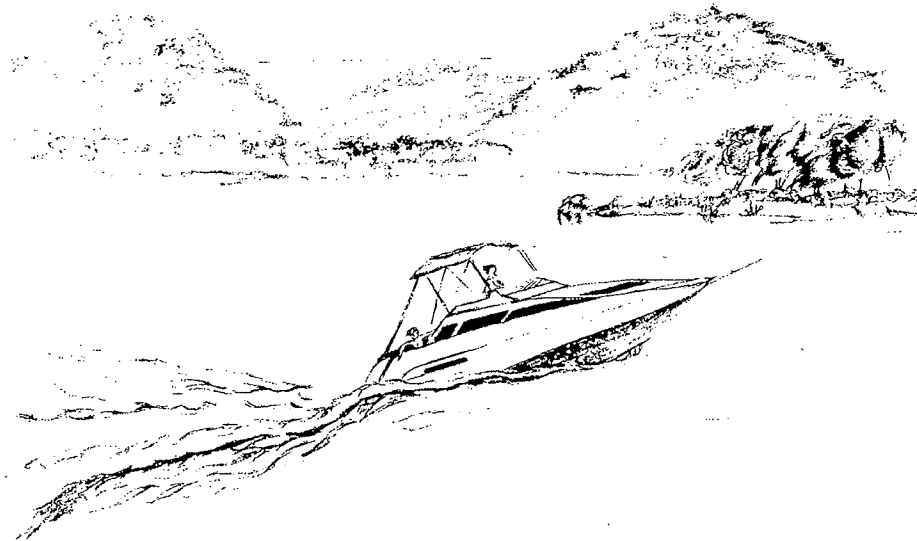
## Special Report

94-S004

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# Recreational Boating Impact Investigations

Upper Mississippi River System, Pool 4  
Red Wing, Minnesota



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February 1994

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

by

Scot Johnson

Minnesota Department of Natural Resources  
Division of Waters  
1801 South Oak Street  
Lake City, Minnesota 55041

in cooperation with the  
U.S. Fish and Wildlife Service  
Environmental Management Technical Center  
FWS Agreement #14-16-0003-89-943, Amendment 7

Prepared for

National Biological Survey  
Environmental Management Technical Center  
575 Lester Avenue  
Anchorage, Alaska 99506

February 1994

This report is derived from the efforts of the Ecological Research and Evaluation Division, Environmental Management Technical Center. At the time of publication of this report, Robert L. Delaney was Center Director, Barry W. Drazkowski was Deputy Center Director, Dr. John W. Barko was Science Technical Director, Dr. David Soballe was Manager of the Physical and Chemical Ecology Group, and Terry D'Erchia was Report Editor.

The opinions and conclusions are those of the author(s) and do not necessarily reflect those of the National Biological Survey, Environmental Management Technical Center, and therefore are not binding on the Environmental Management Technical Center.

This report was developed with partial funding provided by the Long Term Resource Monitoring Program.

Cover graphic  
by Brian Blair

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## 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).

This report should be cited as:

Johnson, S. 1994. Recreational boating impact investigations - Upper Mississippi River System, Pool 4, Red Wing, Minnesota. Report by the Minnesota Department of Natural Resources, Lake City, Minnesota, for the National Biological Survey, Environmental Management Technical Center, Onalaska, Wisconsin, February 1994. EMTC 94-S004. 48 pp. + appendixes (2 pp.)

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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 ( $\nabla$ ) 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).

$$\text{Equation 1. } E = KE + PE = \gamma a^2/2$$

Where E = total energy

KE = kinetic energy

PE = potential energy

$\gamma$  = 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. McLellan, 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

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

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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 <sup>1</sup>	12-15, 30 max <sup>2</sup>
Wave train duration	40 sec <sup>1</sup>	20-26 sec., 50 max <sup>2</sup>
Average wave height	< 10 inches <sup>4</sup>	10 inches <sup>2</sup>
Maximum wave height	12 inches <sup>3</sup>	25 inches <sup>2</sup>
Speed of wave	5 FPS <sup>1</sup>	≈ 8 FPS <sup>4</sup>
Ratio peak 10 hours	1 <sup>5</sup>	140-170 <sup>5</sup>
Average number per week	70 <sup>5</sup>	1,500-2,000 <sup>5</sup>

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)

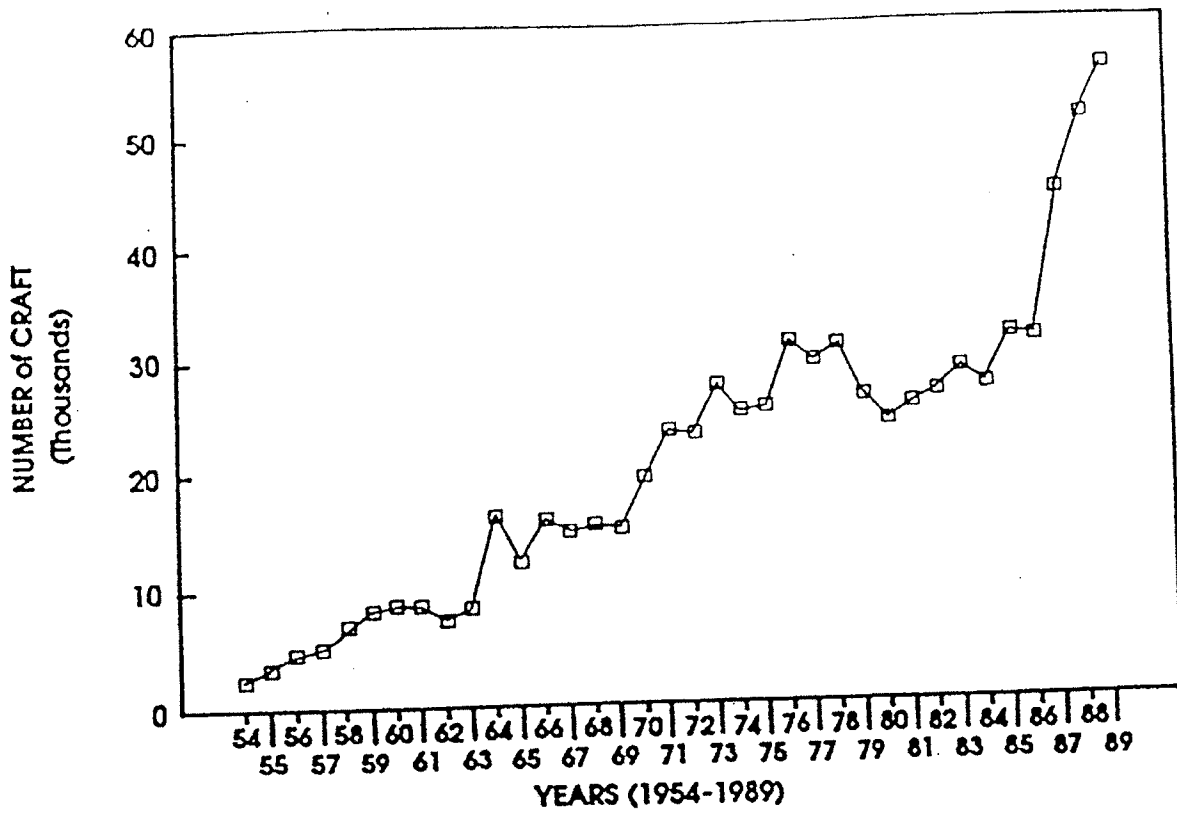


Figure 1. Combined recreational water traffic yearly totals at Lock and Dams 1 through 4

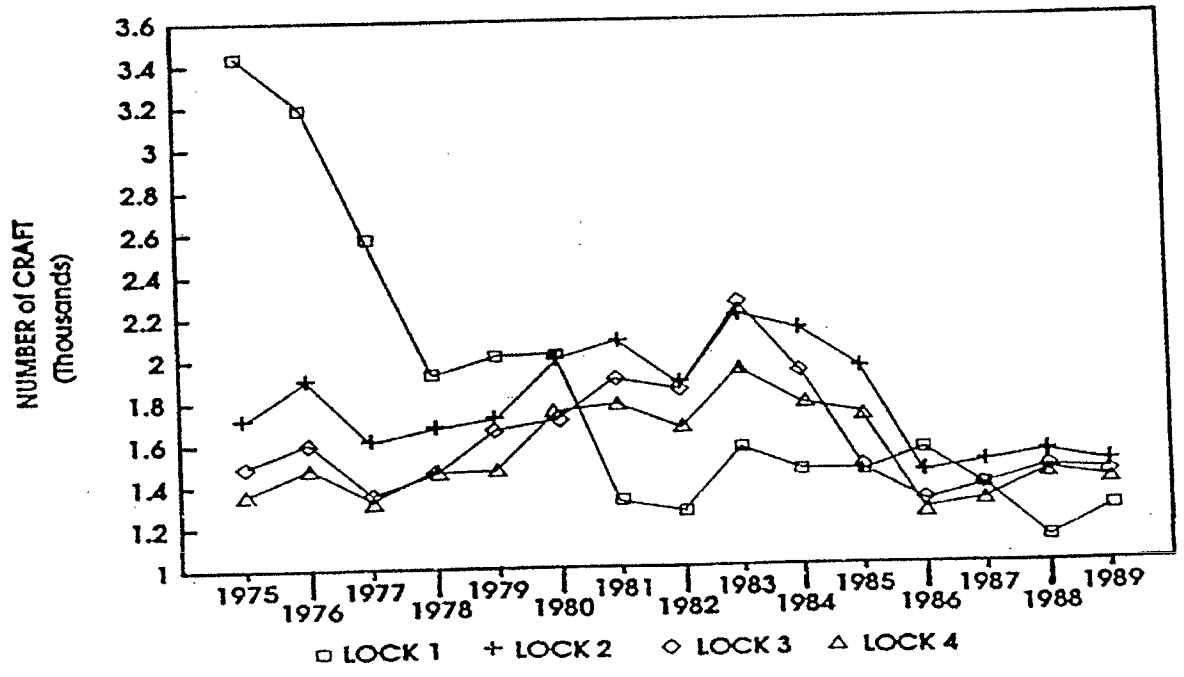


Figure 2. Commercial traffic at Lock and Dams 1 through 4



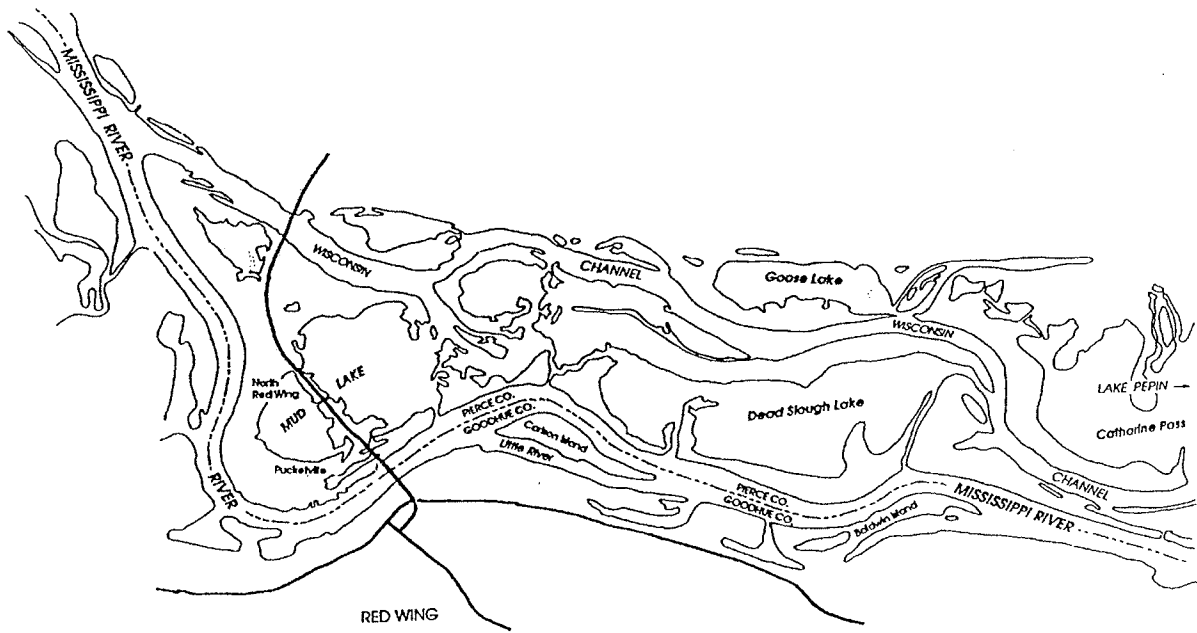


Figure 4. Red Wing study area

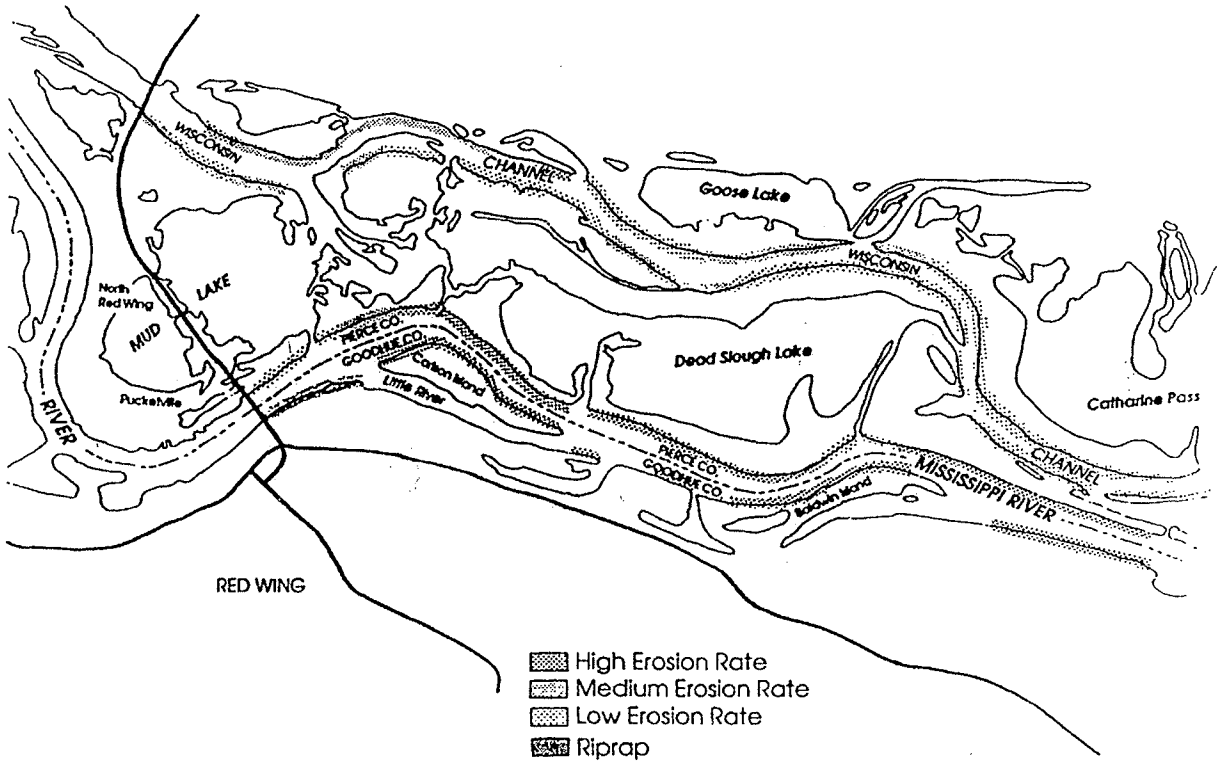
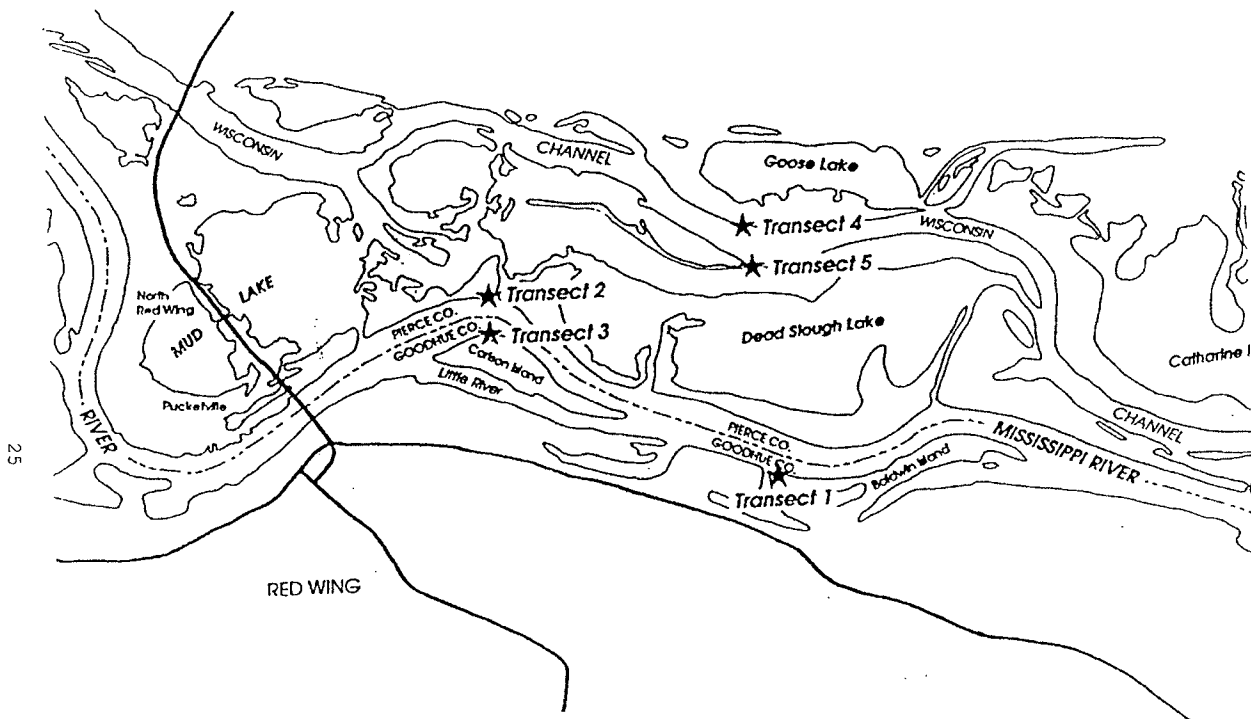


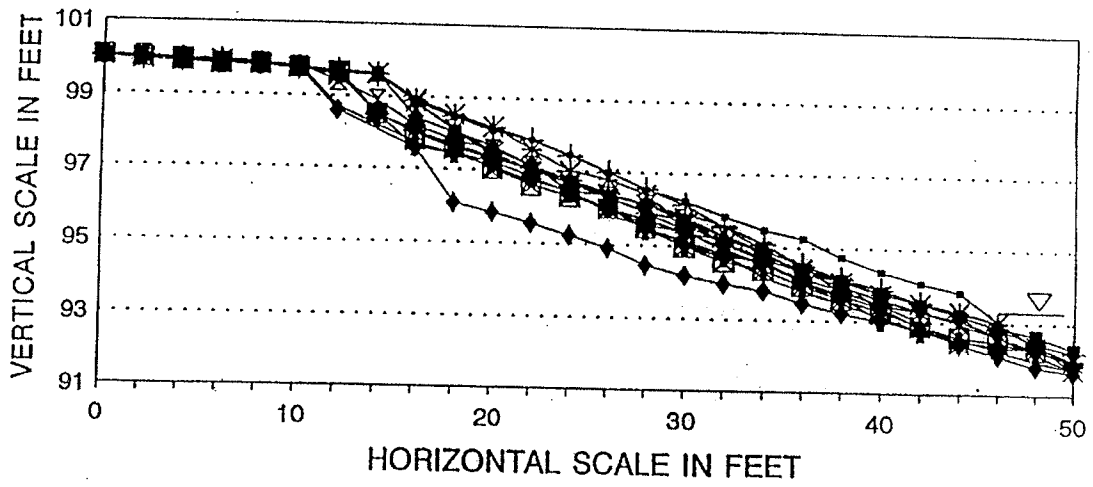
Figure 5. Qualitative erosion assessment results





25

Figure 6. Quantitative shoreline survey transect locations



SURVEY DATES

- ← 05/15/89    + 10/23/89    \* 05/21/90    ■ 08/10/90    × 09/10/90    ◆ 04/17/91    ★ 05/21/91    ⊗ 06/07/91  
 † 07/03/91    ▼ 08/09/91    ☆ 09/20/91    ⊠ 11/20/91    ‡ 03/06/92    → 05/15/92    ♦ 09/18/92

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

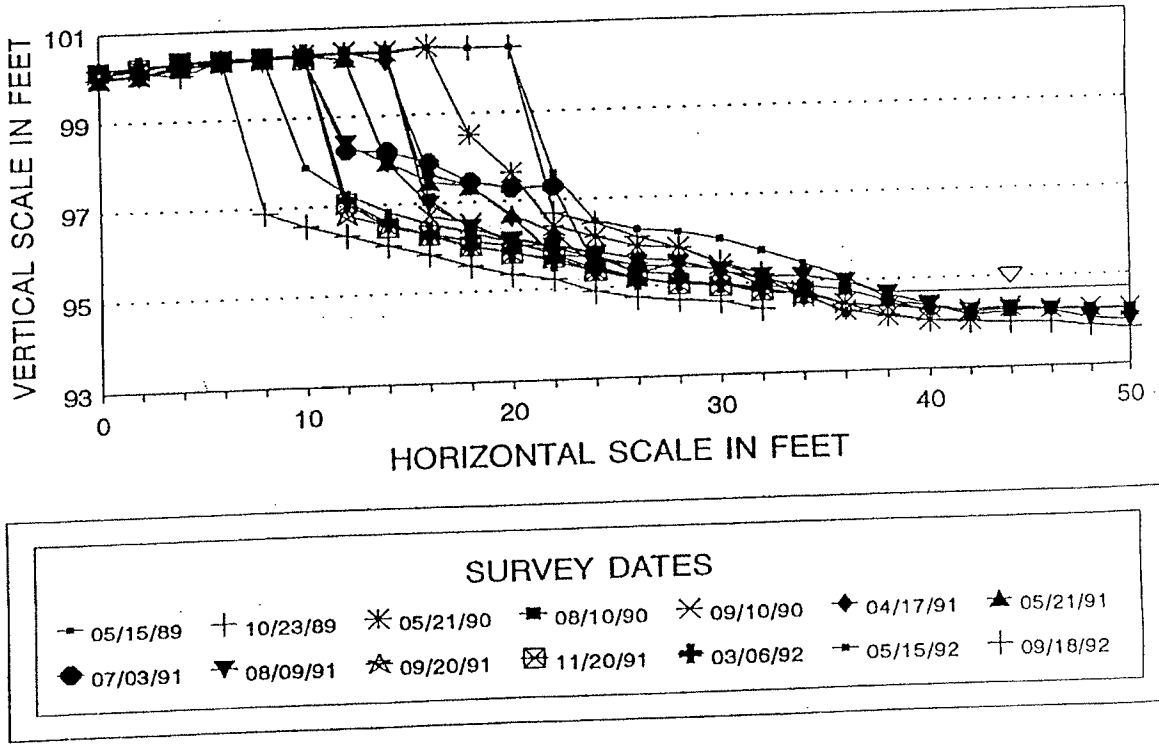
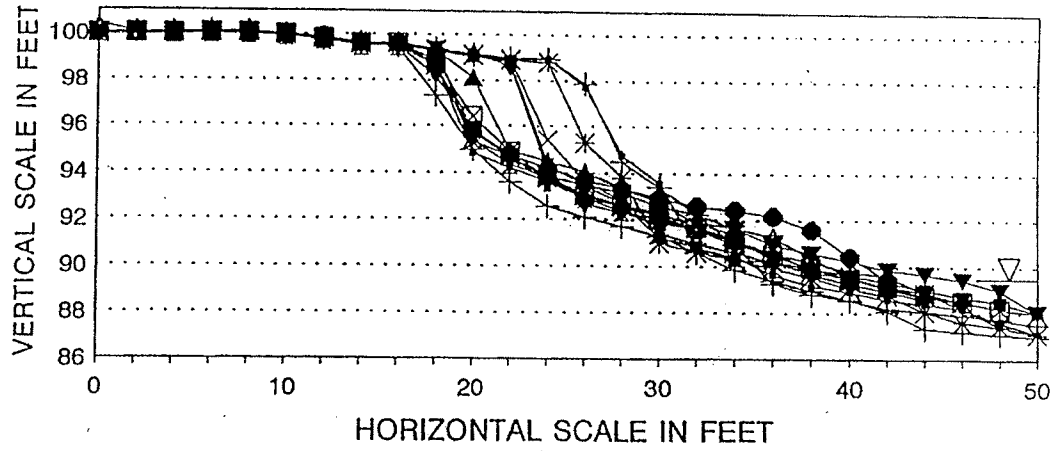


Figure 8. Transect 2, river mile 789.8 - Main Channel outside meander bend



SURVEY DATES															
→	05/15/89	+	10/23/89	*	05/21/90	■	08/10/90	×	09/10/90	◆	04/17/91	▲	05/21/91	⊗	06/07/91
●	07/03/91	▼	08/09/91	☆	09/20/91	⊠	11/20/91	+	03/06/92	→	05/15/92	+	09/18/92		

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

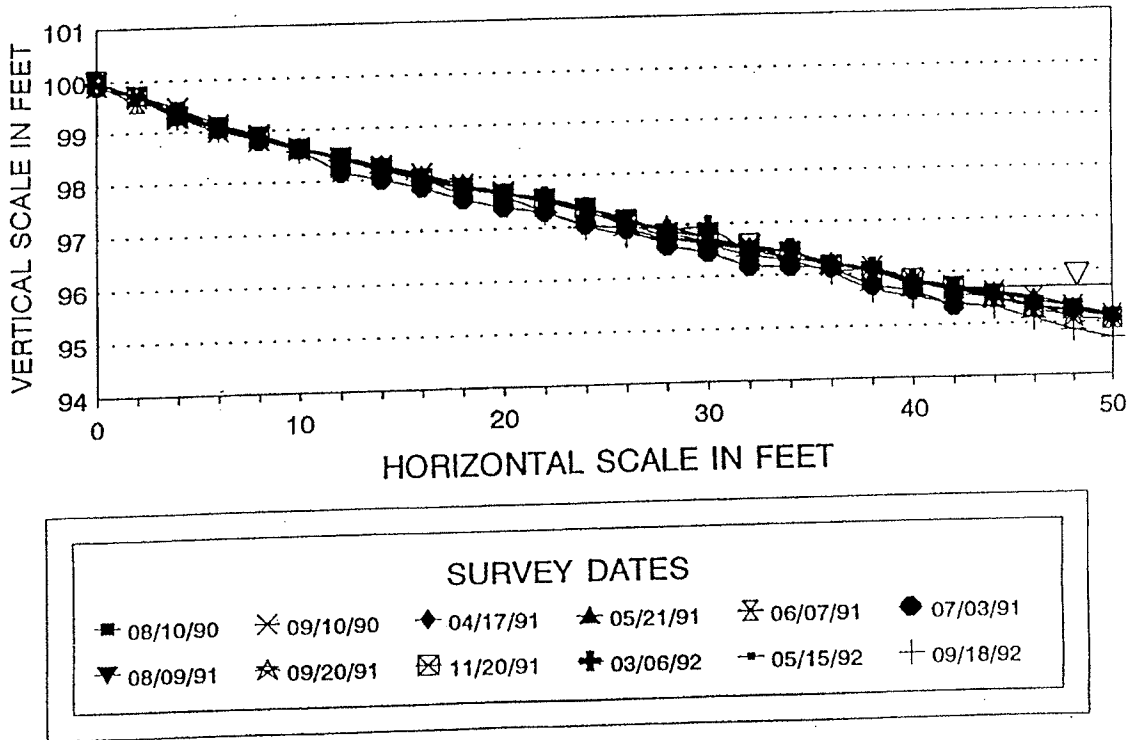


Figure 10. Transect 4, river mile 788.8 - Wisconsin Channel inside meander bend

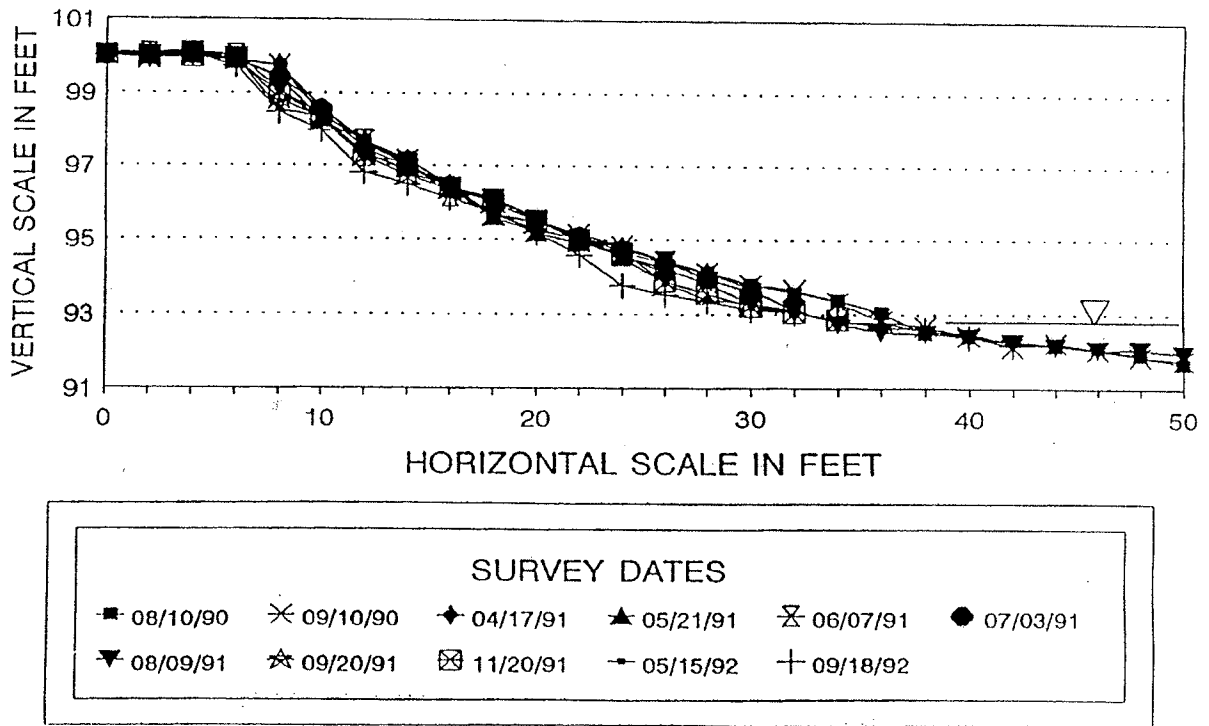


Figure 11. Transect 5, river mile 788.8 - Wisconsin Channel outside meander bend

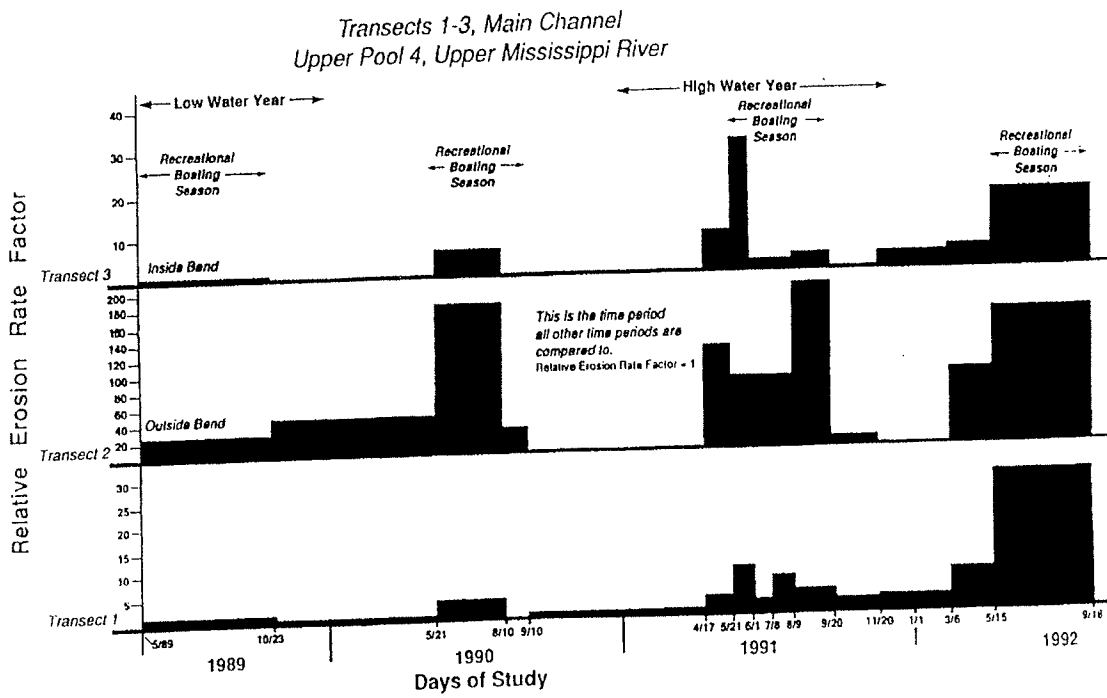


Figure 12. River shoreline relative erosion rates

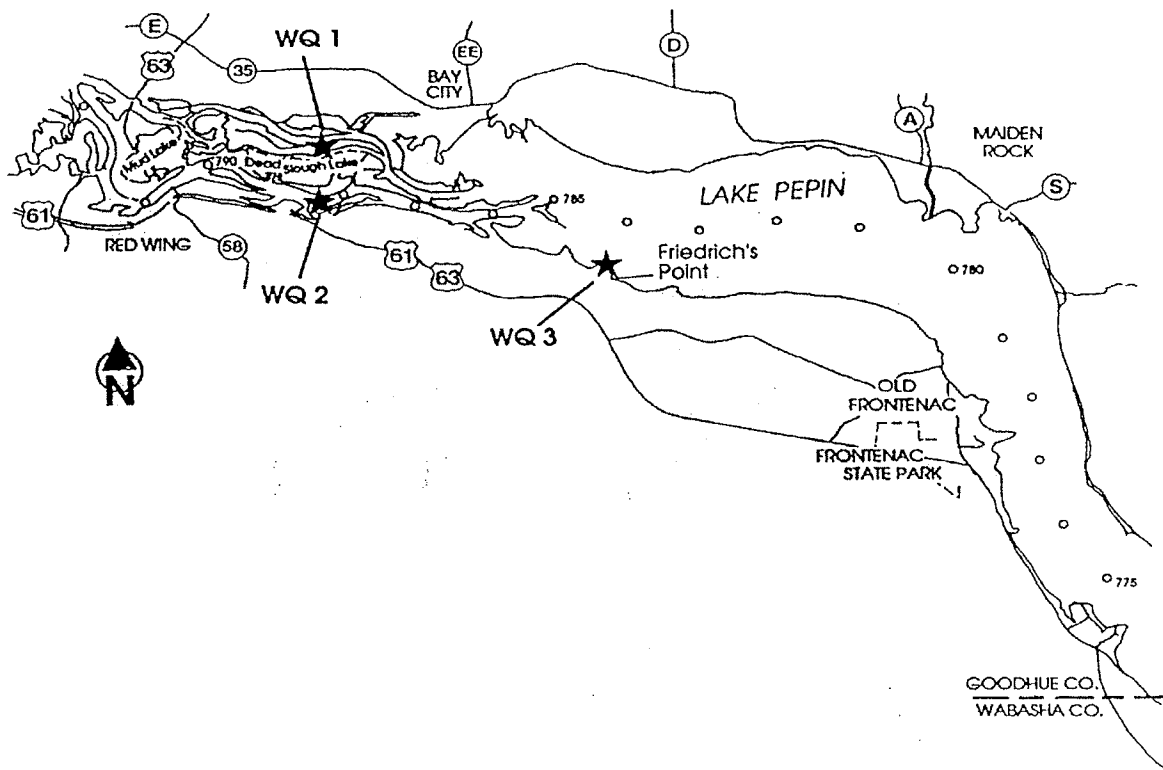
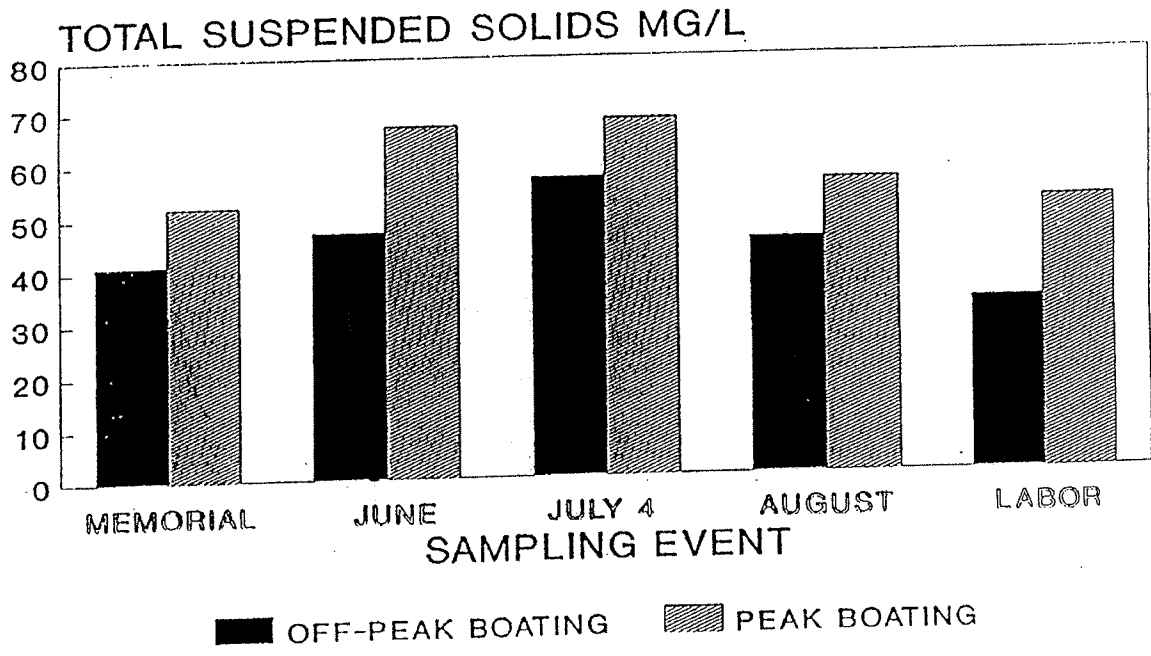


Figure 13. Water quality sampling locations for 2-m integrated samples





OFF-PEAK VALUES ARE MEAN VALUES

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

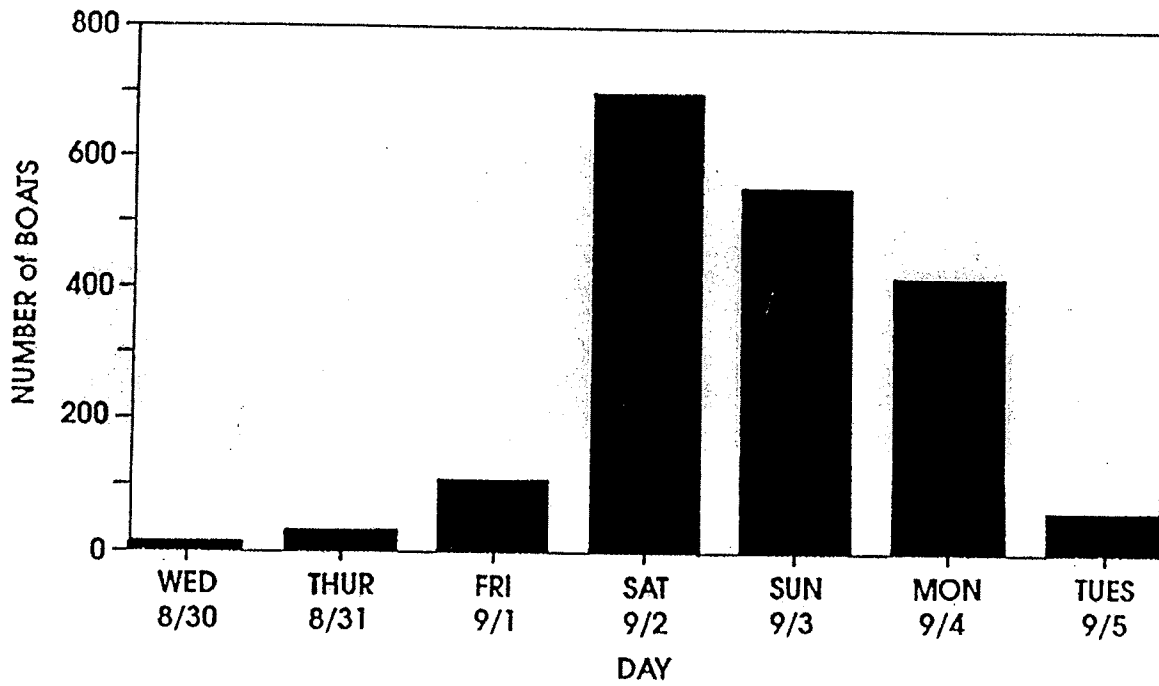


Figure 15. Typical holiday/weekend recreational boating activity levels

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

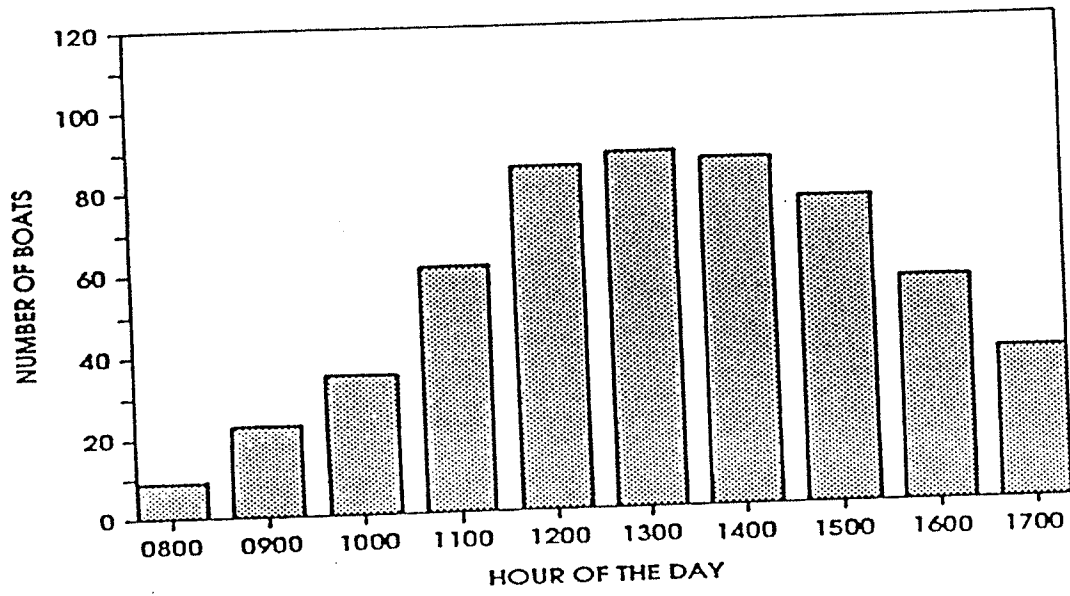


Figure 16. Typical holiday weekend daily distribution of boat passages (adapted from Bhowmik et al. 1991)

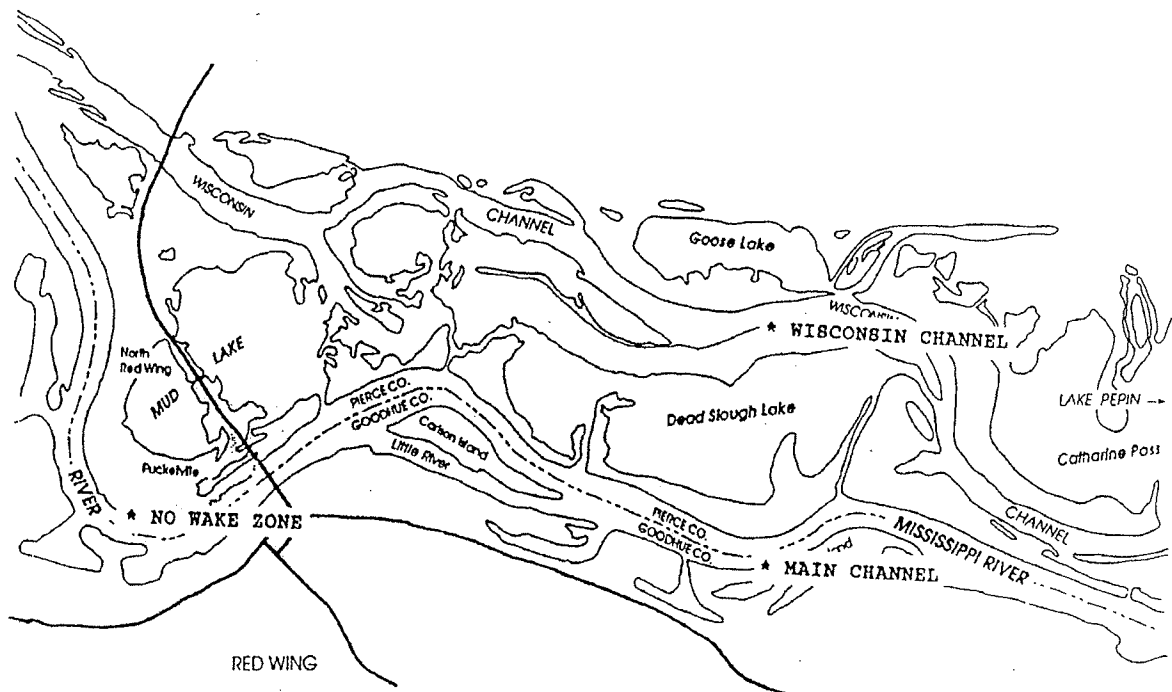


Figure 17. Location of discrete water samplers

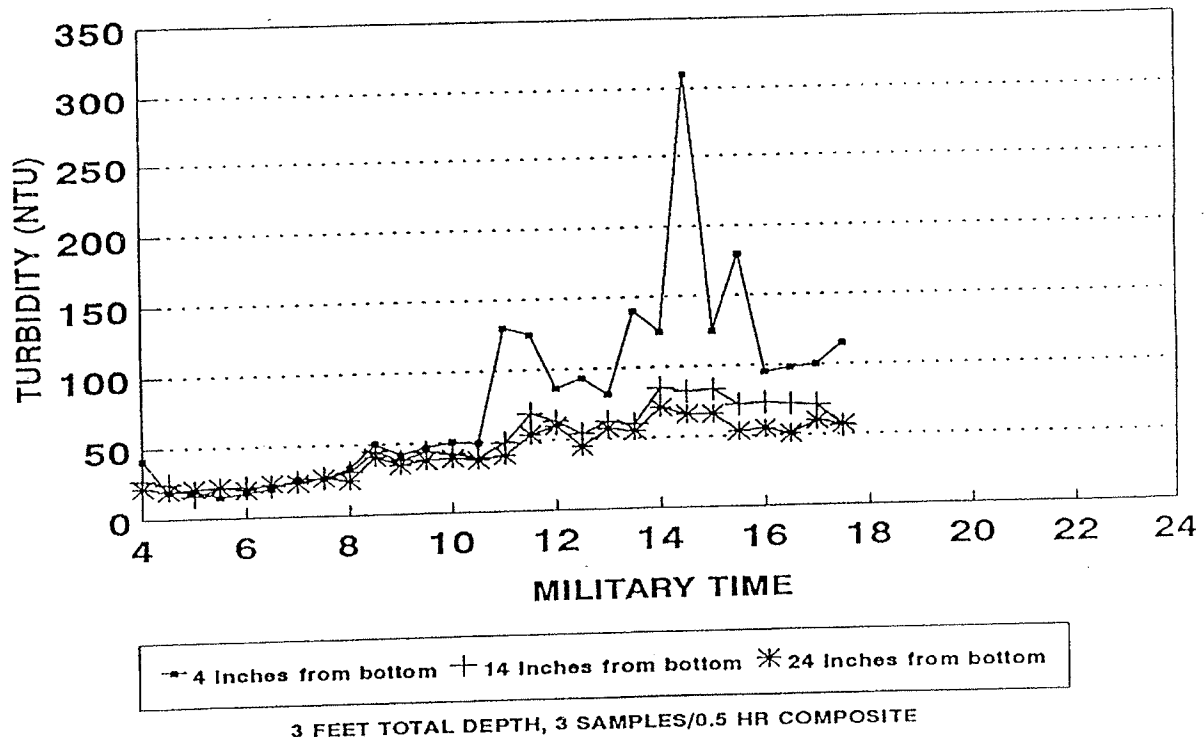


Figure 18. Main Channel water column turbidity at three different depths on Saturday, July 17, 1991

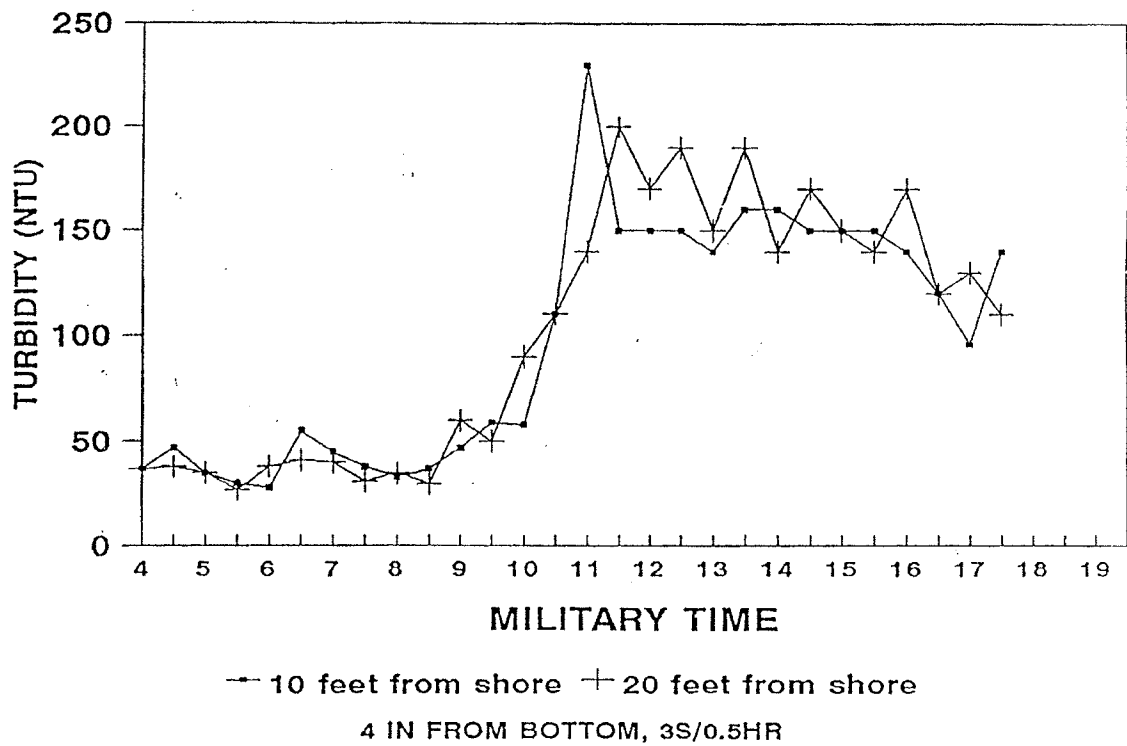


Figure 19. Main Channel turbidity at 10 and 20 feet from shore on Sunday, August 4, 1991

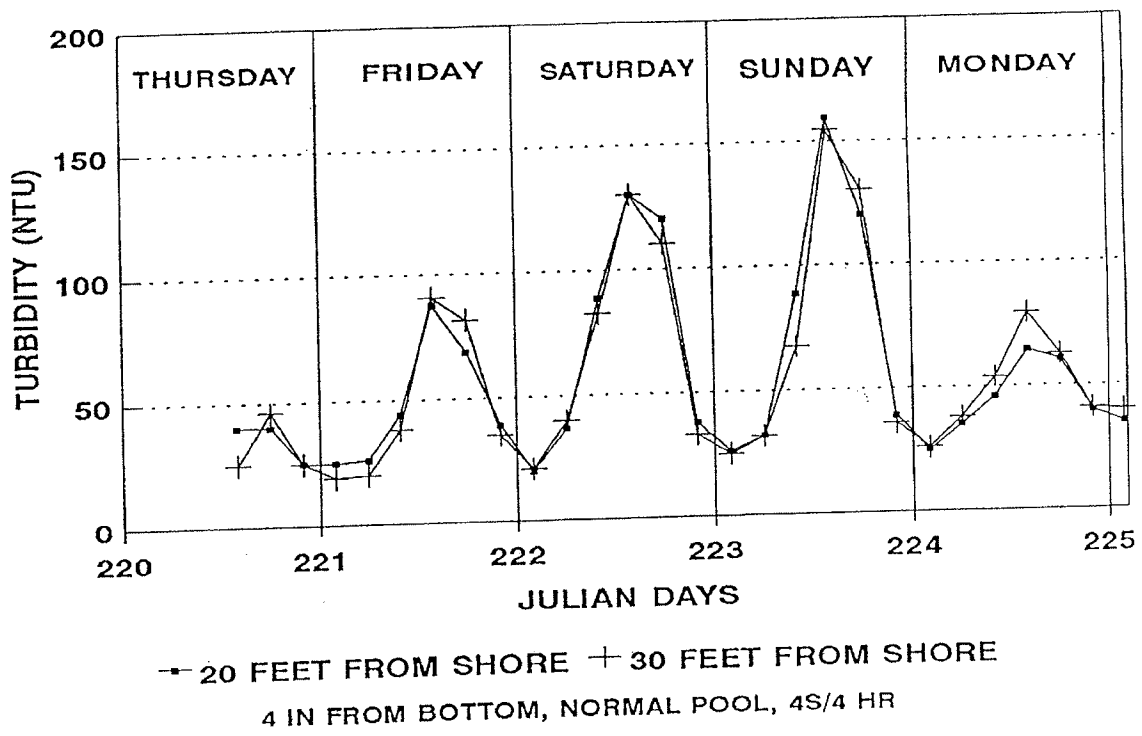


Figure 20. Main Channel turbidity at 20 and 30 feet from shore Thursday, August 8, to Monday, August 13, 1991

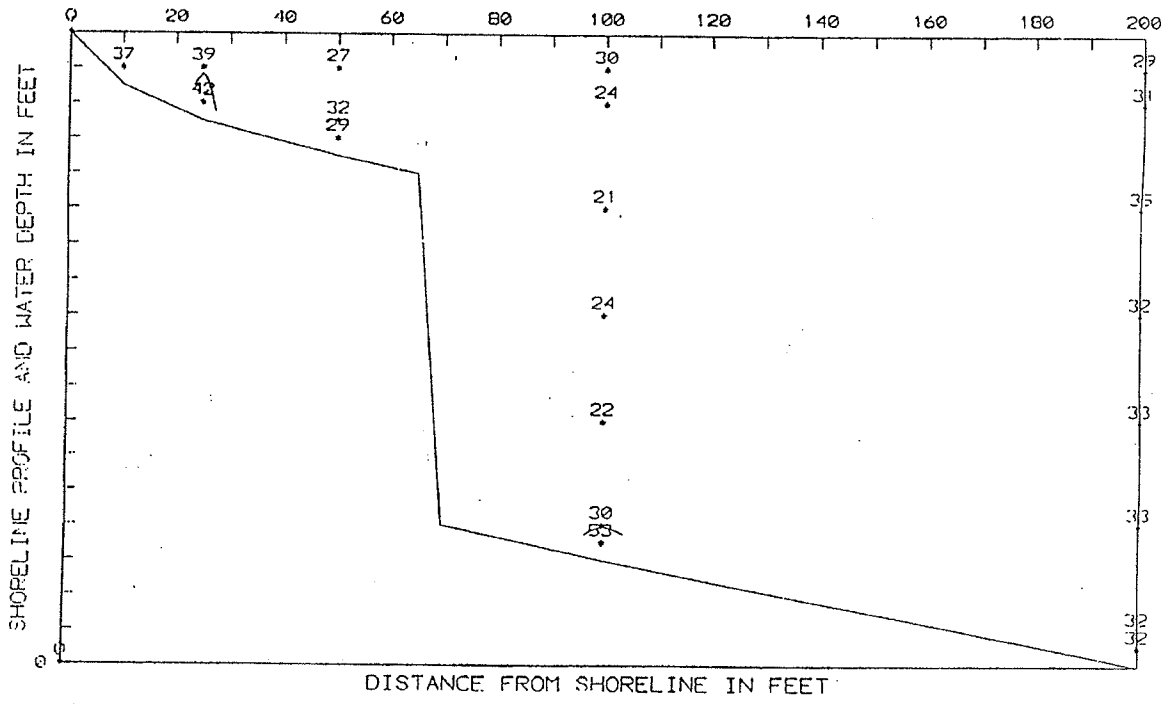


Figure 21. Run 1, 7 a.m., Saturday, August 1, 1992; contour plot of turbidity values



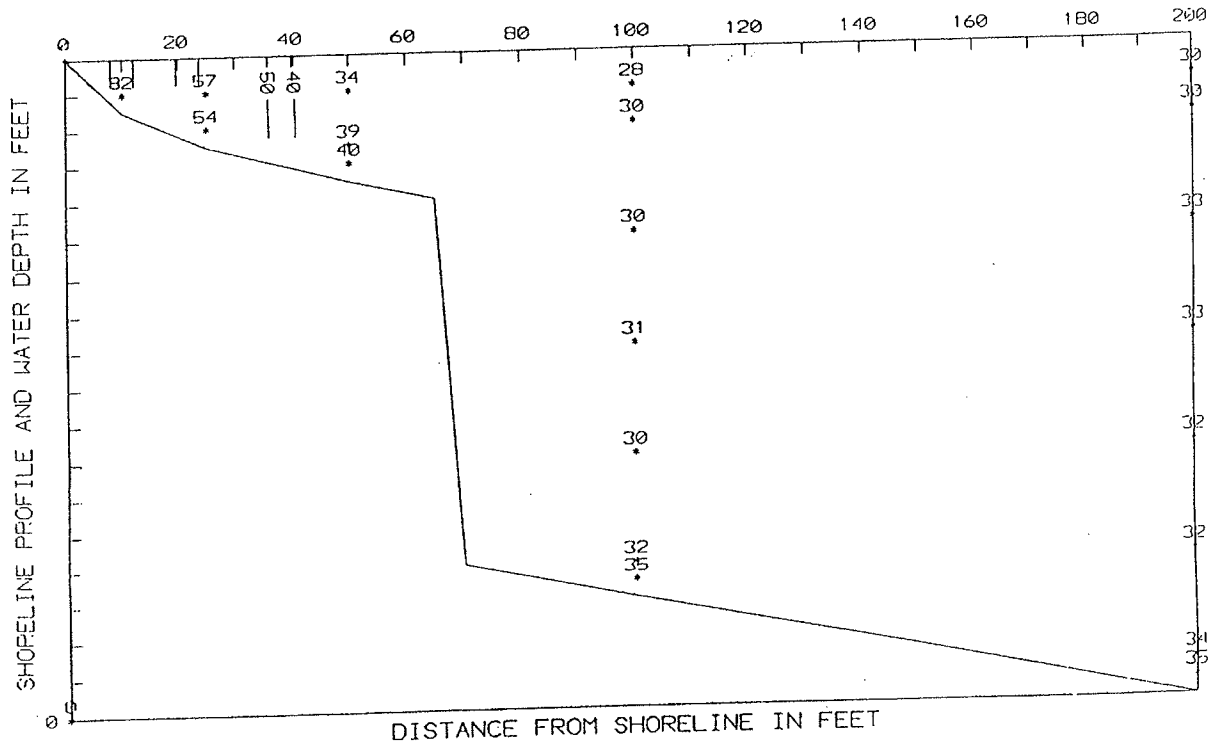


Figure 22. Run 2, 10 a.m., Saturday, August 1, 1992; contour plot of turbidity values

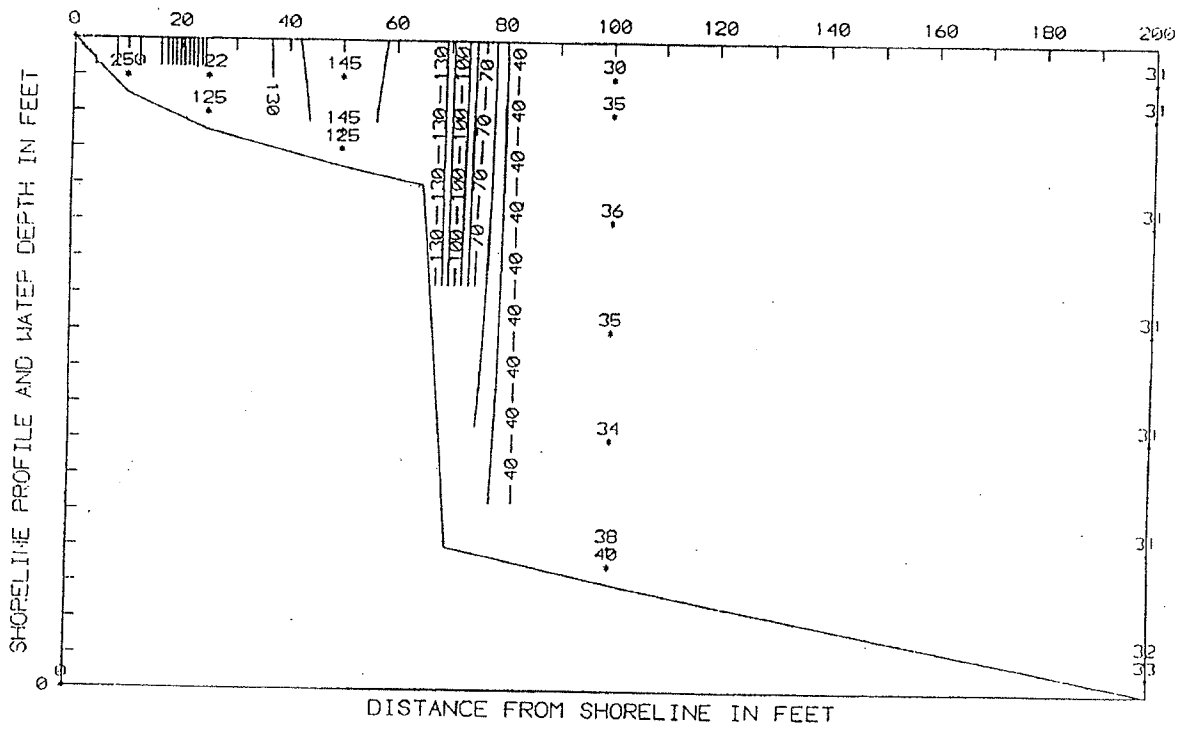


Figure 23. Run 3, 1 p.m., Saturday, August 1, 1992; contour plot of turbidity values

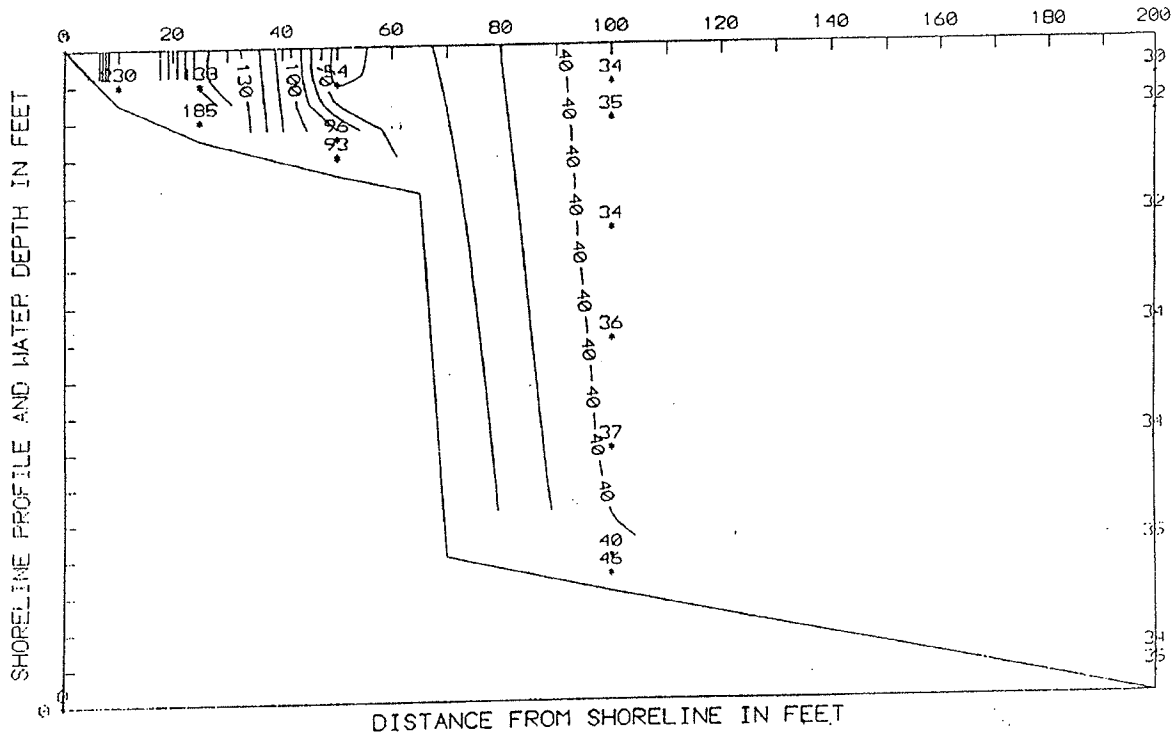


Figure 24. Run 4, 4 p.m., Saturday, August 1, 1992; contour plot of turbidity values

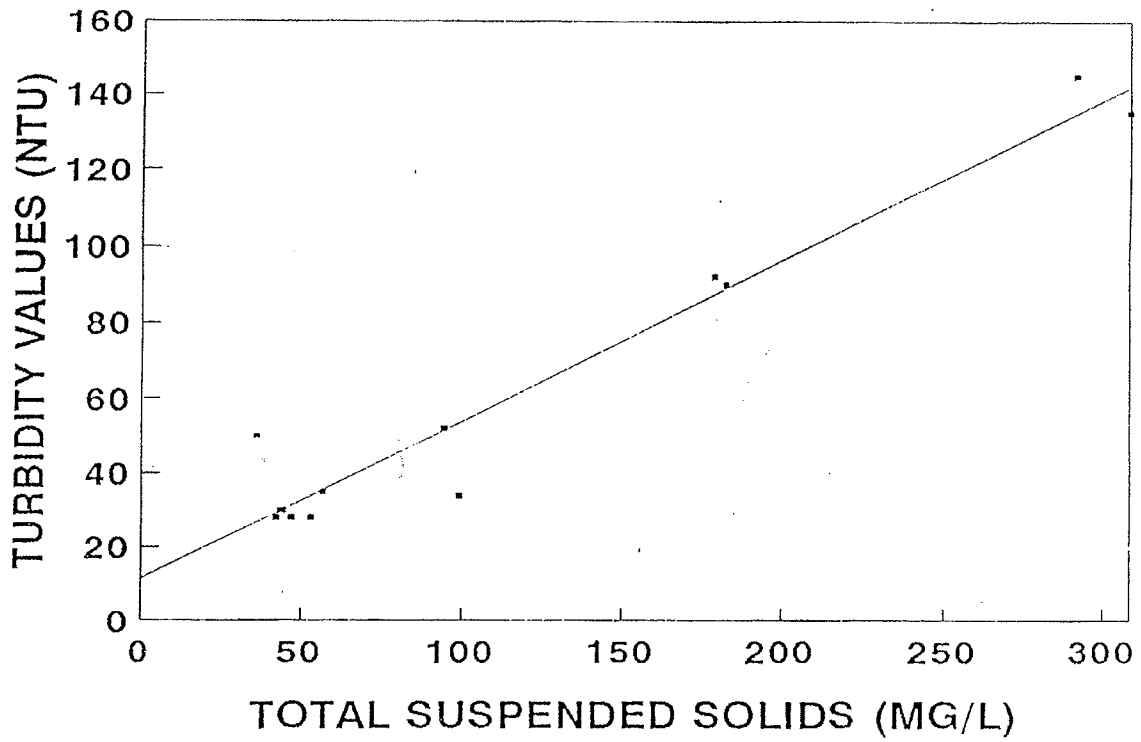


Figure 25. Main Channel turbidity and total suspended solids trend analysis

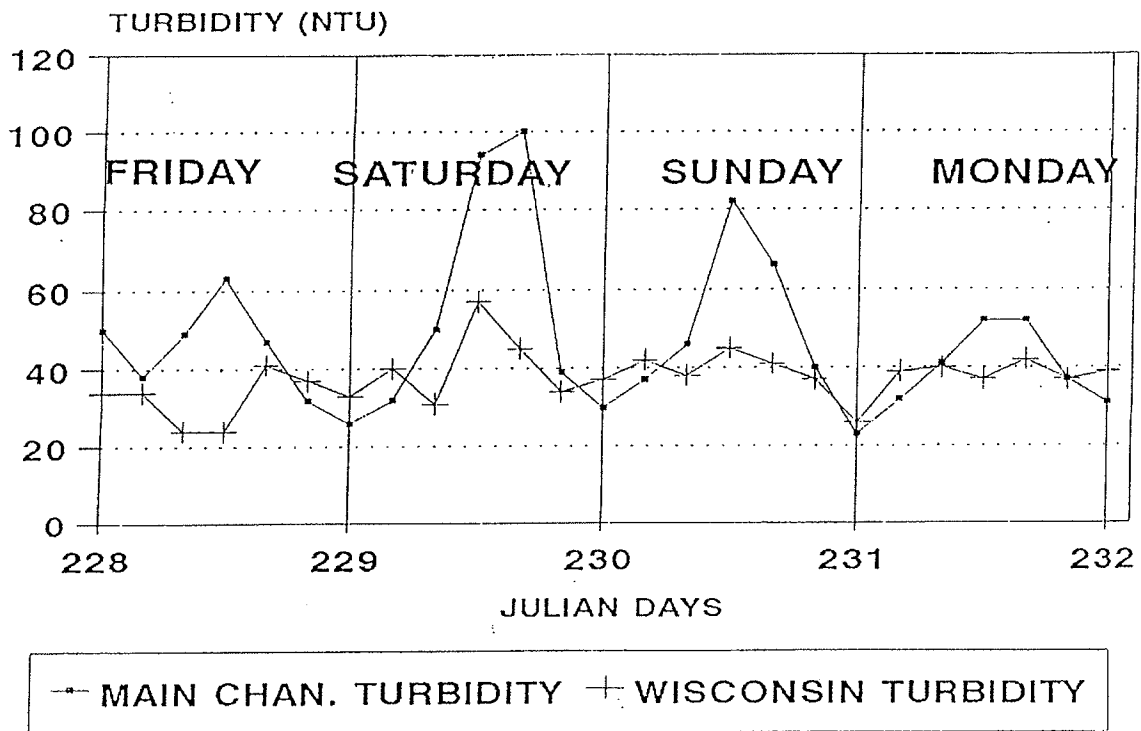
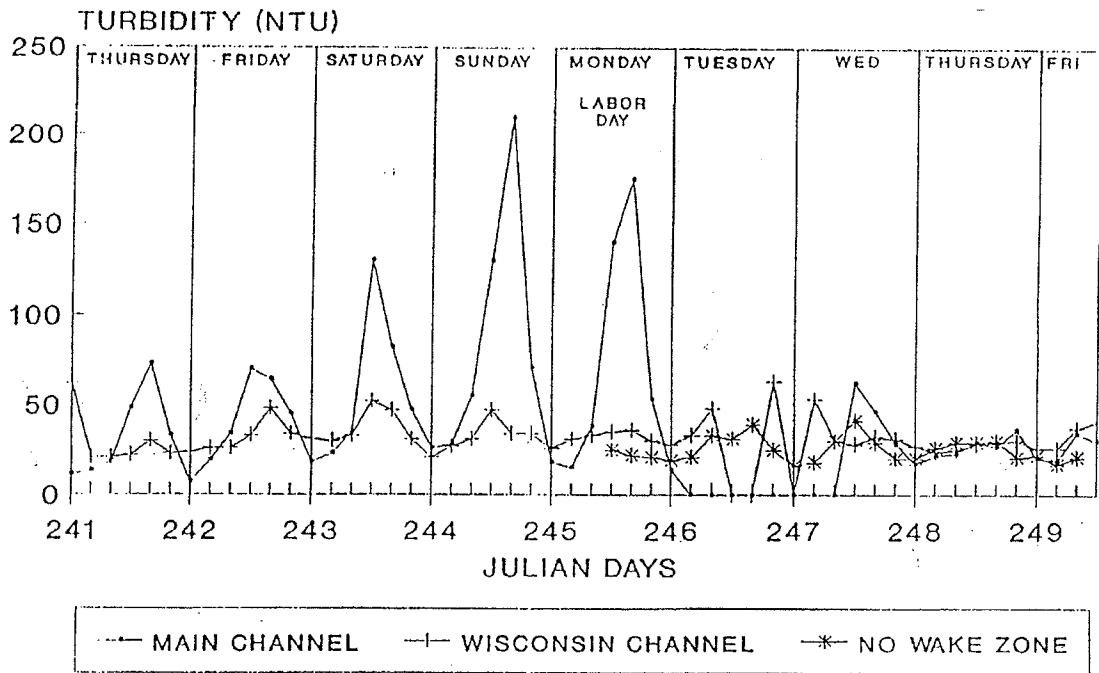
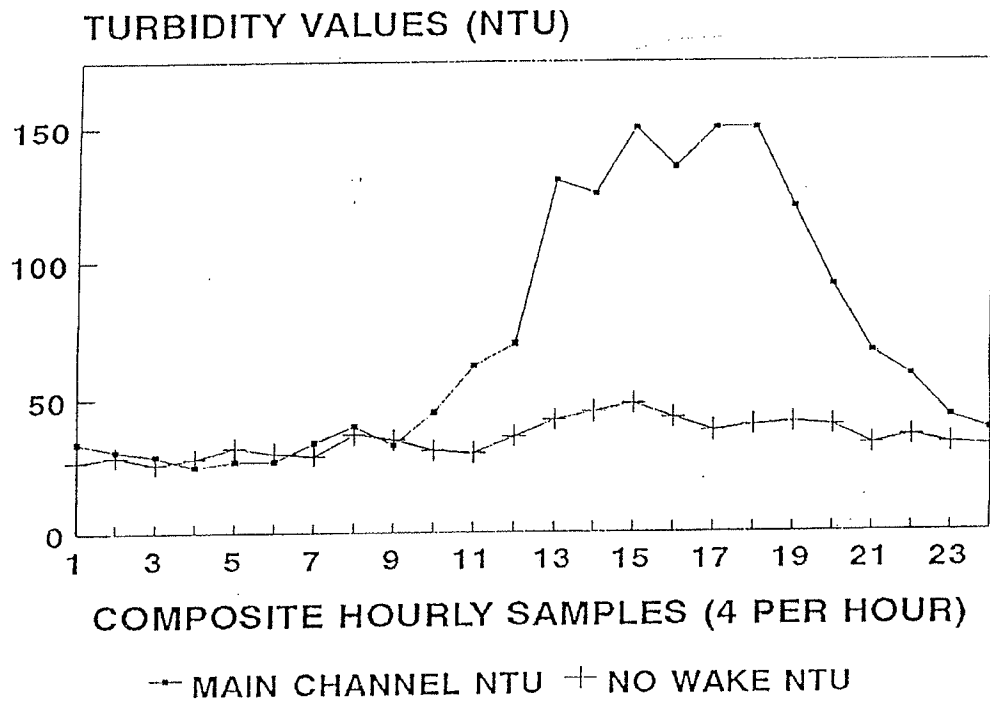


Figure 26. Main Channel and Wisconsin Channel turbidity values August 15-19, 1991



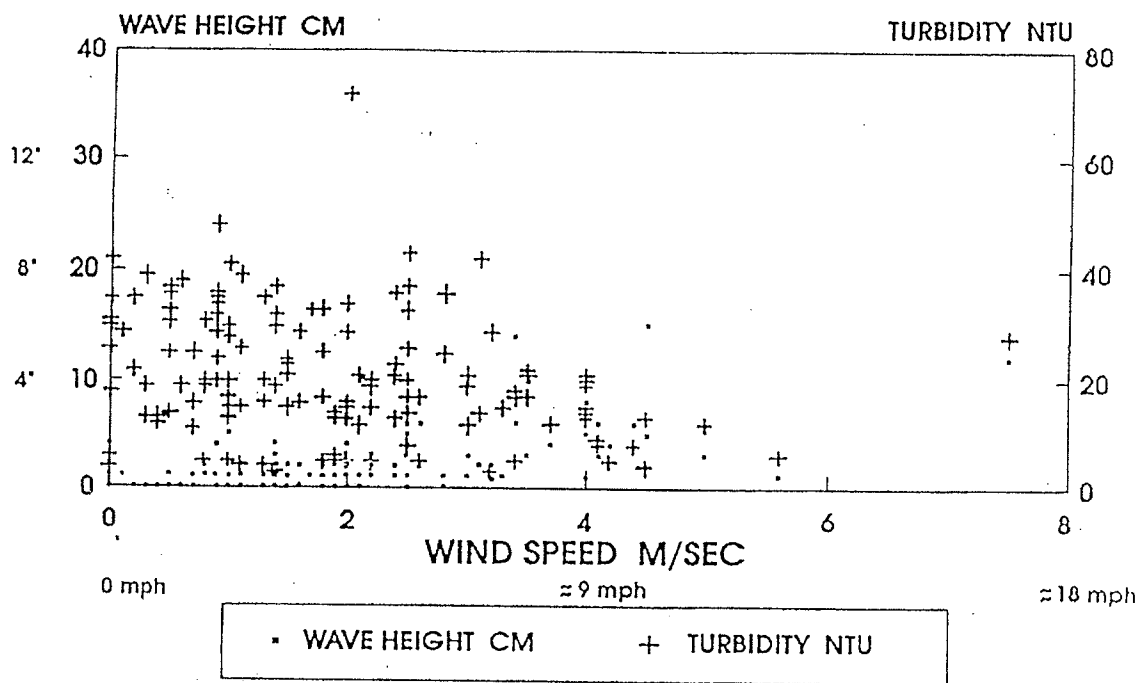
10 CM FROM BOTTOM, NORMAL POOL, 4S/4 HR

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



Average Wind Velocity, 155 Measurements

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	TOTAL PHOSPHORUS	TOTAL NITROGEN	KJELDAHL NITROGEN	AMMONIA NITRATE	CHLOR A	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 (UMHOS/CM)	SECCHI DISC (CM)
5/22/91	15:00	300	31	269	110	5.2	25.8	0.190	1.80	4.1	80.4	0	NA	1.73	0.00	0.10	12.2	7.6	18	433	50
5/27/91	10:00	400	47	340	150	6.8	40.2	0.190	1.96	3.9	24.0	0	352	2.55	0.02	0.06	20.3	7.5	26	499	48
5/27/91	15:00	410	56	340	150	7.6	49.4	0.183	1.81	3.7	22.4	0-3.2	78	1.8	0.02	0.26	31.8	6.8	29	494	41
6/12/91	11:20	500	49	340	100	7.0	42.0	0.291	1.83	5.0	18.8	5-12.3	86	2.65	0.02	0.40	24.8	8.8	36	565	35
6/20/91	11:00	830	56	340	190	8.0	50.0	0.241	1.98	4.0	20.8	1.2-3.4	64	2.15	0.01	0.28	25.2	8.5	36	507	36
6/23/91	09:27	600	48	440	180	7.2	40.8	0.195	1.81	5.3	16.8	3-1.4	240	2.1	0.03	0.40	24.9	8.3	37	565	36
6/23/91	15:30	600	48	390	180	7.4	48.9	0.291	1.70	5.8	19.2	1.0-1.7	240	2.1	0.03	0.40	24.9	8.3	37	512	31
7/3/91	11:30	480	57	390	170	7.5	45.2	0.241	1.94	4.0	31.2	1.1-1.7	NA	1.73	0.01	NA	24.1	6.3	36	515	36
7/4/91	8:15	490	56	390	170	8.0	43.0	0.286	1.90	3.7	20.8	3-2.4	NA	1.98	0.00	NA	23.0	7.6	32	675	29
7/4/91	13:45	490	56	410	150	8.8	58.2	0.230	1.80	2.9	35.2	0	NA	2.19	0.00	NA	23.1	8.8	32	580	30
8/6/91	12:50	490	45	410	150	8.0	32.0	0.251	1.49	2.6	42.4	7-1.0	295	2.1	0.00	NA	21.7	7.2	30	586	33
8/10/91	9:15	480	40	390	140	8.0	39.0	0.231	1.48	2.6	42.4	7-1.0	295	2.1	0.00	NA	21.7	7.4	36	571	34
8/10/91	14:05	450	47	390	130	8.0	32.8	0.187	1.52	2.0	41.8	0-2.5	NA	1.95	0.04	0.18	23.6	8.3	36	506	36
8/29/91	14:35	400	41	410	160	5.2	32.8	0.187	1.52	2.0	41.8	0-2.5	NA	1.95	0.04	0.18	23.6	8.3	36	571	34
9/2/91	8:45	490	55	400	150	7.8	30.2	0.232	1.48	1.8	38.2	0	NA	1.95	0.04	0.18	23.6	8.3	36	571	34
9/2/91	14:45	460	38	410	150	7.8	30.2	0.232	1.48	1.8	38.2	0-1.0	52	2	0.00	0.06	25.0	7.1	30		

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

DATE	TIME	TOTAL SOLIDS	SUSPENDED SOLIDS	TOTAL DISSOLVED SOLIDS	TOTAL VOLATILE SOLIDS	SUSPENDED VOLATILE SOLIDS	TOTAL PHOSPHORUS	TOTAL NITROGEN	KJELDAHL NITROGEN	AMMONIA NITRATE	CHLOR A	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 (UMHOS/CM)	SECCHI DISC (CM)
5/22/91	13:35	360	36	340	130	5.6	30.4	0.184	1.80	5.3	33.0	1.7-2.2	182	1.92	0.02	1.00	19.9	8.0	72	535	54
5/27/91	8:12	440	49	370	140	6.4	36.8	0.189	1.81	6.4	24.0	CALM	45	2	0.02	0.35	20.1	7.2	39	534	50
5/27/91	16:47	430	52	380	130	7.8	44.4	0.211	1.76	6.3	27.2	1.3-1.8	57	1.8	0.04	0.39	23.0	6.6	30	549	42
6/12/91	12:00	510	49	390	170	7.0	42.0	0.297	1.93	5.8	21.6	3-1.5	84	1.8	0.00	0.31	24.5	5.6	NA	550	28
6/20/91	12:15	810	60	390	190	11.0	64.0	0.310	1.78	8.5	12.8	1.7-4.4	72	1.69	0.02	0.13	22.0	6.1	42	605	NA
6/23/91	8:15	850	75	390	190	10.0	57.0	0.271	1.89	9.8	14.4	1.8-2.9	86	1.95	0.01	0.22	24.5	5.6	NA	605	NA
6/23/91	13:15	520	40	390	160	7.8	50.2	0.207	1.86	4.8	23.2	0-10	270	1.78	0.01	0.25	25.0	5.8	35	606	30
7/3/91	12:50	520	56	390	160	10.0	80.0	0.235	1.87	4.3	20.0	0-4	298	1.75	0.00	0.28	24.1	6.3	36	566	37
7/3/91	8:15	820	60	390	190	10.0	58.0	0.436	2.03	4.2	22.4		NA	1.9	0.00	NA	22.0	7.3	33	570	39
7/4/91	18:00	320	60	390	140	8.0	30.0	0.249	1.10	3.0	26.8	2.2-2.8	NA	1.9	0.00	NA	23.1	7.4	38	375	38
8/6/91	13:30	450	44	390	140	8.0	35.0	0.218	1.43	3.2	30.1	4-7	300	2	0.00	0.13	27.4	7.2	35	802	25
8/10/91	8:00	470	49	390	180	9.8	46.4	0.297	1.49	3.8	30.1	4-7	300	2	0.00	0.13	27.4	7.2	35	566	38
8/10/91	14:30	300	30	390	100	8.0	32.2	0.205	1.81	2.1	37.6	0	NA	2.1	0.00	0.14	24.1	6.8	35	590	41
8/29/91	13:35	400	40	390	100	8.8	19.2	0.268	1.47	1.8	34.4	0-8	82	2	0.01	0.14	24.1	6.8	35	590	41
9/2/91	7:51	490	28	400	150	8.8	19.2	0.268	1.47	1.8	34.4	0-8	208	2	0.02	0.10	26.5	7.3	39	561	23
9/2/91	13:35	500	52	400	150	9.4	42.8	0.203	1.86	1.6	36.4	3-1.3	208	2	0.02	0.10	26.5	7.3	39		

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

DATE	TIME	TOTAL SOLIDS	SUSPENDED SOLIDS	TOTAL DISSOLVED SOLIDS	TOTAL VOLATILE SOLIDS	SUSPENDED VOLATILE SOLIDS	TOTAL PHOSPHORUS	TOTAL NITROGEN	KJELDAHL NITROGEN	AMMONIA NITRATE	CHLOR A	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 (UMHOS/CM)	SECCHI DISC (CM)
5/22/91	10:40	430	55	360	130	5.2	28.8	0.153	1.82	6.4	22.4	0.28-0.3	51	3	0.2-0.3	0.33	20.7	7.8	22	535	70
5/27/91	15:18	430	39	370	150	8.4	46.8	0.193	1.76	6.3	27.2	0.28-0.3	100	3	0.04	NA	23.8	6.8	25	516	60
6/12/91	10:00	460	39	400	180	6.8	32.4	0.204	1.84	5.4	22.4	3.0-3.4	80	1.8	0.30	0.52	26.0	5.7	00	610	40
6/20/91	9:40	480	28	450	170	6.0	22.0	0.217	1.94	6.6	14.4	3.8-4.4	99	2.06	0.43	NA	22.2	6.2	24	596	34
6/23/91	18:25	450	28	350	170	6.0	22.0	0.217	1.84	4.8	20.8	3.2-8.4	70	1.5	0.12	NA	23.8	6.8	28	596	41
7/3/91	12:23	500	52	390	190	6.4	28.6	0.226	1.79	4.3	21.6	0.4-1.1	293	1.77	0.02	NA	24.1	6.3	28	576	37
7/4/91	8:45	460	34	390	150	6.4	28.6	0.226	1.79	4.3	21.6	0.4-1.1	293	1.77	0.02	NA	24.1	6.3	28	576	37
7/4/91	15:15	480	38	390	180	7.4	30.6	0.238	1.13	4.2	24.8	2.8-4.8	304	1.7	0.07	NA	22.7	7.5	27	587	40
7/4/91	18:30	420	31	350	130	6.4	24.6	0.207	1.22	2.9	28.6	4-8	302	1.6	0.00	NA	21.8	6.9	34	544	NA
8/10/91	8:30	450	47	390	140	8.8	38.2	0.293	0.92	3.0	30.4	0	NA	2	0.00	NA	24.0	8.2	36	544	NA
8/10/91	13:30	430	33	400	140	8.4	24.6	0.229	1.12	3.0	45.2	4-8	353	1.9	NA	NA	27.2	7.3	44	603	NA
8/23/91	18:05	690	68	400	170	8.8	49.2	0.206	1.83	2.1	30.3	1.4-0.2	166	2.1	0.08	NA	23.9	6.3	45	582	27
9/2/91	8:21	470	48	400	150	6.4	36.6	0.285	1.84	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	6.0	34.0	0.282	1.83	1.5	36.4	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 SOILS  
LAB AND FIELD MEASUREMENTS

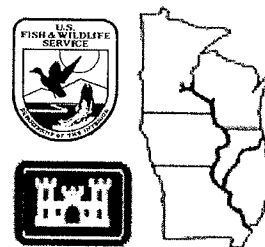
<b>TSS</b>	<b>NTU</b>	<b>Regression Output:</b>	
36.2	50	Constant	
42.3	28		11.47700
43.7	30	Std Err of Y est	9.363277
44	30	R Squared	0.949673
44.4	30		
44.5	30	No. of Observations	15
47.1	28	Degrees of Freedom	13
53.3	28		
57	35	X Coefficient(s)	0.424035
94.4	52	Std Err of Coef.	0.27073
99.1	34		
179.3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

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0705-0188
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1205, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0705-0188), Washington, D.C. 20503			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 1994	3. REPORT TYPE AND DATES COVERED	
4. TITLE AND SUBTITLE Recreational Boating Impact Investigations - Upper Mississippi River System, Pool 4, Red Wing, Minnesota		5. FUNDING NUMBERS FWS Agreement #14-16-0003-89-943, Amendment 7	
6. AUTHOR(S) Scot Johnson			
7. PERFORMING ORGANIZATION NAME AND ADDRESS Minnesota Department of Natural Resources Division of Waters 1801 South Oak Street Lake City, Minnesota 55041			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Biological Survey Environmental Management Technical Center 575 Lester Avenue Onalaska, Wisconsin 54650		10. SPONSORING/MONITORING AGENCY REPORT NUMBER 94-S004	
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT Release unlimited. Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161		12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) 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.			
14. SUBJECT TERMS Upper Mississippi River, recreational boating, shoreline erosion, water quality, surface waves, contributing influences, geomorphology,		15. NUMBER OF PAGES 48 pp. + appendixes (2 pp.)	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

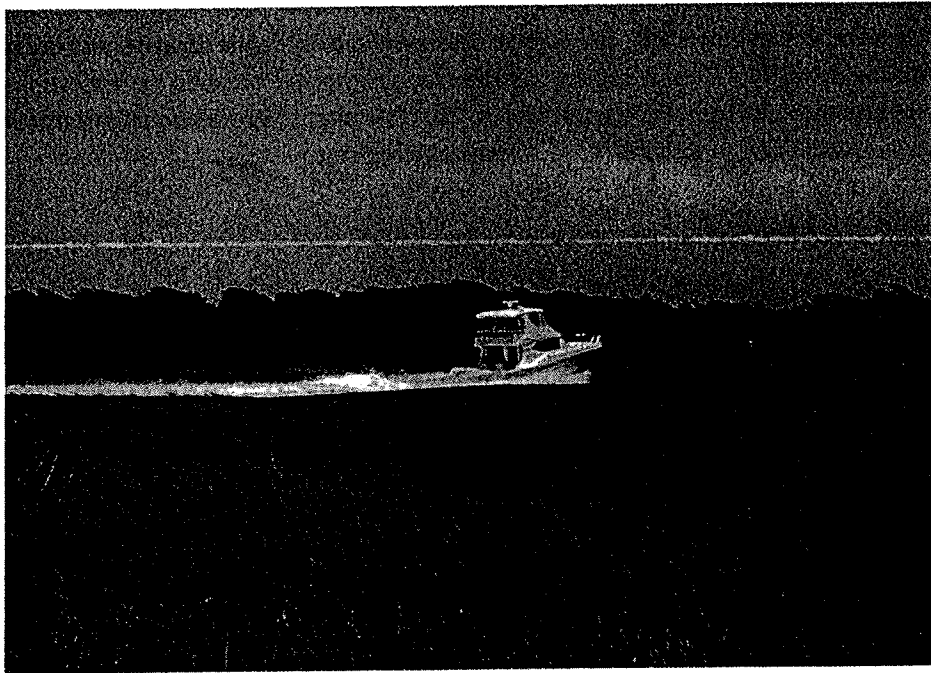
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The Long Term Resource Monitoring Program (LTRMP) for the Upper Mississippi River System was authorized under the Water Resources Development Act of 1986 as an element of the Environmental Management Program. The mission of the LTRMP is to provide 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.

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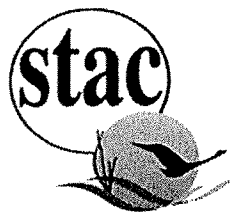


# **Review of boat wake wave impacts on shoreline erosion and potential solutions for the Chesapeake Bay**



**STAC Review Report**

**Fall 2016**



**STAC Publication 17-002**

## About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in various ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the Watershed. For additional information about STAC, please visit the STAC website at [www.chesapeake.org/stac](http://www.chesapeake.org/stac).

Publication Date: May 12, 2017

Publication Number: 17-002

### Suggested Citation:

Bilkovic, D., M. Mitchell, J. Davis, E. Andrews, A. King, P. Mason, J. Herman, N. Tahvildari, J. Davis. 2017. Review of boat wake wave impacts on shoreline erosion and potential solutions for the Chesapeake Bay. STAC Publication Number 17-002, Edgewater, MD. 68 pp.

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STAC Administrative Support Provided by:

Chesapeake Research Consortium, Inc.  
645 Contees Wharf Road  
Edgewater, MD 21037  
Telephone: 410-798-1283  
Fax: 410-798-0816  
<http://www.chesapeake.org>

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## **Review Panel**

Donna Marie Bilkovic, Virginia Institute of Marine Science, College of William & Mary (STAC)

Molly Mitchell, Virginia Institute of Marine Science, College of William & Mary

Jenny Davis, NOAA Center for Coastal Fisheries and Habitat Research

Elizabeth Andrews, Virginia Coastal Policy Center (VCPC), William & Mary Law School

Angela King, Virginia Coastal Policy Center, William & Mary Law School

Pam Mason, Virginia Institute of Marine Science, College of William & Mary

Julie Herman, Virginia Institute of Marine Science, College of William & Mary

Navid Tahvildari, Department of Civil and Environmental Engineering, Old Dominion University

Jana Davis, Chesapeake Bay Trust

## **External Reviewers**

Anson Hines, Smithsonian Environmental Research Center

Marina Liacouras, Elizabeth River Crossings OpCo, LLC

Craig Vogt, Craig Vogt Inc. - Ocean & Coastal Environmental Consulting

Linda Walters, University of Central Florida

## **Acknowledgements**

The Review Team gratefully acknowledges the constant and critical contributions of Rachel Dixon (Chesapeake Research Consortium, STAC Coordinator) throughout this review process.

We also thank Ken Moore, David Parrish, Bruce Michael, Mark Trice, and Brian Smith for providing Chesapeake Bay continuous water quality monitoring data.

The Virginia Coastal Policy Center wishes to thank W&M Law School students Sarah Edwards, Kristin McCarthy and Emily Messer for their assistance with this report.

## Executive Summary

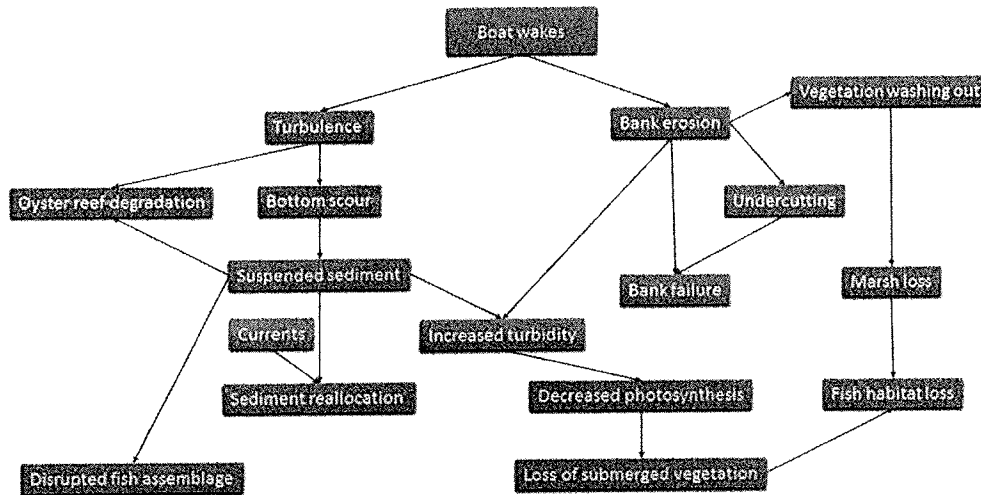
The goal of this technical review was to evaluate 1) the potential impacts of boat generated waves on shoreline stability and attendant ecosystem properties, and 2) policy options to minimize any adverse effects. We reviewed available literature, examined relevant data and information from Chesapeake Bay, discussed modeling approaches and highlighted data gaps to further quantify effects on shorelines and ecosystems, and detailed available management and policy actions to minimize potential boat wake impacts. The major findings are:

- 1) The literature review indicates an unequivocal connection between boat wake energy and shoreline erosion, sediment resuspension and nearshore turbidity.
- 2) There is not currently enough data to determine the extent (spatially and in magnitude) to which boat wakes are contributing to erosion or turbidity of the Chesapeake Bay.
- 3) Recommended next steps are to identify highly vulnerable waterways and implement management or policy actions to minimize adverse effects.

The Chesapeake Bay Commission (CBC) requested that the Scientific and Technical Advisory Committee (STAC) of the Chesapeake Bay Program (CBP) conduct a technical review that addresses five focal areas: (i) State of the science of known effects of boat generated waves on shoreline stability and ecosystem structure and function; (ii) Specific implications and concerns for Chesapeake Bay restoration and shoreline management, including an analysis of continuous turbidity data in relation to boating activity; (iii) Modeling approaches and data requirements for assessing boat wake wave effects on shorelines; (iv) Data gaps and research needs to quantify effects on shorelines and ecosystems; and (v) Relevant management and policy actions in Chesapeake Bay that could be adopted to minimize potential boat wake impacts to shorelines and Bay resources.

Boat wakes have been shown to have erosive effects on shorelines (e.g., Castillo et al. 2000, Bauer et al. 2002), scour the bottom of the shoreface, and temporarily decrease water clarity (e.g., U.S. Army Corps of Engineers (USACE) 1994, Asplund 1996). In addition to shoreline erosion, boat wake impacts include vegetative damage and disruption of faunal communities (Parnell and Koefoed-Hansen 2001). Boat wake energy is event-dependent and is influenced by the vessel length, water depth, channel shape, and boat speed (Sorensen 1973, Glamore 2008). Wakes are most destructive in shallow and narrow waterways because wake energy does not have the opportunity to dissipate over distance (FitzGerald et al. 2011). Although boat wakes are periodic disturbances, in comparison to wind waves, they can be a significant source of erosive wave force due to their longer wave period and greater wave height, even when they represent

only a small portion of the total wave energy (Houser 2010). Our review of the literature demonstrated that even small recreational vessels within 150 m (~500 ft.) of the shoreline are capable of producing wakes that can cause shoreline erosion and increased turbidity (e.g., Zabawa and Ostrom 1980). Vegetated shorelines can effectively attenuate waves in certain settings; however, there is a limit to this capacity particularly if there is frequent exposure to boat wakes.



**Figure 1. Diagram showing potential impacts from boat wakes to some different aquatic resources. Adapted from Liddle and Scorgie 1980. Blue boxes are drivers of change. Yellow boxes are changes in ecosystem structures and functions. Green boxes are impacts on living resources.**

In the Chesapeake Bay, our analysis of long-term (~3 year) turbidity data indicate that there is a likely nexus between turbidity of small waterways, shoreline erosion, and boating activity. However, the relationships between these factors were weak due the lack of direct information and the need to use proxy measures of boating (i.e., number of piers in an area), past erosion experience (i.e., shoreline armoring) and boat wake experience (i.e., distance to the 1-m contour). These results, in combination with past studies that controlled for boat wake activity, are an indication that boat wake activity could significantly contribute to shoreline erosion and poor water clarity in some Bay creeks and tributaries.

In addition, boating activity likely contributes to the desire to armor shorelines (CCRM 2017), reducing and fragmenting the natural Bay habitats. In each of the three tidal creek systems with

relatively high boating activity that were examined for this review (Lafayette River, Sarah Creek, and Lynnhaven River), approximately 25% of the low energy shoreline (i.e., shoreline not expected to have active erosion from wind-waves) has been armored, suggesting another source of erosion - possibly boating. In turn, armored shorelines can also contribute to erosion of adjacent downdrift shorelines. Living shorelines, more beneficial from a habitat perspective than armor (Bilkovic et al. 2016), could be considered a more palatable alternative than hard shoreline armor in cases in which no degree of erosion can be tolerated. Management strategies to minimize adverse impacts by addressing boating behavior (e.g., speed limits) rather than shoreline modifications are preferred to be most protective of the environment.

Policy makers who are concerned about boat wakes may want to use existing models of boat wake erosive potential (e.g., BoMo, Decision Support Tool) to inform decisions on where to put no-wake zones or other boat policies. However, at this time, we do not have sufficient data to run either model for the Chesapeake Bay. Concerns about the impacts of boat wakes on Bay shorelines have been voiced for at least 30 years (e.g., Zabawa and Ostrum 1980), leading to some regulation of boat wakes through reduced speed requirements in certain water bodies. Virginia, Maryland and Delaware localities have demonstrated authority and willingness to establish wake restrictions, but have not done so comprehensively nor with Bay-wide coordination. Evidence suggests that boat wake erosion impacts achievement of three of the CBP Restoration Goals: preservation/restoration of tidal marshes (through enhanced shoreline erosion), preservation/restoration of seagrass beds (through enhanced bottom erosion and increased local turbidity), and water clarity improvements (through increased local turbidity).

We recommend that this issue be addressed by two means:

- 1) First, because we have enough evidence to suggest an impact of boat wakes, protective policy measures should be adopted in highly vulnerable systems to reduce current boat wake energy.
- 2) Second, data should be collected that allow a more thorough analysis of the extent of the problem throughout the Bay.

These two processes need not be consecutive, but may need to occur concurrently. In locations where shoreline erosion has been attributed to boating activity with a resultant significant adverse effect on resources and property, policy actions need not wait on new data.

Recommended science, management, and policy actions include:

- Develop predictive models to quantify the relative contribution of boat wake induced erosion to overall shoreline erosion to inform water quality, habitat restoration, and shoreline protection management strategies.
- Collect needed data to identify shores vulnerable to erosion from boating (specific data needs defined below), and to calibrate and validate predictive models. Then, develop a definition for, and classification scheme of, small tidal waterways with the greatest likelihood for significant boat wake wave shoreline erosion.
- Incorporate boat wake induced turbidity and erosion when siting Bay Restoration activities (e.g., wetland/submerged aquatic vegetation (SAV) restoration).
- Investigate the opportunities within the Bay states to implement no-wake zones or other wake reduction strategies (navigation buffers from shore, speed limits, boat size restrictions, boat bans) for addressing shoreline erosion where public safety is not also a concern. In Virginia, current implementation of no-wake zone requires a finding of public safety concern and erosion is a second consideration. Empanel an expert group from the appropriate Bay jurisdictions to develop and recommend a uniform boat wake policy in the Chesapeake Bay.

Recommended data needs include:

- High resolution recreational boating intensity information (the number of vessels that pass by on an average day, vessel types, vessel speeds, vessel traffic patterns).
- Information on recreational boating trends in small waterways.
- Information on the location, extent and level of enforcement of no-wake zones throughout the Bay.
- Data on grain size of bottom sediments in all the Bay tributaries and small creeks; even a simple categorization of sand and fines would be useful.
- Data on wave height (measure for wave energy) and suspended sediment concentration (a

measure for potential erosion).

- High resolution shallow water bathymetry is needed throughout the Bay. If data even exist, most are 50-100 years old in these areas.

This review found that boat generated waves, particularly in shallow and narrow waterways, can increase turbidity, erode shorelines, compromise coastal habitats, and disrupt ecosystems. This has the potential to impede progress towards several Bay restoration goals, particularly habitat restoration and water quality improvement. Not accounting for potential boat wake effects during the planning and implementation of Bay restoration activities may compromise the attainment of Bay Program goals. Further, incorporating the boating effects into the Bay Model may help to reduce uncertainty and ensure that restoration projects are sited in the most favorable settings.

## Background and scope of the review

The Chesapeake Bay Commission (CBC) requested that the Scientific and Technical Advisory Committee (STAC) of the Chesapeake Bay Program (CBP) conduct a technical review of the relevant information on the potential impacts of boat generated waves on shoreline stability and attendant ecosystem properties, and provide advice on available policy actions to minimize any adverse effects. This request was made in January 2016; the request was approved by the STAC in March 2016, and the review was initiated in June 2016. The request to the STAC (see Appendix I) from the CBC was that the review be focused on the following topics:

1. Evaluate the state of the science of known effects of boat generated waves on shoreline stability and other ecosystem components (e.g., vegetative habitat, faunal community composition),
2. Identify data requirements to effectively model the potential effect of boat wake waves on shorelines,
3. Identify data gaps and research needs, and
4. Determine existing and potential policy actions to reduce adverse effects of boat wake waves on shorelines. Describe political and legal challenges for designating no-wake zones in Chesapeake Bay. Are there case studies of no-wake zone designation and/or evaluation of response from management action in the Bay that can be learned from?

STAC was also asked to address several questions related to *(i)* erosion and sediment inputs caused by boat wake waves, *(ii)* existing and needed data to develop best management practices to minimize shoreline erosion from boat wake waves, and *(iii)* political and legal challenges associated with policy actions to reduce boat wakes.

### Questions of Interest:

1. What is the relative contribution of sediment inputs from boat wake-induced shoreline erosion in Chesapeake Bay?
2. Are these types of sediment inputs currently represented in the Bay Watershed Model?
3. Would expanding no-wake zones be beneficial to the Bay?
4. Are there other policy options besides no-wake zones to consider?

To be responsive to the CBC request, the STAC assembled a team of 9 professionals with backgrounds in sediment dynamics, shoreline erosion, coastal management and policy, environmental engineering, coastal engineering, estuarine shoreline systems, and estuarine ecology to assimilate relevant information in the form of a technical white paper. The document

was then reviewed by additional external reviewers for further input to ensure critical areas of expertise were well-represented.

The body of the review is organized into the following 6 sections:

1. Evaluation of the state of the science of known effects of boat generated waves on shoreline stability and other ecosystem components
2. Specific Chesapeake Bay implications and concerns
  - a. Examination of continuous data for evidence of elevated turbidity from boating activity
  - b. Case study that describes boat-wake induced erosion implications for city-managed property in the Lafayette River, VA
3. Modeling approaches and data requirements to assess the potential effect of boat wake waves on shorelines
4. Data gaps and research needs
5. Management and policy in Chesapeake Bay
6. Summary and Recommendations

## **Section 1: State of the Science**

Shoreline erosion is a natural process that can be exacerbated by human activities. Natural drivers of shoreline erosion include wind waves, currents, and sea level rise (SLR). Human activities that exacerbate erosion include shoreline hardening (armoring) and boat wake impacts. It is not possible to visually distinguish between the natural and human-induced components of erosion; these must be deduced from measure of human use of an area combined with wind wave erosion models.

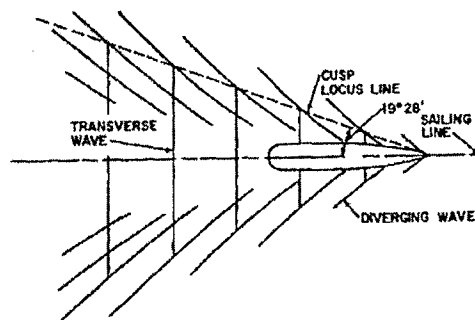
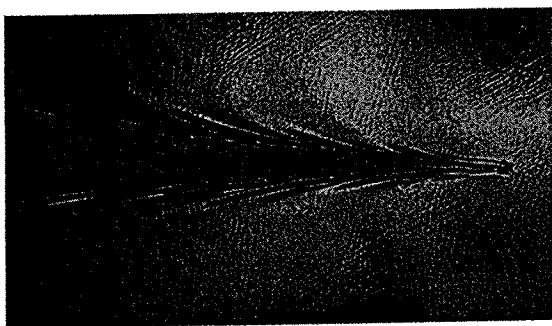
This report focused on boat wake-induced erosion, but this should not be interpreted to mean that the other drivers of erosion are unimportant in the Chesapeake Bay. Historic Virginia shoreline erosion rates can be found at the Shoreline Studies, VIMS website (<http://vims-wm.maps.arcgis.com/apps/webappviewer/index.html?id=cd5cf9b788d0407fb9ba5ffb494e9bae>). Historic Maryland shoreline erosion rates can be found at Maryland Department of Natural Resources (<http://www.mgs.md.gov/publications/maps.html>).

### **Boat wake dynamics**

As a boat travels through the water, it displaces water, effectively pushing it to the side and creating a pressure gradient that radiates outward in a wave form. Forward movement of the



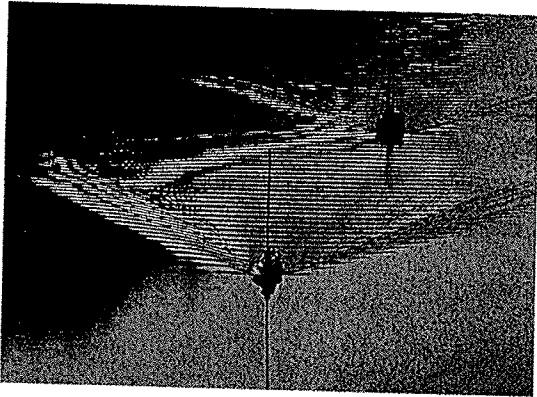
bow creates a series of symmetrical waves that propagate away from the bow at oblique angles, while the stern generates a single transverse wave that travels in the same direction as the vessel (Sorenson 1973). The point at which bow and stern waves interact (known as the cusp), is the region of maximum wave height (Maynard 2001, Figure 2). Waves that fall between the cusp points are smaller than the maximum height. The cumulative result is that each boat passage generates a complex series of waves known as a wave train, which propagate away from the sailing line at an angle that is dictated by hull shape and vessel speed. The specific characteristics of the waves generated by each passage are dependent on a multitude of factors including water depth, vessel length and speed, displacement (loading), hull shape, and the presence of natural waves and currents, among others (Maynard 2001). Given the complexity of predicting waves in a natural system, it is valuable to understand the basic traits of idealized waves.



**Figure 2. Pattern of vessel-generated waves in deep water. Diagram from Sorenson 1973.**  
**Photo by Edmont - Own work, CC BY-SA 3.0,**  
<https://commons.wikimedia.org/w/index.php?curid=6920796>

Waves that travel in water that is deeper than  $1/2$  of their wavelength (the distance between two successive wave crests) are referred to as deep water waves. The motion of deep water waves do not penetrate the full depth of the water column, thus these waves have little impact on the bottom sediments (Sorenson 1997, Hill et al. 2002). As a deep water wave travels away from the sailing line, wave height will decrease with distance traveled as wave energy spreads out along the wave crest. Given a long enough transit in deep water, much of the wave energy will distribute over a wide area before reaching a shoreline. In deep water, the speed at which a wave moves away from its point of generation is largely a function of wavelength; waves with longer wavelengths travel faster than those with shorter wavelengths. As faster waves overtake slower ones, waves produced by one boat may merge with those produced by a different boat (Figure 3),

or with wind waves. Merging of waves from different sources can be constructive (resulting in higher wave heights) or destructive (resulting in decreased wave heights) depending on whether they merge crest to crest, or crest to trough. In most cases, the interaction of waves from a variety of sources results in a water surface that appears highly disordered.



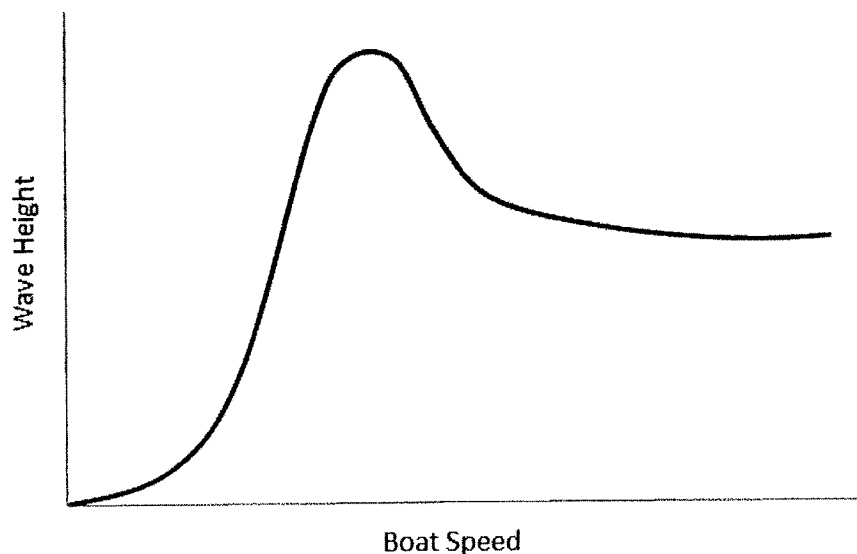
**Figure 3. Boat wakes from different boats interact, changing wake patterns. Photo by Arpingstone, <https://commons.wikimedia.org/w/index.php?curid=5957943>**

Waves that travel through water depths that are less than  $1/20$  of their wavelength are referred to as 'shallow water waves'. Waves that fall between deep and shallow water wave categories (when water depth is greater than  $1/20$  but less than  $1/2$  of wavelength) fall into the "transitional" category. The movement of both transitional and shallow water waves is influenced by water column depth because the energy associated with both types reaches all the way to the sea floor. Deep water waves traveling toward a shoreline will therefore eventually become transitional and shallow water waves due to changes in water column depth. Shallow water waves can influence the seafloor by causing sediment resuspension and, conversely, the friction created by wave motion interacting with the seafloor can influence waveform. As a wave travels into shallow water, interaction with the seafloor causes a decrease in the forward speed of the wave train and a concomitant increase in wave height (shoaling) until the wave eventually breaks (Parnell and Kofoed-Hansen 2001). As a result, waves of low amplitude and long wave-length that seem trivial in deep water, may result in large plunging breakers when they reach the shoreline.

The size and shape of boat wakes are strongly influenced by hull type and speed. Planing hulls are designed to ride on top of the water. Displacement hulls (e.g., sailboats, trawlers and large ships) are not capable of planing but rather, ride in the water, pushing it to the side as they move forward. The amount of water displaced is equivalent to the weight of the vessel, thus very large

displacement hulls like tanker ships displace large volumes of water, resulting in the creation of wakes with large wave heights. The shape of a hull further influences its wake characteristics. A catamaran, a single-hulled vessel, and a jet ski will all produce different wakes. Previous investigators have shown that a boat towing a water skier will produce a wake with greater wave energy than the same boat when not towing (Baldwin 2008). All other factors being equal, a positive correlation exists between the size of a vessel and the size of its wake (Hill et al. 2002, Fonseca and Malhotra 2012).

The single best predictor of the size of the wake that any given boat will produce is the speed at which the vessel is traveling (Sorenson 1973, Zabawa and Ostrom 1980, Fonseca and Malhotra 2012), although this relationship is not linear for planing hulls. When planing vessels are operating in displacement mode (such that the bow of the boat is fully supported by the water), wake size increases with speed. The maximum wake is produced at the point just before a vessel transitions to planing mode (this range of speeds is commonly referred to as transition mode). When speed is increased enough that the vessel is fully “on plane”, wake sizes begin to decrease as less of the boat is in the water. This relationship between speed and wake size is illustrated in Figure 4. It is important to note that while all planing vessels will produce a curve with this same general pattern, the curve is slightly different for each boat and each set of operating conditions (Stumbo et al. 1999).



**Figure 4. Wave height as a function of speed in planing hull vessels. Adapted from Maynord 2001.**

Efforts to quantify the impacts of boat wakes on shorelines are complicated by the fact that each boat passage produces waves with a unique set of characteristics (McConchie and Toleman 2003). As a result, many previous efforts to establish wake management strategies have used wave height, or wave energy based criteria (Stumbo et al. 1999, Glamore 2008).

Wave energy, given as:

$$E = 1/8 \rho g H^2 L$$

(where  $\rho$  = water density,  $g$  = gravity,  $H$  = wave height, and  $L$  = wavelength) is proportional to both the height and length of a wave. As wave energy increases with wave height squared, wave height provides a reasonable proxy for erosive force. Wave height is also more easily estimated by the casual observer than wave energy (Nanson et al. 1994). Wave energy dissipates with distance from the boat thus, the smaller a wave is at the onset, and the farther from the shoreline it is generated, the less energy it will contain when it reaches the shoreline and the less likely it is to cause erosion.

### **Site specific factors that control impact of boat wakes on shoreline erosion**

#### ***Local vessel usage***

The amount of boat wake energy impacting a given shoreline is a function of not only the size and speed of vessels passing that shoreline, but also the frequency of vessels (Zabawa and Ostrom 1980, Glamore 2008). Highly traveled waterways are more likely to experience boat wake-induced shoreline erosion than less frequently travelled waterways. Further, because wave energy decays with distance from the boat, narrow waterways in which boats must pass closer to shore are more likely to experience wake-induced erosion from both direct wave impact, and wave energy reflected from the opposite shoreline, than wider channels (Nanson et al. 1994, FitzGerald et al. 2011; Table 1).

It should be noted that shallow draft vessels (like personal watercraft) with the ability to run at high speed in shallow nearshore water may play a disproportionate role in shoreline erosion simply by virtue of their ability to operate close to shore where waves have little chance to dissipate. However, when run in a manner similar to that of a small boat (i.e., in a straight line) personal watercraft were found to generate smaller lower energy waves than boats (McConchie and Toleman 2003).

**Table 1.** Published values of measured wave heights vs. vessel speed at varying distances from the sailing line: \* indicates planing hull, \*\* indicates displacement hull. These data are excerpts from the larger data sets published by a) Zabawa and Ostrum 1980, Chesapeake Bay and b) Sorenson 1973. For context, waves as small as 10 cm result in erosion of sediments from vegetated shorelines (Coops et al. 1996), and marsh survival is compromised when waves exceed 30 cm, even 5% of the time (Schafer et al. 2003, Roland and Douglas 2005).

Boat	Distance From Sailing Line (m)	Speed of Boat Travel (knots ((km hr <sup>-1</sup> ))	Max wave height (m)
26' (8 m) Uniflight*	100	10 (19)	0.41
	100	26 (48)	0.29
	150	10 (19)	0.37
	150	27 (50)	0.21
16' (5 m) Boston Whaler*	50	10 (19)	0.22
	50	24 (44)	0.13
	150	12 (22)	0.14
	150	27 (50)	0.07
45' (14 m) Tugboat**	30	6 (11)	0.2
	30	10 (19)	0.5
	150	6 (11)	0.1
	150	10 (19)	0.3
263' (80 m) Barge**	150	10 (19)	0.2
	300	10 (19)	0.1

### *Wave energy at site*

In many instances, the cumulative impact of boat wakes is often small relative to that of wind waves (Laderoute and Bauer 2013). In a study of boat wake versus wind-wave energy at multiple sites within Chesapeake Bay, Zabawa and Ostrom (1980) determined that <5% of total annual shoreline wave energy was attributable to boats. The sites included in this study were along either the mainstem of the South and Severn Rivers, or on smaller creeks and coves near each river. All sites were selected based on being popular areas for boating/water skiing and being relatively sheltered from wind. Several more recent studies have found similar results with respect to the total amount of wave energy attributable to wind vs. boating activity (Knutson et al. 1990, Houser 2010, Fonseca and Malhotra 2012).

While total cumulative wave energy associated with boating impacts is often less than that of wind waves, the height of the largest boat generated waves can substantially exceed that of the largest wind waves. Winds represent an almost constant source of low to moderate wave energy while large boat wakes represent a comparatively rare but high energy event that may be responsible for significant damage to some shorelines. Houser (2010) estimated that while cumulative boat wake energy accounts for less than 5% of total wave energy on the Savannah River, they account for more than 30% of total wave force acting on shorelines. The disproportionately high wave force relative to total wave energy associated with boat wakes in this study was attributed to the fact that the Savannah River is heavily trafficked by large displacement hull vessels that generate large amplitude, long period waves. Further, the relative amount of wave energy attributable to boats vs. wind has been shown to change throughout the year due to seasonal changes in boat usage (Zabawa and Ostrom 1980, Maynard et al. 2008).

### *Shoreline characteristics*

Shoreline profiles influence erosion rates with ramped (gently sloping) and scarped (vertical shore profile) marsh shorelines experiencing greater wave thrust and consequently higher erosion than terraced shorelines (characterized by a step-like profile) under the same wave conditions (Tonelli et al. 2010). In Boston Harbor, the highest rates of shoreline retreat were shown to occur along high elevation shorelines (bluffs of >10 m; FitzGerald et al. 2011). In this case, the high erosion was attributed to wave-induced undercutting of the shoreline that eventually led to slumping of large sections of the bank.

As waves come into contact with a shoreline they may either shoal and break, or be refracted, thus further contributing to the wave energy of nearshore waters. The amount of wave energy

that is reflected along a given stretch is heavily influenced by the amount of shoreline modification. Hard, vertical structures like bulkheads and seawalls are purported to reflect much of the incoming wave energy, thus resulting in an overall increase in nearshore energy (NRC 2007). Shoreline geometry further influences wave energy as headlands are impacted by wave energy from a variety of directions while embayed shorelines may experience greater influences from refracted wave energy (Priestas et al. 2015).

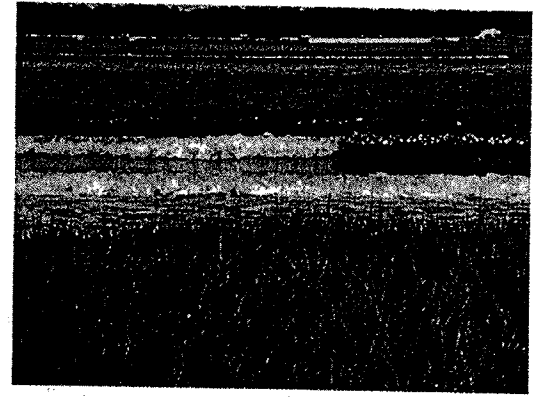
### *Water Levels*

The impact of waves is even more challenging to predict along tidally influenced shores, as water levels and tidal flow interact to determine the effect of incoming wave energy on a shoreline (Tonelli et al. 2010). Along shorelines that are fronted by extensive tidal flats, much of the incoming wave energy will be dissipated over the tidal flats, effectively buffering the shoreline from wave attack. The lower the water level, the more influence a tidal flat exerts on water column dynamics. River stage plays a similar role. In the Kenai River, Alaska, Maynard et al. (2008) demonstrated higher shoreline erosion rates when peak boating conditions corresponded to times of high river flow and decreased erosion, despite high boat activity, during lower flow conditions. They noted that during low flow conditions, much of the wave energy was lost due to contact with gravel sediments near the river margins. Tonelli et al. (2010) have modeled the impacts of waves along salt marsh shorelines and showed that wave thrust on a shoreline increases with rising tide levels until the tide is just above the marsh surface elevation, at which point, wave thrust on the shoreline decreases sharply. Houser (2010) demonstrated this effect with wave sensors in the Savannah River. The importance of tidal stage is further supported by Marani et al. (2011) who demonstrated a strong relationship between wind wave energy and measured marsh edge retreat by considering wind data only from periods when marsh was not flooded.

Tidal flows may further influence the ultimate fate of eroded sediments by providing a mechanism for their dispersal. Bauer et al. (2002) used back-scatter sensors to measure the concentration of suspended solids in the water column after individual boat passages. Their data indicated that suspended solid concentrations (SSC) returned to background values within a few minutes of each boat passage, despite much longer calculated settling times. These data suggest that once suspended, the particles are carried downflow by currents, thus representing a net loss of sediment from the site.

## *Vegetation*

Whether waves of a given size will result in significant levels of sediment resuspension and/or shoreline erosion is further influenced by sediment characteristics and the presence or absence of shoreline vegetation. Soils with a high sand content have been shown to be more easily eroded than finer-grained sediments (Feagin et al. 2009). Shorelines that are vegetated tend to have finer-grained sediments than non-vegetated shorelines due to the incorporation of decaying organic matter (Craft et al. 2002). As a result, the presence of living root material in shoreline soils results in a stronger soil that is less easily eroded (van Eerd 1985, Francalanci et al. 2013). Additionally, shoreline vegetation like marsh plants combats erosion by attenuating wave energy (Yang et al. 2012, Möller et al. 2014; Figure 5) and this response is proportional to both the height and density of the vegetation (Möller 2006). The presence of even a narrow band (on the order of 1 m wide) of marsh vegetation in front of the shoreline has been shown to result in decreased rates of shoreline erosion (Currin et al. 2015). Vegetated shorelines and marshes in particular are limited to regions of relatively low wave energy, thus their geographic extent limits the opportunity to minimize the impacts of incoming wave energy. Recent wave tank modeling results show that marsh vegetation is adapted to short period, high frequency wind waves, but may not be as resilient to long-period ship-generated waves (Silinksi et al. 2015).



**Figure 5. Marsh vegetation helps attenuate wave energy and binds the sediment, reducing erosion. Photo from NOAA/NCCOS.**

## **Boat wakes and shoreline stability**

Shoreline change may include shoreline erosion and resuspension in the foreshore environment, although sediment can be transported landward as well. The balance of transport (whether the shoreline erodes or accretes) depends on the size of the wake (Osborne and Boak 1999, Houser 2011). Most studies found the effects of boat wakes on the shoreline are dependent on many factors. Site-specific conditions such as water depth, bank profile, type, size and supply of sediment and bank resistance can control suspended-sediment concentrations (McConchie and Toleman 2003, Hughes et al. 2007). In coastal areas subject to significant wave action, boat wakes may have a negligible effect on shoreline stability. However, in sheltered coastal, estuarine, and river environments, boat wakes may be the leading cause of shoreline erosion



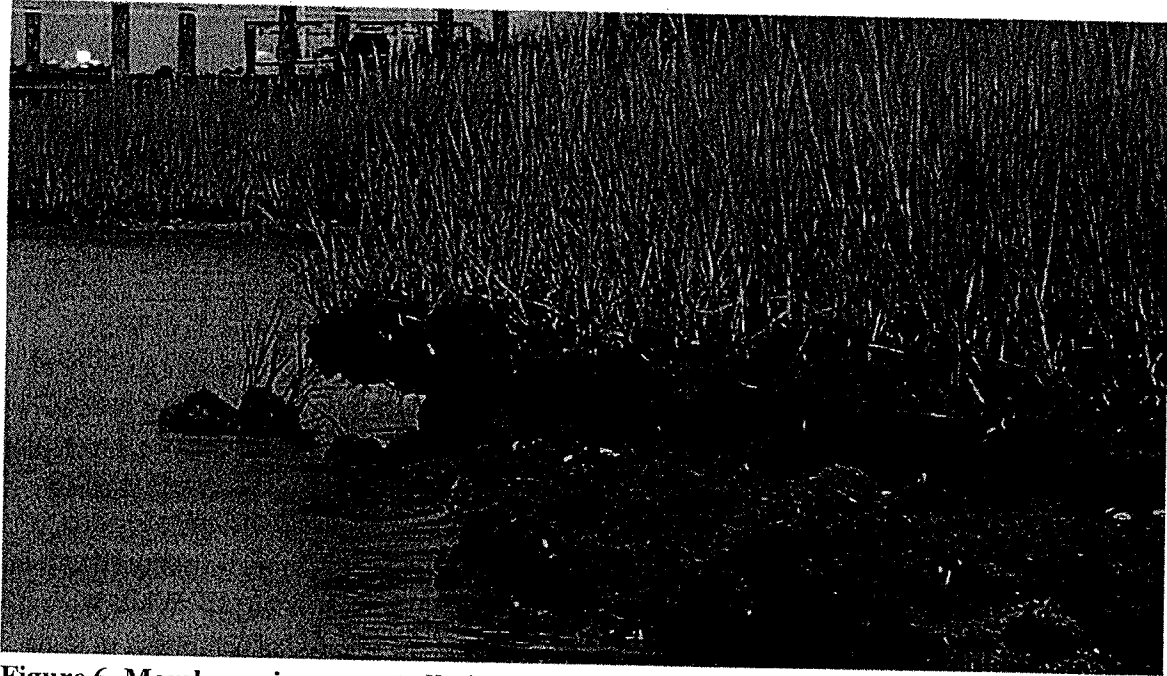
(Gourlay 2011; Figure 6).

### *Shoreline erosion*

There are many anecdotal accounts of boating activity leading to shoreline erosion; however, documenting the role that boat wakes play in the rate of shoreline change is complicated by the fact that any single boat passage (aside from the case of very large displacement vessels) will not produce a measureable change in shoreline position. It is, rather, the cumulative effect of many boat passages that result in shoreline change and these effects can be difficult to discern from those of wind waves. To further complicate matters, in narrow channels boat wakes may reflect off one shore, cross the channel, hit the opposite shore and return to the original shore for a second impact. In suspected cases of boat-wake induced shoreline erosion, often few data exist regarding the shoreline position and natural rate of shoreline change before the impact of boats was suspected. This lack of “control” data makes it challenging to quantify the amount of shoreline change that is attributable to boat wakes alone.

Many studies of boat wake-induced shoreline erosion have focused on the effects of large shipping vessels and high-speed passenger ferries (Kirkegaard et al. 1998, Parnell and Kofoed-Hansen 2001, Soomere et al. 2005, Schroevers et al. 2011). While fewer efforts have focused on the cumulative impacts of recreational boating (Cox and Macfarlane 2004), there is a developing body of literature that demonstrates the negative impacts of small boats on shoreline stability. Among the current published literature relating recreational boat traffic to shoreline erosion, most take the approach of relating boat passages to changes in water column turbidity (Bauer et al. 2002, Cox and Macfarlane 2004, Baldwin 2008, Laderoute and Bauer 2013). While increased turbidity is not a direct measure of erosion (i.e., it is possible for suspended sediments to settle back into their original location) most water bodies experience some level of flow, and settling times for small particles are long, making it likely for suspended sediments to be carried away from their original location. In the Sacramento River, a series of current meters and backscatter profilers were installed on a shallow bank on the river margin in a shoreline-perpendicular transect (Bauer et al. 2002). This instrumentation allowed researchers to evaluate the wave characteristics and amount of sediment suspension associated with individual boat passages. The data were used to model erosion rates on a per-boat basis. The results indicated that each boat passage resulted in 0.01 - 0.22 mm of erosion at a given location on the shoreline. These rates were well-supported by measured rates of cumulative shoreline erosion after multiple (hundreds of) boat passages. The variability in erosion potential of shorelines makes it unlikely that these specific rates will apply to shorelines in other regions; however, they demonstrate that the additive effect of multiple boat passages can lead to measurable erosion.

When boat frequency and/or speed are reduced, measured rates of bank retreat have been shown to decline dramatically (Nanson et al. 1994). On the Gordon River, Tasmania, Nanson et al. (1994) documented an average erosion rate of  $1 \text{ m yr}^{-1}$  on a stretch of the river without speed restrictions. Erosion rates along that same stretch decreased to  $0.3 \text{ m yr}^{-1}$  when boat speeds were restricted to  $17 \text{ km h}^{-1}$ . Erosion rates decreased further (to  $0.06 \text{ m yr}^{-1}$ ) when boat passages along that same stretch were limited to 1 per day.



**Figure 6. Marsh erosion reportedly induced by boat generated waves on Lynnhaven River, Virginia. Photo by Bill Fleming.**

### ***Resuspension***

Observation and research regarding the effects of boat wakes on sediment movement have been ongoing for decades (e.g., Nanson et al. 1994, Osborne and Boak 1999, Gourlay, 2011). Resuspension of bottom sediments in shallow water may occur in the foreshore, in shallow waters, and adjacent to channels after boat passage (Figure 7). Increased turbidity varies in its persistence. In river systems, suspension events may be short-lived, even with very fine sediments, because the suspension plumes are carried downstream (Bauer et al. 2002). In other settings, such as Venice Lagoon, Italy, elevated concentrations persisted for nearly an hour (Rapaglia et al. 2011). The popularization of personal watercraft, with their exceptionally

shallow drafts, has brought boating activity to regions of water bodies which have historically seen little boating traffic. Turbulent prop or jet wash have the ability to resuspend bottom sediments. In field studies, boat speed, size, and water depth were the critical factors affecting resuspension on an unnamed lake bed (Beachler and Hill 2003).



**Figure 7. Imagery capture of boating-induced resuspended sediment along shoreline (upper left of image).**

### **Boat wake impacts to specific resources**

Commercial and recreational boating can have a wide-array of adverse effects on aquatic resources, including direct physical impacts from boat contact with the bottom, noise disturbance, as well as those effects resulting from physical disturbances to the bottom sediments, nearshore habitats and shorelines from boat generated waves. The latter is often understudied and thus less well-understood. Though other boating impacts on a resource may be significant, the primary focus of this report is on boat generated wave impacts.

### *Oyster reefs*

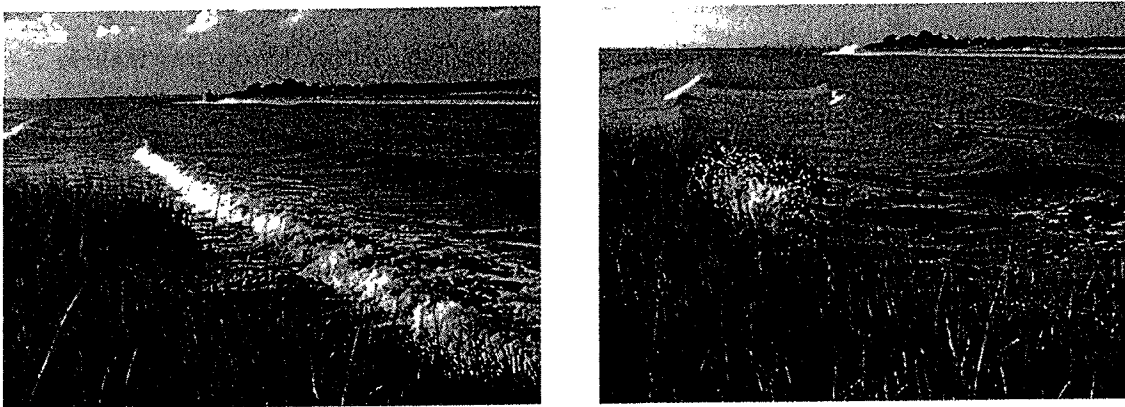
The distribution of intertidal oyster reefs is strongly shaped by wave energy, such that natural intertidal reefs do not occur in high wave energy settings. In Pamlico and Core sounds, North Carolina, Theuerkauf et al. (2016) found that the distribution of intertidal oyster reefs was limited to a fairly narrow range of wave energies, but that wave energy did not limit the occurrence of oysters on hard substrates like rock jetties and seawalls. In Chesapeake Bay, intertidal reefs were once prevalent; for over 100 years oysters supported one of the Bay's most valuable fisheries with tens of millions of bushels of oysters removed each year. This massive shell removal led to the flattening of reefs, with oyster reefs now largely subtidal in the Bay (Hargis and Haven 1999). While there have been many anecdotal accounts of boating-related impacts on oyster reefs, empirical data are limited. In the Indian River Lagoon, Florida, Grizzle et al. (2002) described a pattern of dead margins (evidenced by piles of shells that had apparently originated as living oysters dislodged off of the reef, pushed above high tide line by subsequent wakes, and then perished due to exposure) on the seaward side of oyster reefs that faced navigation channels and hypothesized that boat wakes were responsible. Survival of oyster spat on these same reefs was later found to be significantly lower than on reefs that were not impacted by boat traffic (Wall et al. 2005). Experimental evidence from this same system indicates that waves as small as 2 cm can result in the movement of both individual oysters and small clusters of oysters (Campbell 2015).

### *Salt marshes and beaches*

As previously described, salt marsh vegetation can help to stabilize sediments and dissipate wave energy. Both of these functions can result in decreased erosion rates relative to those of unvegetated shorelines. The benefit of shoreline vegetation does have limits however, as marsh vegetation only exists along relatively low energy shorelines. Efforts to establish the wave energy threshold for marsh survival suggest that marshes will not exist naturally along a coast line where incident wind-generated waves exceed 0.3 m, even 5% of the time (Schafer et al. 2003, Roland and Douglas 2005). Previous efforts to quantify the impact of boat wakes on shorelines suggest that waves of 0.3 m are likely when navigation channels are within 150 m of the shoreline (Table 1, Figure 8). As 0.3 m may represent the threshold of survival, there is likely to be a gradient of wave heights beneath this threshold which span the range from conditions where marshes thrive, to those where chronic erosion occurs. Evidence from wave tank experiments suggests that waves as small as 10 cm result in erosion of sediments from vegetated shorelines (Coops et al. 1996). Furthermore, several researchers have demonstrated positive correlations between wind-wave power along a shoreline and measured rates of

shoreline retreat (Schwimmer 2001, Marani et al. 2011).

Studies have shown a direct impact of boat wakes on tidal marsh stability (e.g., Castillo et al. 2001, Allison 2005, Houser 2010) although not all of the studies concluded that boat wakes were the primary source of annual erosion. Boat wakes seem to contribute significantly to shoreline change where boat activity is regular, concentrated, close to the shore and in small tidal creeks, but may be less important than wind waves in other systems. Although the impacts are generally framed as tidal marsh loss, a study of vegetative community change in San Francisco marshes attributes a shift from intertidal *Schoenoplectus californicus* to submerged aquatic vegetation to shoreline erosion caused by recreational boating (Watson and Byrne 2012). Personal watercraft (Jet skis) have the ability to operate in very shallow water including marsh channels. Within three National Estuarine Research Reserve (NERR) marshes (North Carolina, South Carolina, and New Hampshire), a significant change in turbidity from personal watercraft passages was demonstrated; in addition, the speed and the weight of passengers created higher waves and more turbidity (Anderson 2002). Much less research has been directed to the question of the effects of boat wakes on non-vegetated shores (beaches), but sand entrainment and movement offshore was attributed to jet boat wakes in a controlled experiment on the Snake River (Mussetter et al. 2007).



**Figure 8. Waves generated by boat passages along the Atlantic Intracoastal Waterway, NC. Photo from NOAA/NCCOS.**

### ***Submerged Aquatic Vegetation***

Boat wakes and wash can cause erosion of submerged aquatic plant roots in freshwater and marine waters. The susceptibility of freshwater aquatic plants to erosion can be variable and

may be related to the petiole cross-sectional area (Liddle and Scorgie 1980). Direct damage to seagrasses from contact with propellers, anchors, and moorings has been well-documented (e.g., Williams 1988, Walker et al. 1989, Dawes et al. 1997, Hallac et al. 2012). However, boat wake wave impacts are less understood for seagrasses. Boat generated waves can have indirect impacts on seagrasses through increased suspended sediments that lead to reduced light availability and elevated nutrients (Koch 2002, Koch et al. 2006). Seagrasses have relatively high minimum light requirements (11-20% of surface light) in order to thrive (Durante 1991, Dennison et al. 1993); therefore, wave-induced increases in water turbidity can be detrimental to seagrasses. Unfortunately, there is limited quantitative information regarding this impact. Research from a shallow sandy bay in Massachusetts suggests that turbidity may be sufficiently elevated (reducing light by more than 60%) in areas with heavy boating, particularly at low tide, to be detrimental to eelgrass; however, the sandy sediment resuspended from boating resettled within 1-2 hours, much quicker than wind-driven events (Crawford 2002). A single study from Chesapeake Bay observed a minimal negative impact of boat generated waves on seagrass light availability likely because at the study site (Hopkins Cove, MD) boat waves were very small compared with naturally occurring waves (Koch 2002). Additional study is needed on seagrasses in other systems to more fully estimate the potential effect of boat generated waves.

### *Estuarine fauna*

Boat generated waves can have direct and indirect effects on fish. Direct effects may include temporary increases in water turbidity or wave energy that physically disrupt fish assemblages (Whitfield and Becker 2014). Indirect effects may result because of physical disturbances to the bottom sediments (resuspension) and nearshore habitats (seagrasses, wetlands) from boat generated waves. Frequent and intense boating activity may enhance seagrass blade movement ('flapping') that can cause reduction in the abundance and diversity of invertebrate prey resources (Bishop 2008). Experimental studies in the littoral zone of freshwater have demonstrated that wave velocities corresponding to waves generated by small recreational boats caused ~10% of benthic invertebrates (e.g., amphipods) to dislodge and become more vulnerable to predation as well as a reduction in foraging success for certain littoral fish species (Gabel et al. 2011). Beyond immediate habitat and prey disruptions, long term damage and fragmentation to structural habitat such as seagrasses and salt marshes from regular exposure to elevated turbidity and/or physical stress from waves has the potential to change fish assemblages and productivity (Fagherazzi et al. 2013). Boat generated waves may erode the essential habitats of diamondback terrapin (*Malaclemys terrapin*) – marshes and nesting beaches (Schwimmer 2001).

## ***Birds***

There are few studies on the effect of boating on birds and little effort to tease the effect of boat wakes from the suite of possible disturbances (noise, visual, proximity, etc.). Exposure to rapid and repeated movement of personal watercraft significantly increased flushing of least terns (*Sternula antillarum*) on a marsh island in New Jersey. Motorboats prompted a similar, though significantly smaller, response. Terns relocated nesting sites opposite the boating channel and experienced greater rates of nest loss due to flooding (Burger 2003). Of 6 wading birds species (great egret (*Ardea alba*), tri-colored heron (*Egretta tricolor*), snowy egret (*Egretta thula*), great-blue heron (*Ardea herodias*), yellow-crowned night heron (*Nyctanassa violacea*), and green heron (*Butorides virescens*), all but the snowy egret displayed boat-induced flushing response and lower numbers of birds post-disturbance. Environmental factors (weather, wind speed, time of day, air temperature) and prey availability have documented effects of avian habitat use and behavior, potentially masking disturbance effects (Peters and Otis 2006). Colonial nesting grebes construct over-water nests which are subject to both wind and boat generated wave-induced failure (Allen et al 2008). Nests with adequate vegetative protection are three times more likely to hatch eggs than unprotected nests. A loss of endangered California light-footed clapper rail nesting habitat (*Spartina foliosa*, low marsh) is attributed to personal watercraft and boat wake erosion (Dayton and Levin 1996). Anecdotal linkages between boat wakes and a decline in common tern and black skimmer populations have been made by the Maryland Coastal Bays Program and the Program has initiated a “no-wake” sign program (Holloway 2015).

## **Section 2: Specific Chesapeake Bay implications and concerns**

### **Recreational boating**

Recreational boating is a highly prevalent and an economically important water-related activity in Chesapeake Bay (Lipton 2007, Murray et al. 2009). In Virginia, there are nearly 250,000 registered boats (Virginia Department of Game and Inland Fisheries, data from 1997-2012). In Maryland, there are nearly 200,000 registered boats, and an additional 57,000 non-registered vessels (Environmental Finance Center, University of Maryland 2013). The majority of the boats are small, trailered vessels, the trend however is for boat owners to ‘trade up’ for larger boats (Maryland’s Recreational Boating and Infrastructure Plan 2004). According to the US Coast Guard National Recreational Boating Survey (2012), the annual number of days spent boating is 2,547,000 for Marylanders and 5,600,000 for Virginians; these numbers include boat

days spent on non-power boats. The economic downturn from 2008 to about 2013 showed a decrease in boat registrations in Maryland while the last several years have shown an uptick in sales and registrations. Moreover, as coastal populations grow, more development is occurring along shallow tidal creeks which has increased boating traffic from shallow creeks to main water bodies (CCRM 2010). From 2002 to 2009 in Virginia, increases in pier construction were highest in new residential areas (increased housing density and low-intensity development) near small creeks (Isdell 2014). These low energy tidal creeks with relatively little wind-driven waves are sheltered environments that tend to allow for the proliferation of marsh and seagrasses. Furthermore, these shallow creek habitats may be particularly sensitive to sediment resuspension and shoreline erosion from boat wake waves.

The Chesapeake Watershed Agreement (2014) designates a goal to “Expand public access to the Bay and its tributaries through existing and new local, state and federal parks, refuges, reserves, trails and partner sites”. To accomplish that goal, a defined outcome is to *add 300 new public access sites, by 2025, with a strong emphasis on providing opportunities for boating, swimming and fishing, where feasible*. The intent of the goal is to, in part, increase stewardship and local economies; however, this goal may be in conflict with other water quality and habitat restoration Bay goals in some areas.

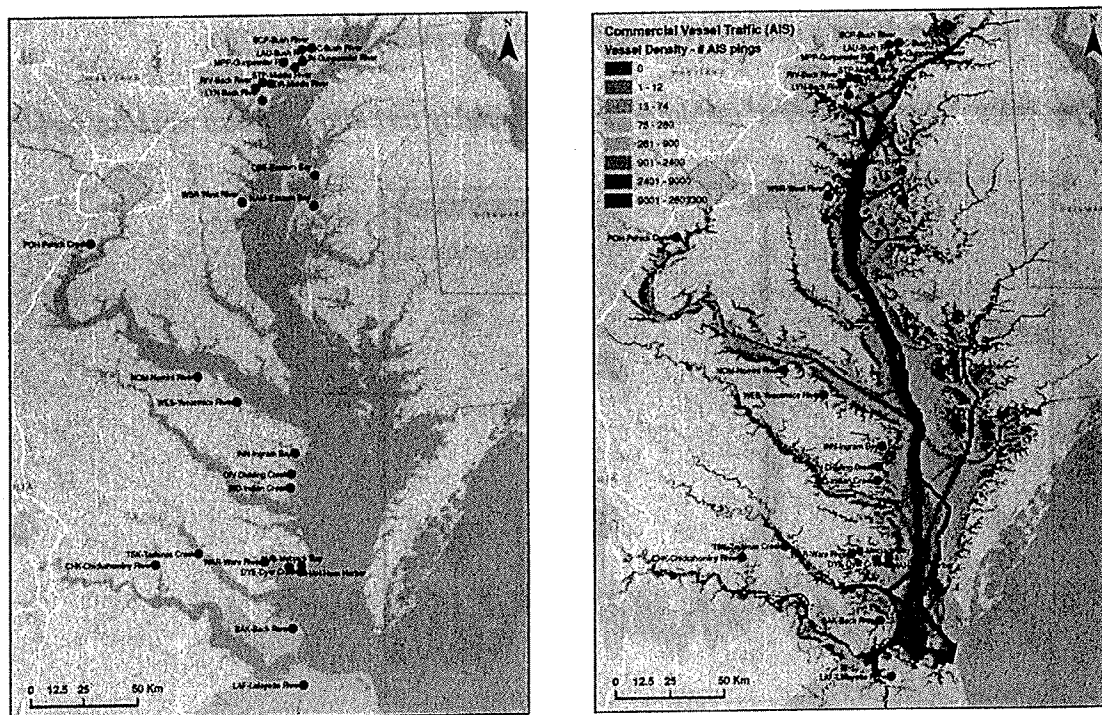
#### ***Is there evidence of elevated turbidity induced by recreational boating in Chesapeake Bay?***

Recreational boating has been shown to induce an elevation in turbidity above ambient conditions in lake systems because of shore erosion and/or resuspension of sediments from boat wave wakes, resulting in temporally low water clarity on weekends and holidays (e.g., USACE 1994, Asplund 1996). We hypothesized that this trend might be seen in the Chesapeake Bay because there are generally higher levels of recreational boating intensity during the weekend and during major warm-weather holidays (i.e., Memorial Day, July 4th, Labor Day) than during the week. Water quality monitoring in the Chesapeake Bay includes programs that capture continuous measurements of water quality (e.g., dissolved oxygen, turbidity) taken from fixed, shallow water monitoring stations ([www.vecos.org](http://www.vecos.org), [www.eyesonthebay.net](http://www.eyesonthebay.net)). We tested the hypothesis that turbidity was affected by recreational boating at 26 sites at which continuous monitoring data were available in the Chesapeake Bay (Virginia N=14; Maryland N=12 stations; Figure 9-map of stations, Table S1). These stations are typically affixed to a pier near the shore (most stations are within 50 meters of the shore).

To minimize the likelihood of commercial vessel traffic and the opportunity for wind waves as significant influencing factors on nearshore turbidity patterns, monitoring stations with moderate



to high exposure to commercial vessel traffic and/or located on the mainstem of major tributaries were not considered for the analysis. Using data on ship traffic patterns collected by the U.S. Coast Guard through the Automatic Identification System (AIS) and summarized for Chesapeake Bay at 1 km x 1 km grid cells for the interval 2009 through 2014 (spatial data source: Bilkovic et al. 2016; and the Marine Cadastre <http://marinecadastre.gov/ais>), the total number of pings recorded in the vicinity of the monitoring station was determined (Figure 9). AIS is an onboard navigation safety device that transmits and monitors the location and characteristics of large vessels in U.S. and international waters in real time. The Marine Cadastre provides AIS data filtered and summarized into one-minute intervals, with each record representing a ship's location every minute. All monitoring stations used in the analysis were in reaches with low or no commercial traffic; half of the stations were in reaches with no pings, 11 stations had < 500 pings, and 2 sites had less than 2000 pings for the entire 6-year record.



**Figure 9. Distribution of long-term water quality monitoring stations in Chesapeake Bay used in analysis of turbidity patterns (L). Commercial vessel traffic density in relation to monitoring stations. All stations were in low or no commercial traffic reaches (R).**

Turbidity data included in the analysis were from May through September when recreational

boating is expected to be prevalent in certain periods (e.g., weekends and holidays) and allow for comparison with other periods in which boating is less prevalent (e.g., weekdays). Most stations had 3 years of data with the exception of 4 MD sites that had 2 years of available data. For stations with more than 3 years of data, we extracted the 3 most recent years. Raw turbidity data were nearly continuous over the 3-year time period (readings every hour). To summarize the information, weekend/holiday and weekday turbidity was averaged across each year from May-Sept, excluding data flagged as suspect when they were greater than 10% of the data. The three years of data were then averaged together for a single weekend/holiday and weekday measure for each site. Due to the fact that monitoring activities were not explicitly designed to evaluate boat wake impacts on shoreline erosion or elevated turbidity, we developed a turbidity index to capture relative change in turbidity between weekends and weekdays averaged over the entire time period examined. This approach was taken to remove all other environmental variables (sediment sources, storms, tidal flow, etc.) out of the measured response, as these variables were assumed to be the same for a station over weekend and weekdays (Figure 10).

$$\text{Turbidity Index} = (\text{mean weekend turbidity} - \text{mean weekday turbidity}) \div \text{mean weekday turbidity}$$

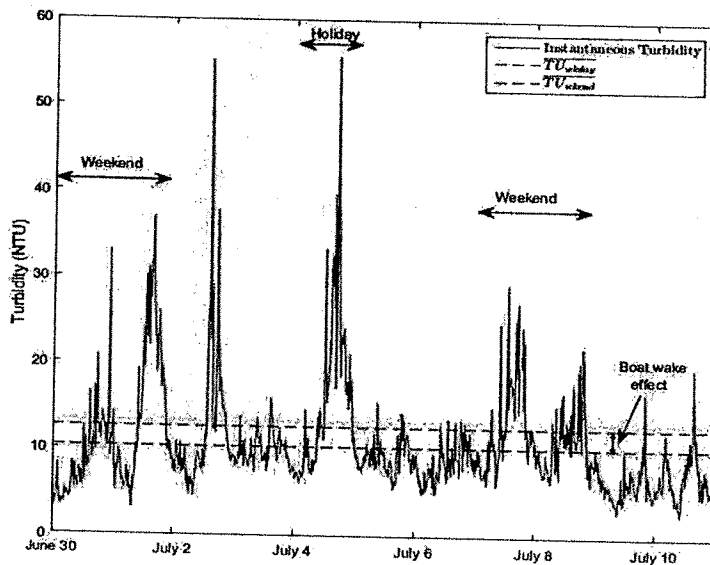


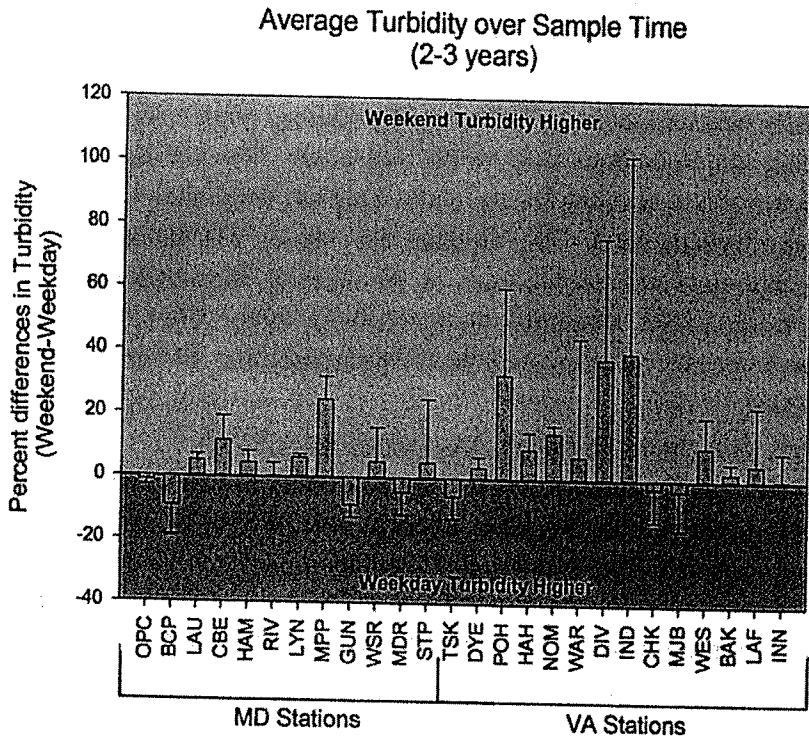
Figure 10. Elevated turbidity associated weekends and July 4th, 2007 in Pohick Creek, Virginia.  $TU_{wkday}$  shows the mean turbidity on weekdays in May through September of 2007-2009, and  $TU_{wkend}$  is the mean turbidity on weekends and holidays in the same time frame.

We considered four site-specific factors that may influence the magnitude of change in turbidity that recreational boating could elicit at each station, including: distance to navigational depth (m), maximum fetch (m), shoreline armoring (bulkhead, seawall, or riprap revetment), and boating intensity. Analyses of the effect on turbidity of the various factors for each station location were conducted in ArcGIS 10.1 as follows:

- Distance to navigational depth was estimated as the distance (m) from the station to the 1-m depth contour. The 1-m depth contour was chosen as the cut-off for navigable depth to be inclusive of small watercraft (e.g., jet-ski).
- Relative boating intensity was estimated by summing the number of piers and marinas upriver of the monitoring station on both sides of the tidal creek. The number of marinas was multiplied by a factor of 5 to account for the heavy boat use associated with these facilities relative to that of private piers. The Mobjack Bay station was an exception; the waterway was so wide that piers and marinas only on the northern shore (where the station is located) and those upriver tributaries on the northern shore were counted. Information on piers and marinas was extracted from Chesapeake Bay Shoreline Inventory: CCRM-VIMS; [http://ccrm.vims.edu/gis\\_data\\_maps/shoreline\\_inventories/index.html](http://ccrm.vims.edu/gis_data_maps/shoreline_inventories/index.html)).
- Fetch (distance over water that the wind blows in a single direction) was estimated for 16 directions (N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, NNW) originating from each shoreline location and the maximum fetch value was extracted.
- The presence of shoreline armoring at the location of the monitoring station was determined using aerial imagery and the Chesapeake Bay Shoreline Inventory, noted above.
- The effect of the four site-specific factors (boating intensity, maximum fetch, distance to 1-m depth, and presence of armoring) on the relative difference in turbidity over weekends/holidays compared to weekdays was examined using a General Linear Model (GLM). Boating intensity, maximum fetch, and distance to 1-m depth were log-transformed prior to the analysis to meet test assumptions.

Water quality monitoring station characteristics used in the analysis are shown in Table S1. The majority of the stations examined (n=19; 73%) possessed elevated turbidity on the weekends in comparison to weekdays; however the percent difference was low for many of these stations (<5% turbidity difference, 42% of stations with a positive turbidity index). Of the 7 stations that possessed a negative turbidity index (higher turbidity during the week), only 2 stations were

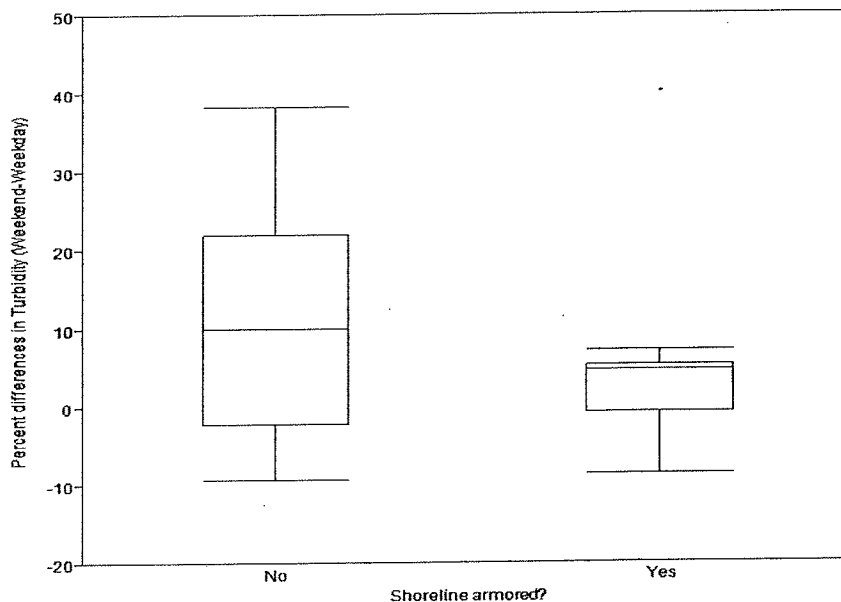
more than 5% higher during the week (Figure 11, Table S1). None of the site-specific factors examined were statistically significantly associated with the turbidity index (GLM:  $X^2 = 3.14$ ;  $p=0.53$ ). On unarmored shores, the turbidity index was higher on average during the weekend than weekday (TI=10.5%  $\pm$  15.1%) in comparison to armored shores (TI=4.5%  $\pm$  11.3), though this pattern was not significant likely due to high variability between stations.



**Figure 11. Comparison of weekend turbidity measures in comparison to weekday measures. Positive values indicate relatively higher turbidity during the weekend than the week possibly because of increased recreational boating intensity during the weekend. Negative values indicate relatively higher turbidity during the week than weekend.**

The analysis provides support for the hypothesis (shown in previous studies) that boating activity is correlated with increased turbidity in local waterways. However, some waterways did not show an uptick in turbidity on the weekends and holidays. There are four potential explanations for this, and it is possible that more than one explanation is relevant to a given station. First, our measure of boating intensity was imprecise as we have no data on the actual number of boats and

personal watercraft that pass by a given station. Some of the small creeks with few piers may actually experience heavy recreational traffic. Second, the turbidity sensor may be located too far offshore to be influenced by shoreline erosion and resuspension so it is missing the signal. Third, all data were not from the same set of years. Since there are many more weekdays than weekends, a storm is statistically more likely to occur on a weekday. In years with multiple storm events, the storm-induced turbidity may be dampening out a weekend-weekday signal. Last, effective shoreline armoring reduces shoreline erosion, dampening the turbidity signal (see Figures 12 and 13). It is likely that in areas with heavy boat traffic, at least a portion of the shoreline has been armored in response to boat wake erosion, creating a circular issue where heavy boat traffic is driving armoring which is dampening the erosion signal, making it appear that boat influence in the waterway is low.



**Figure 12. The presence of armoring may be influencing the variability in turbidity measures. Armoring prevents bank erosion, reducing the turbidity signal and is likely a result of a combination of high boat activity and long fetches (see Fig. 13). Armoring potentially can increase bottom resuspension through wave reflection, but this was not apparent in our analysis.**

Resolution of the first three issues mentioned above would require intensely detailed data analysis or the collection of new data. However, we have attempted to address the fourth issue in a separate analysis, below.

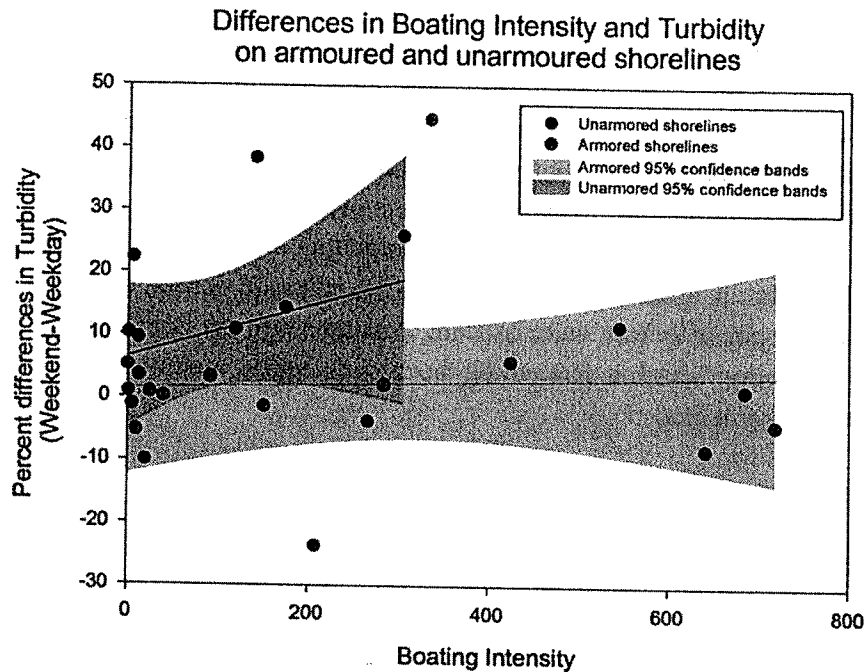
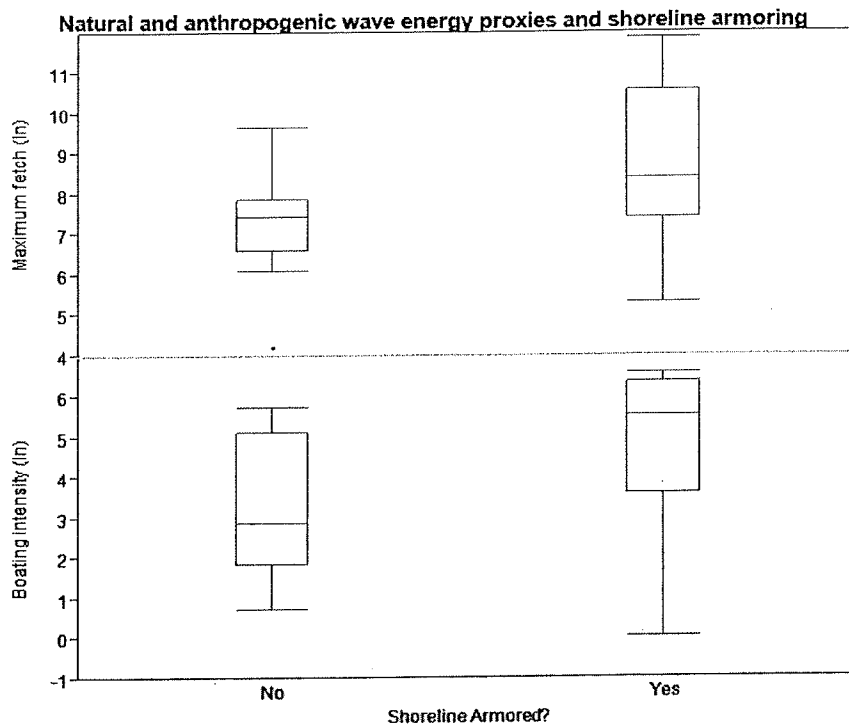


Figure 13. While boating intensity was not significantly related to observed differences in weekend-weekday turbidity, there is some suggestion along unarmored shores that boating may be elevating local turbidity within some waterways. There is uncertainty as to whether armoring is a response to boat wake-induced shoreline erosion, particularly in low wind-wave energy waterways.

#### *Shoreline armoring in response to erosion from boat wakes*

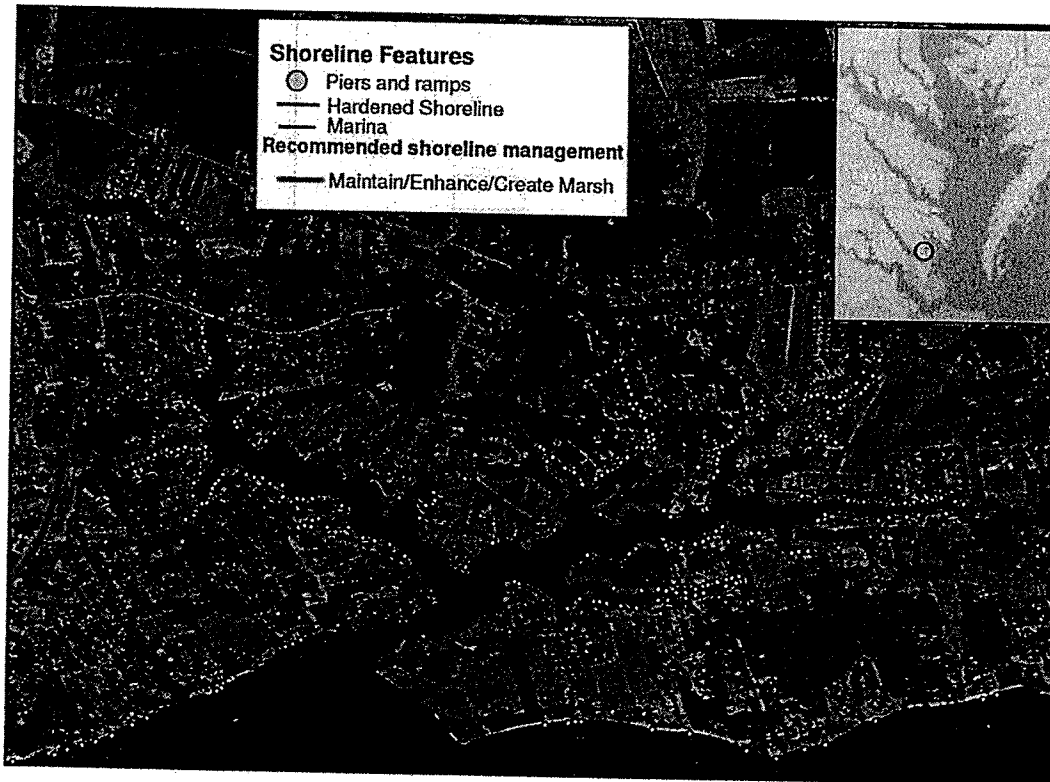
Anecdotally, people cite boat wake erosion as a reason for armoring their shorelines. However, it is very difficult to disentangle the effects of boat wakes versus wind waves on shoreline erosion; both shorelines with a long maximum fetch (potential for high wind-wave energy) and high boating intensity (potential for frequent boat wake energy) seem to be armored (Figure 14) which is one indication of active shoreline erosion. One-way ANOVAs of maximum fetch and high boating intensity by shoreline armoring were both significant ( $p=0.05$  and  $0.03$ , respectively). Maximum fetch and boating intensity are somewhat correlated with each other, likely because people build more piers on wide creeks and open shorelines. However, this correlation complicates the analysis and a different approach is necessary to try to apportion erosion causes.



**Figure 14. Shorelines with either high boating intensity or high maximum fetch are significantly more likely to be armored. This suggests that both sources of wave energy (one natural and one anthropogenic) are associated with shoreline erosion.**

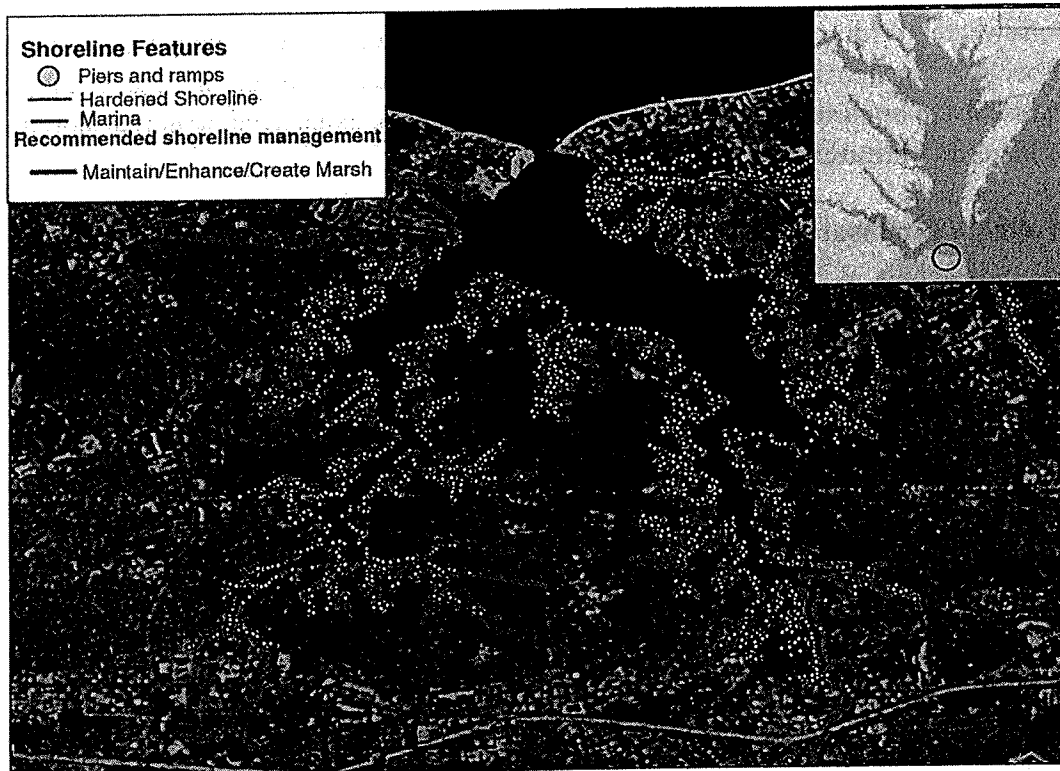
The comparison of recommended shoreline management options on the basis of physical conditions (e.g., fetch, bathymetry) with the ‘actual’ management approach applied (e.g., bulkhead, riprap, create marsh) can provide some insight into whether shores were armored in areas which are not anticipated to have active erosion. We used a Shoreline Management Model (SMM) that identifies appropriate shoreline management activities on the basis of local physical conditions including fetch, bathymetry, intertidal habitats (e.g., marsh, beach, etc.), riparian condition, and bank condition/height along Virginia’s tidal shores (CCRM 2015). The model does not account for boat activity since it is difficult to quantify remotely. If areas that were anticipated to have low erosion are being heavily armored, this is a potential indication of heavy boating activity and boat wake energy. As an example, we compared the recommended shoreline management approaches to existing armoring (bulkhead, riprap revetment) for two tidal creek systems in Virginia known to have relatively high recreational boating (Figures 15 and 16). In both instances, armoring occurred along approximately a quarter of the shorelines with physical conditions conducive to using marsh enhancement/maintenance alone as a means

to secure shorelines. This suggests another source of shore erosion, possibly boating, or some concern or interest other than erosion, has resulted in armoring of shores (along with the attendant adverse effects of armoring) in physical settings where it should not be necessary based on physical conditions.



**Figure 15. Sarah Creek, VA is a rapidly developing tidal creek with relatively low wind wave energy and relatively high boating pressure including the presence of several marinas. On the basis of physical conditions, the recommended shoreline protection approach is to maintain or enhance marsh for 83% of the shoreline. Of that shoreline, 28% has armoring (revetment, bulkhead) currently.**





**Figure 16. Lynnhaven River, Virginia Beach, Virginia is an example of a shallow-water tidal system under intense development pressure. In this system, very shallow creeks have been dredged to provide residential boat access and there continues to be pressure to dredge additional creeks (Bilkovic 2011). On the basis of physical conditions, the recommended shoreline protection approach is to maintain or enhance marsh for 74% of the shoreline. Of that shoreline, 22% has armoring (revetment, bulkhead) currently.**

*What is the relative contribution of sediment inputs from boat wake induced shoreline erosion in Chesapeake Bay?*

Patterns of elevated weekend turbidity compared to weekday turbidity may be evidence of boat wake wave-induced elevated turbidity. However, there are two potential sources of sediment that may influence nearshore turbidity measures. New sediment may be added to a system from shoreline (bank) erosion or existing sediment may be temporarily resuspended. It can be very challenging to precisely quantify the sediment inputs from shoreline erosion. For example, sand that is resuspended settles more quickly than fines (e.g., mud). Sites with elevated turbidity may

be from nearby shoreline erosion of fines, or advection of fines from resuspension or shoreline erosion elsewhere. With sufficient data, the relative significance of each source may be inferred from the sediment composition (grain-size) on the shore and nearshore bottom, tidal excursion, and the presence of armoring. Periodic elevated turbidity along extensively armored shorelines is likely the result of resuspension.

### Erosion effects from boat wakes

#### *Case study of Lafayette River, VA*

Tidal marsh extent in the Lafayette River, VA has declined over time, concurrent with population expansion. Tidal wetland loss from 1944-1977 was quantified as 588.76 acres (or a 55% loss) and was attributed to the urbanization of the watershed (Priest 1999; Figure 17). Most of the losses are attributed to direct human action (filling or dredging of wetlands, etc.); the Lafayette River was significantly altered during the study period for both residential and commercial purposes. However, the cause of other losses are harder to directly define, but in some instances anecdotal observations suggest that shore erosion and marsh loss can be attributed to boating.

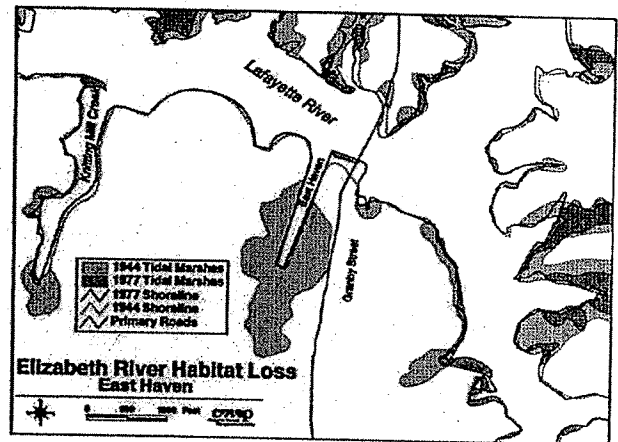
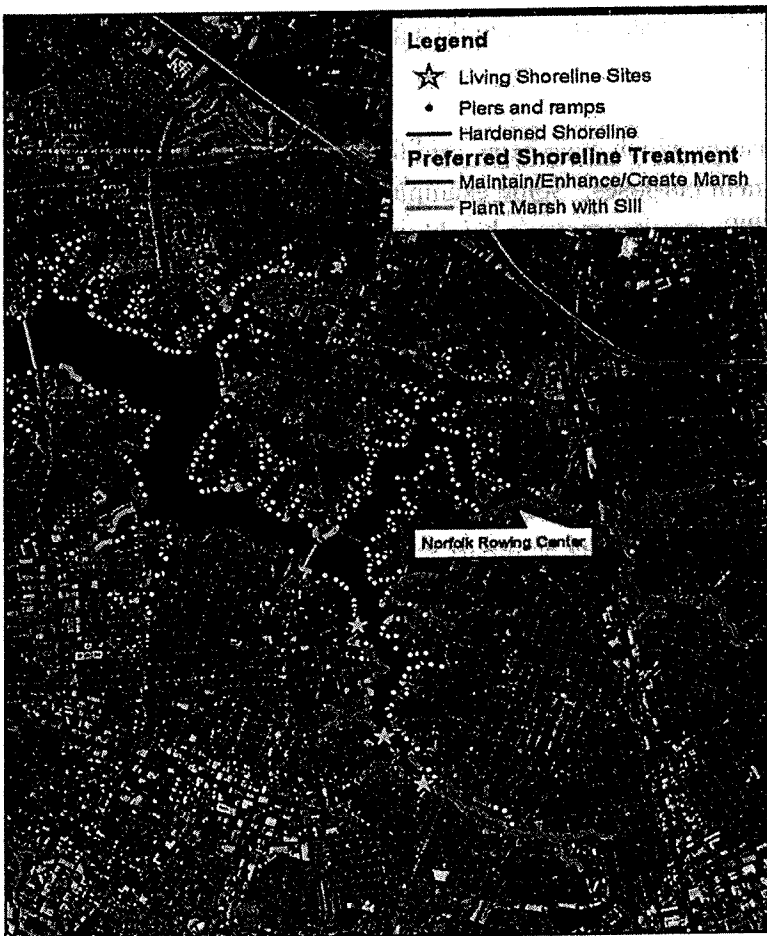


Figure 17. Changes in tidal marshes in the Lafayette River between 1944 and 1977. Map from Priest 1999.

As previously noted, *in situ* shoreline change due to boat wake induced erosion is difficult to assess and quantify. Nevertheless, coastal managers and shoreline property owners are reasonably certain that boat wakes play a role in shoreline erosion, in some cases significantly, especially in narrow, shallow waterways. As one example, Justin Schafer, a lifelong resident and employee of the City of Norfolk, has been observing the shoreline of the Lafayette River his whole life and has spent the last 20 years rowing on the river out of the Norfolk Rowing Center at Lakewood Park (northeast of the East Haven area shown in Figure 18). The club has boats on the water 7 days a week for 9 months of the year and 2-3 times a week in the winter. The club uses jon boats as chase boats and they frequently travel close to shore creating a wash on the fringing marsh and causing an increase in observable turbidity. Mr. Schafer has noticed that the fringe marsh that was about 15 feet wide in the 1990's is now about 2-3 feet wide. The boat operations, observed turbidity, and loss of marsh fringe has all led Mr. Schafer to question the

role of boat wakes in shoreline erosion along this reach of the River. As the club is located near the head of navigable tidal waters and has a fetch less than 1/4 mile, there is little opportunity for the generation of wind-driven waves. While other factors including tidal (ebb/flood) erosion and sea level rise have a likely role in the changes that have been seen on the River, Mr. Schafer is convinced that erosion from power boat waves have contributed to the erosion of the shoreline (Justin Shafer, personal communication, September 2016). This observation is further supported in that 31% of the Lafayette River low-energy shoreline has been armored where physical conditions suggest that marsh vegetation alone would be protective (Figure 18).



**Figure 18. Lafayette River, Virginia. On the basis of physical conditions, the recommended shoreline protection approach is to maintain or enhance marsh for 78% of the shoreline. Of that shoreline, 31% has armoring (revetment, bulkhead) currently.**

### **Section 3: Modeling approaches and data requirements to effectively model the potential effect of boat wake waves on shorelines**

The first step in determining the impact of boat wakes on shoreline erosion is to evaluate the boat wake energy occurring along the shoreline and the stability of the shoreline. To determine the appropriate management action, it may be helpful to compare the boat wake energy to the background wind-wave energy (Glamore 2008). In areas where the wave energy attributable to boat wake waves is significantly less than that of wind waves, management actions directed at boat wakes may have limited utility. However, scale of the waves matters as much as the persistence of the impact; a few large boat wake waves can do a great deal of damage compared to persistent small wind generated waves.

There are a number of different measures which have been used for determining the erosive potential of boat wakes for management purposes. Some examples include: wave energy (e.g., Decision Support Tool, Glamore 2008), maximum wave height within the wave train (e.g., Nanson et al. 1994, Parnell and Kofoed-Hansen 2001), and wave speed (e.g., Australian Maritime College 2003). Deciding on an appropriate measure is complicated since every measure is, in some sense, a proxy for the actual impact of the boat wake on the shore. Total wave train energy is a cumulative combination of wave height and wave period for all waves generated by the wake, so it may be the best measure to use, even if it does not entirely capture the erosive force of the waves. Total wave train energy can be estimated from maximum wave height using a derived equation (Glamore 2008). The energy of the total wave train can be modeled for boats based on their size (using Froude Numbers for various boat types), speed and distance from the shore (both measured in areas of interest) following the methods of Glamore (2008) or Świerkowski et al. (2009).

One potential approach to understanding shoreline energetics is through the deployment of wave sensors. This results in an unambiguous determination of wave climate but the results are highly site-specific and it can be challenging to tease apart the impact of wind vs. boats. The most accurate predictive method to estimate shoreline erosion is the application of high-fidelity hydrodynamic models that account for waves, currents, and morphological changes under these effects. Site-specific wave, current, and bathymetric data, if available, can be used to initialize the models and erosion data can be used for calibration and validation. The validated model can then be applied to a large domain. Another approach, perhaps preferable (depending on available expertise), is to estimate values of wave energy based on empirically derived relationships between wind, boat activity and wave climate. Cumulative wind-wave energy can

currently be calculated across the entire Chesapeake Bay using either a fetch-based model (such as Wave Exposure Model, or WEMo) or a hydrodynamic model (such as SLOSH, Sea, lake, and overland surges from hurricanes). These models are highly dependent on the quality of available bathymetric data and these data are currently limited for small creeks where the potential for boat-induced erosion is greatest. Such models also require high quality wind data. Sources for wind data include local airports, buoys, and other weather stations.

To estimate boat wake energy experienced at a given location, it is critical to know: 1) the number of boats that pass by on an average day; 2) how big the boats are; 3) how far they are from the shore; 4) how fast each boat is going; and 5) shoreline bathymetry. There is no repository of this information for the Chesapeake Bay; therefore, modeling shoreline boat wake energy over large spatial scales requires making broad assumptions.

Shoreline susceptibility to erosion is difficult to measure on a large scale. There are several proxies which can be used in combination, although this approach has its difficulties. Spatial analysis of shoreline type (hardened, forested, emergent wetland, sand bank, etc.) and shoreline topography can provide a general overview of susceptibility to erosion (Cowart et al. 2011, Currin et al. 2015). There are databases of shoreline armoring for the Chesapeake Bay in the CCRM inventories ([http://ccrm.vims.edu/gis\\_data\\_maps/shoreline\\_inventories/index.html](http://ccrm.vims.edu/gis_data_maps/shoreline_inventories/index.html)) and armored areas can be considered to be stable. Shoreline type is available through the USGS National Land Use Land Cover database but the spatial resolution (30 m) doesn't allow for determination of changes over small spatial scales (Chesapeake Bay Conservancy is currently working to produce a similar product with 1 m resolution). Lidar data resources for VA are available at <http://virginialidar.com/index.html> and for MD at <http://imap.maryland.gov/Pages/lidar.aspx>. By mapping areas of concern based on shoreline characteristics (unvegetated shores with high vertical relief would rank highest for erosion concern) against proximity to frequently travelled navigation channels, it may be possible to rank areas in terms of their general susceptibility to erosion.

In an effort to determine the relative importance of boat wakes to erosion on the Atlantic Intracoastal Waterway in NC, Fonseca and Malhotra (2012) applied a dual modeling approach using the freely available WEMo in conjunction with a prototype boat wake model (BoMo). The output of both models include representative wave energy, significant wave height, and shear stress at the seafloor. The value of this approach is that it allows for direct comparisons of wind and boat wake energy (assuming that one has the necessary data concerning number, size and speed of passing boats) and because it provides shear stress values, which can be used to

estimate the degree of sediment movement (as a proxy of erosion). However, in order to make this estimation, it is necessary to know sediment grain size and that data is not available on a wide scale. At this time, BoMo is still in the prototype stage and not publicly available.

The most accurate predictive tools for shoreline erosion due to wind- or boat generated waves are hydrodynamic models that account for wave generation, currents, sediment transport, and bed level change (e.g., Delft 3D). Hydrodynamic models require detailed data on bathymetry, wind, tides, and sediment properties.

#### **Section 4: Data gaps and research needs**

The dearth of quantified information on the effects of boat wakes and wash on Chesapeake Bay shoreline erosion limits accounting within the Bay Model for contributions of boat-induced erosion to the sediment loads in the Bay. At the same time, any efforts to develop new policies, or enforce existing ones, are hampered by a lack of specific evidence of the extent and magnitude of the adverse effects of boating on shoreline erosion, private property, water quality, habitat or other ecosystem services.

Specific data needs include:

- High-resolution recreational boating intensity information (e.g., the number of vessels that pass by on an average day, vessels types, vessel speeds, vessel traffic patterns).
- Information on trends of recreational boating in small waterways.
- Information on the location, extent and level of enforcement of no-wake zones throughout the Bay.
- Measurements of waves and suspended sediment concentration (SSC); such data, acquired in representative shorelines with high boat activity, can provide insight into the dependency of erosion on wave climate.
- Data on grain size of bottom sediments in all the Bay tributaries and small creeks. Even a simple categorization of sand and fines would be useful.
- High resolution shallow water bathymetry is needed throughout the Bay. If data even exist, most are 50-100 years old in these areas.

## **Section 5: Management and Policy in Chesapeake Bay**

*Editor's Note: Citations for this section can be found at the end of this report in Endnote citations: Management and Policy in Chesapeake Bay [1]*

### **Existing and Potential Policy Actions to Reduce Adverse Effects of Boat Wake Waves on Shorelines in the Chesapeake Bay**

Cooperation of three states is required to successfully implement a Bay-wide boat wake policy. Virginia, Delaware, and Maryland border the Bay and have the authority to govern boating activity along their shorelines. Localities in each of these states have adopted policies regarding boat wake restrictions. Virginia, a state that follows the “Dillon Rule” of strict construction [2], has expressly delegated authority to the Virginia Department of Game and Inland Fisheries to administer the Commonwealth’s boating laws and also has authorized localities to implement boat wake restrictions. Virginia has not established no-wake zones for specific water bodies in its code or regulations. Maryland has established boat speed limits for three water bodies in its state code and granted authority to the Maryland Department of Natural Resources to regulate the operation of vessels, which they did in agency regulations. Some localities also have enacted their own wake restrictions. The Delaware State Code delegates regulatory authority to the Department of Natural Resources and Environmental Control regarding the operating requirements of vessels, and some localities also have enacted their own restrictions. Like Virginia, Delaware has not established no-wake zones for specific water bodies in its code or regulations. In both Maryland and Delaware, localities are permitted to adopt local restrictions on the subject, but only if such restrictions conform to state law. Thus, within each of the three coastal states, some localities have implemented their own boat wake policy, with only Virginia broadly authorizing localities to adopt ordinances to establish no-wake zones based on public safety and erosion concerns. A uniform boat wake policy in the Chesapeake Bay therefore is achievable if each coastal locality were to agree to adopt the same requirements. Cooperation between the states via the Chesapeake Bay Program is an option for them to come to agreement to achieve that, even though the water quality model for the Chesapeake Bay total maximum daily load (TMDL) currently does not distinguish sediment erosion caused by boat wakes when it accounts for sediment from shoreline erosion.

#### ***The Regulatory Framework in Virginia, Maryland, Delaware, and Pennsylvania***

In Virginia, “any county, city or town may, by ordinance, establish ‘no-wake’ zones along waterways within the locality in order to protect public safety and prevent erosion damage to adjacent property,” with notice to the Virginia Department of Game and Inland Fisheries

(VDGIF) [3]. Although the term “property” is not defined, the context of “erosion damage” indicates that the statute is intended to prevent shoreline erosion, in addition to protecting public safety. However, the VDGIF requires that both public safety concerns and erosion damage concerns be met for a ‘no-wake’ zone to be established [4]. In other words, erosion concerns alone are not a sufficient basis to seek imposition of a ‘no-wake’ zone. Several localities have implemented such ordinances for specific areas within their jurisdiction [5]. In addition, the VDGIF’s regulations require that motorboats must slacken their speed when approaching or passing vessels, piers, docks, boathouses, and persons in the water or using water skis or surfboards “to the extent necessary to avoid endangering persons or property by the effect of the motorboat's wake.” [6]

Additionally, an individual or business in Virginia may apply to their local county board of supervisors to request the placement of a regulatory waterway marker such as a ‘no-wake’ zone using an application provided by VDGIF [7]. The process is that a county board of supervisors or city council hears the request at a public meeting and decides whether to approve, approve with modifications, or disapprove the request. Once the governing body makes a recommendation, the application is forwarded to VDGIF, which must reach the same decision in order for the ‘no-wake’ zone to be approved. A law enforcement officer will visually inspect the proposed location to determine whether the position is accurate and report back. The state then makes its final decision, which can be different than the county’s decision but rarely is [8].

It is also of interest to note that in Virginia, the federal government has imposed a no-wake zone in Back Bay, just outside the Chesapeake Bay watershed. The no-wake zone is in effect within 150 yards (137 meters) of the shoreline within the Back Bay Wildlife Refuge. The regulation was promulgated by the US Army Corps of Engineers in an effort to protect the environment and increase boating safety (Glass 2006) [9].

Maryland has implemented boat wake and/or speed restrictions by statute (Maryland State Code), state-wide regulation (Maryland Department of Natural Resources’ (DNR) regulations), and local regulation (municipal ordinances such as for the cities of Annapolis and Cambridge). The Maryland State Code itself sets speed limits for the Severn River, Seneca Creek, and Monocacy River [10]. The State Code also delegates the regulation of the operation of water vessels to the DNR [11], and clarifies that municipalities may not establish any local regulation which does not conform with DNR’s regulations [12].

The DNR defines various speed limits in the Code of Maryland Regulations, including



“[r]estricted 6 knots . . . ,” which prohibits a person from operating a vessel more than 17 feet in length “[a]t a boat speed in excess of 6 knots . . . ; or [t]o cause an objectionable or excessive wake” [13]. Additionally, a “[m]inimum wake zone” prohibits a person from “operat[ing] a vessel in excess of the slowest possible boat speed necessary to maintain steerage under prevailing wind and sea conditions not to exceed 3 knots . . . .” [14]. The DNR regulations apply these definitions to various areas designated by the regulations, which include regions of the eastern and western shore of the Chesapeake Bay [15]. Some of the restrictions only apply to certain times of the year, such as during boating season, or only on Saturdays, Sundays, and state holidays [16]. DNR cites to provisions of the State Code as authority for adopting the various speed limits [17]. In addition to the Maryland state-imposed speed limits and the DNR’s definitions and restricted areas, municipalities such as Annapolis and Cambridge also have exercised authority to implement speed limits. The Cambridge municipal code states that “[a] person may not propel or navigate any motor-driven watercraft in any of the waters of the city, except the Choptank River, at a speed greater than six miles per hour, nor create a wash which endangers persons or property” [18]. Annapolis imposes broader language that merely requires vessel operators to proceed “in a safe manner with due regard for the safety of persons and property” and includes considerations of “traffic conditions, proximity to other vessels, weather, speed, wake size, size of vessel, condition of the vessel and its equipment, and presence or absence of required safety equipment” [19].

Similarly, the State Code of Delaware delegates regulatory authority to the Department of Natural Resources and Environmental Control (DNREC) with respect to, among other things, the operating requirements of vessels [20]. The DNREC regulations define “slow-no-wake” to “mean as slow as possible without losing steerage way and so as to make the least possible wakes” [21]. The DNREC regulations limit vessel speed to “slow-no-wake” within 100 feet of various structures such as docks and launching ramps, as well as swimmers [22]. Additionally, the City of Dover ordinance similarly restricts speeds under the Silver Lake Bridge and at specified hours [23]. For example, the Town of Smyrna ordinance states, “Power boats shall be operated on Lake Como at ‘no-wake’ speed which shall mean as slow as possible without losing steerage and so as to make the least possible wake [24]. This will almost always mean speeds of less than five miles per hour.” The City of Dover ordinances similarly restrict speeds around the Silver Lake Bridge and during specified hours [25].

While Pennsylvania territory does not front directly on the Bay itself, it is worth noting their policies on boat wakes on the Susquehanna River, since it runs into the upper Bay at the Susquehanna flats near Havre de Grace, Maryland. The Consolidated Statutes of Pennsylvania

authorize the Fish and Boat Commission (FBC) to administer and enforce rules and regulations regarding the operation of boats [26]. Among other things [27], FBC regulations define “slow, no wake speed” as the “slowest possible speed of a motor boat required to maintain maneuverability so that wake . . . created . . . is minimal” [28] and establish special regulations by county [29]. The special regulations for Lancaster County establish slow, no-wake speeds for areas in Lake Aldred and the Susquehanna River [30].

In summary, Virginia specifically authorized the adoption of and delegated the implementation of boat speed restrictions to localities. Maryland and Delaware address boat speed restrictions in various authorities – state code, state agency regulations, and localities’ ordinances, but specify that local ordinances must conform to state law. Virginia is the only state to expressly recognize shore erosion as a factor to consider in restricting wakes/boat speed, but localities in Maryland and Delaware presumably have the authority to implement restrictions to address both safety and shore erosion concerns since their laws reference “property”. Since the Bay states take different approaches to regulating boat wakes and speeds, it would be beneficial to empanel an expert group with representation from the appropriate Bay jurisdictions to develop a recommended uniform boat wake policy for the Chesapeake Bay in order to achieve consistent shoreline protection.

#### ***Boat Wake Policies Established For Other Shallow Estuaries***

Comparing the management strategy for other shallow water estuaries may be helpful when considering options for establishing a boat wake restriction policy in the Chesapeake Bay. Some examples of similar estuaries are Biloxi Bay in Mississippi, Narragansett Bay in Rhode Island, and Pamlico Sound in North Carolina.

Mississippi State Code designates that the Commission on Marine Resources, through the Department of Marine Resources, shall exercise the duties and responsibilities of the Mississippi Boat and Safety Commission with respect to marine waters [31]. DMR regulations under this authority include the designation of no wake zones generally [32], specific no wake zones [33], and temporary specific no wake zones [34]. Examples of coastal Mississippi localities with boat wake restrictions include the cities of Gautier [35] and Gulfport [36].

The General Laws of Rhode Island authorize the Department of Environmental Management (DEM) to “establish maximum speeds for boats in the public harbors in the state of Rhode Island at five (5) miles per hour, no-wake” [37]. Additionally, the General Laws specifically state that the adoption of an ordinance or local law identical to state laws and regulation is not prohibited

[38], and that subdivisions of the state may make formal application to DEM, after public notice, for special rules and regulations regarding the operation of vessels within the subdivision's territorial limits [39]. As a result, many coastal localities have adopted wake restrictions [40].

The North Carolina State Code authorizes the North Carolina Wildlife Resources Commission, a state agency, to implement wake zone policies [41]. This strategy is part of the Boating Safety Act, the purpose of which is "to promote safety for persons and property in and connected with the use, operation, and equipment of vessels, and to promote uniformity of laws relating thereto" [42]. The Commission is specifically authorized to adopt rules "to prohibit entry of vessels into public swimming areas and to establish speed zones at public vessel launching ramps, marinas, or vessel service areas and on other congested water areas where there are demonstrated water safety hazards" [43]. In addition, a locality can petition the Commission for wake rules for waters within the locality's territorial limits. [44]. The Commission may adopt rules applicable to local areas of water that it finds to be "heavily used for water recreation purposes by persons from other areas of the State and as to which there is not coordinated local interest in regulation" [45]. As a result, almost every coastal county of North Carolina has speed/wake restrictions for specified areas [46].

North Carolina utilizes a state agency to promote uniformity in coastal regulations. This strategy has resulted in boat wake restrictions, set forth in agency regulation, for almost all coastal counties. Capturing such restrictions within the agency's regulations ensures consistent language between the restrictions and increases the public's access to the information. With the goal of reaching similar uniformity across the Chesapeake Bay, oversight and coordination at the state agency level could be a useful tool. A panel of experts from the appropriate Bay jurisdictions could develop a recommended uniform policy for boat wake restrictions that could be used by all of the states surrounding the Bay. Another option would be to pursue an amendment to the Chesapeake Bay Watershed Agreement or an interstate compact between the three states to achieve uniform requirements throughout the Bay. These options are more difficult because there likely will be an unwillingness to undertake amendments to the Chesapeake Bay Watershed Agreement in the near future due to the difficult and time-consuming nature of the agreement process, and a formal interstate compact requires Congressional approval.

### *Alternative Strategies to Combat Wake-Induced Shoreline Erosion*

One alternative strategy to regulating boat wakes and speeds is to impose a ban on motorboats altogether in the Bay. Motorboat bans have been successfully implemented in small lakes and ponds that are isolated waterbodies and are particularly environmentally sensitive. One example

of this is Quimby Pond in Maine, where motorboats were banned after excess phosphorous from soil erosion was found to be partially responsible for the deteriorating water quality and algal bloom in the pond [47]. However, despite these successes in small, isolated lakes and ponds, imposing a Bay-wide ban on motorboats is likely not a feasible option, as it would present both a daunting and unpopular task that would be difficult to enforce. This strategy is unlikely to gain support across Virginia, Maryland, and Delaware because these coastal states' economies rely heavily on both recreational and commercial boating – two activities that would be greatly restricted by a motorboat ban.

In addition to motorboat bans and boat wake restrictions, various shoreline armoring strategies also may be used to combat erosion caused by boat wakes. Hard armoring is the use of physical barrier structures in a fixed location to stop wakes and contain the shoreline sediment [48]. These structures include bulkheads, riprap, seawalls, groins, and revetments. Although these structures effectively reduce erosion from boat wakes for that property protected, they also decrease natural habitat and water quality [49] and can lead to erosion of adjoining downdrift shorelines due to deflected wave energy or lack of sediment supplies to maintain the shorelines. Other forms of armoring utilize living shoreline strategies, which are preferred because they strengthen the endurance of the shoreline and build resilience to boat wakes by using natural sediment and vegetation [50].

The Code of Virginia encourages the use of living shorelines as a stabilization strategy and provides for a general permit for localities to use to authorize living shoreline projects [51]. Specifically, the Code designates living shorelines "as the preferred alternative for stabilizing tidal shorelines in the Commonwealth" [52]. The Code calls for the Virginia Marine Resources Commission, in cooperation with the Virginia Department of Conservation and Recreation, the Virginia Department of Environmental Quality, local wetlands boards, and the Virginia Institute of Marine Science to establish the authorization process and create guidance for the permit implementation [53]. Additionally, in 2016 the Virginia legislature provided an exemption from local taxation for approved living shoreline projects [54] and in 2015 they authorized the State Water Control Board to provide loans from the Virginia Water Facilities Revolving Fund to local governments to establish living shorelines or to provide low-interest loans or other incentives to individuals to assist in establishing living shorelines [55].

Similar to Virginia, Maryland also has designated nonstructural strategies as its primary form of shoreline stabilization [56]. Any structural shoreline stabilization measure will only be approved by the Department of the Environment with a showing that nonstructural strategies are not

feasible [57]. As a result, Maryland mandates the use of nonstructural strategies such as living shorelines to prevent erosion over any other structural measure. To assist with erosion prevention projects, the state established the Shore Erosion Control Construction Loan Fund, which may be administered to persons, municipalities, or counties to design and construct beach protection projects [58]. Delaware delegated “authority to enhance, preserve, and protect public and private beaches” to the Department of Natural Resources and Environmental Control [59]. This authority includes the responsibility to “prevent and repair damages from erosion of public beaches,” which includes constructing and repairing armoring structures [60]. The Department of Natural Resources and Environmental Control regulates all beach protection measures through a permit system [61]. Although the Delaware Code does not specifically address “living shorelines”, the Department’s regulations state that efforts must be made to use “shoreline erosion control methods that best provide for the conservation of aquatic nearshore habitat, maintain water quality, and avoid other adverse environmental effects,” including but not limited to vegetation, revetments and gabions [62]. Structural erosion control measures are allowed where it can be shown that nonstructural measures would be ineffective in controlling erosion; and “[w]hen engineering feasibility and effectiveness considerations are equal” the shoreline erosion control method used must be the one with the least adverse environmental impact [63]. Nonstructural measures also are preferred for shoreline stabilization work in low wave energy areas with wetlands or no significant shoreline erosion, and eroding areas where combinations of structural and nonstructural measures would be a practicable and effective method to control erosion [64]. The regulations for siting and designing new marinas also discourage the installation of bulkheads by requiring evidence that no practicable alternative is available [65]. Furthermore, the regulation also states that any shoreline protection structure must be designed to have minimal adverse effects on the aquatic resources [66]. Discouraging the use of bulkheads and focusing on minimal adverse effects suggest that living shorelines are preferred. The Delaware Living Shoreline Committee has implemented several significant living shoreline projects in the state. The Living Shoreline Committee is a “voluntary group of state, private, and non-profit professionals coordinating research, funding and opportunities for living shoreline projects in Delaware” [67]. Furthermore, funding for shoreline preservation and protection is available through the state’s Beach Preservation Fund, which provides bonds for shore stabilization projects [68]. Pennsylvania, by contrast to Virginia, Maryland, and Delaware, has no statute or regulations related to living shorelines.

## Summary and Recommendations

Studies outside the Chesapeake Bay and anecdotal evidence along the Bay waterways indicate that boat wakes and wash can cause shoreline erosion and adverse impacts on aquatic fauna and their habitats. Published values generally indicate that recreational vessels within 150 m (~500 ft) of the shoreline can produce waves large enough to result in significant shoreline erosion. It should be noted that vessels traveling further offshore can still produce erosive boat wakes; the magnitude of a vessels' impact is a function of vessel size and speed. A 150 m setback may help to reduce erosion in a channel that is frequented by smaller recreational vessels while a much larger setback may be necessary to combat erosion along waterways used by large commercial vessels. It is also notable that whether, and to what extent, boat wakes will lead to shoreline erosion is dependent on site-specific bathymetry. Vegetated shorelines can effectively attenuate waves in certain settings; however, there is a limit to this capacity particularly if there is frequent exposure to boat wakes. For marsh shorelines, it has been shown that waves as small as 10 cm result in erosion of sediments (Coops et al. 1996), and marsh survival is compromised when waves exceed 30 cm, even 5% of the time (Schafer et al. 2003, Roland and Douglas 2005).

Virginia, Maryland, and Delaware localities have demonstrated authority and willingness to establish wake restrictions, but have not done so comprehensively nor with Bay-wide coordination. North Carolina has an effective approach that provides authority to a state agency to establish wake restrictions and that has resulted in wake restriction policies for almost all of its coastal localities set forth in state regulations. Coordination of wake restrictions between the Chesapeake Bay states, based on the assessment of wake damage in this STAC review, could be achieved via a multi-state agreement or program, and would result in greater policy consistency Bay-wide.

### ➤ **Are boat wake induced sediment inputs currently represented in the Bay Watershed Model?**

No, the water quality model for the Chesapeake Bay total maximum daily load (TMDL) currently does not distinguish sediment erosion caused by boat wakes when it accounts for sediment from shoreline erosion. Although it could be an important factor, because we do not have comprehensive data throughout the Bay to accurately distinguish boat wake induced erosion, it is premature to include this factor in the model.

➤ **Would expanding no-wake zones directed at reducing boat wake impacts be beneficial to the Bay?**

It is likely that in narrow, low energy waterways or along extremely sensitive shorelines with relatively high boating activity, establishing additional no-wake zones would reduce shoreline erosion and related ecosystem impacts. However, there may be challenges to enforcement of additional areas and/or expanded existing no-wake zones. This strategy also involves tradeoffs as no-wake zones result in increased travel times (Fonseca and Malhotra, 2012). An alternative approach to no-wake zones could involve establishing a minimum distance that navigation channels must pass from the shoreline where possible.

➤ **What other management options might mitigate shoreline erosion from recreational boating?**

In addition to the establishment of no-wake zones, other management options to ameliorate boat wake impacts fall into two categories: 1) shoreline management and 2) management of recreational boating activities.

Shoreline erosion is a natural and necessary process supporting the persistence and resilience of coastal wetlands and in many cases, the best and most ecologically appropriate shoreline management solution is to maintain natural shorelines. In areas where shoreline management treatments become necessary, for instance to decrease erosion and the resulting landward migration of the shoreline and reduce adverse impacts to infrastructure, treatments to protect the shoreline from boat wakes are no different than protection of the shoreline from wind waves. Both Maryland and Virginia encourage 'living shorelines' or nonstructural shoreline stabilization measures as the preferable method for shoreline erosion control, with Maryland requiring them unless they can be proved to be infeasible, and both states providing loan assistance to support their installation. Virginia has a streamlined General Permit process to encourage living shoreline use. In Delaware structural erosion control measures are allowed where it can be shown that nonstructural measures would be ineffective in controlling erosion.

Management of boating activities could include the placement of restrictions on boat size in small bays, creeks, and estuaries (an approach recommended by Glamore (2008), speed limits, navigation buffers from the shore, or motorboat bans. Historically, many narrow creeks have been dredged to allow larger boats into the waterway. Since boat wake energy is positively correlated with boat size, this increases the boat wake energy in these narrow systems. In addition, in narrow waterways boats are passing very close to the shoreline by default.

Minimizing boat size in small waterways would help minimize boat wake exposure. However, anecdotally, small waterway wake-induced erosion is frequently blamed on personal watercraft. There are no data to verify this claim, but if true, limiting boat size in small waterways may not successfully prevent erosion and turbidity. Speed limits have been implemented in Maryland and Delaware primarily due to safety concerns, but the limits functionally reduce boat wake energy and thereby associated erosion. In areas of great environmental sensitivity, motorboat bans, or limits on motor size, have been implemented to eliminate adverse impacts on natural resources.

### **Primary Recommendations**

- Develop predictive models to quantify the relative contribution of boat wake induced erosion to overall shoreline erosion to inform water quality, habitat restoration, and shoreline protection management strategies.
- Collect data necessary to identify shores vulnerable to erosion from boating, and to calibrate and validate predictive models. Data needs identified in this report include recreational boating usage patterns, boat generated wave energy and currents, shallow-water bathymetry, shoreline slope and vegetation characteristics, suspended sediment concentration as a measure of potential erosion, and shoreline erosion rates. Then, develop a definition for, and classification scheme of, small tidal waterways with the greatest likelihood for significant boat wave shoreline erosion.
- Incorporate boat wake induced turbidity and erosion when siting Bay Restoration activities (e.g., wetland/submerged aquatic vegetation (SAV) restoration).
- Investigate the opportunities within the Bay states to implement no-wake zones or other wake reduction strategies (navigation buffers from shore, speed limits, boat size restrictions, boat bans) for addressing shoreline erosion where public safety is not also a concern. In Virginia, current implementation of a no-wake zone requires a finding of a public safety concern and erosion is a second consideration. Empanel an expert group from the appropriate Bay jurisdictions to develop and recommend a uniform boat wake policy in the Chesapeake Bay.



## Literature Cited

- Allen, J.H., G.L. Nuechterlein, and D. Buitron. 2008. Bulrush mediation effects on wave action: Implications for over-water nesting birds. *Waterbirds* 31(3): 411-416.  
doi:<http://dx.doi.org/10.1675/1524-4695-31.3.411>
- Allison, B. 2005. Characterization of Sediment Movement in Tidal Creeks Adjacent to the Gulf Intra-Coastal Waterway at Aransas National Wildlife Refuge, Austwell, TX: Study of Natural Factors and Effects of Barge-Induced Drawdown Currents. College Station, TX: Texas A&M University, M.S. Thesis, 64 p.
- Anderson, F.E. 2002. Effect of wave-wash from personal watercraft on salt marsh channels. *Journal of Coastal Research* SI(37): 33-49.
- Asplund, T. R. 1996. Impacts of motorized watercraft on water quality in Wisconsin lakes. Wis. Dep. Nat. Res. Bur. Research, Madison, WI. PUBL-RS-920-96. 46 p.
- Australian Maritime College. 2003. Vessel Wash Impacts on Bank Erosion, Noosa River and Brisbane River. Technical Report # 01/G/18 for Moreton Bay Waterways and Catchment Partnership.
- Baldwin, D.S. 2008. Impacts of recreational boating on river bank stability: wake characteristics of powered vessels. Report of the Murray Catchment Management Authority. Murray-Darling Freshwater Research Centre, Wodonga, Victoria.
- Bauer, B.O., M.S. Lorang, and D.J. Sherman. 2002. Estimating boat-wake-induced levee erosion using sediment suspension measurements. *Journal of Waterway, Port, Coastal and Ocean Engineering* 128: 152-162.
- Beachler, M.M. and D.F. Hill. 2003. Stirring up Trouble? Resuspension of Bottom Sediments by Recreational Watercraft. *Lake and Reservoir Management* 19(1): 15-25.
- Bilkovic, D.M. 2011. Response of tidal creek fish communities to dredging and coastal development pressures in a shallow-water estuary. *Estuaries and Coasts* 34(1): 129-147.

- Bilkovic, D.M. and M.M. Mitchell. 2013. Ecological tradeoffs of stabilized salt marshes as a shoreline protection strategy: effects of artificial structures on macrobenthic assemblages. *Ecological Engineering* 61: 469-481.
- Bilkovic, D.M., H.W. Slacum, Jr., K.J. Havens, D. Zaveta, C.F.G. Jeffrey, A.M. Scheld, D. Stanhope, K. Angstadt, and J.D. Evans. 2016. Ecological and Economic Effects of Derelict Fishing Gear in the Chesapeake Bay: 2015/2016 Final Assessment Report. Prepared for Marine Debris Program, Office of Response and Restoration, National Oceanic and Atmospheric Administration. <https://marinedebris.noaa.gov/reports/effects-derelict-fishing-gear-chesapeake-bay-assessment-report>
- Bilkovic, D.M., M. Mitchell, P. Mason, and K. Duhring. 2016. The role of living shorelines as estuarine habitat conservation strategies. *Coastal Management Journal* 44: 161-174.
- Bishop, M.J. 2008. Displacement of epifauna from seagrass blades by boat wake. *J. Exp. Mar. Biol. Ecol.* 354(1): 111-118.
- Burger, J. 2003. Personal watercraft and boats: Coastal conflicts with common terns. *Lake and Reservoir Management* 19(1): 26-34.
- Campbell, D. 2015. Quantifying the effects of boat wakes on intertidal oyster reefs in a shallow estuary. Thesis. University of Central Florida.
- Castillo, J. M., C.J. Luque, E.M. Castellanos, and M.E. Figueroa. 2000. Causes and consequences of salt-marsh erosion in an Atlantic estuary in SW Spain. *Journal of Coastal Conservations* 6: 89-96.
- Center for Coastal Resources Management (CCRM). 2010. Virginia Institute of Marine Science. Shallow water dredging. *Rivers and Coasts*. Winter 2010, Vol. 5, No. 1. <http://www.ccrm.vims.edu/publications/pubs/rivers&coast/Winter2010.pdf>
- Center for Coastal Resources Management (CCRM). 2015. Shoreline Management Model, Version 4. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.
- Center for Coastal Resources Management (CCRM). 2017. Shoreline Permit Database. Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia.

Coops, H., N. Geilen, H.J. Verheij, R. Boeters, and G. van der Velde. 1996. Interactions between waves, bank erosion and emergent vegetation: an experimental study in a wave tank. *Aquatic Botany* 53: 187-198.

Cowart, L., R.D. Corbett, and J.P. Walsh. 2011. Shoreline change along sheltered coastlines: insights from the Neuse River Estuary, NC, USA. *Remote Sensing* 3: 1516-1634.

Cox, G. and G. Macfarlane. 2004. Vessel wash impacts on bank erosion – Maroochy River: Lower Maroochy River, Code Hole Upper Maroochy River, Upstream of the David Low Way Bridge, Moreton Bay Waterways and Catchments Partnership, Brisbane, Australia 169 p.

Craft, C., S. Broome, and C. Campbell. 2002. Fifteen years of vegetation and soil development after brackish-water marsh creation. *Restoration Ecology* 10: 248-258.

Crawford, R.E. 2002. Secondary wake turbidity from small boat operation in a shallow sandy bay. *Journal of Coastal Research* SI(37): 50-65.

Currin, C., J. Davis, L. Cowart Baron, M. Malhotra and M. Fonseca. 2015. Shoreline change in the New River Estuary, North Carolina: rates and consequences. *Journal of Coastal Research* 31: 1069-1077.

Dawes, C.J., J. Andorfer, C. Rose, C. Uranowski, and N. Ehringer. 1997. Regrowth of the seagrass *Thalassia testudinum* into propeller scars. *Aquatic Botany* 59: 139-155.

Dayton, P.K., and L.A. Levin. 1996. Erosion of cordgrass at Kendall-Frost Mission Bay reserve. California Sea Grant. Biennial Report of Completed Projects 1992-94. 179 p.

Dennison, W.C., R.J. Orth, K.A. Moore, J.C. Stevenson, V. Carter, S. Kollar, P.W. Bergstrom, and R.A. Batiuk. 1993. Assessing water quality with submersed aquatic vegetation. *BioScience* 43: 86-94.

Duarte, C.M. 1991. Seagrass depth limits. *Aquatic Botany* 40: 363-377.

Environmental Finance Center, University of Maryland. 2013. Recreational Boating and Fiscal Analysis Study. [https://efc.umd.edu/assets/boating\\_analysis\\_final\\_report\\_-\\_noaa\\_added.pdf](https://efc.umd.edu/assets/boating_analysis_final_report_-_noaa_added.pdf)

- Fagherazzi, S., G. Mariotti, P.L. Wiberg, and K.J. McGlathery. 2013. Marsh collapse does not require sea level rise. *Oceanography* 26(3): 70-77.
- Feagin, R.A., S.M. Lozada-Bernard, T.M. Ravens, I. Möller, K.M. Yeagei, A.H. Baird, and D.H. Thomas. 2009. Does vegetation prevent wave erosion of salt marsh edges? *Proceedings of the National Academy of Sciences of the United States of America*. 106: 10109-10113.
- FitzGerald, D. Z. Hughes, and P. Rosen. 2011. Boat wake impacts and their role in shore erosion processes, Boston Harbor Islands National Recreation Areas. *Natural Resource Report NPS/NERO/NRR-2011/403*. National Park Service. Fort Collins, Colorado.
- Fonseca, M. and A. Malhotra. 2012. Boat wakes and their influence on erosion in the Atlantic Intracoastal Waterway, North Carolina. *NOAA Technical Memorandum NOS NCCOS #143*. 24 p.
- Francalanci, S.M., S. Bondoni, M. Rinaldi, and L. Solari. 2013. Ecomorphodynamic evolution of salt marshes: experimental observations of bank retreat processes. *Geomorphology* 195: 53-65.
- Gabel, F., S. Stoll, P. Fischer, M.T. Pusch, and X.F. Garcia. 2011. Waves affect predator-prey interactions between fish and benthic invertebrates. *Oecologia* 165(1): 101-109.
- Gittman, R.K., J. Fodrie, A.M. Popowich, D.A. Keller, J.F. Bruno, C.A. Currin, C.H. Peterson, and M.F. Piehler. 2015. Engineering away our natural defenses: an analysis of shoreline hardening in the US. *Frontiers in Ecology and the Environment* 13: 301-307.
- Gittman, R.K., C.H. Peterson, C.A. Currin, F.J. Fodrie, M.F. Piehler, and H.F. Bruno. 2016. Living shorelines can enhance the nursery role of threatened estuarine habitats. *Ecological Applications* 26: 249-263.
- Glamore, W.C. 2008. A Decision support tool for assessing the impact of boat wake waves on inland waterways. *International Conference on Coastal and Port Engineering in Developing Countries*. 20 p. Retrieved from: <http://pianc.org>.
- Glass, J. 2006. No-wake zone imposed on parts of Back Bay. *The Virginian-Pilot*. June 28, 2016. Retrieved from: [http://pilotonline.com/news/local/environment/no-wake-zone-imposed-for-parts-of-back-bay/article\\_ef4a5523-7ffa-54ff-8245-4a5c4dc3ae59.html](http://pilotonline.com/news/local/environment/no-wake-zone-imposed-for-parts-of-back-bay/article_ef4a5523-7ffa-54ff-8245-4a5c4dc3ae59.html)

Gourlay, T. 2011. Notes on shoreline erosion due to boat wakes and wind waves. CMST research report 2011-16. Center for Marine Science and Technology. Curtin University. 10 p.

Grizzle, R.E., J.R. Adams, and L.J. Walters. 2002. Historical changes in intertidal oyster (*Crassostrea virginica*) reefs in a Florida lagoon potentially related to boating activities. Journal of Shellfish Research. 21: 749-756.

Hallac, D.E., J. Sadle, L. Pearlstine, F. Herling, and D. Shinde. 2012. Boating impacts to seagrass in Florida Bay, Everglades National Park, Florida, USA: links with physical and visitor-use factors and implications for management. Marine and Freshwater Research 63(11): 1117-1128.

Hargis Jr, W.J. and D.S. Haven. 1999. Chesapeake oyster reefs, their importance, destruction and guidelines for restoring them. Oyster reef habitat restoration: a synopsis and synthesis of approaches. Virginia Institute of Marine Science Press, Gloucester Point, VA. 329-358.

Hill, D.F., M.M. Beachler, and P.A. Johnson. 2002. Hydrodynamic impacts of commercial jet-boating on the Chilkat River, Alaska. Alaska Department of Civil and Environmental Engineering, Pennsylvania State University.

Holloway, L. 2015. Boat Wakes Could Jeopardize Endangered Birds in Ocean City. WBOC Channel 16. July 7, 2015. Retrieved from: <http://www.wboc.com/story/29490965/boat-wakes-could-jeopardize-endangered-birds-in-ocean-city>

Houser, C. 2010. Relative importance of vessel-generated and wind waves to salt marsh erosion in a restricted fetch environment. Journal of Coastal Research 262: 230-240.

Houser, C. 2011. Sediment Resuspension by Vessel-Generated Waves along the Savannah River, Georgia. Journal of Waterway, Port, Coastal and Ocean Engineering 137(5): 246-257.

Hughes, Z.J., D.M. FitzGerald, N.C. Howes, and P.S. Rosen. 2007. The Impact of Natural Waves and Ferry Wakes on Bluff Erosion and Beach Morphology in Boston Harbor, USA. Journal of Coastal Research SI(50): 497-501.

Isdell, R.E. 2014. Anthropogenic modifications of connectivity at the aquatic-terrestrial ecotone in the Chesapeake Bay. M.S. Thesis. College of William & Mary, Williamsburg, Virginia, USA.

- Kirkegaard, J., H. Kofoed-Hansen, and B. Elfrink. 1998. Wake wash of high-speed craft in coastal areas. in: Proceedings of the 26th International Coastal Engineering Conference. 325-337.
- Knutson, P.L., H.H. Allen and J.W. Webb. 1990. Guidelines for vegetative erosion control on wave-impacted dredged material sites. Technical Report D-90-13. U.S. Army Corps of Engineers, Vicksburg. MS.
- Koch, E.W. 2002. Impact of boat-generated waves on a seagrass habitat. *Journal of Coastal Research* 37: 66-74.
- Koch, E.W., L.P. Sanford, S.N. Chen, D.J. Shafer, and J.M. Smith. 2006. Waves in seagrass systems: Review and Technical Recommendations. U.S. Army Corps of Engineers (No. ERDC-TR-06-15).
- Laderoute, L. and B. Bauer. 2013. River bank erosion and boat wakes along the Lower Shuswap River, British Columbia. Regional District of North Okanagan Fisheries and Oceans Canada. Final Report.
- Liddle, M.J. and H.R.A. Scorgie. 1980. The effects of recreation on freshwater plants and animals: a review. *Biological Conservation* 17(3): 183-206.
- Lipton, D. 2007. Economic Impact of Maryland Boating in 2005. Marine Economic Specialist. University of Maryland Sea Grant Extension Program.
- Marani, M., A. S'Alpaos, S. Lanzoni, and M. Santalucia. 2011. Understanding and predicting wave erosion of marsh edges. *Geophysical Research Letters* 38: L21401.
- Maryland's Recreational Boating and Infrastructure Plan: A comprehensive assessment of recreational boating facilities and recommendations for ecologically sounds and cost-effective project selection. June 2004. [http://dnr.maryland.gov/boating/Documents/Boating\\_Plan05.pdf](http://dnr.maryland.gov/boating/Documents/Boating_Plan05.pdf)
- Maynard, S. 2001. Boat waves on Johnson Lake and Kenai River, Alaska. Technical Report U.S. Army Corps of Engineers. (No. ERDC/CHL-TR-01-31).
- Maynard, S.T., D.S. Biedenham, C.J. Fischenich, and J.E. Zufelt. 2008. Boat-Wave-Induced bank erosion on the Kenai River, Alaska. Technical Report U.S. Army Corps of Engineers. (No. ERDC TR-08-5)

McConchie, J.A. and I.E.J. Toleman. 2003. Boat wakes as a cause of riverbank erosion: a case study from the Waikato River, New Zealand. *Journal of Hydrology (NZ)* 42: 163-179.

Möller, I. 2006. Quantifying saltmarsh vegetation and its effect on wave height dissipation: Results from a UK east coast saltmarsh. *Estuarine, Coastal and Shelf Science* 69: 337-351.

Möller, I., M. Kudella, F. Rupprecht, T. Spencer, M. Paul, B.K. van Wesenbeeck, G. Wolters, K. Jensen, T.J. Bouma, M. Miranda-Lange, and S. Schimmels. 2014. Wave attenuation over coastal salt marshes under storm surge conditions. *Nature Geoscience* 7(10): 727-731.

Murray, T., J. Kirkley, and D. Lipton. 2009. Assessment of the Economic Impacts of Recreational Boating in the City of Hampton. Virginia Institute of Marine Science, College of William & Mary.

Mussetter, R.A., M.D. Harvey, and S. Parkinson. 2007. Boat wake erosion of sand bars in Hells Canyon of the Snake River, Idaho and Oregon. Proceedings of the 2007 World Environmental and Water Resources Congress; Tampa, FL; USA; 15-19 May 2007. DOI:10.1061/40927(243)392

Nanson, G.C., A. Von Krusenstierna and E.A. Bryant. 1994. Experimental measurements of river-bank erosion caused by boat-generated waves on the Gordon River, Tasmania. *Regulated Rivers: Research and Management* 9: 1-14.

National Research Council (NRC). 2007. Mitigating Shoreline Erosion along Sheltered Coasts. Washington D.C.: The National Academies Press, 188 p.

Osborne, P.D. and E.H. Boak. 1999. Sediment Suspension and Morphological Response under Vessel-Generated Wave Groups: Torpedo Bay Auckland, New Zealand. *Journal of Coastal Research* 15(2): 388-398.

Parnell, K.E. and H. Kofoed-Hansen. 2001. Wakes from large high-speed ferries in confined coastal waters: Management approaches with examples from New Zealand and Denmark. *Journal of Coastal Management* 29: 217-237.

Peters, K.A., and D.L. Otis. 2006. Wading bird response to recreational boat traffic: Does flushing translate into avoidance? *Wildlife Society Bulletin* 34(5): 1383-1391.

- Priest, W.P. III. 1999. Historic Wetland Loss in the Elizabeth River. The Virginia Wetlands Report 14(3): 1-7.
- Priestas, A.M., G. Mariotti, N. Leonardi and S. Fagherazzi. 2015. Coupled wave energy and erosion dynamics along a salt marsh boundary, Hog Island Bay, Virginia, USA. Journal of Marine Science and Engineering 3: 1041-1065.
- Rapaglia, J., L. Zaggia, K. Ricklefs, M. Gelinas, and H. Bokuniewicz. 2011. Characteristics of ships' depression waves and associated sediment resuspension in Venice Lagoon, Italy. Journal of Marine Systems 85: 45-56.
- Roland, R.M. and S.L. Douglas. 2005. Estimating wave tolerance of *Spartina alterniflora* in coastal Alabama. Journal of Coastal Research 21: 453-463.
- Schafer, D.J., R. Roland, and S.L. Douglass. 2003. Preliminary evaluation of critical wave energy thresholds at natural and created coastal wetlands. WRP Technical Notes Collection ERDC-TN-WRP-HS-CP-2.2, U.S. Army Corps of Engineers, Vicksburg, MS.
- Schroevens, M., B.J.A. Huisman, M. van der Wal, and J. Terwindt. 2011. Measuring ship induced waves and currents on a tidal flat in the Western Scheldt estuary. IEEE/OES 10: 123-129.
- Schwimmer, R. 2001. Rates and processes of shoreline erosion in Rehoboth Bay, Delaware, USA. Journal of Coastal Research 17: 672-683.
- Soomere, T., R. Poder, K. Rannat, and A. Kask. 2005. Profiles of waves from high-speed ferries on the coastal area of Tallin Bay. Proceedings of the Estonian Academy of Science and Engineering 11: 245-260.
- Sorenson, R.M. 1973. Water waves produced by ships. Journal of the Waterways Harbors and Coastal Engineering Division: proceedings of the American Society of Civil Engineers 99: 245-256.
- Sorenson, R.M. 1997. Prediction of vessel-generated waves with reference to vessels common to the upper Mississippi River System. Interim report for the Upper Mississippi River, Illinois Waterway System Navigation Study. U.S. Army Engineer District, Rock Island.
- Stumbo, S., K. Fox, F. Dvorak, and L. Elliot. 1999. The prediction, measurement, and analysis of wake wash from marine vessels. Marine Technology 36: 248-260.



Świerkowski, L., E. Gouthas, C.L. Christie, and O.M. Williams. 2009. Boat, wake, and wave real-time simulation. in: SPIE Defense, Security, and Sensing (pp. 73010A-73010A). International Society for Optics and Photonics.

Theuerkauf, S.J., D.B. Eggleston, B.J. Puckett and K.W. Theuerkauf. 2016. Wave exposure structures oyster distribution on natural intertidal reefs, but not on hardened shorelines. *Estuaries and Coasts*. DOI: 10.1007/s12237-016-0153-6.

Tonelli, M., S. Fagherazzi, and M. Petti. 2010. Modeling wave impact on salt marsh boundaries. *Journal of Geophysical Research* 115: C09028.

U. S. Army Corps of Engineers (USACE). 1994. Cumulative impacts of recreational boating on the Fox River - Chain O' Lakes area in Lake and McHenry Counties, Illinois: Final Environmental Impact Statement. Environ. and Social Anal. Branch, U.S. Army Corps of Engineers, Chicago, IL. 194 p.

United State Coast Guard. 2012. National Recreational Boating Survey.

<https://www.uscgboating.org/library/recreational-boating-servey/2012survey%20report.pdf>.

van Eerdt, M.M. 1985. The influence of vegetation on erosion and accretion in salt marshes of the Oosterschelde, The Netherlands. *Vegetatio*. 62: 367-373.

Walker, D.I., R.J. Lukatelich, G. Bastyan, and A.J. Mc-Comb. 1989. Effect of boat moorings on seagrass beds near Perth, Western Australia. *Aquatic Botany* 36: 69-77.

Wall, L.M., L.J. Walters, R. E. Grizzle, and P.E. Sacks. 2005. Recreational boating activity and its impact on the recruitment and survival of the oyster *Crassostrea virginica* on intertidal reefs in Mosquito Lagoon, Florida. *Journal of Shellfish Research* 24: 965-973.

Watson, E.B., and R. Byrne. 2012. Recent (1975-2004) vegetation change in the San Francisco estuary, California, tidal marshes. *Journal of Coastal Research* 28(1): 51-63.

Whitfield, A.K. and A. Becker. 2014. Impacts of recreational motorboats on fishes: a review. *Marine Pollution Bulletin* 83(1): 24-31.

Williams, S.L. 1988. *Thalassia testudinum* productivity and grazing by green turtles in a highly disturbed seagrass bed. *Marine Biology* 98: 447-455.

Yang, S.L., B.W. Shi, T.J. Bouma, T. Ysebaert, and X.X. Luo. 2012. Wave attenuation at a salt marsh margin: A case study of an exposed coast on the Yangtze Estuary. *Estuaries and Coasts*. 35: 169-182.

Zabawa, C. and C. Ostrom. 1980. The role of boat wakes in shoreline erosion in Anne Arundel County, Maryland. Final Report to the Coastal Resources Division, Maryland Department of Natural Resources.

### **Endnote citations: *Management and Policy in Chesapeake Bay***

[1] The Virginia Coastal Policy Center wishes to thank W&M Law School students Sarah Edwards, Kristin McCarthy and Emily Messer for their assistance with this section.

[2] In a “Dillon Rule” state, local government authority is limited to those powers that are conferred expressly or by necessary implication by the state legislature. *Board of Supvrs. v. Horne*, 216 Va. 113 (1975); *Commonwealth v. County Bd. of Arlington*, 217 Va. 558 (1977); BLACK’S LAW DICTIONARY, 523 (9th ed. 2009).

[3] Va. Code Ann. § 29.1-744(D) (2001). “No wake zone” is defined in the Code as “operation of a motor boat at the slowest possible speed required to maintain steerage and headway.” Va. Code Ann. § 29.1-700.

[4] Based on discussions with VDGIF boating and policy staff, Oct. 2016.

[5] *See, e.g.*, Alexandria, Va., Code § 6-3-9(c) (1986); Bedford County, Va., Code § 10-21 (1999); Chesapeake, Va., Code § 86-9 (1970); Gloucester County, Va., Code § 21-2 (1995); Hampton, Va. Code § 7-26 (2006); Norfolk, Va., Code § 25.2-177 (2007); Virginia Beach, Va., Code §§ 6-111, 6-112.1 (1989).

[6] 4 Va. Admin. Code § 15-390-80. In addition, Virginia Code requires that motorboats slacken speed and control wakes near certain structures and swimmers. Va. Code Ann. § 29.1-744.3.

[7] Va. Code Ann. § 29.1-744(E) (2001).

[8] Based on discussions with VDGIF boating and policy staff, Oct. 2016.

[9] Jon W. Glass, *No-Wake Zone Imposed for Parts of Back Bay*, The Virginian-Pilot Online (June 28, 2006), [http://pilotonline.com/news/local/environment/no-wake-zone-imposed-for-parts-of-back-bay/article\\_ef4a5523-7ffa-54ff-8245-4a5c4dc3ae59.html](http://pilotonline.com/news/local/environment/no-wake-zone-imposed-for-parts-of-back-bay/article_ef4a5523-7ffa-54ff-8245-4a5c4dc3ae59.html).

[10] Md. Code Ann., Nat. Res. § 8-725.2, 725.5-6 (2002).

[11] Md. Code Ann., Nat. Res. § 8-704(c) (2007).

[12] Md. Code Ann., Nat. Res. § 8-704(f) (2007).

[13] Md. Code Regs. 08.18.01.03 (2004).

[14] *Id.*

- [15] Md. Code Regs. 08.18.07.01-02 (2016).
- [16] *Id.*
- [17] Md. Code Regs. 08.18.01.00 (1992).
- [18] Cambridge, Maryland Code of Ordinances Sec. 19-30(C) (2012).
- [19] Annapolis, Maryland Code of Ordinances Sec. 15.10.070 (2016).
- [20] Del. Code Ann. tit. 23 § 2114(b)(4).
- [21] 7 Del. Admin. Code § 3100-2.1.
- [22] 7 Del. Admin. Code § 3100-6.1.2.
- [23] Del. Code Ann. tit. 23 § 2121.
- [24] Smyrna, Delaware Code of Ordinances Sec. 46-58(h) (1995).
- [25] Dover, Delaware Code of Ordinances Sec. 74-122 (2012).
- [26] 30 Pa. Cons. Stat. § 5100, 5121.
- [27] *See, e.g.*, 58 Pa. Code § 103.3(a) (establishing a “slow, no wake speed” for special areas such as within 100 feet of docks, swimmers, etc.); 58 Pa. Code § 103.16 (mandating a general rule to operate watercraft at a safe speed, establishing that the FBC may set forth specific restrictions of slow, no wake speed by general or special boating regulations, and establishing that the FBC may set numerical (mile per hour) speed limits by general or special boating regulations); and 58 Pa. Code § 107.5(a) (establishing that a slow, no wake speed restriction exists for streams less than 200 feet across, unless FBC special regulations state otherwise).
- [28] 58 Pa. Code § 103.2.
- [29] 58 Pa. Code §§ 111.1 - .72.
- [30] 58 Pa. Code § 111.36.
- [31] Miss. Code Ann. § 59-21-111.
- [32] 22 Miss. Admin. Code, Pt. 16, Ch. 7.
- [33] 22 Miss. Admin. Code, Pt. 16, Ch. 8.
- [34] 22 Miss. Admin. Code, Pt. 16, Ch. 9.
- [35] Gautier, Mississippi Code of Ordinances Sec. 15-2 (“All bayous and canals within the municipal boundaries...shall be a ‘minimum wake’ zone.”).
- [36] Gulfport, Mississippi Code of Ordinances Sec. 2-106 (2015) (“No personnel shall operate any boat or watercraft in the yacht basin at a speed greater than five (5) miles per hour or a speed leaving a noticeable wake, whichever is the lesser.”).
- [37] 46 R.I. Gen. Laws § 22-9(c) (1977).
- [38] 46-22 R.I. Gen. Laws § 14(a) (1977).
- [39] 46-22 R.I. Gen. Laws § 14(b) (1977).
- [40] Bristol, Rhode Island Code of Ordinances Sec. 8-41; Cranston, Rhode Island Code of Ordinances Sec. 12.24.020; East Providence, Rhode Island Code of Ordinances Sec. 13-86;

Jamestown, Rhode Island Code of Ordinances Sec. 78-27; Narragansett, Rhode Island Code of Ordinances Sec. 82-161; New Shoreham, Rhode Island Code of Ordinances Sec. 9-91; Newport, Rhode Island Code of Ordinances Sec. 12.28.051; North Kingston, Rhode Island Code of Ordinances Sec. 7-80; Providence, Rhode Island Code of Ordinances Sec. 11-9; South Kingstown, Rhode Island Code of Ordinances Sec. 4-23; Tiverton, Rhode Island Code of Ordinances Sec. 14-229; Warren, Rhode Island Code of Ordinances Sec. 10.21; Warwick, Rhode Island Code of Ordinances Sec. 24-6.

[41] N.C. Gen. Stat. § 75A-15 (2006).

[42] N.C. Gen. Stat. § 75A-1 (1959).

[43] N.C. Gen. Stat. § 75A-15 (2006).

[44] *Id.*

[45] *Id.*

[46] *See, e.g.*, 15A N.C. Admin. Code 10F.0302 - .0376. Counties subject to the rules and policies of the Coastal Resources Commission include: Beaufort, Bertie, Brunswick, Camden, Carteret, Chowan, Craven, Currituck, Dare, Gates, Hertford, Hyde, New Hanover, Onslow, Pamlico, Pasquotank, Pender, Perquimans, Tyrrell, and Washington. All of these counties, except Bertie and Gates, have boat speed/wake restrictions.

[47] Me. Rev. Stat. Ann. tit. 12 § 13068-A(16) (2003).

[48] C.S. Hardway, Jr. & R.J. Byrne, *Shoreline Management in Chesapeake Bay*, Virginia Inst. of Marine Sci. (Oct. 1999).

[49] *Id.*

[50] *Id.*

[51] Va. Code Ann. § 28.2-104.1 (2014).

[52] *Id.*

[53] *Id.*

[54] Va. Code Ann. § 58.1-3666, Ch. 610, 2016 Va. Acts of Assembly.

[55] Va. Code Ann. § 62.1-229.5, Ch. 474, 2015 Va. Acts of Assembly.

[56] Md. Code Ann., Nat. Res. § 8-1808.11 (2008).

[57] *Id.*

[58] Md. Code Ann., Nat. Res. § 8-1005 (2004).

[59] Del. Code Ann. Tit. 7 § 6803(b) (2005).

[60] *Id.*

[61] 7 Del. Admin. Code § 5102(1983).

[62] 7 Del. Admin. Code § 7504-4.10.1.2 (2006). “Shoreline erosion control structure or measure” is defined in the regulation as “any activity or structure which provides for stabilization of the shore or bank of a watercourse including, but not limited to, a bulkhead, breakwater,

gabion, groin, jetty, rip-rap revetments, seawall, vegetation, and/or grading of banks.” 7 Del. Admin. Code § 7504-§ 1.0 (2006).

[63] 7 Del. Admin. Code § 7504-4.10.1.2 (2006).

[64] 7 Del. Admin. Code § 7504-§ 4.10.1.3.

[65] 7 Del. Admin. Code§ 7501-1.0, -11.4.3 (2006).

[66] *Id.*

[67] Delaware Living Shoreline Committee,

<http://dnrec.maps.arcgis.com/apps/MapJournal/index.html?appid=371a244682084370a78d0a54c5edb27a#detail> (last visited Sept. 23, 2016).

[68] Del. Code Ann. tit. 7, § 6808 (1953).

Table S1. Chesapeake Bay Monitoring station characteristics for analysis of weekend-weekday turbidity changes.

State	Site	Station Name	Turbidity Index	Max Fetch (m)	Number of docks & piers	Number of marinas	Boating intensity	Distance to 1-m depth	Armoring on site	Years of data
VA	BAK	Back River	2.3	35068	278	1	283	3	Yes	2010-2012
VA	CHK	Chickahominy Haven	-2.7	1563	256	2	266	0	No	2006-2008
VA	DIV	Dividing Creek	38.2	1223	141	0	141	46	No	2013-2015
VA	DYE	Dyer Creek	3.5	1326	13	0	13	25	No	2010-2012
VA	HAH	Horn Harbor	9.4	608	12	0	12	38	No	2010-2012
VA	IND	Indian Creek	40.2	63393	289	9	334	129	Yes	2013-2015
VA	INN	Ingram Bay	0.2	45262	665	4	685	150	Yes	2013-2015
VA	LAF	Ashland Circle	4.9	436	25	0	25	13	Yes	2012-2014
VA	MJB	Mobjack Bay	-3.4	23571	703	3	718	170	Yes	2010-2012
VA	NOM	Nomini Bay	14.4	2761	170	1	175	197	No	2007-2009
VA	POH	Pohick Creek	32.8	1895	6	0	6	9	No	2007-2009
VA	TSK	Taskinas Creek	-5.8	66	1	0	1	0	No	2013-2015
VA	WAR	Ware River	7.1	138671	208	0	208	136	Yes	2010-2012
VA	WES	Yeocomico River	10.4	2012	105	3	120	194	No	2007-2009
MD	LYN	Back River - Lynch Point	6.0	4032	621	8	424	40	Yes	2014-2015
MD	RIV	Back River - Riverside	0.0	2571	621	8	40	31	Yes	2014-2015
MD	BCP	Bush River - Church Point	-9.4	4551	165	6	20	15	No	2008-2010
MD	LAU	Bush River - Lauderick Creek	4.9	4147	165	6	0	130	Yes	2005-2007
MD	OPC	Bush River - Otter Point Creek	-1.3	1835	165	6	5	697	No	2013-2015
MD	CBE	Eastern Bay - CBEC	11.4	15269	461	17	1	0	No	2006-2008
MD	HAM	Eastern Bay - Hambleton Point	4.3	13825	564	11	545	136	Yes	2005-2007
MD	GUN	Gunpowder River - APG at Edgewood	-8.8	4548	649	5	641	45	Yes	2003-2005
MD	MPP	Gunpowder River - Mariners Pt Park	24.4	428	649	5	305	0	No	2003, 2005
MD	MOR	Middle River - Cutter Marina	-4.6	197	1191	32	10	0	Yes	2003-2005
MD	STP	Middle River - Strawberry Point	4.9	1788	1191	32	151	31	Yes	2003, 2005
MD	WSR	West River - Shady Side	5.0	1118	683	25	92	5	Yes	2005-2007

## Appendix I: STAC Technical Review Request

### Evaluating boat wake wave impacts on shoreline erosion and potential policy solutions

The Chesapeake Bay Commission (CBC) requested that STAC conduct a technical review of the relevant information on the potential impacts of boat generated waves on shoreline stability and attendant ecosystem properties, and provide advice on available policy actions to minimize any adverse effects.

STAC was also asked to address several questions related to (i) erosion and sediment inputs caused by boat wake waves, (ii) existing and needed data to develop best management practices to minimize shoreline erosion from boat wake waves, and (iii) political and legal challenges associated with policy actions to reduce boat wakes.

#### Background:

Salt marshes have weak resistance to wave action (Fagherazzi et al. 2013) and boat wakes have been shown to negatively impact shoreline stability in salt marshes (Castillo et al. 2001). Boat wake impacts include shoreline erosion, vegetative damage, and impacts to the faunal communities (Parnell and Koefoed-Hansen 2001). Although periodic disturbances (compared to wind waves) boat wakes can be a significant source of erosive energy. In one study, it was discovered that although boat wakes only accounted for about 5% of the wave energy at a site, due to their longer height and period, they accounted for 25% of the cumulative wave force (Houser 2010).

Shoreline erosion due to boat wakes is related to the number of boats passing (frequency of the disturbance) and the energy of the total wave disturbance (calculated by speed, vessel size and distance from channel; Glamore 2008). Wake effects are particularly significant in areas of restricted depth and width (FitzGerald et al 2011), such as tidal creeks. In these systems, they can undercut banks and have significant impact to marshes, especially in areas where synergistic impacts may have reduced marsh soil strength.

#### Review focus areas:

1. Evaluate the state of the science of known effects of boat generated waves on shoreline stability and other ecosystem components (e.g., vegetative habitat, faunal community composition, nearshore TSS concentration).
2. Identify data requirements to effectively model the potential effect of boat wake waves on shorelines
3. Identify data gaps and research needs
4. Determine existing and potential policy actions to reduce adverse effects of boat wake

waves on shorelines. Describe political and legal challenges for designating no-wake zones in Chesapeake Bay. Are there case studies that can be learned from in the bay of no-wake zone designation and/or evaluation of response from management action?

**Questions of interest:**

1. What is the relative contribution of sediment inputs from boat wake induced shoreline erosion in Chesapeake Bay?
2. Are these types of sediment inputs currently represented in the Bay Watershed Model?
3. Would expanding no-wake zones be beneficial to the Bay?
4. Are there other policy options besides no-wake zones to consider?

**Overview of review approach:**

To be responsive to the CBC request, we are proposing to form a core review panel to assimilate relevant information in the form of a white paper. Once a draft technical review is complete, the document will be disseminated to additional external reviewers for further input to ensure critical areas of expertise are well-represented.

**Proposed Timeline**

June 1 2016	Begin technical review
Sept 30 2016	Draft review document completed by core team
October 2016	External review
December 2016	Core Team synthesizes external reviewer comments into final document
January 2017	Internal document review by STAC
February 2017	Final Report released
Spring 2017	Report to Chesapeake Bay Commission