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Analysis of Physical Effects of Commercial Vessel Passage Through The Great Lakes Connecting Channels

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This report examines the physical effects of vessel passage with variations in vessel size as they might impact upon the Great Lakes Connecting Channels. Effects considered include drawdown and surge, ship waves, and propeller wash. The report serves as a guide to the effects of vessel size and points out geographical areas where a change in vessel size could influence sediment transport and shore structure damage.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ANALYSIS OF THE PHYSICAL EFFECTS OF COMMERICAL VESSEL PASSAGE THROUGH THE GREAT LAKES CONNECTING CHANNELS.

James L. Wuebben
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INTRODUCTION

This investigation was conducted in conjunction with the Great Lakes Connecting Channels Study. The overall study was undertaken by the Detroit District of the U.S. Army Corps of Engineers to examine ways of increasing the capacity of the Great Lakes waterways. This report examines the physical effects of vessel passage with variations in vessel size. The areas considered are the United States shorelines along the St. Marys, St. Clair and Detroit Rivers, as well as a hypothetical harbor.

This investigation uses basic theory and empirical data to determine regions within the study area where the hydraulic effects of a change in vessel size might be significant. Effects considered include drawdown and surge, ship waves, and propeller wash. A severe constraint on the study was the extremely short time frame available. This limited useable information to literature and data already in hand. No data collection or field verification was possible, and the depth of analysis and reliability of results are correspondingly restricted. The report should serve as a guide to the effects of vessel size, and point out geographical areas where a change in vessel size could influence sediment transport and shore structure damage.

STATEMENT OF PROBLEM

Vessel passage through channels and harbors may result in changes in water flow created primarily by bow and stern waves, propeller wash, and drawdown and surge. These changes in flow in turn may result in the movement of particulate materials (both on the shoreline and on the channel bottom) resulting in possible physical effects on shoreline erosion, transport of sediment, turbidity, shore structure damage, and related chemical/biological effects. This study is to address the effects of change in vessel size and fleet mix depending on which of three alternative proposals is adopted. The first alternative is to take no action, which provides the basis for comparison in this study. A second alternative primarily consists of rehabilitation of the existing system, and the resulting fleet mix is equivalent to the no action alternative. A third alternative is to construct a new lock at Sault Ste. Marie, Michigan, capable c transiting the largest ships now sailing on the Great Lakes. This : ru alternative would cause a change in fleet mix relative to the other options.

For the purposes of this study, we are to consider vessels in 5 different vessel classes based on length, as shown in Table 1 below. As will be shown later, however, a definition of class based solely on vessel length is not adequate for the purpose of this study. Vessel length is of minor importance in all three ship effects to be considered. Instead, the vessel characteristics of primary importance are draft and beam. Due to the shallow drafts required to pass through the connecting channel, however, draft is essentially unchanged for classes 5 though 10.

Vessel beam does tend to increase with class, but as shown in Figure 1, the relation is not unique. Figure 1 was prepared by reviewing the dimensions of vessels in various size classes listed in Greenwood's Guide to Great Lakes Shipping (Greenwood 1979). Examining the median vessel beam shows that classes 6 and 8 have equivalent beams, while the beam of class 7 is greater than class 8. Median ship dimensions by vessel class are shown in Table 2.

Data on the projected fleet mixes were provided by the Detroit District for vessels passing through the Soo Locks for the three action alternatives. Figure 2 summarizes the total transits by vessel class for the no action and rehabilitation alternatives. Figure 3 presents the same information for the alternative of constructing a new large lock. The major difference between the two figures is that the new lock alternative indicates a relative reduction of traffic in classes 5 through 8 while class 10 traffic increases somewhat. The data suggests that there would be 5 more class 10 vessels resulting in an annual increase of 460 transits by class 10 vessels. At the same time transits by other vessels would decrease by 1333. The total number of transits by all vessels would decrease by 873. No projections were provided for the St. Clair and Detroit Rivers.

A cursory review of the projected transit frequencies suggests that if vessel traffic could be managed such that class 10 vessels had no greater impact than class 8 vessels, then vessel impacts would actually be reduced since total transits would be reduced for the new lock alternative. As will be shown later, vessel speed regulation would allow this to be done.

BACKGROUND

There are several ways in which vessel passage might affect sediment transport and shore structures, including ship wave action, propeller wash, and other hydraulic effects. In addition, during navigation in ice, damage might occur by the direct movement of ice in contact with vessels, by disruption of natural ice-cover characteristics, and by interactions between ship-related water movements and the ice cover.

The significance of these various effects depends on a number of local conditions, such as bathymetry, water levels, soil conditions, ice conditions, shoreline and shore structure composition and geometry, ambient water currents, and waves.

In this section the significance of these various factors will be reviewed on a general basis to provide background for the site-specific analyses in later sections. Since the objective of this investigation is to analyze the significance of an increase in vessel size, a major effect of ship passage may not be considered significant for this report if the changes in vessel size considered here do not significantly alter the magnitude of the effect.

Ship Waves

Waves are the mode of action normally associated with ship-induced damage in the nearshore zone. When a ship sails in ice-free, open water, a system of diverging and transverse waves develops. Diverging waves are those that form the familiar V-shaped wave pattern associated with ship passage. Transverse waves are oriented normal to the sailing line and form a less noticeable wave train that follows the vessel. As these waves propagate, their amplitude decays. According to Sorenson (1973) the transverse waves decay more rapidly, such that the divering waves become dominant with distance from the sailing line.

Due to the decay of the waves as they propagate and to the interaction of these two dissimilar wave sets, the generated wave heights are a strong function of position. In deep water these waves form a constant pattern and meet to form a locus of cusps at an angle of about 19°28' to the sailing line. This angle becomes greater in shallow water.

The maximum wave height occurs at the locus of the cusps. The wave heights at this locus decrease at a rate that is approximately inversely proportional to the cube root of the distance from the disturbance. Except in very shallow water this decay is caused primarily by the distribution of energy along the crest of the wave (Sorenson 1973).

WAVE PREDICTION

Sorenson (1973) states:

> " .... the analytical approaches for calculating the water surface patterns of waves generated by a given hull form have not yet been perfected. Wave patterns can be calculated with reasonable accuracy for hulls of very simplified form moving in deep water at not too great a speed. As the hull geometry becomes more complex and the water motion increases, the methods become much less satisfactory."

Unfortunately, the state of the art for ship wave prediction has not improved significantly since that was written. In particular, little information is available to deal with nearshore wave prediction and the ability of those waves to cause sediment transport or shoreline erosion. A review of literature has located information useful in assessing the relative effect of vessel size on ship generated waves, but the actual wave heights calculated by the different relations vary widely.

The height of ship-generated waves is mainly a function of vessel speed (Gates and Herbich 1977). Table 3 gives the heights H_{max} of waves generated by boats with displacements from 3 to 5420 tons. These data were derived from measurements in the Oakland Estuary. Note the small range of wave heights generated at equivalent speeds by vessels of very different sizes and types.

Figure 4 was developed by Ashton (1974) from the data presented by Sorenson (1973). Although this figure ignores depth and draft effects, hull form and other parameters known to influence wave heights, there is remarkably little scatter. The figure shows the strong relation between wave height and ship velocity.

One method of estimating the height of a ship-generated bow wave in deep water is presented in Saunders (1957):

$$h = K_w \left(\frac{B}{L_E}\right) \frac{V^2}{2g} \qquad (1)$$

where h = height of the water surface at the bow (ft)

K_w = coefficient

B = ship beam (ft)

L_E = entrance length, or the distance from the bow to the parallel midbody (ft)

V = ship velocity (ft/s)

g = acceleration due to gravity (ft/s^2).

According to Helwig (1966), the bow and stern of a ship are responsible for most of a ships wave making ability, and ships with equivalent bow and stern geometries but differing parallel midbody lengths will produce waves of the same magnitude. For cargo vessels with long, parallel midbodies, K_w is relatively constant at 1.133. Since we do not have sufficient information on entrance lengths for the various vessel classes, we will use $L_E/L = 0.416 - 0.000235L$ (Gates and Herbich 1977). Then using equation 1, we can illustrate the effect of vessel size for typical vessels in the various size classes, as shown in Table 4.

Although using actual hull geometries are likely to alter the values in Table 4, it can still serve as a guide to the effect of vessel size. For example, the difference in near ship wave heights for a ship traveling 10 ft/s is 0.39 ft greater for a class 10 ship than for a class 5 vessel. In contrast, a class 10 vessel traveling 8 ft/s produced a wave similar to a class 5 vessel at 10 ft/s. In other words, a reduction in vessel speed of 2 ft/s would eliminate any increase in wave height.

While the magnitude of the wave heights calculated above should not be considered accurate for conditions in the areas of concern to this report, they do indicate that vessel speed is much more important than vessel size and geometry for the range of ship sizes considered here. Also, these calculated wave heights are near-ship waves. Since bow waves decay in approximately inverse porportion to the cube root of the distance from the sailing line, the wave heights and the differences between wave heights will be reduced significantly as the wave propagate away from the ship.

A joint study by the Detroit District, U.S. Army Corps of Engineers and the St. Lawrence Seaway Authority (USACE and SLSA 1972) was conducted to measure wave heights on the Detroit and St. Clair Rivers. In analyzing their data they differentiated only between upbound and downbound vessels (which reflects the relative velocity in a river system) and between ocean-class and inland ships.

In their analysis they fitted analytical curves to their field data, which showed some scatter. Although they did not examine the effect of vessel size, they compared the wave heights generated by ocean versus inland ships (Fig. 5). This distinction reflects a basic difference in hull geometry; in addition, inland ships tend to be larger. Figure 5 shows that the difference in wave heights developed from field measurements for the two classes of ships is slight. The figure considers only upbound ships along a channel that is roughly 3500 ft offshore.

Figure 6 includes inland vessel only. Here, however, the water has a velocity of about 1.3 mph, which accounts for the difference in wave heights for upbound and downbound ships. The channel is roughly 3500 ft offshore.

Figure 7 also compares the wave heights of upbound and downbound ships, but here the sailing line is only about 400 ft offshore. This results in higher waves than shown in Figure 6. The water velocity in the area averages 2.2 mph. It should also be noted from these figures that even for the maximum posted speed limit of 14 mph their measured wave heights are less than 0.5 ft.

Another important consideration is the water depth. This has been treated by using the ratio of water depth to ship draft (Johnson 1958). As the depth d becomes shallower relative to the draft D, wave heights change. However, this is most important in the case of loaded vessels, and for the range of vessel classes considered here the loaded draft is governed by project depth and is thus invariant.

For channels that are not only shallow, but also restricted laterally wave heights can change due to hydrodynamic interaction with the channel. An empirical relation for estimating the near-ship wave heights in a restricted channel was presented by Balanin and Bykov (1965)

$$h = \frac{2.5\ V^2}{2g}\left[1 - \left(1 - \frac{1}{\left(4.2 + \frac{A}{a}\right)^{1/2}}\right)\left(\frac{\frac{A}{a} - 1}{\frac{A}{a}}\right)^2\right] \tag{2}$$

where A is the cross-sectional area of the channel and a is the cross-section of the ship. Although this equation ignores the effects of hull geometry, it does provide a means for evaluating the influence of a restricted channel on wave heights. Figure 8 was prepared for a range of ship speeds and blockage ratios.

For example, a class 5 ship (a = 1530 ft^2) sailing through Lake Nicolet on the St. Marys River (a = 69,270 ft^2) at 12 ft/s would generate a wave of about 12.0 ft. A class 10 ship (a = 2677 ft^2) at the same speed would create a wave of 1.35 ft or 0.35 ft higher. In contrast, the same ships sailing through Little Rapids Cut (A = 17,670 ft^2) would produce waves of 2.1 ft and 2.8 ft respectively for a difference of 0.7 ft in wave heights. For this latter case, if the class 10 vessel were traveling at 10 mph, the generated wave heights would be equal.

A comparison of wave heights between this method and that of Saunders discussed earlier reveals that at low blockage ratios the calculated wave heights agree reasonably well, but as ships occupy a larger portion of the channel cross-section, wave heights increase markedly. Although a number of other wave equations were also reviewed, each were developed for specific site conditions. There is no strong justification for selecting one over another except that the Balanin-Bykov approach allows us to examine the effect of vessel size in restricted channels. A more objective choice would require the collection of field data. The data shown in Figure 5 through 7 is not directly useable for verification since those values were obtained at some distance from the sailing line, and the available wave height predictive equations yield near-ship values. Since the maximum generated wave heights have been shown to decay inversely to approximately the cube root of distance from the sailing line (Sorenson 1973), it would be expected that nearshore wave height would be significantly less.

Ofuya (1970) examined wave data collected on the St. Clair, Detroit and St. Lawrence Rivers and developed an empirical plot of the decay of maximum wave heights with distance from the sailing line (Fig. 9). Although the data is not presented in a form in which the effect of vessel size can be evaluated, it does provide data on the decay of waves produced by ships on the Great Lakes Connecting Channels.

For example, following his lines for ships sailing at 15 and 20 ft/s, we see that the maximum wave heights at 500 ft from the sailing line differ by about 0.3 ft while at 1500 ft, they differ by only 0.05 ft. Although we looked at the relative decay of waves generated by different vessel speeds, it would apply equally well to waves generated by different ships. That is, if a class 10 vessel had created a wave 0.3 ft higher than a class 5 vessel traveling at the same speed, the decay of wave heights would result in a wave height difference of only 0.05 ft, 1000 ft away.

The above example is important in understanding the data shown earlier from Sorensen (1973) and the USACE-SLSA (1972). The change in near ship wave heights with vessel size is relatively small; Carruthers (1966) concluded that a 45% change in vessel length would result in a change in generated wave heights of less than 0.5 ft. Since the difference in near ship wave heights is small, the difference will rapidly become insignificant with distance from the sailing line. This explains why the data in Figure 5 shows a very slight difference between wave heights generated by ocean-going and lake bound ships even though the ocean ships are typically much smaller and have finer bows which would indicate a reduced wave-making capability.

In summary, it appears that the effect of vessel size on nearshore wave heights should be small except for shorelines very close to the ship track. Lacking appropriate field data for verification or perhaps calibration any magnitudes calculated are subject to question. Certainly the effect of vessel class as defined by overall length is meaningless. Numerous authors (such as Carruthers 1966, Helwig 1966, Brebner et al. (1966)) have concluded that ship length has very little effect on wave height. According to Sorenson (1973) a ship's wave making capability depends primarily on the speed of the ship, and to a lesser extent, on the hull form, draft and water depth below the keel.

Although the beam of ships tend to increase with ship length, this is not a unique relation and a ship in a lower length class may in fact be wider. In addition, the hull geometry depends more on the intended use of the ship than its length, and draft is fixed by channel depth rather than length. Thus, there is no direct relation between vessel class and the parameters important to a ship's wave making capability. In fact, Ofuya (1970) in his study of ship waves on the Great Lakes Connecting Channels concluded that the essential parameters influencing wave height were ship speed and distance from the sailing line. He was unable to factor out the effects of vessel size due to the small amount of scatter caused by factors other than vessel speed.

Sediment Movement by Wave Action

In addition to the lack of predictive capability for ship waves, there is almost no information available to examine their ability to cause sediment movement. For the purposes of this study we will assume that ship waves are similar to wind driven gravity waves. This will then allow us to use linear (Airy) wave theory which has been used to examine coastal sediment transport.

In contrast to sediment transport in rivers, waves present an unsteady, oscillatory flow field. As a consequence the net sediment transport is the possibly small difference between the total amount of sediment being moved back and forth. In purely sinusoidal wave motion, the net sediment transport would be zero.

In his study of shoreline erosion due to ship and wind waves, Ofuya (1070) was unable to directly link ship wave characteristics and sediment transport. Instead, he approximated the ability of a wave to transport sediment in terms of its capacity to do work. In his work this took the form of H^2T, where H is the wave height and T is the period of the wave. Again, Ofuya was unable to discriminate the effect of vessel size, but Figure 10 from his work readily shows the importance of vessel speed on erosion potential. For ship waves measured 600 ft from the sailing line, the waves generated by a ship passing at 10 ft/s would have almost 2.5 times more energy than a ship moving at 16 ft/s. Presumably the quantity of sediments moved is proportional to this energy. No method was found to quantitatively estimate sediment movement.

If we assume that linear wave theory is applicable for the case of ship waves, we can calculate the horizontal component of the wave velocities at any depth by (USACERC 1977)

$$u = \frac{H}{2}\frac{gT}{L}\frac{\cosh\left[2\pi(z+d)/L\right]}{\cosh(2\pi d/L)}\cos\left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right) \tag{3}$$

where H = wave height

T = wave period

L = wave length

z = vertical distance from the water surface

d = water depth

x = horizontal distance

t = time

The maximum horizontal velocities occur at the top and bottom of an orbit, in which case the equation reduces to

$$u = \frac{H}{2}\frac{gT}{L}\frac{\cosh\left[2\pi(z+d)/L\right]}{\cosh(2\pi d/L)} \tag{4}$$

Based on ship wave recordings collected by the Detroit District (USACE 1974), we can estimate that the wave period was about 3.5 s for the passage of the Frank Armstrong off Six Mile Point on the St. Marys River. Then in a water depth of 3 ft, the wave celerity would be

$C = \sqrt{gd} = 9.83$ ft/s

Therefore, the wavelength would be

$L = cT = 34$ ft.

Calculating the maximum near bottom horizontal velocity for a one foot wave using equation (4), yields $U \approx 1.22$ ft/s.

According to the Shore Protection Manual (USACERC 1977), wave induced bottom velocities between 0.4 and 1 ft/s are sufficient to initiate sand motion. The also present figure developed by Inman (Fig. 11) which related the near bottom water velocity required to initiate motion for various size sediments. Taking an average value of critical velocity (0.5 ft/s) they prepared Figure 12 which shows the wave height required to initiate sediment motion in various depths of water. Figure 12 is based on linear wave theory, and is relevant only for sand sized sediment. No information was found to deal with cohesive bed materials. However, they would be more resistant to erosion than fine sand. Thus, the use of Figure 12 should be conservative.

Based on Figure 12, wave heights in excess of about 0.3 ft are sufficient to initiate sediment movement in 3 ft of water, and a 0.5 ft wave will move sediment in 6 ft of water.

Since a search of the literature did not reveal a better criterion for the onset of sediment motion, a 0.5 ft nearshore wave height will be employed. It must be remembered however that water motion in waves is oscillatory. Thus sediment motion does not necessarily imply erosion. Sediment may continue to move back and forth with little net transport.

In order to assess the increase in sediment movement with increasing wave, we will use Ofuya (1970) energy approach. That approach assumes that a wave's ability to transport sediment is related to its energy which is related to wave height as $E \propto H^2$. Thus, doubling the wave height would lead to a four-fold increase in sediment transport.

Propeller Wash

During vessel passage the bottom and possibly the sides of a channel may be subjected to a propeller-driven water jet. The velocities within the jet are indeed high. Fuehrer and Romisch (1977) cite an equation by

Robakiewicz that estimates the initial jet velocity induced by a screw

$$V_o = n\, D \sqrt{\frac{2\, K_T\, D^2}{F}}$$

where n = screw rpm

D = propeller diameter

K_T = thrust coefficient (0.25 - 0.50)

$F = \frac{\pi\, D^2}{4}$

For a ship such as the Cason J. Callaway with a 17.5 ft prop turning 90 rpm at full speed, V_o would be about 24 ft/s. Of course, the diameter of the jet would increase with distance behind the prop, resulting in a decrease in jet velocity. According to Fuehrer and Romisch (1977), this jet spread would be about 12 to 13° relative to the jet centerline, and they propose a relation for velocity along the centerline of

$$\frac{V_{x,\,max}}{V_o} = A \left(\frac{X}{D}\right)^a \qquad (6)$$

where $V_{x,max}$ = centerline velocity at distance X

X = horizontal distance from jet

a = −0.6 for a jet influenced by a channel bottom

A = coefficient dependent on degree of jet limitation

The coefficient A is dependent on water depth, and distance from the prop axis to the bed. No general relation for A is available, but they did give an example for the case where the ratio of distance from propeller axis to the channel bed, h_p, divided by the propeller diameter was $h_p/D = 3.72$. This example is reproduced in Figure 13. For the existing draft limitation in the Great Lakes connecting channels of 25.5 ft and a propeller diameter of 17.5 ft, this would be equivalent to a channel depth of 56 ft. In many sections of the connecting channels where the depth is nominally 27 ft, $h_p/D = 0.61$ for a ship such as the Callaway. In that case, the jet would be more confined and velocities would be correspondingly higher.

Assuming a Gaussian distribution of velocities within the jet, Fuehrer and Romisch (1977) propose that the radial velocity distribution can be described as

$$\frac{V_{xr}}{V_{x,max}} = e^{-22.2\ (r/x)^2} \tag{7}$$

where V_{xr} = velocity at a distance x from the prop and a distance r from the jet centerline

They further state that the maximum bed velocity will occur at a distance of

$$\frac{X}{D} = \frac{h_p}{D} \tan \alpha \tag{8}$$

Behind the ship, where α = 13° for our case. Based on these simplified equations and empirical correction factors, they present a relation for bottom scour velocity as shown in Figure 14. Situation z in the figure is relevant to the present study. If this relation holds, we can see that for the Callaway operating in a 30 ft channel, $V_s/V_o \approx 0.75$ so that velocities at the bed would be 18 ft/s. This is in the general range of velocities found by Fuehrer and Romisch (1977) in their model studies (20 to 26 ft/s) and those calculated by Liou and Herbich (1976) (18.6 ft/s) for the tanker Texas California running at 18 knots at a draft/depth ratio of 0.83.

Several things should be noted about the calculations above. They are simplified equations and assumed that the ship was operating at full speed in a shallow channel. A primary problem in quantitatively addressing the effects of propeller wash is a lack of information on propeller characteristics and operating speeds. Beyond that would be the difficulty of relating propeller thrust to vessel class. Figure 15 shows the required horsepower to propel the vessel St Clair at various operating speeds. These model results show that the horsepower to propel a ship may vary significantly due to changes in bow and stern geometry. Even though the ship size is essentially unchanged.

Since all ships are assumed to be traveled at the speed limit in a given cross-section with the draft fixed by project depth, the propeller thrust has less to do with the resistance to motion caused by the hull. This resistance to motion is primarily composed of skin friciton along the wetted surface of the ship and wave making resistance. The total open water resistance can be described as Comstock (1967)

$$R_T = \frac{k\ \gamma_w\ B\ h_w^{\ 2}}{2} + \left(C_{f_I} + \Delta C_f\right)\frac{\rho\ S\ V_o^{\ 2}}{2} \tag{9}$$

where k = a coefficient

γ_w = specific weight of water

B = ship's beam

h_w = generated wave height

$C_f = 0.075/(\log VL/\upsilon - 2)^2$

$\Delta C_f = 0.0004$

ρ = density of water

S = wetted surface area

V = ship velocity

L = ship length

υ = kinematic viscosity of water

From equation (9) it can be observed that ship length enters into the frictional drag on a ships hull through its contribution to the wetted surface area of the ship, but has little effect on the wave making resistance. In contrast, the skin friction varies as the square of the velocity. Thus a change in ship length from 600 ft (class 5) to 1000 ft (class 10) would increase the frictional resistance by about 67% while a modest increase in ship speed from 8 to 10 mph would increase the resistance by 56%.

Considering the wave making resistance, the velocity effects are even more significant since the resistance varies as the square of the generated wave height. As discussed earlier, this wave height in turn varies as the square of the ship speed making the wave resistance proportional to V^4. Ship length (and thus vessel class) plays a minor role in the wave resistance.

A further complication arises in assessing required horsepower when a ship enters shallow water or a restricted channel. Comstock (1967) presents a chart developed by Schlicting for estimating the reduction in vessel speed due to shallow water interaction. As shown in Figure 16, a ship the size of the Callaway sailing in a water depth of 35 ft with a power setting equivalent to 20 ft/s in deep water would actually achieve 17 ft/s. Thus, to maintain a speed, a higher propeller thrust would be required.

For a channel that is not only shallow, but is also restricted laterally, the situation is more extreme. Comstock (1967) presents an extension of Schlicting's work by Landweber that deals with this case as shown in Figure 17. The curve of V_I/V_∞ vs $V_\infty/\sqrt{gh}$ accounts for the change in wave making resistance while the other curve accounts for other hydrodynamic effects. For the case of the Callaway, traveling in a rectangular channel 1000 ft by 30 ft at a power setting equivalent to 20 ft/s in open water would result in an actual velocity of 16.4 ft/s.

In summary, although there are technqiues for estimating the velocity of propeller jets, they are empirical and without corroborating measurements to determine the correct values of coefficients, their use in defining actual scour velocities is questionable at best. Their use is further restricted due to a lack of information on propeller characteristics and operating speeds. An example calculation for a class 8 ship operating in a 30 ft channel at full speed showed near bottom velocities of 18 ft/s. Even if the propeller thrust were reduced by half, the near bed velocities would be more than sufficient to scour the bed. It would appear that ships in classes 5 through 10 would all be capable of scouring the bed when fully loaded in a channel at project depth.

For the present studies, vessel class is based solely on ship length. As such, vessel class plays a secondary role in determining propeller thrust. By far the most important factor is vessel speed, followed by cross-sectional area and hull geometry. Beyond determining the jet produced by a ship, the depth of the channel will determine if velocities sufficient to scour the bed occur.

In their study of propeller erosion in Harburg, Liou and Herbich (1976, 1977) concluded that ship draft to water depth is the predominant factor affecting sediment movement by propeller. They found that little movement occurred for $h_p/D > 2$.

For deep draft ships $h_p/D < 1$ very large bottom velocities occurred, capable of moving most naturally occurring sediment sizes. For a 25.5 ft draft ship, this simplistic criterion would indicate a high probability of scour for water depths less than 34 ft and relative safety for depths greater than 50 ft.

Drawdown Surge

Although ship waves and other hydrodynamic effects of vessel passage have been studied in terms of vessel maneuverability and power requirements, the effects of vessel passage on natural flow patterns and distribution and other environmental factors are not yet understood. Information for periods of ice cover is almost nonexistent.

When a vessel is in motion, even in deep water, the water level in the vicinity of the ship is lowered, along with the ship itself (this is called vessel squat). This effect increases as the vessel's speed increases or as the water depth decreases. When a ship enters restricted water areas, there is a considerable change on the flow pattern about the hull. In shallow water the water passing beneath the hull must pass at a faster rate than in deep water, and as a result there is a pressure drop beneath the vessel, increasing vessel squat. In a channel that is restricted laterally, vessel squat is also exaggerated; the bow of a vessel may also be pushed away from one side of the channel while the stern is drawn toward it. These effects can occur independently when a channel is restricted laterally or vertically and unrestricted in the other direction.

There is, however, another problem associated with the water level drop caused by the presence and movement of a ship in restricted waters. This water level drop is, in effect, a trough extending from the ship to the shore and moving along the river or channel at the same velocity as the ship. As the ship's speed increases, the moving trough deepens.

For the restricted sections of the Great Lakes channels, this effect might most easily be envisioned as a channel constriction. The conservation of energy principle applied to subcritical flow in an open channel as flow passes through a channel constriction indicates that the water surface will drop as the flow passes through the constricted portion of the channel.

The energy relation (neglecting losses) takes the form of

$$\frac{V_1^2}{2g} + Y_1 = \frac{V_2^2}{2g} + Y_2 \qquad (10)$$

where V_1 and Y_1 = velocity and depth prior to the constric-

V_2 and Y_2 = velocity and depth within the constrict passage

g = acceleration due to gravity.

This is combined with the continuity relation:

$$Q = A_1V_1 = A_2V_2 \qquad (11)$$

where Q is th discharge and A_1 and A_2 are areas available for flow before and within the constriction, respectively. Before eqs 10 and 11 can be applied in this form, the unsteady flow with the passage of a ship should be converted to steady flow by adding a velocity vector to the flow sections equal but opposite to the vessel speed.

The phenomenon of nearshore drawdown and surge during vessel passage may be explained in terms of the moving trough. In sufficiently deep water the moving trough appears as a fluctuation of the elevation of the water surface. To an observer in a shallow or nearshore area where the depressed water level approaches or reaches the riverbed, the water level appears to recede from the shoreline as the ship passes; this is followed by an uprush and finally a return to the normal level after the vessel-induced surface waves are damped.

Using the energy-continuity model it is possible to have critical flow in the constricted area between ship and shore. Energy considerations require the water level to rise in front of the ship before the trough develops if the ship's speed is increased beyond that required for the initiation of critical flow. An observer on the shore would then see the water level rise before observing the effects of the moving trough.

The water level and directional water velocity were measured during previous work at a number of locations along the St. Marys, St. Clair and Detroit Rivers under different conditions as ships passed. Some of this information is presented here to illustrate the effects of vessel passage.

To analyze the mechanics of sediment transport during vessel passage, two-dimensional, near-bottom velocity measurements were made (Wuebben, et. al., 1978). An example of these measurements is presented in Figure 18 for a passage of the *Cason J. Callaway* at Six Mile Point on the St. Marys River. The point of observation was approximately 500 ft offshore in 10 ft of water, while the navigation track was another 700 ft offshore. The ambient .stream water velocity was approximately 0.3 ft/s. The direction of the near-bottom water movement rotated 360° during the passage of the *Callaway*, with velocities in all directions significantly greater than the ambient downstream current.

Figure 19 illustrates the trough effect near the shoreline and the complex velocity pattern that developed at an offshore point because of vessel passage. The velocity direction at any particular point is indicated by an arrow, with the magnitude of the velocity and time as the axes.

The velocity meter was located approximately 130 ft from the shore in 3 ft of water. The velocities shown were measured within 8 inches of the bottom. The water-level gauge was located near the shore in about 8 inches of water. The ship that caused the situation illustrated in Figure 6 was the *J. Burton Ayers*, moving upriver near Nine Mile Point on the St. Marys River under ice-free conditions. The *Ayers* is 620 ft long and has a 60-ft beam and a midship draft of 23 ft. The vessel was traveling at 15.5 ft/s and passed approximately 800 ft from the shore.

Figure 20 shows ice-level changes at three offshore locations near Six Mile Point on the St. Marys River. There was an ice cover on the river approximately 15 inches thick. The ship passing the section was the Seaway Queen, moving upriver at 12.6 ft/s. The ship is 720 ft long, with a beam of 72 ft and a midship draft of 17 ft. It passed 1000 ft offshore. The typical river cross section at this location is shown in Figure 21.

The two lower curves in Figure 20 illustrate ice-level changes at two distances from the shore on a line approximately normal to the direction of ship movement in different depths of water (labeled E_1 and E_2). The top curve (labeled H_1) shows the ice-level change at a point of 150 ft upstream on a line parallel to the line containing points E_1 and E_2. The time at which the bow and stern crossed the perpendicular range line (E or H) is indicated by dashed lines. The figure illustrates the trough effect in different depths of water at differing distances from shore, as well as the movement of the trough with the ship's passage. The time displacement between E_1 and H corresponds to the distance between the two range lines divided by the ship's speed.

Figure 22 shows ice-level changes (the ice was 11 inches thick) the associated velocity pattern near the bottom as the Edward L. Ryerson passed down river. The range line is the same as E in Figure 20. The ice level and velocity pattern were measured about 300 ft from the shore, where the river depth is about 6 ft. The ship is 730 ft long, has a beam of 75 ft and a draft of approximately 26 ft, and was traveling at 10.3 ft/s about 1000 ft offshore. Figure 22 illustrates the velocity pattern and the ice-level response to the moving trough for a downbound vessel. Ice-level fluctuations as large as 2.6 ft from trough to crest have been observed. We will now examine how variations in vessel size affects drawdown and surge.

Sensitivity of Drawdown Mechanism

In this section we will use the energy and continuity equations to form a one-dimensional model of the drawdown mechanism. For the long, parallel midbody ships of interest in this study, vessel length is insignificant in determining drawdown (McNown 1976). Further, it does not even enter into the calculations used here. The primary ship dimensions important in determining drawdown are the beam and draft of the ship. As discussed earlier, there is no unique relation between beam and vessel class, and no relation whatsoever between draft and class. Thus, discussion of the variation of drawdown in terms of vessel class is meaningless except for a general trend of beam increasing with class.

For illustrative purposes, we can consider the relative importance of the pertinent variables by examining the deviations they cause from an ideal case. We will call the basic case a ship with a 25-ft draft and 100-ft beam traveling in a rectangular channel 35 ft deep and 2000 ft wide. The ship velocity relative to the water is 12 ft/s. This case is plotted as the central point on Figure 23.

Figure 23 shows that other things being equal the effect of deepening a channel is roughly equivalent to increasing the vessel draft. However, since an increase in vessel draft beyond the present 25.5 ft limit would require deepening the channel over a width several times greater than the ship width (or accurately increasing water elevation over the entire river width), the net effect would be to reduce the percentage of the channel occupied by the ship. ce the blockage of the channel would be reduced, the drawdown would also decrease.

Figure 23 also indicates that an increase in draft is more important than an equivalent increase in beam. This is simply a matter of geometry. A one foot change in draft occurs over the entire width of the ship (which is at least twice the draft for the ships considered). A one foot increase in beam would only add to the submerged area of the ship over the current operating draft.

It is also evident from Figure 24 that vessel speed is by far the most important parameter in determining drawdown. As will be shown later, vessel speed reductions of one or two miles per hour will typically offset the effect of increasing vessel sizes from class 5 and 10.

Figure 24 illustrates the drawdown for a single ship passing through channels of equal top width and channel depth but varying shape factor. Other values being equal, a ship passing through a typical natural channel (roughly parabolic) would cause a greater disturbance than if it passed through a rectangular channel but less than in a channel similar to some sections of the St. Marys River, where the shape factor might be as low as 0.3. While this observation appears simple, it is important in understanding why the effects of ship passage are much more severe on the St. Marys River than on the other connecting channels. A similar argument can be made for channel width.

Sediment Movement Potential

The potential for shore damage due to drawdown is a direct function of the change in hydraulic conditions initiating sediment transport or increasing transport rates. For sediment transport to occur, near-bottom or nearshore water velocities must overcome a sediment particle's resistance to motion. During vessel passage large and rapid changes in river velocity and direction can occur.

Three modes of transport of granular bottom sediments have been observed during both ice-covered and ice-free conditions (Wuebben et al. 1978). They are 1) bed load, which is typified by a pattern of slowly migrating sand ripples on the riverbed, 2) saltation load, the movement of individual sand grains in a series of small arcs beginning and ending at the riverbed, and 3) explosive liquefaction, in which bottom sediment is rapidly resuspended due to a rapid change in the pore-water pressure gradient.

Vessel passage affects the magnitude of bed load transport, and it also causes significant (but temporary) changes in the direction of sand ripple migration. Saltation transport has often been observed with the passage of large vessels. This can be explained by the ship-induced velocity increases discussed earlier.

In addition to these alterations in water velocity, the changes in water surface elevation during ship passage can occur more quickly than the pore pressure in the riverbed soil can adjust. If the decrease in water pressure on the riverbed during the passage of the moving trough occurs faster than the change in soil pore pressure, a net uplift force on the soil near the surface will occur. After the trough passes and the water level rises, the process reverses and there is a net downward force on the riverbed sediment. As the ship passage cycle is repeated, this mechanism, in conjunction with gravity acting downslope, encourages a net offshore migration of sediment that is in addition to any transport due to water velocities alone.

On several occasions, explosive liquefaction has been observed on the St. Marys River during the passage of large, heavily loaded vessels at speeds higher than normal. Explosive liquefaction of the bed has been observed by divers working in the surf zones of lakes and oceans, and often may also be observed from shore as waves break. In the presence of a reasonably horizontal velocity field, the action occurs in two steps. Initially the bed expands upward somewhat. Immediately the uppermost part of the bed disperses into suspension, and the temporarily suspended mass moves in the water current. In the absence of a current the bed simply quakes or expands, and individual particles move upward. Bed equilibrum is rapidly reestablished by gravity. Although potentially quite important, the process is not understood adequately and the effect of vessel size cannot be assessed.

Since the drawdown and surge me nism usually sets up water velocities in opposite directions, their ffects tend to cancel. However, a natural currents or a sloped bottom can combine with vessel effects to cause a net sediment transport upstream or downstream and offshore towards the navigation channel.

Figure 25 shows velocity and stage measurements at Nine Mile Point on the St. Marys River (Alger 1978). Sediment transport was also measured for this passage. The vessel was the Sir James Dunn moving upriver at 10 mph. The sand bottom began to move at about 65 seconds, at which time the velocity pattern was downriver and offshore and the water level was dropping rapidly. The back side of the trough followed, with a generally upstream velocity pattern.

A pattern of four sediment traps was used to measure sediment transport. One trap faced upriver, one toward the shore, one downriver and one away from the shore (Fig. 25). The traps were calibrated over a 20-minute period with no boat traffic; none of the traps collected any sediment in this ambient condition. The sediment traps were also placed at this location on a day when wind waves of about 1-foot amplitude were present without vessel passage. All traps collected sediment. Waves due to winds were negligible as the Sir James Dunn passed. The traps were left in place as the Sir James Dunn passed and were removed immediately afterward to retrieve any sediment collected. The sediment in each trap was carefully weighed (Fig. 25). The traps were located near the staff gauge at 50.5 ft in 1.6 ft of water. Field observations and the velocity-stage relations for upbound vessels at this site show that bottom sediment moves both downstream and upstream during vessel passage; however, the apparent net effect is upstream and slightly offshore, as indicated by the vector diagram of sediment trap load shown on Figure 25. This, of course, assumes that a vessel produces sufficient drawdown and velocity to move the bottom materials.

A composite sample from the four traps was analyzed for size gradation. The results show the same soil properties as the upper few centimeters of the bottom. Apparently, this vessel passage translocated all soil sizes at this location. Although these measurements were informative in that they showed a net migration of all sediment sizes, the sampling techniques were not sufficiently refined to allow quantitative predictions.

Ideally an assessment of the potential for sediment movement would be based on the bed shear stress developed by the drawdown-induced water movements. In many practical problems, the determination of the shear stress presents a major difficulty. As discussed earlier, the drawdown induced water movements are three-dimensional and unsteady, making normal shear stress calculation methods (such as energy slope or velocity profile slope) meaningless. For this reason velocity is often accepted as the most important factor in assessing channel stability. A maximum acceptable velocity for which no scouring will occur can be developed, but the accuracy of such a simplified approach is limited.

The only system-wide documentation for soil conditions available were the boring logs contained in the Draft Interim Feasibility Study for the Great Lakes Connecting Channels and Harbors Study (USACE 1984) and a report by Gatto (1980). These soil conditions were compiled to describe nearshore and channel soil conditions at each cross-section considered. These data sources provide only very general soil descriptions such as soft clay, hard clay, silt, sand, gravel, etc. This further limits detailed examination of sediment movement potential.

Using velocity as a scour criterion we might select from several sources of velocity-scour relationships. Figure 26 is from Stelczer (1981). It shows a minimum scour velocity at a sediment grain size of about 0.3 mm. At lower grain sizes cohesive forces increase the shear required to initiate motion while at higher grain sizes the greater particle masses make them more difficult to move. The figure also indicates the inexactness of the approach by showing upper and lower limits on required velocities which cover a substantial range. Since our soil descriptions do not include grain size, however, it would be tenuous to use an estimated value and use this plot.

Figure 27 presents data from the USSR (Simons and Senturk 1976) to deal with scour of cohesive soils. The study of erosion of cohesive soils even under unidirectional currents is difficult since it involves not only complex mechanical phenomena, but also chemical and physical bonding of the individual particles. The shear stress required to erode a cohesive soil is significantly influenced by the amount and type of clay present, microscopic and macroscopic clay properties, water content, pH and water temperature, the consolidation of clay among other conditions (Kamphuis and Hall 1983). Even the simplistic presentation in Figure 27 requires data beyond that presently available, but it serves to show the significant variations in scour velocities that occur.

Lacking a more accurate approach that can be employed with available data, we will use the approach of Fortier and Scobey as presented in Simons and Senturk (1976). As shown in Table 5, they related a variety of simple soil descriptions to scour velocities. For the Great Lakes Connecting Channels, the most applicable column is the clear water values.

To examine the relative magnitude of potential sediment movement, we will again use velocity. A review of sediment transport equations by Laursen (1956) shows a wide variation in the importance of velocity as shown in Table 6. However, as a general rule, sediment transport increases with flow velocity to the fourth power at low discharges and increases with flow velocity to the eighth power at high discharges (Shen 1971). Since we are dealing with conditions near the inception of motion, we will assume that sediment transport will vary with velocity to the fourth power.

Shore Structure Damage

The objective of this section is to evaluate the change in incidence of damage to shore structures resulting from a change in vessel size. Damage could occur due to water currents, water-level fluctuations or ice movement. There has been no documentation or reports of structural damage due to ship-induced water currents, so any contribution due to a change in vessel size cannot be assessed.

Structures might perhaps be damaged by ship-induced waves during open water conditions. However, there has been no documentation of this occurring and hence cannot be assessed. As dicussed in an earlier section the contemplated changes in vessel size should have only a small influence on the size of open-water waves. During winter ice conditions ship waves are damped within a short distance and would be insignificant.

Based on a review of literature and personal experience, it appears that the most damage may be caused by ship-induced drawdown, particularly drawdown during periods of ice cover.

The degree to which the shore structures of the Great Lakes systems are damaged by ice varies greatly according to the -inner of ice action. Winter navigation, by disrupting the normal ice-cover characteristics, may aggravate any natural ice-related damage.

1) Static ice forces, which arise from an ice sheet touching a structure subject to thermal expansion and contraction or subject to steady wind or water drag forces.

2) Dynamic ice forces, which arise from ice sheets or floes that move against a structure due to water currents or wind, or

3) Vertical ice forces, which are due to a change in water level and require the adhesion of floating ice to structures.

For small structures in rivers the dynamic horizontal and vertical ice forces are typically the most critical. A more detailed discussion of this topic may be found in Wuebben (1983a).

Horizontal ice forces. Depending on the size and strength of an ice floe, the horizontal force exerted on a structure depends on the strength of the ice sheet and its failure mode (bending, crushing or shearing) or the magnitude of the force driving the ice sheet (wind or water current).

Forces on shore structures due to direct horizontal ice loading are controlled more by the frequency of vessel passage than by the size of the vessel. Typically ships do not directly transfer forces to a structure through the ice unless they come very close to shore. Rather, they may break up or dislodge ice, allowing it to be moved by natural wind, waves or water currents against a structure. Any change in force due to a change in vessel size is negligible in view of the relatively modest change in size proposed and the similarity of hull forms.

Vessel size could influence horizontal ice loading, however, because a large ship causes larger water-level fluctuations than a smaller one traveling at the same speed. These larger water-level fluctuations might be sufficient to disrupt otherwise stable ice formations, allowing the ice to be moved by natural forces.

Vertical ice forces. A major source of damage is the vertical movement of an ice sheet. On any large body of water the water level constantly fluctuates. Coastal variations are primarily due to tides, while on large lakes, barometric pressure fluctuations, wind set-up, runoff and seiche action contribute. During periods of open water the normal fluctuations are relatively harmless. In conjunction with an ice sheet that is firmly attached to marine structures, these fluctuations can exert large vertical forces through the floating ice cover.

The structures that typically suffer the most damage are light-duty, pile-supported piers, such as those constructed for pleasure boaters. Designed for summer activity, the support piles have very little skin resistance to an upward force. When the water level rises, the buoyant ice sheet lifts the pile from the soil, and the void under the bottom tip of the pile fills in. When the water level drops, the weight of the ice is supported by the skin friction and point bearing of the pile. Since the pile is not driven into the soil as easily as it is pulled out, if the water level continues to drop, the ice will break and the ice sheet will drop relative to the pile. The ice may then refreeze to the pile but at a lower position on the pile. This process occurs in cycles throughout the winter, gradually "jacking" the pile completely out the soil.

DAMAGE CRITERIA

The objective of this study is to evaluate the change in incidence of damage to shorelines or shore structures due to a change in vessel size. A detailed analysis in which ship-induced forces are compared with the stability and strength characteristics of each structure or shore area could lead to a prediction of damages for known site conditions. However, the field data necessary for such an analysis are not available in sufficient detail.

Instead our analysis will center on identifying areas in which ship effects are great enough to have a potential for damage; we will then examine the influence of an increase in vessel size on those areas. The areas potentially affected by vessel passage will be selected on the basis of field experience, an analytical prediction of ship effects, and other available documentation.

The major problem in this analysis is in defining the level of ship-induced effects that is unacceptable. In the case of sediment transport we cannot realistically require that ships cause no sediment motion, even if we could predict the transient, ship-induced threshold of motion in the large, irregular channels under consideration. Small sediment dislocations should not necessarily be considered damage, particularly since natural currents, waves, recreational boating and other factors may be much more significant.

At the other extreme, ships may cause large water-level fluctuations and currents that would definitely cause unacceptable levels of sediment transport, shoreline erosion and structural damage, as well as affecting recreation and personal safety. The increase in significance of ship effects between these extremes is gradual, so it is difficult to define an unacceptable condition. The definition of damage based on vessel size is further complicated because the magnitude of ship-induced effects is heavily influenced by vessel speed, and the damage potential is affected by the water level and the site geometry and composition.

Vessel speed and water level are particularly significant because they are variable and can significantly alter ship effects. As shown earlier, a ship within existing size limits can cause greater damage than a larger ship if it travels faster. Although speed limits are in effect for many of the areas under consideration, several years of field experience on the Great Lakes connecting channels show that these limits are often violated. In almost all cases, properly designed and enforced speed limits would eliminate damage due to vessel passage. There are problems in certain cases, however, in allowing ships sufficient power to maintain control, and there is some debate about penalizing smaller vessels by requiring them to travel at lower velocities that are based on the requirements of larger ships.

The water level is another factor beyond the scope of vessel effects alone, and yet it is a very important consideration. As shown in Figure 28 for a shore profile on the St. Marys River, during a high-water period both natural and ship-induced forces are free to act directly on the low bluff at the waters edge. This bluff is frequently considered to be the shoreline by many property owners. If the water level was lower, the water would not act directly against this "shore." Persistent erosive forces might eventually erode the water's edge back to the bluff; in the interim the rate of material loss would be less since the mild slope would dissipate energy more efficiently and sloughing of the bluff would not occur.

The water level presents another problem in analyzing ship effects. On a typical river there is a more or less distinct relationship between stage and discharge, so that for any given water datum it is possible to estimate flow velocities. Since the Great Lakes Connecting Channels connect very large lakes, their flow rates are determined by the levels of the two lakes far more than the hydraulic resistance of the channels. This means that ambient water velocities could be the same for different stages, or even that higher discharges could pass at lower stages. Thus, although the channel cross-sectional area is significant, water velocity is far more important and cannot be related to stage. Only average values of water velocity were used.

In summary, a lack of detailed information on ship and channel charactersitics as well as an extreme limitation on time prevents more than a simplistic assessment of the effects of vessel size. No useable criterion was found for propeller wash, except that it would appear that all vessels in classes 5 through 10 would be capable of scouring the bed within the shallow dredged areas of the connecting channels.

For ship-induced waves, it is possible to compare the wave heights generated by vessels of varying size. The threshold of motion caused by ship waves is estimated using linear wave theory to predict orbital velocities and relating them to estimated scour velocities. Beyond the threshold of motion, it is estimated that sediment transport increases in proportion with the wave height squared.

For drawdown and surge, the energy and continuity equations were used to estimate the velocities resulting from ship passage. Based on estimated maximum permissible velocities from Fortier and Scobey it was determined whether sediment movement might occur. Beyond the threshold of motion it was determined that sediment transport would increase in proportion with water velocity to the fourth power.

Finally, damage to small shore structures due to open water waves has received little analysis but appears to be minimal. During periods of ice the ship generated waves are quickly damped. Likewise drawdown and surge appears negligible for open water, but becomes extremely important for navigation in ice. The data for ice conditions only concern gradual water-level fluctuations and crude estimates of horizontal forces. Ship-induced forces due to ice are largely unknown. Very small water-level fluctuations (4 or 5 inches) applied gradually may cause damage, while a transient fluctuation due to the passage of a ship of the same magnitude may pass faster than the structure can respond. Also, the major effect of vessel passage is a lowering of the water level, while the major structural damage mechanism is the uplifting force due to a rise in water level. The rise in water level due to ship passage is normally much smaller than the drawdown, rarely more than half.

As a result criterion used in the site-specific analysis for damage to small structures will be a drawdown of 1 foot and will apply only to periods of navigation in ice. This same criterion was used in an earlier study of vessel size (Wuebben 1983b).

In the following section, these criteria will be used to examine the effect of vessel size within the connecting channels. Throughout, it must be remembered that the criteria are very simple and that supporting data are limited to nonexistent. Although absolute magnitudes calculated are subject to question, the relative magnitudes should allow a comparison of the vessel effects with size.

SITE-SPECIFIC ANALYSIS

Based on the preceding development and available information on site conditions along the Great Lakes connecting channels, the problem will now be reviewed on a site-specific basis. Due to several uncontrolled variables (vessel speed, water levels, etc.) the results here are only approximate. The calculations use low-water data (using the International Great Lakes Datum), which should be conservative. The magnitude of the ship effect would be less at the higher water levels that normally exist.

It should be stated again that the objective was not to predict the magnitude of any damage due to vessel passage, but to predict the potential for damage due to increased vessel size. Thus, the potential damage areas listed were selected on the basis of a significant change in vessel effects, not just on susceptibility to navigation-related damage.

St. Marys River

The following description of the St. Marys River is excerpted from the U.S. Coast Pilot (NOAA 1981):

> The St. Marys River forms the outlet of Lake Superior, connecting it with Lake Huron. From Whitefish Bay, at Point Iroquois and Gros Cap, the river flows in a general southeast direction to Lake Huron at Point De Tour, a distance of from 63 to 75 miles, according to the route traversed.
>
> From Point Iroquois to the canals, a distance of 14 miles, there are six vessel courses, and the channel has a least width of 1,200 feet, with a least depth of 28 feet. Navigation around the rapids at Sault Ste. Marie is provided for by canals and locks on both the United States side and the Canadian side. Between the lower approaches of the canals and the upper end of the Little Rapids Cut into Lake Nicolet, the Bayfield Channel has a depth of 28 feet over a width varying from 1,500 to 1,890 feet.
>
> At the head of Sugar Island, about 2 miles below the canal locks, the channel divides. One route (for small craft) passes to the north and east of Sugar Island through Lake George and East Neebish, with limiting width of about 150 feet and depth of 12 feet. The main vessel route passes to the west of Sugar Island, through Lake Nicolet, with least width of 600 feet and least depth of 27 feet. Between Lake Nicolet and Munuscong Lake two channels are provided, passing on each side of Neebish Island. The west Neebish Channel, for the use of downbound traffic, passes west of the island, with least width of 300 feet and least depth of

> 27 1/2 feet .... The Middle Neebish Channel, for upbound traffic, leads from the head of Munuscong Lake to the east and north of Neebish Island, and has a least width of 500 feet, the westerly 300 feet has a least depth of 27 feet and the easterly 200 feet a depth of 21 feet.... On the vessel courses in Munuscong Lake and the lower river the depth is 28 feet or more for a least width of 1,000 feet upbound and 860 feet downbound.

The St. Marys River is shown in Figure 29. The nine reaches shown are from Carey's (1980) work and are divided according to general site conditions.

The available cross sections and site information used to calculate the effects of vessel passage are given in Appendix A. Data includes channel depth, top width, area, shape factor, speed limits, and estimates of water velocities required to cause scour in the channel and at the shore. It should be noticed that at many locations the channel is either very unsymmetric or the sailing line is much closer to one shore than another. For these locations separate equivalent channel characteristics are given relative to each shoreline as a means of improving the results of ship effect calculations. The cross-sections listed in Appendix A are referenced in feet along the river above and below the locks. For reference several cross-sections on Figure 29 have their distance from the locks indicated.

Figure 30 summarizes the important aspects of channel geometry along the river. The channels are split in half to distinguish the non-symmetrical nature of the channel cross-sections as required for the wave and drawdown calculations. In this figure the solid line represents the east side, while the dashed line represents the west side. Since upbound and downbound traffic does not always sail in the same track, separate values are given for each case.

Drawdown and Surge

Figure 31 shows the results of drawdown calculations along the length of the St. Marys River for vessels traveling at the current speed limits. A comparison of the six plots in Figure 31 show that drawdown is greater for upbound ships. This is expected since any ambient water movement would affect the relative velocity of the ship. Further, for the three combinations of ship dimensions shown, the worst case is the class 10 ship at a draft of 25.5 ft. As discussed earlier, increasing draft to 27.5 ft indicates an increase in water depth also. Since a change in water level increases the cross-sectional area of the channel far more than the corresponding increase in ship area, the channel blockage and thus drawdown will be reduced.

Figure 32 illustrates the distribution of ship-induced velocities along the St. Marys River for the same cases used in Figure 31. In addition to the solid and dashed lines showing induced velocities on the east and west shore of the channel, there are additional lines showing estimates of the velocity required to initiate sediment movement. Where these scour velocities indicate a value of 10 ft/s it actually means that the channel or shore is resistant to erosion. This could mean a channel carved in rock, or a shoreline that has been protected.

Examining Figure 32, we can see that the class 5 ship traveling at the existing speed limit should not cause scour except in the area around Johnsons Point on Neebish Island and perhaps some nearshore scour slightly upstream from Rock Cut. Examining instead the worst case of a class 10 vessel at 25.5 ft draft traveling upbound scour might also occur near Brush Point above the locks and some nearshore scour near Nine Mile Point on Sugar Island. Estimating shoreline lengths from Figure 32 would indicate that roughly 5 additional miles of river could be exposed to scour by a class 10 vessel than a class 5 vessel.

For the documented river cross-sections falling within areas which Figure 32 indicates as potential damage areas, a more detailed analysis was conducted. Appendix B contains plots for each of these cross-sections at three water level datums (LWD, LWD+1, LWD+2). The plots themselves indicate expected levels of drawdown and average ship-induced velocities vs ship cross-sectional area. The table included at the beginning of the appendix gives the ship areas for typical vessels within each class. Each figure also shows curves relating predicted vessel effects at the existing speed limit, speed limit +1, and speed limit +2, in both the upbound and downbound directions. Finally, estimated scour velocities based on channel and shoreline soils data are shown on the velocity plots.

For example, on cross-section -230+84, we can compare a class 5 vessel to a class 10 vessel by entering the LWD plot at ship areas of 1530 ft^2 and 2678 ft^2. Thus, for an upbound ship at the existing speed limit, we would expect drawdowns of 0.40 ft and 0.61 ft, while velocities would be 4.3 ft/s and 4.6 ft/s. Comparing this with the scour velocities shown, we see that each ship is capable of initating motion of channel and bed sediments, but that the velocity (and hence sediment transport capacity) is increased only slightly.

For these same ships we can also examine the effect of velocity. Due to the reduction in relative velocity, either ship traveling downstream would generate velocities less than that required to initiate motion. It should be noted that until the present, class 10 vessels have typically traveled upbound light and downbound loaded, so that appears a class 10 vessel could pass without scour.

Further it can be noted, that while a class 10 ship downbound at the speed limit (SL) would cause no scour, downbound class 5 vessel at the speed limit +2 would be capable of initiating movement of soil.

Comparing the ship-induced effects at the different water datums, it becomes very clear that the magnitude of the effects are sharply reduced. For example, for cross-section -230+84 discussed above, a downbound class 10 vessel traveling at the speed limit +2 (SL +2) would barely exceed the scour velocities and would probably not be significant.

Although the figures in Appendix B would allow a cross-section by cross-section discussion of the entire matrix of variables requested in the scope of work, such a discussion would be tedious and very difficult to follow. That matrix includes five vessel classes, six speed limits, five draft and depth combinations, two scour velocities, the occurrence of sediment movement and the relative magnitude of transport. Since Appendix B allows those values to be found when required, our discussion will instead focus on the net impact of a change in fleet mix in areas where it appears significant.

Reviewing data on the expected change in fleet mix provided by the Detroit District, it appears that the major difference occurs in the number of class 10 vessels if the new lock alternative is selected. Figures 2 and

3 show the alteration in total transits by various vessel classes depending on the selected alternative. A comparison reveals that the new lock alternative would result in 5 additional class 10 vessels and an extra 460 transits per year at the Soo Locks. At the same time, annual transits in vessel classes 5 through 8 would decrease by 1333. Total transits by all vessels would decrease by 873 during the period from 1990 to 2050. Transits by class 7 vessels would still predominate regardless of which alternative is selected.

Since the class 7 vessels are by far the dominant vessel class, a comparison of the effects of vessel size based on fleet mix will be evaluated by comparing class 7 and 10 ships. Table 7 reviews cross sections in areas that Figure 32 indicated might be subject to scour by drawdown effects. The listed values are the difference between ship-generated velocities and permissible maximum velocities, when the permissible velocities are exceeded. From Table 7 it can be seen that downbound class 10 vessels should cause no scour at existing speed limits (although they did approach or equal the permissible velocities at several points. Between the two vessel classes is less than 0.5 ft/s. It is questionable whether the precision of the analytical work is sufficiently refined to consider this difference significant. At Johnsons Point, a vessel speed reduction of 1.4 mph would eliminate the potential for scour. A reduction of 0.74 mph would make the velocities equivalent to a class 5 vessel at existing speed limits. In Little Rapids Cut, a reduction of 0.5 mph would suffice.

A final column in Table 7 indicates the required reduction in vessel speed such that no drawdown induced scour would occur even for the worst case of a loaded upbound class 10 vessel.

Based on Table 7, it would appear that drawdown induced scour would be eliminated by the following reductions in upbound speed limits (refer to Fig. 20).

Reach	Speed limit reduction mph
1	0
2	0
3	1.5
4	0.5
5	1.0
6	1.5
7	2.0
8	0
9	2.0

It should be noted that no reduction in downbound speed limits appear required. Further, the calculations were performed assuming water levels were at low water datum. Since water levels are typically higher actual ship-induced velocities would be lower. It is also noteworthy that even smaller speed limit reductions would be required to make class 10 vessel effects equal to other vessel classes at existing speed limits.

The final column of Table 8 shows wave heights at the shore for a class 10 vessel assuming that wave heights decay inversely with the cube root of distance from the shoreline. This relation was developed for deep water ship wave decay, but in the absence of a better relation will be used for waves in the connecting channels.

Earlier in the report it was determined that a criterion of a 0.5 ft wave would be used as a threshold value for scour. Although approached or equalled in several areas, it was only significantly exceeded in reach 2. A speed reduction of 1 mph would reduce that value sufficiently.

Ship Waves

Ship wave heights were calculated for all cross-sections using the Balanin-Bykov relation given in equation 1. Since ship waves in restricted channels increase with ship speed and ship size, the worst case would be for a loaded class 10 ship traveling upbound at low water datum. Table 8 contains calculated wave heights at the sailing line for typical class 5, 7 and 10 vessels. Ships were considered to be traveling upbound (except for the downbound channel only through rock cut) at the speed limit, speed limit +1 and speed limit +2. It should be noted that median vessel sizes given in Table 2 show that class 5 and 7 vessels have equivalent cross-sections and thus, for the purpose of this report, equal wave making capability.

Propeller Wash

As discussed earlier, no method was found to effectively deal with the effect of vessel size on scour due to prop wash. However, the depth of the channel for all cross-sections examined is shallow enough to make suspension of bed materials possible. Further work would be required to improve our understanding of this mechanism.

St. Clair River

The St. Clair River is shown in Figure 33. The four reaches shown are from Carey's (1980) work and are divided based on general site conditions. For reference, several cross-sections with their distance from Lake Huron are indicated in feet. The following description of the St. Clair River is excerpted from the U.S. Coast Pilot (NOAA 1981):

> The St. Clair River has two characteristic sections — the lower or delta portion, and the upper or normal channel. The delta portion, commonly known as the St. Clair Flats, is the land and water area at the lower end of the St. Clair River below Chenal Ecarte, Ontario, and formed by the division of the river into a number of distributaries. The most important branch, used for through navigation, is called the South Channel, and it connects Lake St. Clair with the main river through the St. Clair Cutoff Channel.
>
> The distance from the southwest end of the St. Clair Cutoff Channel to the head of Chenal Ecarte via the South Channel is about 11 miles, making the total length of the vessel course from Lake St. Clair to Lake Huron about 39 miles.

The effects of vessel passage were calculated from available cross sections and site information. Due to the size and shape of the river cross section, the effects of vessel passage are not as pronounced as on the St. Marys River. In addition, the channel size and cross-sectional shape are quite uniform over the length of most of the river. Therefore, the hydraulic effects of vessel passage were calculated for only a few sites along the river. The analysis will follow the approach established in the previous section on the St. Marys River.

Figure 34 describes the variation in channel geometry for the U.S. shoreline of the vessel track. Further details are contained in the tables of Appendix A.

Drawdown and Surge

Figure 35 shows the results of drawdown calculations along the length of the St. Clair River. For vessesl traveling at the current speed limits, as discussed in the previous sectior the St. Marys River, the worst case is for the class 10 vessel traveling upbound (Fig. 35b). For this case, the drawdown is approximately twice as large as for the class 5 vessel shown in Figure 35a.

Figure 36 illustrates the distribution of ship-induced velocities along the St. Clair River for the same cases used in Figure 35. In addition, there are lines showing estimates of the velocities required.to initiate sediment motion in the channel and shoreline areas. Where these scour velocities are shown to have a value of 10 ft/s, this really indicates a material resistant to erosion such as rock or man-made protection.

Examining Figure 36, we can see that downbound ships regardless of class should not cause scour. For upbound ships there is a possibility of scour in Reach 1 for ships in classes 5-10 for shoreline areas not already protected. Since a large portion of the St. Clair River shoreline is developed, only very short lengths of shoreline are subject to erosion.

Figure 36 also shows that the riverbed might be subject to scour over a significant portion of its length (from the St. Clair Flats north to Stag Island). Certainly the magnitude of class 10 ship induced velocities are greater than those due to the class 5 vessel, but the river length affected varies only slightly.

For the documented river cross-sections falling within the potential damage areas indicated on Figure 36, a more detailed analysis was conducted. Appendix B contains plots for each of these cross-sections at three water level datums (LWD, LWD+1, LWD+2). The plots themselves indicate expected levels of drawdown and average ship induced velocities vs ship cross-sectional area. A table included at the beginning of the appendix gives the ship areas for typical vessels within each class. Each figure also shows curves relating predicted vessel effects at the existing speed limit, speed limit +1 and speed limit +2 in both the upbound and downbound directions. Finally, estimated scour velocities based on channel and shoreline soils data are shown on the velocity profile.

A discussion of the methodology to interpret the plots of Appendix B is given in the previous section on the St. Marys River. As discussed in the St. Marys River analysis, Table 9 reviews available cross-sections in areas that Figure 36 indicated might be subject to scour by drawdown effects. The listed values are the difference between ship-generated velocities and permissible maximum velocities, when the permissible velocities are exceeded. From Table 9, it can be seen that there is a possibility of scour in Reach 4 in the vicinity of Stag Island and in Reach 1 along Harsens Island and Russels Island. Along the shoreline at cross-section 493+30, there are some nearby unprotected shore areas (as shown on Fig. 36) that could be affected.

For upbound vessels, areas in which class 10 vessels exceeded the scour velocities would also be affected by class 7 vessel transits. It would appear that two areas would benefit from upbound speed limit reductions of about 2.5 mph. Those areas are Reach 1 along Harsens Island and Russels Island, and Reach 4 in the vicinity of Stag Island.

If so much of the shoreline in Reach 1 were not already protected, it would appear that shoreline erosion could be a significant problem. Based on local soil conditions, perhaps downbound vessels would exceed scour thresholds as well as the upbound ships.

Ship Waves

Ship wave heights were calculated for representative cross-sections using the Balanin-Bykov relation of equation 1. Since ship waves in restricted channels increase with ship speed and size, the worst case being a loaded class 10 vessel traveling upbound with the water level at low water datum. Table 10 contains calculated wave heights at the sailing line for class 5, 7 and 10 vessels traveling upbound at the speed limit, speed limit +1, and speed limit +2.

In addition to the calculated wave heights in Table 10, the last two columns are areas of special interest. The column titled ΔH indicates the difference in wave heights generated by a class 5 and 10 ship at existing speed limit. Those values show a significant difference in wave making ability. The final column in Table 10 shows predicted wave heights reaching the shoreline for a class 10 vessel. The calculations assume that wave heights decay inversely with the cube root of distance from the sailing line. This relation was developed based on deep water conditions, but no useable relation was found to better suit our case.

Earlier in the report it was determined that a 0.5 ft wave height criterion would be used as a threshold value for scour. Only one area, Reach 1, exceeds this criterion and only slightly even there. This area has already been proposed as an area to reduce the upbound speed limit based on drawdown effects, any potential problem with wave should also be eliminated.

Propeller Wash

As discussed earlier, no method was found to effectively deal with the effect of vessel size on scour due to propeller wash. However, for the channel depths indicated in Appendix A, it would appear that suspension of bed sediments is possible throughout most of the river. Further work would be required to improve our understanding of this mechanism.

Detroit River

The Detroit River is shown in Figure 37. The ice conditions are described in Appendix A. The following description of the Detroit River and its harbor facilities is from the U.S. Coast Pilot (NOAA 1981):

> The Detroit River has a length of about 32 miles from the Detroit River Light at its mouth in Lake Erie, to Windmill Point Light at the river's junction with Lake St. Clair, its head.
>
> Grosse Ile is the largest island in the Detroit River. It is about 8 miles long and about 1 1/2 miles wide, extending from about the mid-point of the Upper Livingstone Channel at the south end to about the mid-point of the Fighting Island Channel opposite the City of Wyandotte, Michigan, at the north end. The main ship channel passes to the east of the island while the westerly channel of the river, passing west of the island, has been dredged for deep draft navigation from the north down to a point about 2 1/2 miles above the lower end of the island. This dredging has developed the Trenton Channel. Below the south end of the

> Trenton Channel, the natural river has no deep draft navigable channel into the lower river below Grosse Ile.
>
> The Rouge River constitutes a branch channel of the harbor of Detroit, and the related industrial district also extends down the west channel of the lower Detroit River to Ecorse, Wyandotte, and Trenton.... This river discharges into the Detroit River at the southerly limits of the city of Detroit. Its natural course is generally about 150 feet wide in the lower river, below the junction with the short-cut canal...and about 300 feet wide from the canal to the turning basin near the Ford Motor Co. docks. The mouth of the river is flanked by large industrial plants.
>
> The short-cut canal, an artificial connection, about 3,000 feet long, originally constructed by private interests, extends from the Detroit River about one mile below the mouth of the River Rouge in a straight line to a bend in the River Rouge, thus avoiding an S-shaped curve in the lower river course and shortening the distance to upstream points by 5600 feet. This short-cut canal in conjunction with the natural Old River Channel, has created Zug Island. This island is occupied entirely by the facilities of several large industrial corporations.

Available cross sections and site information were used to calculate the effects of vessel passage. Because the river cross sections are large, the effects of vessel passage are slight. In addition, the channel size and cross-sectional shape are quite uniform along the river. The analysis will follow the approach established in the earlier section on the St. Marys River.

Figure 38 describes the variation in channel geometry for the U.S. shorelines of the Detroit River. Further details on river characteristics are contained in the tables of Appendix A.

Drawdown and Surge

Figure 39 shows the results of the drawdown calculations along the length of the Detroit River for vessels traveling at existing speed limits. As discussed earlier in the section on the St. Marys River, the worst case is presented by a class 10 vessel traveling upbound (Fig. 39b). It is apparent in Figure 39 that drawdowns for class 10 vessels are nearly twice that of a class 5 vessel.

Figure 40 illustrates the distribution of ship induced velocities along the Detroit River for the same cases used in Figure 39. In addition, there are lines showing estimates of the velocities required to initate sediment motion in the channel and shoreline areas. Where there scour velocites are shown to have a value of 10 ft/s, this actually indicates erosion resistant material such as rock or man-made protection. It is clear from Figure 40 that essentially the entire shoreline is resistant to erosion.

Examining Figure 40 we can see that downbound ships regardless of class should not cause scour. For upbound ships there is a small area in the vicinity of cross section 1200 that might be subject to channel scour.

For the documented river cross sections in areas that Figure 40 indicates a potential for scour, a more detailed analysis was conducted. Appendix B contains plots for each of these cross sections at three water level datums (LWD, LWD+1, LWD+2). The plots themselves indicate expected levels of drawdown and average ship induced velocites vs ship cross sectional area. A table included at the beginning of the appendix gives the ship areas for typical vessels within each class. Each figure also shows curves relating predicted vessel effects at the existing speed limit, speed limit +1, and speed limit +2 in both the upbound and downbound directions. Finally, estimated scour velocities based on channel and shoreline soils data are shown on the velocity plots.

A discussion on the methodology to interpret the plots of Appendix B is given in the earlier section on the St. Marys River. As discussed in that section, Table 11 reviews available cross-sections in areas that might be subject to scour by drawdown effects. The listed values are the difference between ship generated velocities and permissible maximum velocities, when the permissible velocities are exceeded.

From Table 11 it is apparent that the extensive shore protection along the Detroit River results in shoreline erosion being negligible. There are areas near the upper end of Grosse Ile and through an area near the Ambassador Bridge where channel scour might be possible. The shoal area near Grosse Ile would be protected by an upbound speed limit reduction of 2.5 mph, whereas the area in the vicinity of the Ambassador Bridge would require a reduction of 1 to 1.5 mph. Since the shoreline is resistant to erosion, only the river bed would be affected.

Ship Waves

Ship waves were calculated for representative cross sections using equation 1. As discussed earlier and upbound, class 10 vessel at the maximum draft at low water datum is the worst case. Table 12 contains calculated wave heights at the sailing line for class 5, 7 and 10 vessels traveling upbo at the speed limit, speed limit +1, and speed limit +2.

Although it is interesting to examine the variation in wave heights generated by various vessel classes, an examination of Table 12 shows that our scour criterion of 0.5 ft is not significantly exceeded anywhere on the river. Thus, ship generated waves do not appear to be of major concern on the Detroit River if existing speed limits are observed.

Propeller Wash

As discussed earlier, no method was found to effectively deal with the effect of vessel size on scour due to propeller wash. However, for the channel depths indicated in Appendix A, it would appear that the suspension of bed sediment is possible. Further work would be required to improve our understanding of this mechanism.

Harbor Areas

In the scope of work for this study, it was requested that the effect of vessel size for a "typical harbor" be examined. The only stipulation for this harbor setting was that water velocities would be minimal and vessel speeds would range from 3-5 knots. Since no harbor soil conditions or depths are assumed, the analysis will not be too far removed from the generic discussion contained in the previous background section. Since water velocities are assumed to be negligible, vessel direction will not matter and since harbor depth was not specified, it can only be assumed that it will equal or exceed 27 ft.

Drawdown and Surge

Lacking specified harbor dimensions, the analysis was reduced to calculating drawdown and induced velocities for a 27 ft deep harbor area at various ratios of ship to harbor cross sections. Since the remainder of the report has used units of ft/s rather than knots, the calculations here were prepared in ft/s units. For comparison, 3 knots = 5.1 ft/s and 5 knots = 8.5 ft/s.

Figure 41 shows calculated drawdown values for various ratios of ship to harbor cross-section areas. From Table 2 we see that typical cross-sectional areas for class 5, 7 and 10 vessels are 1530, 1530, and 2677 ft^2. The areas for class 5 and 7 vessels are equal since the draft is fixed by channel depth, and the beams happen to be equal because there is no unique relation between beam and draft. Table 2 was based on a review of the existing Great Lakes Fleet.

If we were to assume a harbor width of 2000 ft, we could see that drawdown at 8 ft/s would be about 0.065 for class 5 and 7 vessels and 0.11 for a class 10 vessel which is hardly significant. For a class 10 vessel traveling at 8 ft/s to achieve a drawdown of 1 ft, it would require a harbor width to be 380 ft or less.

Figure 42 illustrates ship induced velocities in a manner similar to Figure 41. Since no harbor soil conditions were specified, it is difficult to relate the importance of these velocities. A review of Table 5 shows that we might expect permissible, non-scour velocities from 1.5 ft/s for fine sand to about 4 ft/s for clays and gravel. If we again assume that ships are traveling at 8 ft/s in a 27.5 ft deep harbor, a class 10 vessel would initiate sand motion in a harbor less than 675 ft wide, and clays and gravel might move in harbors 340 ft wide. Comparable harbor widths for class 5 and 7 vessels are 385 and 195 ft respectively.

In addition to the calculated wave heights in Table 9, the last 2 columns are of special interest. The second column from the right indicates the difference between calculated wave heights at existing speed limits for class 5 and class 10 vessels.

It is apparent that drawdown and ship induced velocities should not be a major problem in harbor areas. The predominant reason is the very strong influence of velocity. Since specified ship velocities are slow and there is no water velocities, the channels would have to be very narrow for drawdown effects to be significant.

<u>Ship Waves</u>

As with drawdown, the lack of specified harbor characteristics makes detailed discussion of ship wave effects difficult. An examination of the Balanin-Bakov relation for predicting wave heights shown in Figure 8 shows that the size of the harbor should have minimal impact on sailing line wave heights at ship velocities 8 ft/s or less.

Even for the largest blockage ratio (a/A) shown on Figure 8, the wave height would be only 1.25 ft at the sailing line. For a class 10 vessel in a harbor 27.5 ft deep, this would require a channel only 540 ft wide. Even in this very narrow channel, the wave height at the shore would be an insignificant 0.15 ue to the rapid decay of wave height with distance from the sailing line. Again, velocity is the most important factor in determining wave height, and the specified velocities are small. Thus for the harbor conditions considered, ship waves should have negligible impact.

Propeller Wash

As discussed earlier, no methods was found to effectively deal with the effect of vessel size on propeller wash. Due to the very high velocities generated in propeller jets, sediment suspension is a definite possibility. Without better information on propeller characteristics and operating speeds, a detailed analysis is impossible. Further work would be required to improve our understanding of this mechanism.

SUMMARY OF SHIP EFFECTS

The purpose of this section is to summarize the vessel effects analyzed in earlier sections. When these results are examined, several points should be kept in mind. First, due to an extreme time constraint no developmental or field work was possible. As a result, the study consists of simple, empiric analysis with little data for verification or calibration.

Second, ship effects were to be analyzed by a vessel classification system based solely on overall length. As it turns out, vessel length is of little or no significance in the ship effects considered. Further, the ship parameters that are important are either independent of or only weakly related to ship length.

Third, the analysis was carried out for a series of three water level datums, but water level is far less significant than water velocity. Due to the configuration of the Great Lakes Connecting Channels, water level at any cross section is not uniquely related to water velocity.

Finally, studies of erosion conducted on the Great Lakes Connecting Channels (Alger 1978, Gatto 1980, USACE 1974, Wuebben 1983) have found erosion to be quite small. This is important since the potential of ships to initiate sediment movement does not necessarily mean net transport and thus erosion will occur. As discussed earlier, a purely oscillatory wave could suspend considerable quantities of sediment and yet yield no net transport. Similarly, the flow reversals induced by drawdown were shown to have a net transport of sediment much smaller than the gross transport, since transport in opposing directions cancel.

St. Marys River

During a previous study a field survey was conducted to locate shoreline areas potentially subject to erosion (due to any cause). These sites are shown in Figure 43. Some sites were further divided into smaller reaches to reflect minor variations. The length of shoreline potentially subject to erosion in each of these reaches is given in Table 13. The table also shows which of the sites that are currently eroding are also in areas where the ship-induced damage would be influenced by an increase in vessel size. Sediment transport in these areas could be minimized by upbound speed limit reductions of 0.5 to 2.0 mph. If the goal were to reduce class 10 vessel impact to that of some smaller vessel class, the reductions would be even less. In view of the small rates of erosion documented on the St. Marys River, further analysis would be required to determine the actual magnitude of net sediment transport due to ships and the relation of that transport to erosion due to natural causes.

Only three areas along the St. Marys River with existing shore structures are potentially subject to damage due to ship drawdown effects, and then only during winter navigation. The first is near Six Mile Point (Reach 6), but here the structures have been protected with pile clusters. The second is Johnson's Point (Reach 3). Because severe damage has occurred here in the past, an increase in vessel size is not considered as important as the operating characteristics of the vessels (speed and frequency of passage). The third area is the West Neebish Channel, but this area has been closed to winter navigation. Without navigation in ice the effect of an increase in vessel size is negligible.

Ship induced drawdown and surge was the ship effect of most importance on the St. Marys River affecting shore or channel areas on Reaches 3 through 8. Ship waves were only found to be significant in Reach 2. Although it appeared that propeller wash might be significant through most of the St. Marys River, a detailed analysis was not possible.

Areas in which class 10 vessels had the capability of causing significnt vessel effects were gen ...ly found to be affected by other vessel classes as well. Although it was possible to compare the ships relative capacity to move sediment, a lack of data to translate this capacity to net sediment transport made an assessment of the importance of fleet mix extremely complex.

It was not possible to balance off the relative importance of an increase of 460 annual class 10 vessel transits against a decrease of 1333 annual transits by all other vessels. It could be argued, however, that for 460 additional class 10 transits to equal the transport capacity of 1333 transits by smaller vessels, they would each have to move almost 3 times as much sediment. Since transport capacity varies as velocity to the fourth power, the class 10 vessels would have to induce velocities 30% greater than the other vessels.

A review of the ship induced velocities in Appendix B shows that the largest change in induced velocity with ship size occurred at cross-section 145+67W. Even there, the velocities induced by a class 10 was less than 20% greater. This comparison would indicate that the reduction in total transits should offset the increase in vessel transits in terms of transport capacity. In order to compare the actual net transport magnitudes, significant developmental work would have to be accomplished.

St. Clair River

During a previous study a field survey was conducted to locate areas potentially subject to erosion due to any cause (Fig. 44). A legend for the symbols is given in Table 14. The length of shoreline potentially subject to erosion in each of these reaches is given in Table 15. The table also shows which sites are currently eroding and where the ship-induced-damage would be influenced by vessel size. Sediment transport in these areas could be minimized by reductions in upbound vessel speed limits of 2 to 2.5 mph. If the goal were to reduce class 10 vessel impacts to the level of smaller vessel classes, the required reductions would be smaller.

The only area of concern for shore structures on the St. Clair extends from the head of Russell Island to the St. Clair Cutoff. This area, known as the South Channel, has numerous small structures that may be affected by vessel passage during ice conditions. These include 128 walkway docks, 54 boat houses or shelters, 72 boat hoists and a number of other structures.

Ship induced drawdown and surge was found to be the most significant effect on the St. Clair River. Areas of potential significance includes Reach 1 along the shores of Russell's and Harsen's Island and Reach 4 in the vicinity of Stag Island. Ship waves were only slightly above the threshold of motion criterion in Reach 1.

Control of vessel speeds in those areas, and reduction of the upbound speed limits by 2.5 mph should minimize both scour and shore structure problems. Although it appeared that propeller wash might be capable of causing suspension of bed materials through much of the river, a detailed analysis was not possible. Since no fleet mix information was available for the St. Clair River, this aspect could not be addressed, but the simple reasoning used on the St. Marys River could be applied.

Detroit River

During a previous study a field survey was conducted to locate shoreline areas potentially subject to erosion in each of these areas is given in Table 16. There are no areas along the Detroit River where shoreline erosion would appear to be influenced by navigation. There is a small area in the vicinity of site 4 on Figure 45 where there is a slight chance of channel scour. The difference between class 10 and class 7 vessel effects however is slight. A speed reduction of about 1 mph would eliminate this calculated potential. Another area where drawdown could influence channel scour is a shoaling area near the upstream end of Grosse Ile. Here a speed limit reduction of about 2.5 mph would eliminate the potential. Again, effects due to class 10 vessels is only slightly greater than for class 7 ships.

Vessel waves appear to have negligible influence on the Detroit River. Although it appeared that propeller wash could cause the suspension of bed sediments at some locations, a detailed analysis was not possible. Since no fleet mix information was available for the Detroit River, this aspect could not be addressed.

CONCLUSIONS

The potential for shoreline or shore structure damage due to an increase in vessel size was reviewed on both a conceptual and site-specific basis. While it is difficult to predict damage potential, it was possible to estimate where problems might occur if vessel sizes are allowed to increase. A major difficulty in the conduct of the study was the extremely shore time period available. This limited the study to basic theory with a number of necessary simplifying assumptions. In the absence of sufficient data to verify or calibrate the approaches used, the results should be considered preliminary.

Three basic damage mechanisms were considered in the report: vessel waves, propeller wash and drawdown. The methodology to deal with propeller wash effects is minimal, and further work is required. Drawdown and surge appeared to be more significant than vessel wave effects.

While larger ships can definitely cause more damage, the potential for damage caused by the size increases considered here is significant only in severely restricted channels. By far the most significant factor in ship-related damage potential is vessel speed. In almost all areas the effect of an increase in vessel size could be eliminated by decreasing vessel speed by 1-2 mph. Based on a limited analysis of fleet mix/transit frequency data it would appear that the significance of an increase in class 10 vessel traffic would be outweighed by a decrease in total vessel transits.

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LIST OF TABLES

Table 1. Vessel class definitions.

Class	Length (ft)
5	600 - 649
6	650 - 699
7	700 - 730
8	731 - 849
9	950 - 1099

Table 2. Median vessel dimensions by class.

Class	Length (ℓ)	Beam (ft)	Draft (ft)	Area (ft ^{2})
5	627	60	25.5	1530
		60	26.5	1590
		60	27.5	1650
6	676	70	25.5	1785
		70	26.5	1855
		70	27.5	1925
7	728	60	25.5	1530
		60	26.5	1590
		60	27.5	1650
8	782	70	25.5	1785
		70	26.5	1855
		70	27.5	1925
10	1000	105	25.5	2677.5
		105	26.5	2782.5
		105	27.5	2887.5

Table 3. Selected ship-generated wave heights. (After Sorenson 1973.)

Vessel type	Length (ft)	Beam (ft)	Draft (ft)	Displacement (tons)	Water depth (ft)	Speed (knots)	H_{max} (ft) Distance from sailing line (ft) 100	500
Cabin cruiser	23	8.3	1.7	3	40	6	0.7	0.4
						10	1.2	0.8
Coast Guard cutter	40	10	3.5	10	38	6	0.6	1.0
						10	1.5	
						14	2.4	
Tugboat	45	13	6	29	37	6	0.6	0.3
						10	1.5	0.9
Converted air-sea rescue vessel	64	12.8	3	35	40	6	0.3	
						10	1.4	0.8
						14	2.0	1.1
Fireboat (converted tug)	100	28	11	343	39	6	0.4	0.2
						10	1.7	1.0
						14	3.1	2.6
Barge	263.	55	14	5420	42	10	1.4	0.7

Table 4. Effect of vessel size and speed on bow wave height.

Class	L (ft)	B (ft)	B/L_E	V (ft/s)	h (ft)
5	600	60	.36	8	.41
				10	.63
				12	.91
6	690	70	.40	8	.45
				10	.70
				12	1.01
7	730	75	0.42	8	.47
				10	.74
				12	1.06
8	767	70	.39	8	.44
				10	.69
				12	.99
10	1000	105	.58	8	0.65
				10	1.02
				12	1.47

Table 5. Maximum permissible velocities proposed by Fortier and Scobey.

	Mean velocity of Canals ft/s		
Original material excavated	Clear water, no detritus	Water transporting colloidal silt	Water transporting noncolloidal material
1. Fine sand (colloidal)	1.5	2.50	1.50
2. Sandy loam (noncolloidal)	1.45	2.50	2.00
3. Silt loam (noncolloidal)	2.00	3.00	2.00
4. Alluvial silt when noncolloidal	2.00	3.50	2.00
5. Ordinary firm loam	2.50	3.50	2.25
6. Volcanic ash	2.50	3.50	2.00
7. Fine gravel	2.50	5.00	3.75
8. Stiff clay (very colloidal)	3.75	5.00	3.00
9. Graded, loam to cobbles, when noncolloidal	3.75	5.00	5.00
10. Alluvial silt when colloidal	3.75	5.00	3.00
11. Graded, silt to cobbles, when colloidal	4.00	5.50	5.00
12. Coarse gravel (noncollidal)	4.00	6.00	6.50
13. Cobbles and shingles	5.00	5.50	6.50
14. Shales and hard pans	6.00	6.00	5.00

Table 6. Comparison of bed load equations (after Laursen 1956).

Equation	Original form	Reduced form
Duboys (Straub)	$q_B = A_1(\tau - \tau_c)$	$= B_1 n^4 \frac{V^4}{d^{2/3}}$
Schoklitsch (Shulits 1935)	$q_B = \frac{A_2}{d_s^{1/2}} S^{3/2}(q - q_c)$	$= B_2 \frac{n}{d_s^{1/2}} \frac{V^4}{d}$
Meyer-Peter et al. (1934)	$q_B = (A_3 q^{2/3} S - A_4 D)^{3/2}$	$= B_3 n^3 \frac{V^4}{d}$
Wes (1935)	$q_B = \frac{A_5}{n} (\tau - \tau_c)^m$	$= B_5 n^{2m-1} \frac{V^{2m}}{d^{m/3}}$
Shields (1936)	$q_B = \frac{A_6}{d_s} q\ S(\tau - \tau_c)$	$= B_6 \frac{n^4}{d_s} \frac{V^5}{d^{m/3}}$
Brown-Einstein (1950)	$q_B = \frac{A_7}{d_s^{3/2}} \tau^3$	$= B_7 \frac{n^3}{d_s^{3/2}} \frac{V^6}{d}$
Brown-Kalinske (1950)	$q_B = \frac{A_8}{d_s} \tau^{5/2}$	$= B_8 \frac{n^5}{d_s} \frac{V^5}{d^{5/6}}$

Table 7. Exceedence of scour velocities by drawdown, St. Marys River.

Cross-section	Class 7 Down channel (ft/s)	Class 7 Down shore (ft/s)	Class 7 Up channel (ft/s)	Class 7 Up shore (ft/s)	Class 10 Down channel (ft/s)	Class 10 Down shore (ft/s)	Class 10 Up channel (ft/s)	Class 10 Up shore (ft/s)	Non-scour speed reduction (mph)
-230+84	0	0	2.5	2.2	0	0	2.8	2.6	1.8
145+67W	0	0	2.5	4	0	0	3.4	4.9	2.3
145+67E	0	0	2.5	3.9	0	0	2.9	4.4	2.2
182+81E	0	0	0	2.1	0	0	0	2.4	1.7
297+66W	0	0	0	2.0	0	0	0.5	2.2	1.5
297+66E	0	0	0	1.7	0	0	0	0	1.2
414+31E	0	0	0	0.6	0	0	0	0.9	0.8
699+02E	0	0	0	0.6	0	0	0	0.9	.5
881+10	0	0	0	0	0	0	-	-	0
1075+37	0	0	0	1.9	0	0	0	2.9	1.5

Table 8. Calculated wave heights, St. Marys River.

Cross-section	H = wave height (ft) at sailing line Class 5,7			Class 10			ΔH class 10-5	H_o class 10 at shore
	SL	SL+1	SL+2	SL	SL+1	SL+2	SL	SL
430+84	2.57	3.04	3.56	3.47	4.12	4.81	0.92	.29
40+03W	2.73	3.32	3.96	3.64	4.42	5.29	0.9	.51
40+03E	2.62	3.18	3.80	3.50	4.25	5.08	0.88	.49
48+56W	2.98	3.62	4.33	3.96	4.81	5.75	0.98	.55
48+56E	2.96	3.60	4.30	3.94	4.78	5.72	0.98	.56
145+67W	2.50	3.03	3.63	3.34	4.07	4.86	0.84	.41
145+67E	2.31	2.81	3.35	3.10	3.77	4.50	0.79	.32
182+81W	2.22	2.72	3.28	2.96	3.63	4.38	0.74	.32
182+81E	1.79	2.20	2.65	2.41	2.96	3.57	0.62	.18
297+55W	1.16	1.42	1.71	1.57	1.93	2.33	0.41	.12
297+55E	0.92	1.12	1.36	1.25	1.53	1.85	0.33	.08
414+31W	0.71	0.88	1.07	0.97	1.20	1.46	0.26	.06
414+31E	1.34	1.67	2.03	1.82	2.27	2.75	0.48	.17
564+70W	3.97	4.62	5.31	5.44	6.20	7.13	1.36	.52
564+70ED	1.84	2.14	2.47	2.51	2.92	3.36	0.67	.13
564+70WU	2.79	3.25	3.73	3.79	4.40	5.07	1.00	.23
564+EU	2.46	2.86	3.29	3.35	3.89	4.48	0.89	.20
699+02W	2.89	3.51	4.20	3.84	4.67	5.58	0.95	.37
699+02E	2.66	3.23	3.86	3.55	4.31	5.15	0.89	.46
819+43Q	2.85	3.43	4.07	3.81	4.59	5.44	0.96	.47
819+43E	2.20	2.65	3.14	2.97	3.57	4.24	0.77	.31
866+15	1.78	2.17	2.59	2.42	2.94	3.51	0.64	.17
922+21	2.12	2.57	3.07	2.85	2.47	4.14	0.73	.23
997+38	2.00	2.43	2.90	2.69	3.28	3.91	0.69	.27
1075+27	2.83	3.43	4.10	3.76	4.57	5.46	0.93	.50
676+31W	2.59	3.21	3.90	3.43	4.25	5.16	0.84	.28
676+31E	2.41	2.98	3.62	3.20	3.96	4.81	0.79	.33
788+71W	1.25	1.55	1.88	1.69	2.10	2.55	0.44	.14
788+71E	1.96	2.43	2.95	2.63	3.26	3.96	0.67	.28
820+34	3.06	3.79	4.6	4.00	4.96	6.03	0.94	.69
854+98	3.27	4.05	4.92	4.26	5.28	6.42	0.99	.79
881+10	3.46	4.29	5.21	4.49	5.57	6.76	1.03	.86

Table 9. Exceedence of scour velocities by drawdown, St. Clair River.

Cross-section	Class 7 Down channel (ft/s)	Class 7 Down shore (ft/s)	Class 7 Up channel (ft/s)	Class 7 Up shore (ft/s)	Class 10 Down channel (ft/s)	Class 10 Down shore (ft/s)	Class 10 Up channel (ft/s)	Class 10 Up shore (ft/s)	Non-scour speed reduction (mph)
493+30	0	0	2.3	0	0	0	4.0	0	2.7
1358+68	0	0	3.4	0	0	0	4.6	0	2.6
1750+30	0	0	0	2.8	0	0	0	3.4	2.4

Table 10. Calculated wave heights, St. Clair River.

Cross-section	H = wave height (ft) at sailing line Class 5,7			Class 10			ΔH class 10-5	H_o class 10 at shore
	SL	SL+1	SL+2	SL	SL+1	SL+2	SL	SL
453+30	4.33	4.99	5.71	5.81	6.71	7.67	1.48	.28
533+30	4.36	5.03	5.75	5.86	6.76	7.73	1.50	.62
730+00	3.61	4.15	4.73	4.89	5.62	6.41	1.28	.52
1034+80	3.24	3.73	4.26	4.40	5.07	5.78	1.16	.42
1750+30	2.48	2.96	3.47	3.36	3.99	4.69	0.88	.37

Table 11. Exceedence of scour velocities by drawdown, Detroit River.

Cross-section	Class 7 Down channel (ft/s)	Class 7 Down shore (ft/s)	Class 7 Up channel (ft/s)	Class 7 Up shore (ft/s)	Class 10 Down channel (ft/s)	Class 10 Down shore (ft/s)	Class 10 Up channel (ft/s)	Class 10 Up shore (ft/s)	Non-scour speed reduction (mph)
700+00	0	0	3.1	0	0	0	3.6	0	2.5
1217+22	0	0	2.3	0	0	0	2.5	0	1.6
1387+02	0	0	0.7	0	0	0	1.2	0	0.8

Table 12. Calculated wave heights, Detroit River.

Cross-section	H = wave height (ft) at sailing line Class 5,7			Class 10			ΔH class 10-5	H_o class 10 at shore
	SL	SL+1	SL+2	SL	SL+1	SL+2	SL	SL
1520+66	3.37	3.91	4.50	4.55	5.29	6.08	1.18	.51
1217+22	2.40	2.76	3.15	3.26	3.76	4.29	0.86	.29
328+79W	.29	.49	.75	.39	.66	1.01	.10	.05
328+79E	.34	.58	.88	.45	.76	1.16	.11	.06
433+30W	.35	.55	.80	.48	.75	1.08	.13	.05
433+30E	.55	.86	1.24	.72	1.13	1.64	.17	.10
548+10W	2.59	2.98	3.39	3.52	4.05	4.62	0.93	.28

Table 13. Potentially eroding sites along the St. Marys River. (After Gatto 1980.)

Site	Subreach	Visible Changes*	Approximate Length (ft)
1		NAE	4000
2	a	NAE	400
	b	NAE	2000
3	a	NAE	200
	b	NAE	300
4†	a	NAE	7000
	b	NAE	1000
	c	NAE	300
	d	NAE	50
	e	NAE	200
	f	NAE	200
	g	NAE	200
	h	NAE	300
	i	ME	400†
	j	NAE	50
	k	ME	600
	l	NAE	500
	m	NAE	600
5	a	ME	1000†
	b	NAE	4500†
6†	a	ME	600†
	b	NAE	100†
	c	ME	200†
	d	NAE	300
	e	ME	700
	f	NAE	200
7†	a	ME	3800
	b	ME	1100†
8†	a	NAE	300
	b	ME	1400†
9	a	ME	1000
	b	ME	400
10†	a	NAE	100
	b	NAE	200
	c	NAE	200
11†	a	NAE	100
	b	ME	400†
	c	ME	300†
12†		NAE	400
13†		NAE	1200
14		NAE	200†
15	a	NAE	200
	b	NAE	500

Table 13 (Con't).

Site	Subreach	Visible Changes*	Approximate Length (ft)
16†	a	ME	300†
	b	E	300†
	c	ME	2100†
17		NAE	1400
18		NAE	300
19		ME	1500
20†	a	ME	1700†
	b	NAE	1100
21†	a	E	600†
	b	E	200†
	c	E	800†
22†	a	E	900†
	b	E	1000†
23†	a	NAE	200
	b	NAE	600†
24†	a	NAE	200
	b	ME	300
25†		ME	400
26		NAE	3000
27†	a	ME	400†
	b	NAE	400
	c	NAE	200
28		NAE	700
			5660 = 10.7 mi

* NAE: Not Actively Eroding
ME: Minor Erosion
E: Erosion

† Erosion along these sites could be affected by an increase in vessel size.

Table 14. Legend for symbols shown on survey maps.

Potential erosion sites

- E Erosion possible
- N No erosion

Types of shore protection

- m Mixed types (prefix)
- s Scattered types (prefix)
- P Protected
- U Unprotected
- msp Mixed combinations (usually bulkheads and riprap)
- Riprap:
  - r_1 Boulders (natural stone)
  - r_2 Concrete slabs/debris/chunks
  - r_3 Debris (cans, scrap metal, etc.)
  - r_4 Logs

- Bulkheads
  - b_1 Timber
  - b_2 Sheetmetal
  - b_3 Poured concrete
  - b_4 Concrete blocks
  - b_5 Tires
  - b_6 Cemented stone
  - b_7 Rock

- g Gabions
- tc Timber cribs filled with boulders
- gr Groins
- pc Pile clusters

Table 15. Potentially eroding sites along the St. Clair River. (After Gatto 1980.)

Site	Reach	Visible Changes*	Approximate length (ft)
1	a	NAE	50
	b	NAE	100
		NAE	200
	[illegible]	NAE	200
	e	ME	200
	f	ME	500
	g	NAE	100
2	a	NAE	50
	b	ME	50
	c	NAE	1200
	d	ME	100
3	a	ME	2000
	b	ME	800
4†	a	ME	100
	b	ME	100
5†	a	ME	1200
	b	NAE	100
6†		NAE	50
7†	a	ME	200
	b	ME	100
	c	ME	400
8	a	NAE	400
	b	NAE	100
9	a	ME	100
	b	NAE	100
	c	NAE	100
	d	NAE	100
10	a	NAE	50
	b	NAE	100
	c	NAE	50
11	a	E	1000
	b	E	2000
	c	E	200
	d	NAE	100
12	a	NAE	100
	b	ME	400
13	a	NAE	400
	b	NAE	100
	c	NAE	100
14		NAE	200
15		NAE	100
16		NAE	100
17		ME	800
18		NAE	100
19		NAE	200

Table 15 (cont'd).

20†	a	ME	250
	b	NAE	100
	c	NAE	200
21†	a	NAE	200
	b	NAE	200
22†		NAE	500
23†		NAE	300
24†	a	NAE	150
	b	NAE	150
25†	a	NAE	150
	b	NAE	100
			17100 = 3.23 mi

* NAE: Not Activley eroding
ME: Minor Erosion
E: Eroding

† Erosion along these sites could be affected by an increase in vessel size. The total length that could be affected is 2050 feet, or 0.4 miles.

Table 16. Potentially eroding sites along the Detroit River.

Site	Subreach	Visible Changes*	Approximate Length (ft)
1	a	NAE	200
	b	NAE	1100
2	a		300
3	a	NAE	100
	b	NAE	50
	c	NAE	50
4		NAE	200
5		ME	50
6		ME	150
7		ME	50
8		ME	1000
9		ME	50
10		ME	3800
11		NAE	3000
12		NAE	1400
13		NAE	100
14	a	NAE	50
	b	NAE	100
	c	ME	200
15		ME	2000
16	a	ME	800
	b	ME	50
	c	ME	50
	d	ME	1000
	e	ME	300
	f	ME	400
	g	NAE	100
17	a	ME	600
	b	ME	800
18		ME	1000
19	a	ME	2500
	b	ME	800
	c	ME	800
	d	ME	1100
	e	ME	2000
	f	ME	2000
	g	ME	3000
20	a	ME	700
	b	ME	1500
21	a	ME	300
	b	NAE	1000
	c	NAE	100
	d	ME	600
	e	NAE	50
	f	NAE	50
	g	NAE	100

Table 16 (cont'd).

	h	NAE	150
	i	NAE	150
22		ME	200
23		ME	100
			36550 ft = 6.92 mi

* NAE: Not Actively Eroding
ME: Minor Erosion
E: Erosion

LIST OF FIGURES

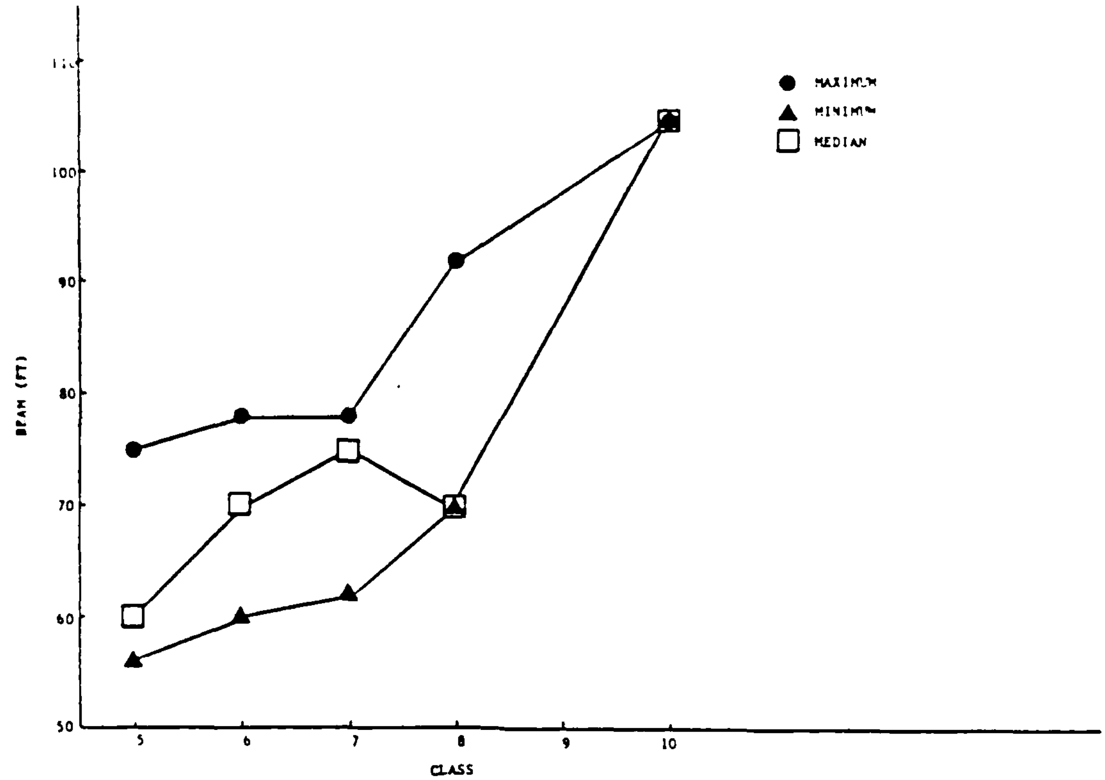


Figure 1 Vessel Beam vs Class

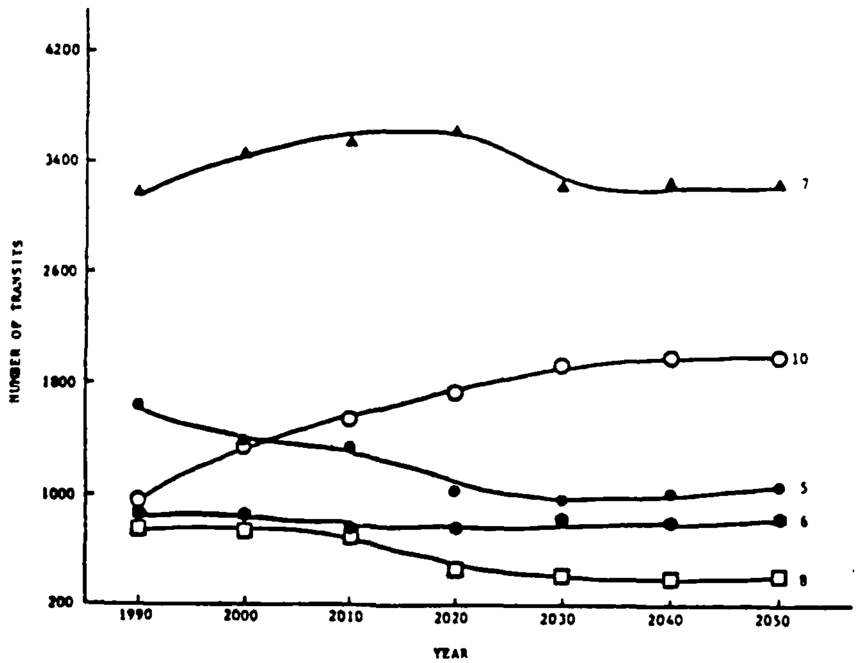


Figure 2 Total Vessel Transit by Class, No Action and Rehabilitation Alternatives

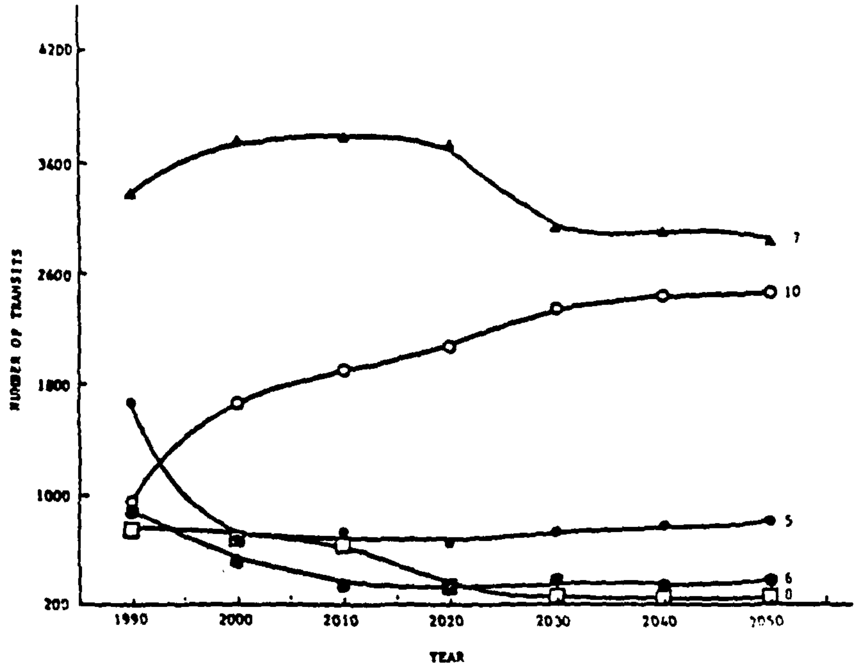


Figure 3 Total Vessel Transits by Class, New Lock Alternative

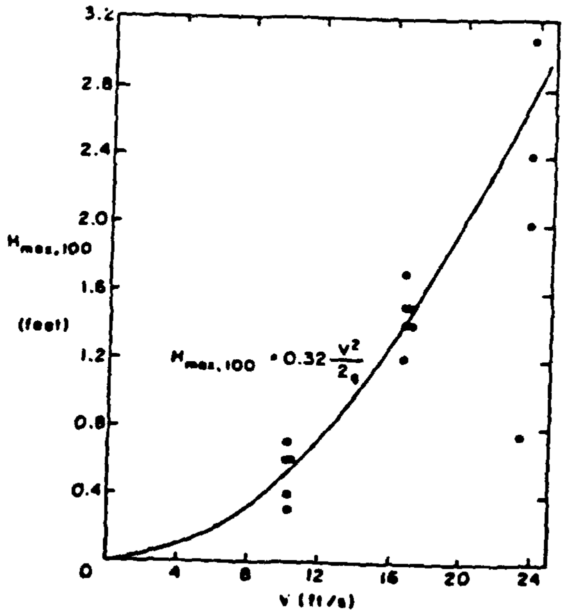


Figure 4 Maximum Wave Heights 100 Feet From the Sailing Line For A Variety of Hull Forms (from Ashton, 1974)

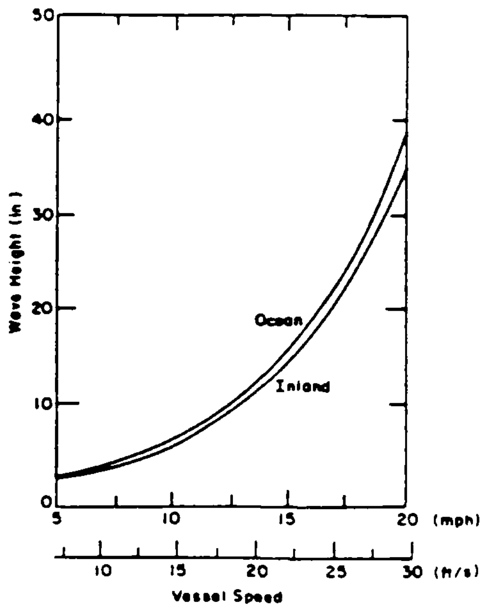


Figure 5 Comparison of Wave Heights Generated by Ocean and Inland Ships (after USACE and SLSA, 1972)

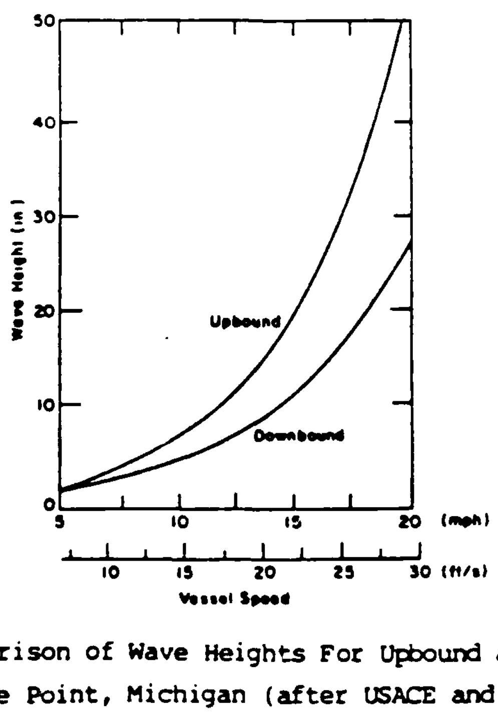


Figure 6 Comparison of Wave Heights For Upbound and Downbound Ships at Grosse Point, Michigan (after USACE and SLSA, 1972)

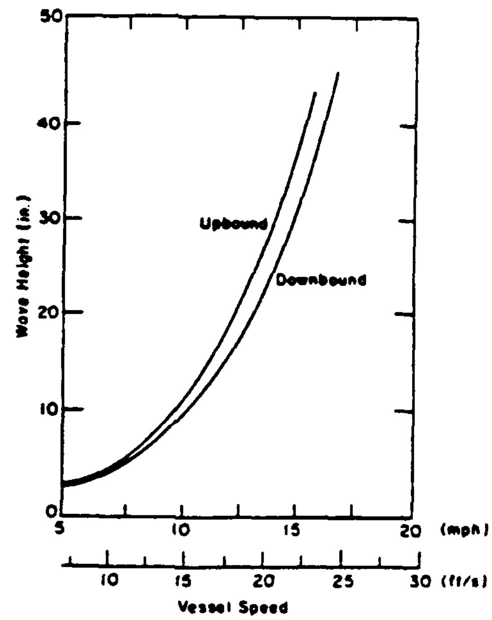


Figure 7 Measured Ship Wave Heights For Upbound and Downbound Ships at Sans Souci (after USACE and SLSA, 1972)

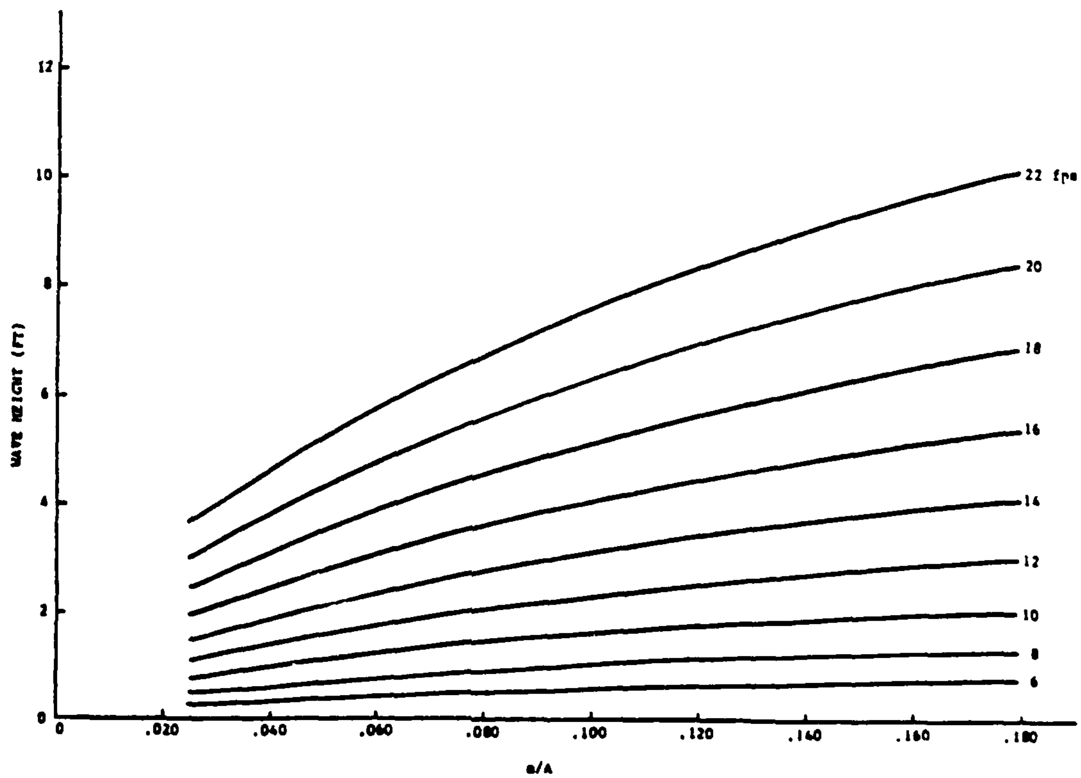


Figure 8 Wave Heights in Restricted Channels

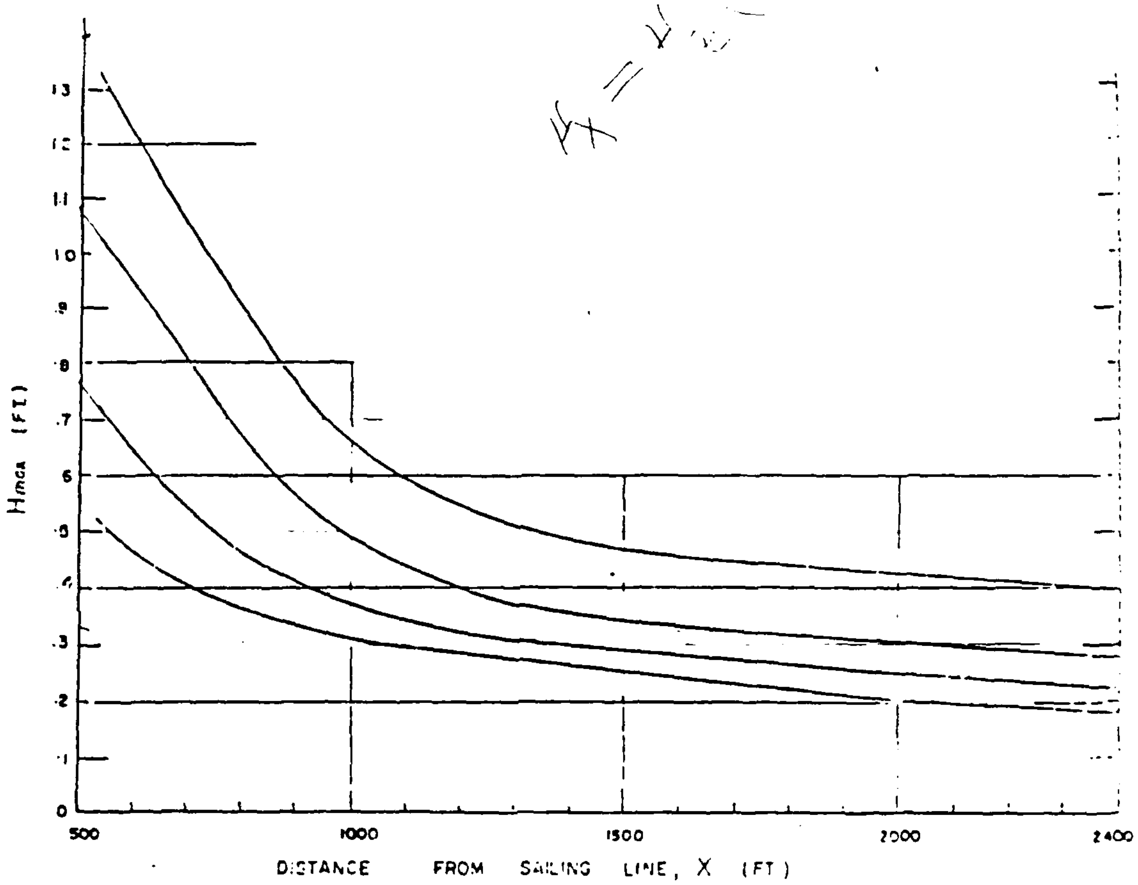


Figure 9 Maximum Wave Height as a Function of Distance From Sailing Line (from OFUYA, 1970)

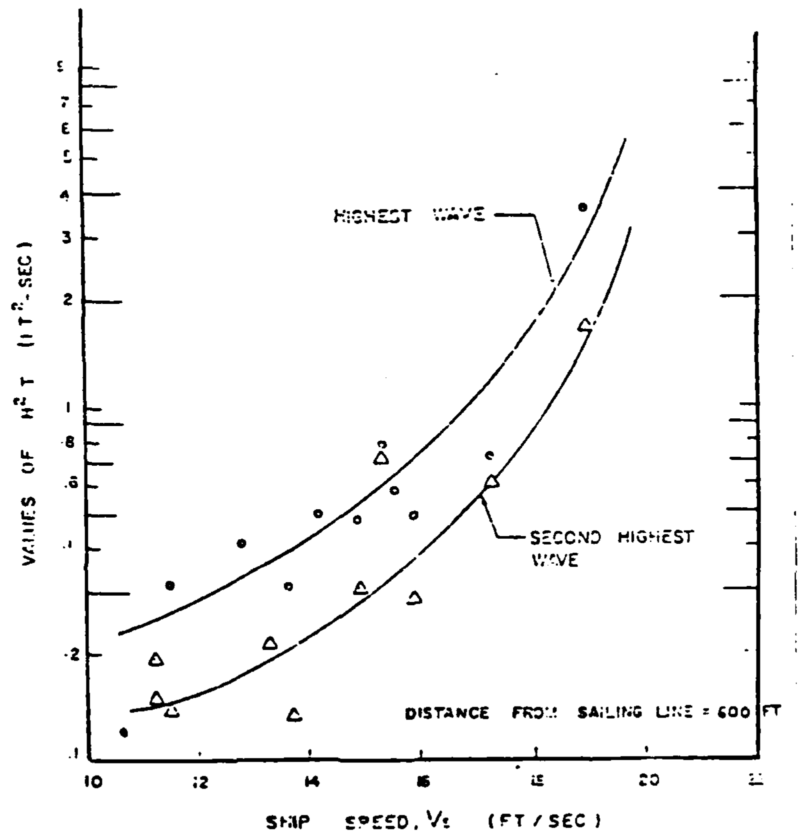


Figure 10 Ship Wave Energy Propagation (from OFUYA, 1970)

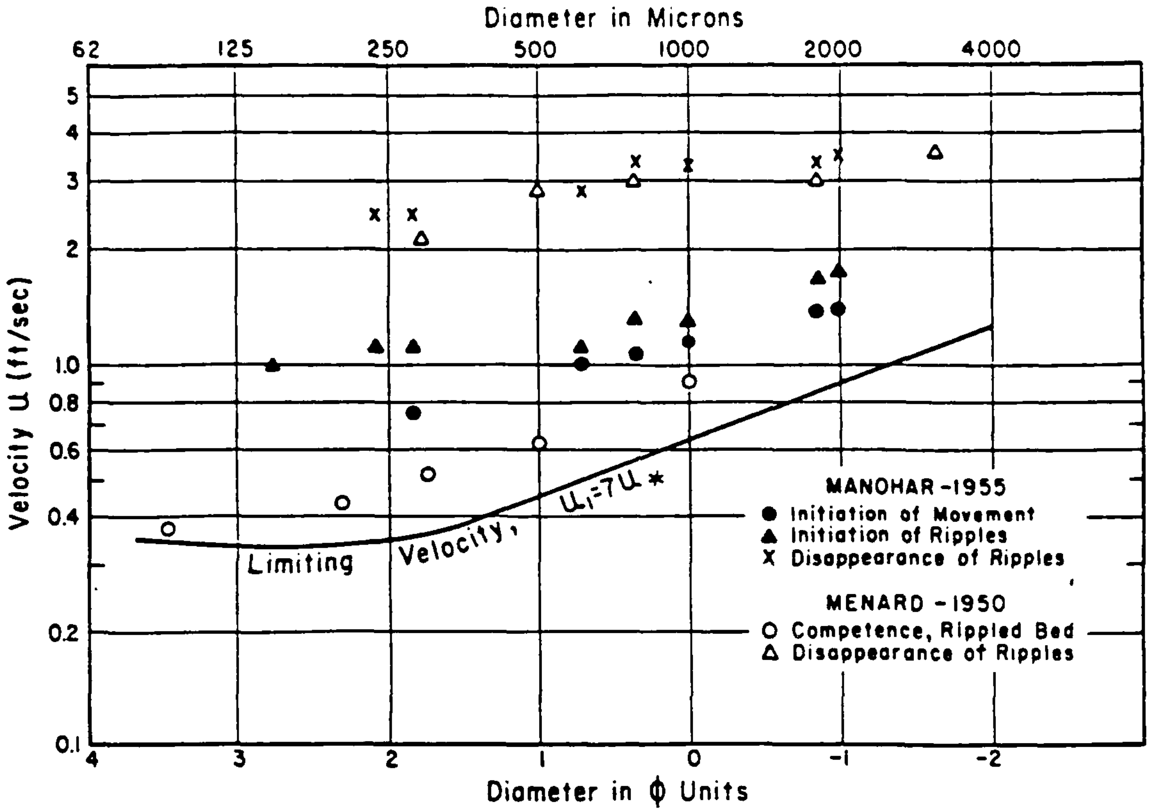


Figure 11 Critical Velocity For Sand Movement (from USA CERC, 1977)

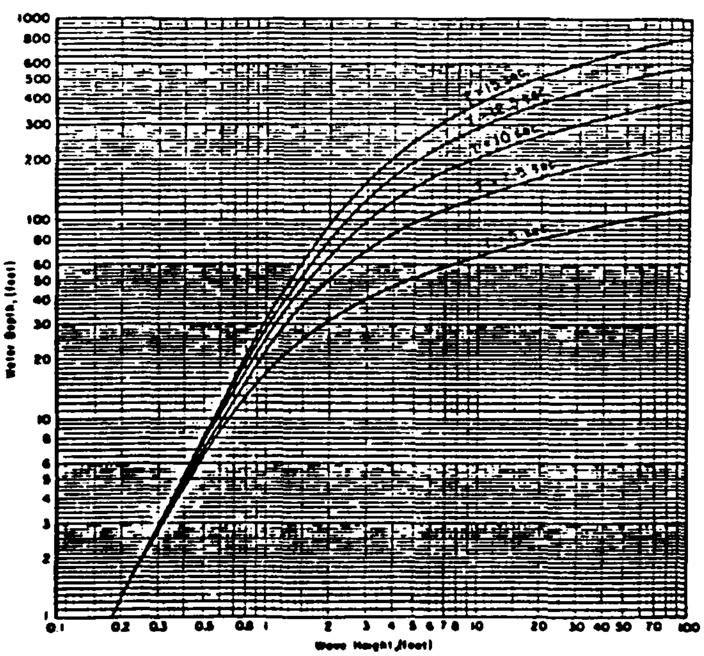


Figure 12 Wave Conditions For Sediment Movement (from USA CERC, 1977)

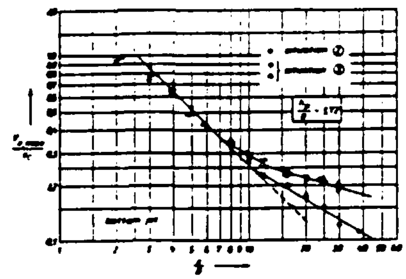


Figure 13 Decay of Propeller Jet Velocity With Distance (from Fuehrer and Romisch, 1977)

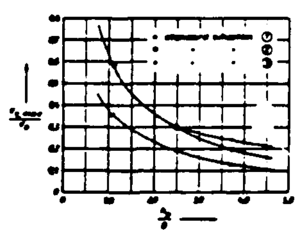


Figure 14 Bottom Velocity Induced by Propeller Jet (from Fuehrer and Romisch, 1977)

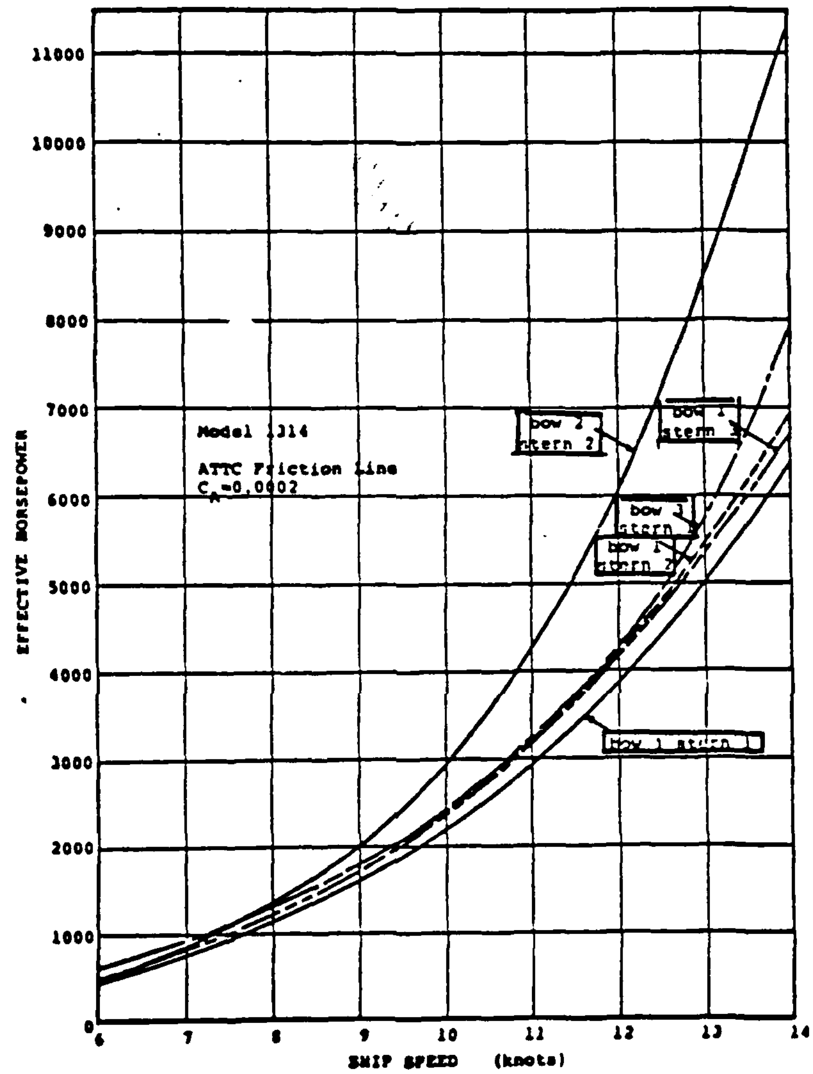


Figure 15 Effective Horsepower vs Speed for the MV St. Clair (from Fischer, 1977)

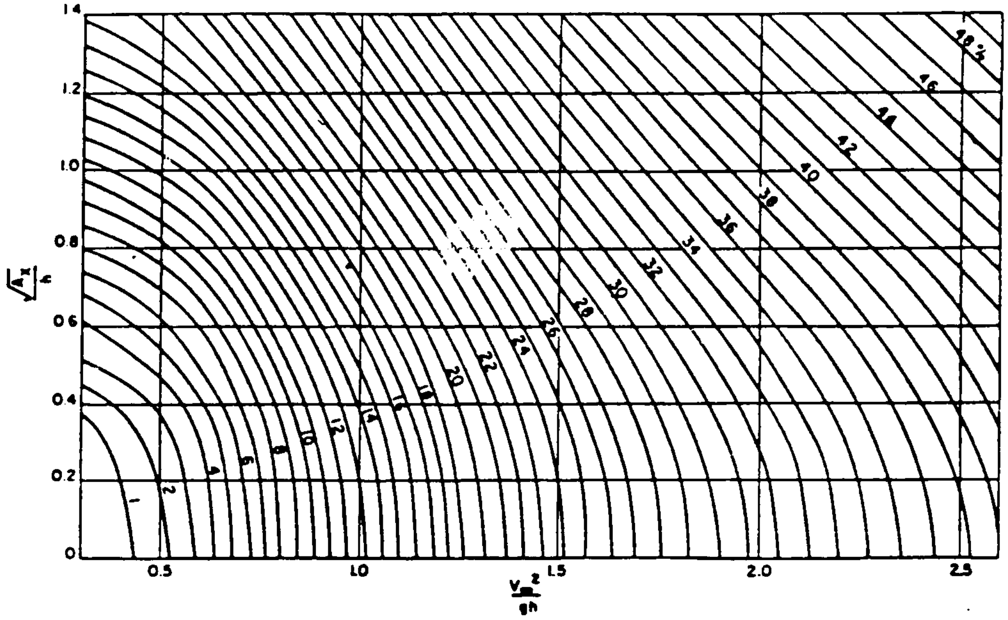


Figure 16 Speed Reduction in Shallow Water (from Comstock, 1976)

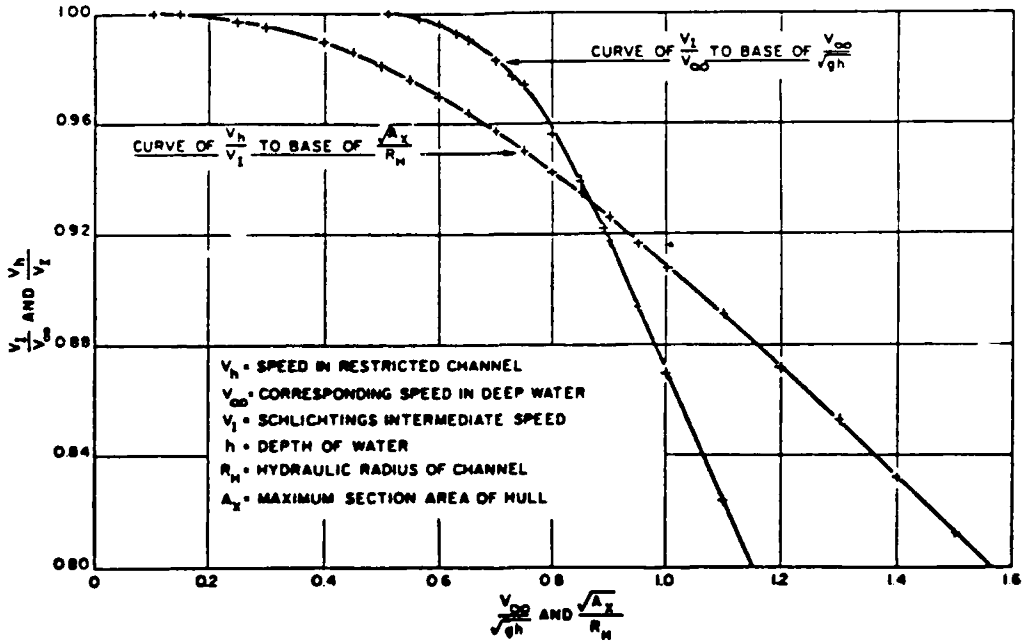


Figure 17 Speed Reduction in Restricted Channels (from Comstock, 1976)

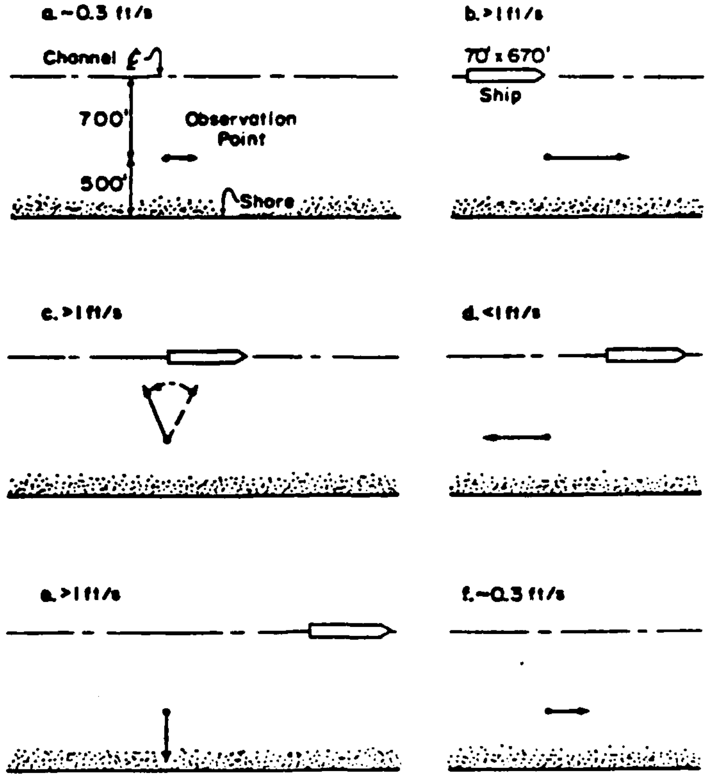


Figure 18 Ship Induced Water Movements

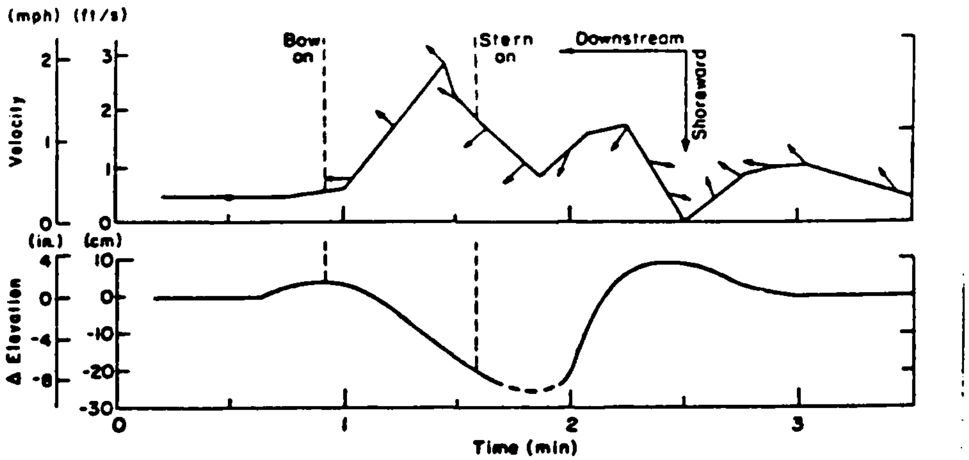


Figure 19 River Level and Near-Bottom Velocity Pattern With an Upbound Ship (from Wuebben et. al. 1978)

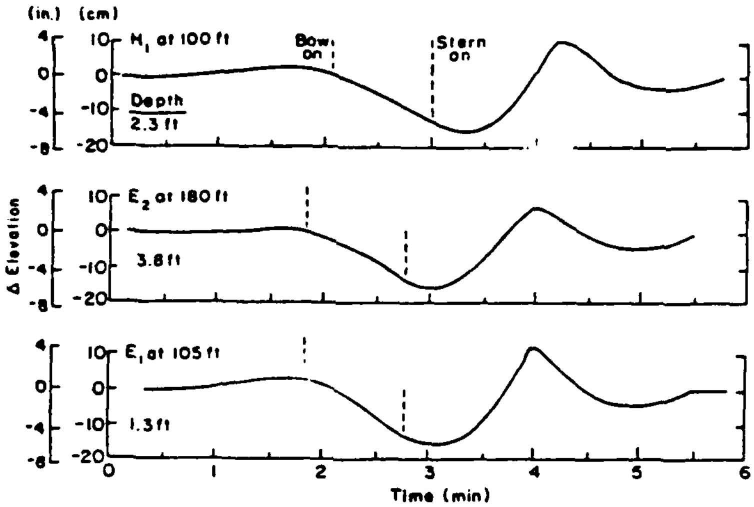


Figure 20 Ice Level Changes With an Upbound Ship (from Wuebben et. al. 1978)

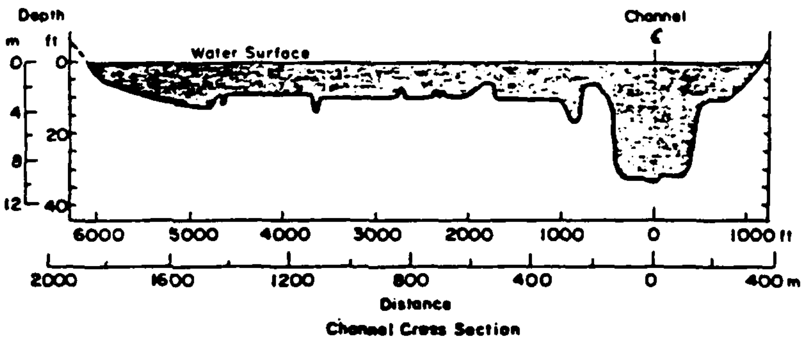


Figure 21 Cross Section of the St. Marys River Near Six Mile Point

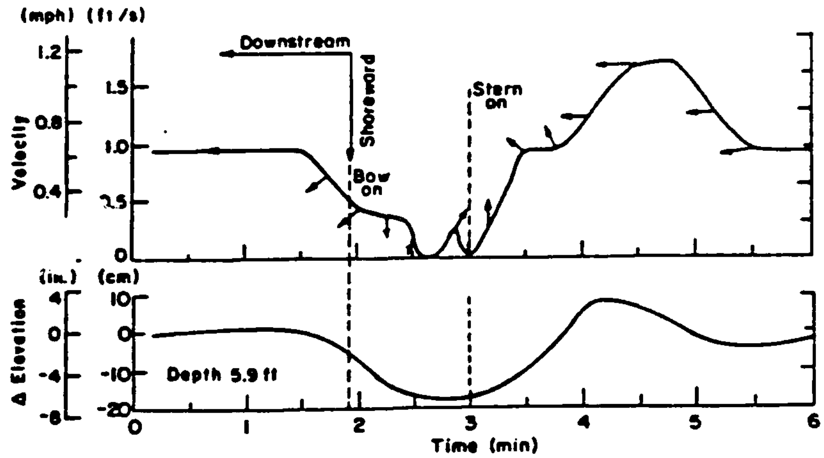


Figure 22 River Level and Near Bottom Velocity Pattern With a Downbound Ship (from Wuebben et. al. 1978)

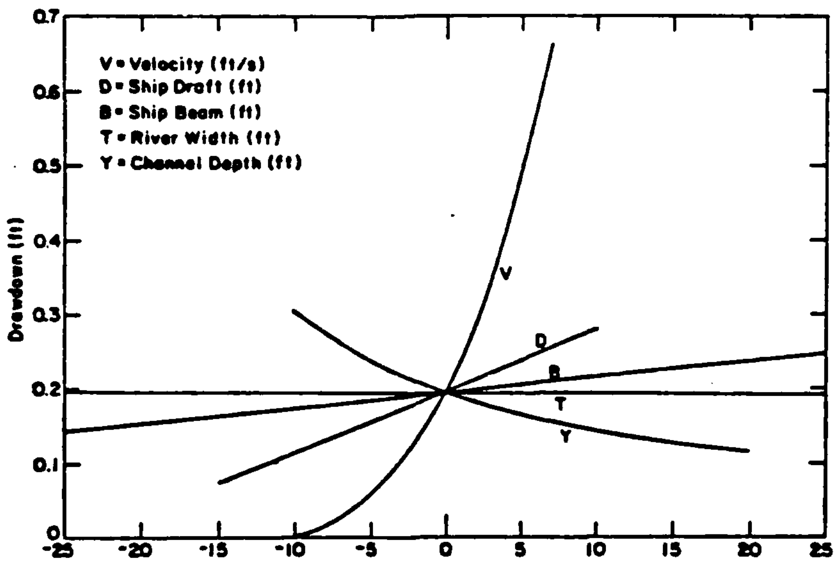


Figure 23 Effects on Drawdown Due to Variation in Parameters From the Basic Case

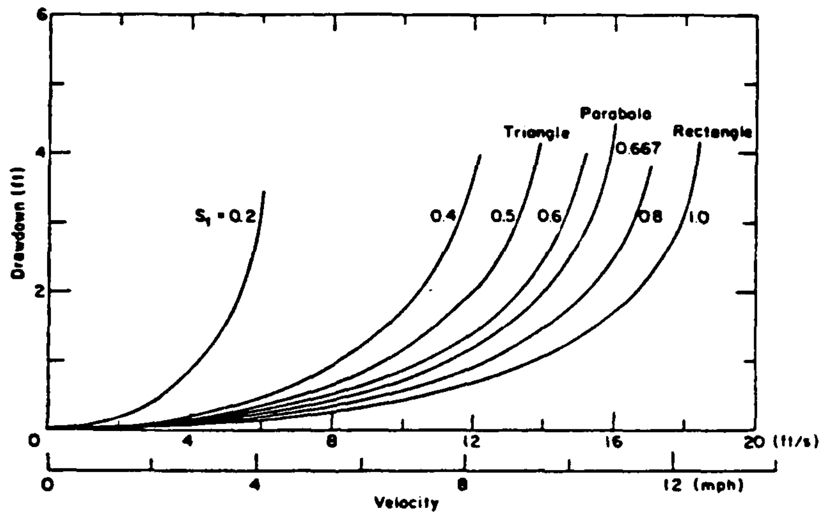


Figure 24 Effect of Channel Shape on Drawdown

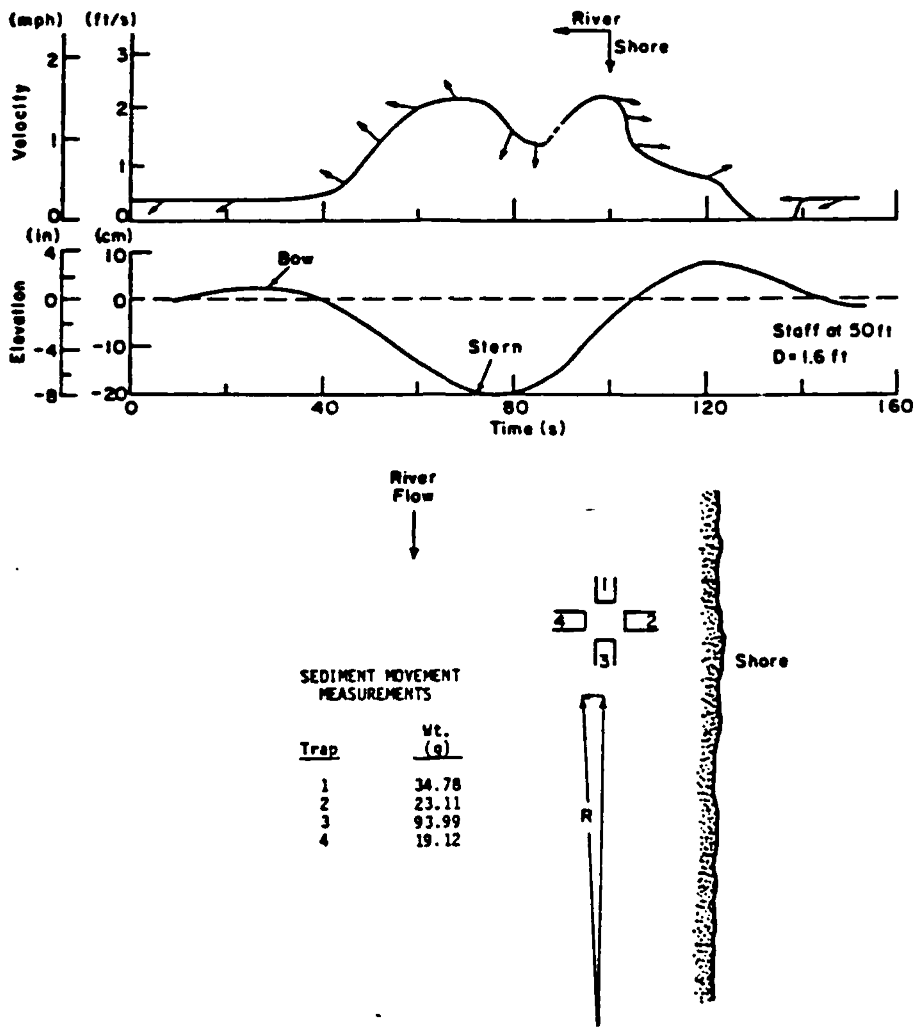


Figure 25 Velocity, Stage and Sediment Movement Measurements at Nine Mile Point During Passage of the Sir James Dunn (after Alger, 1978)

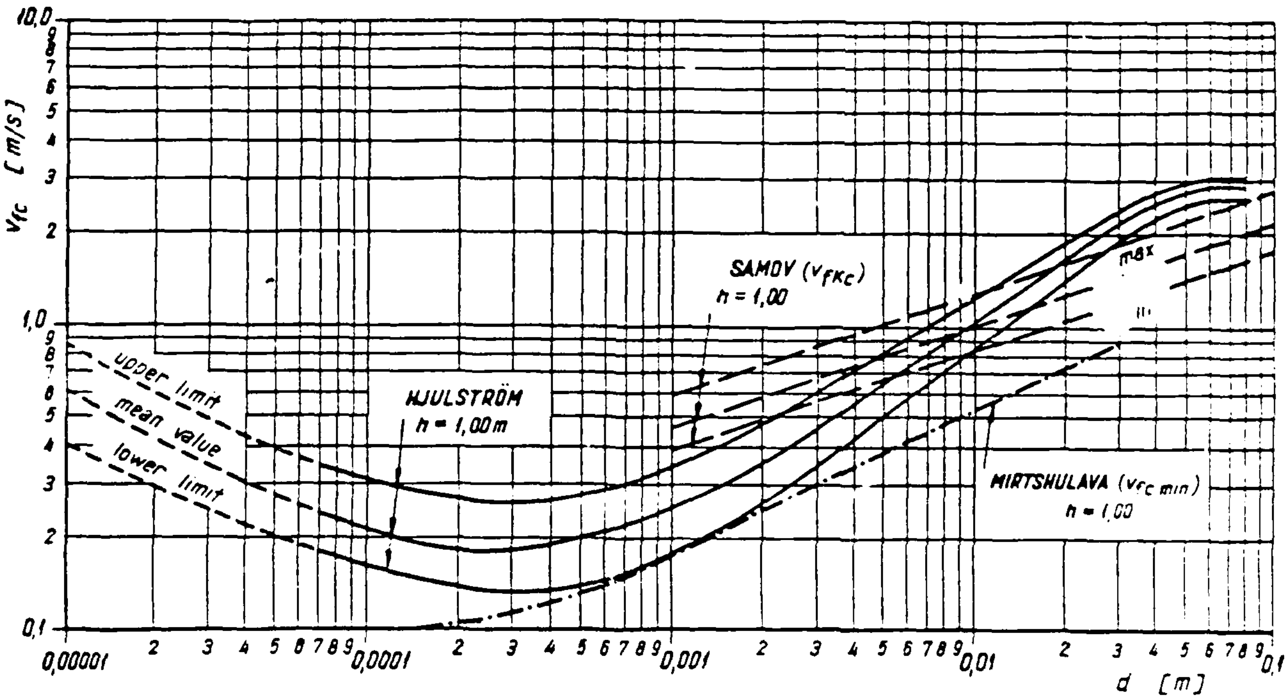


Figure 26 Scour Velocities vs Grain Size (from Stelczer, 1981)

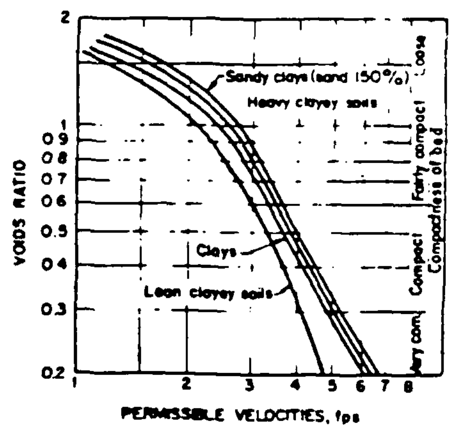


Figure 27 Permissible Velocities For Cohesive Soils, USSR Method (from Simons and Senturk, 1976)

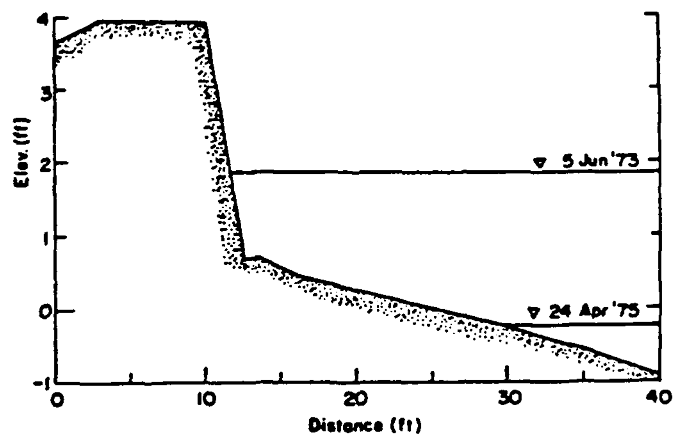


Figure 28 Relation of Water Level to Shore Profile For a Site on the St. Marys River

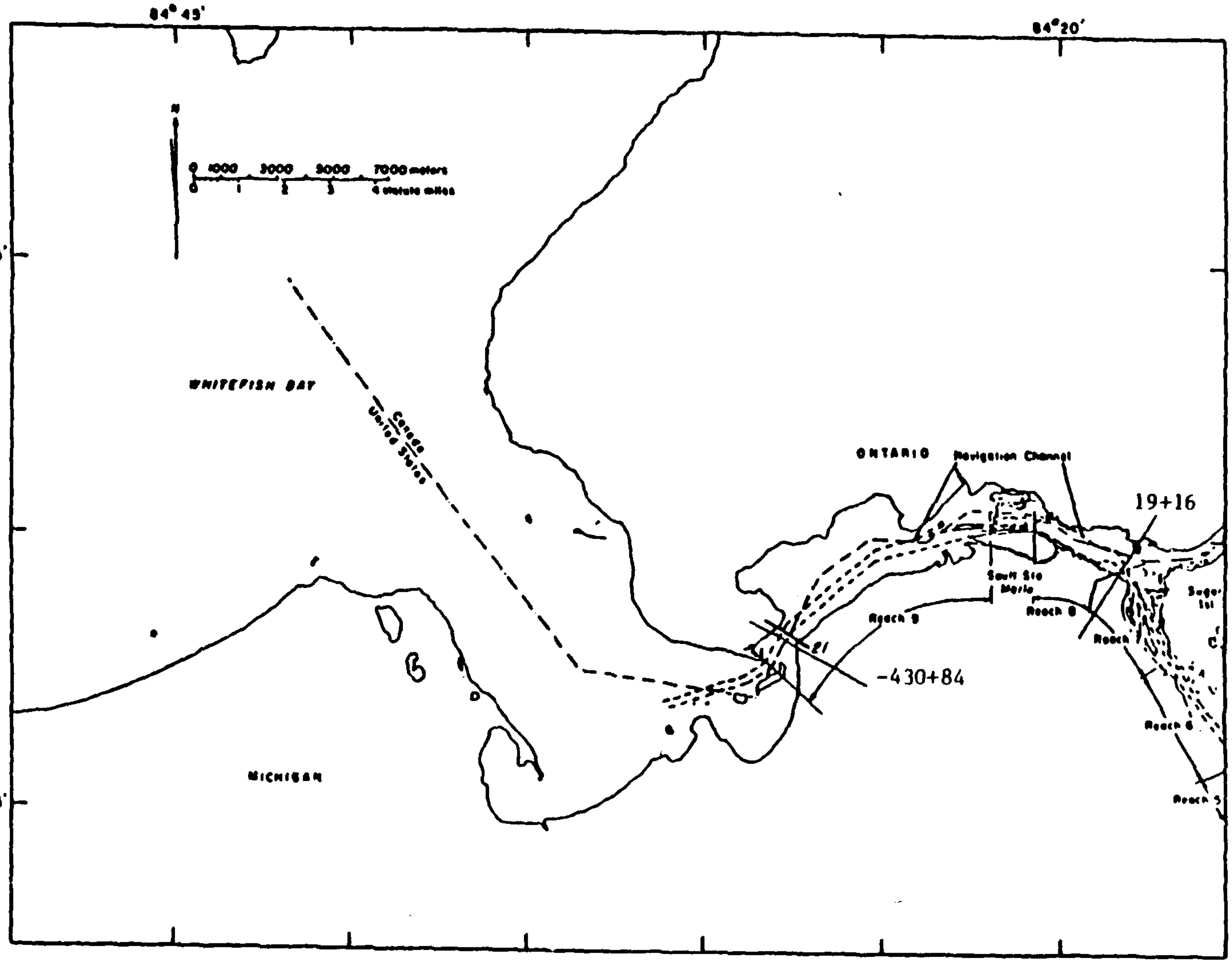


Figure 29 St. Marys River Reaches and Cross Sections

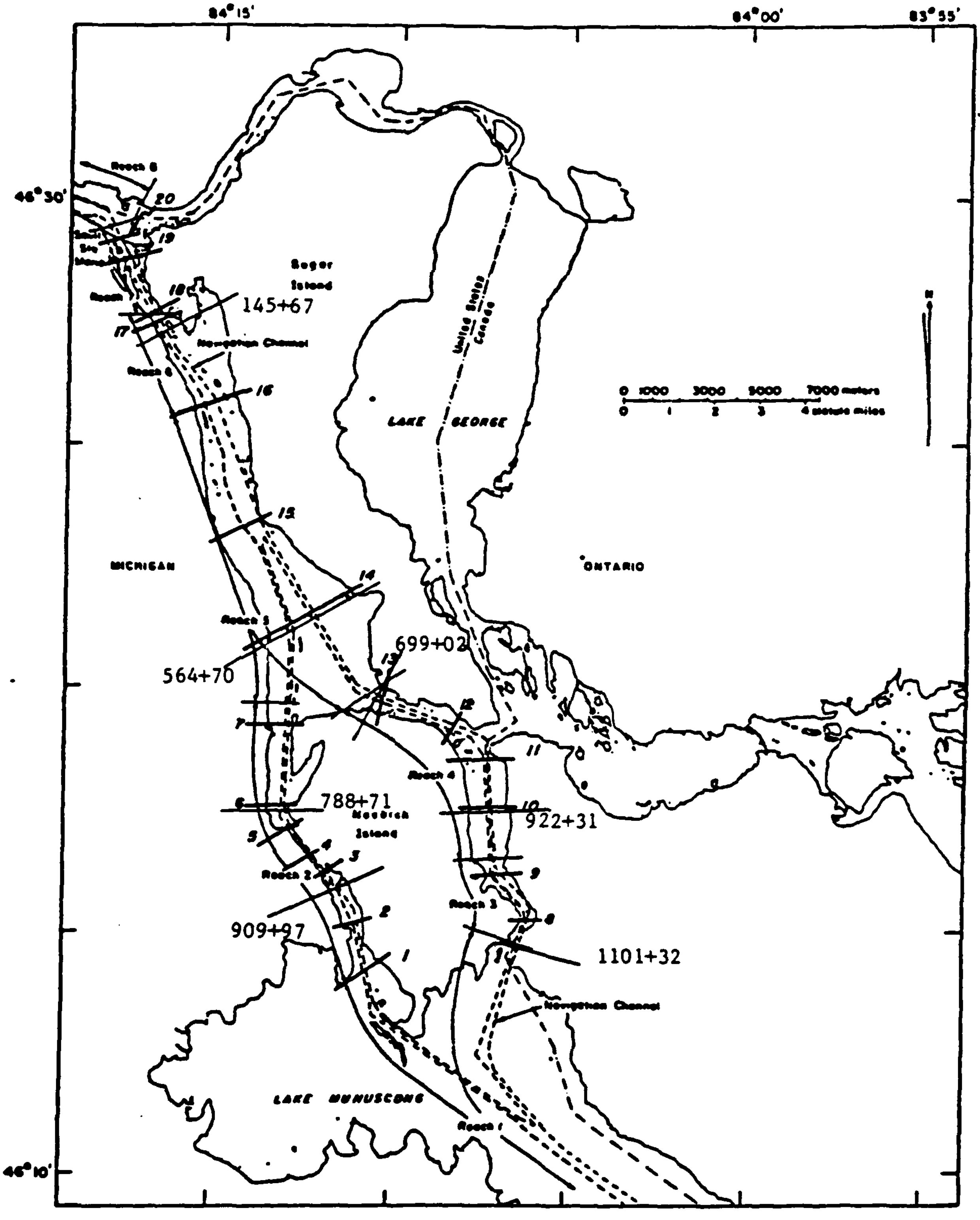


Figure 29 (cont'd).

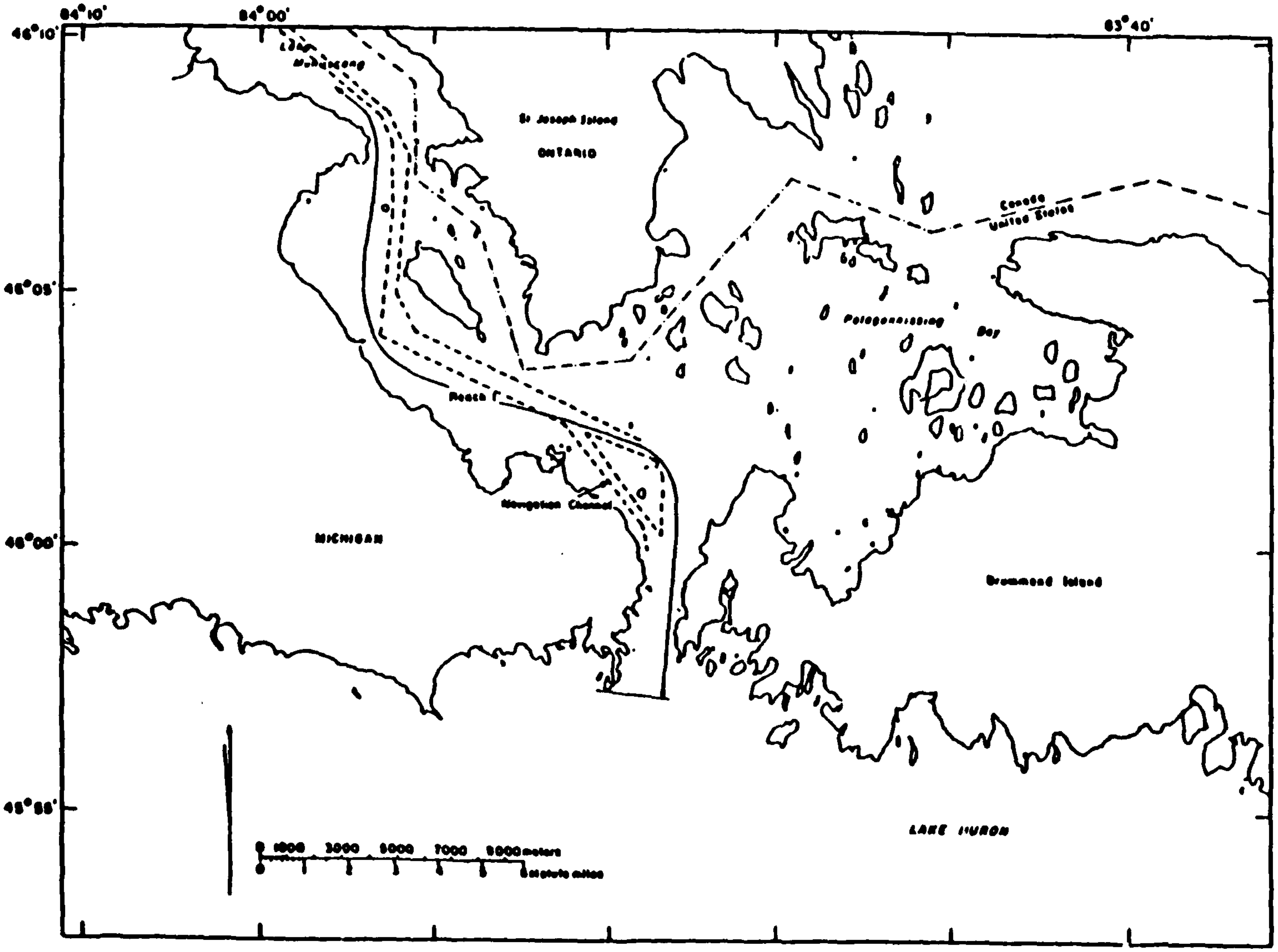


Figure 29(cont'd). St. Marys River reaches and cross sections.

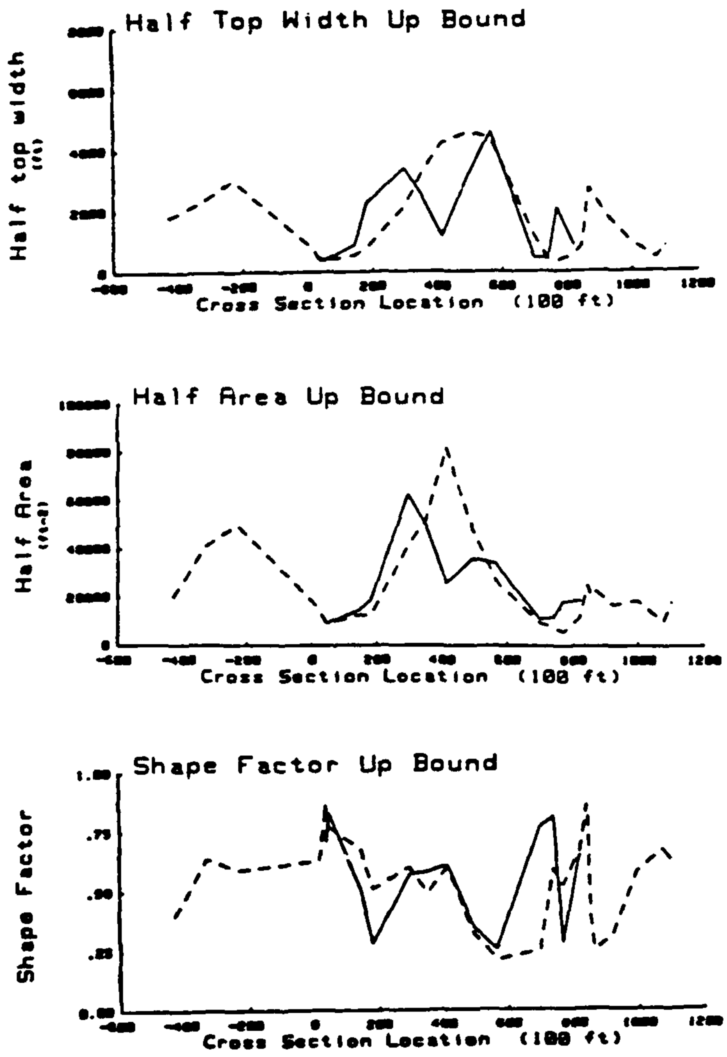


Figure 30 St. Marys River Geometry

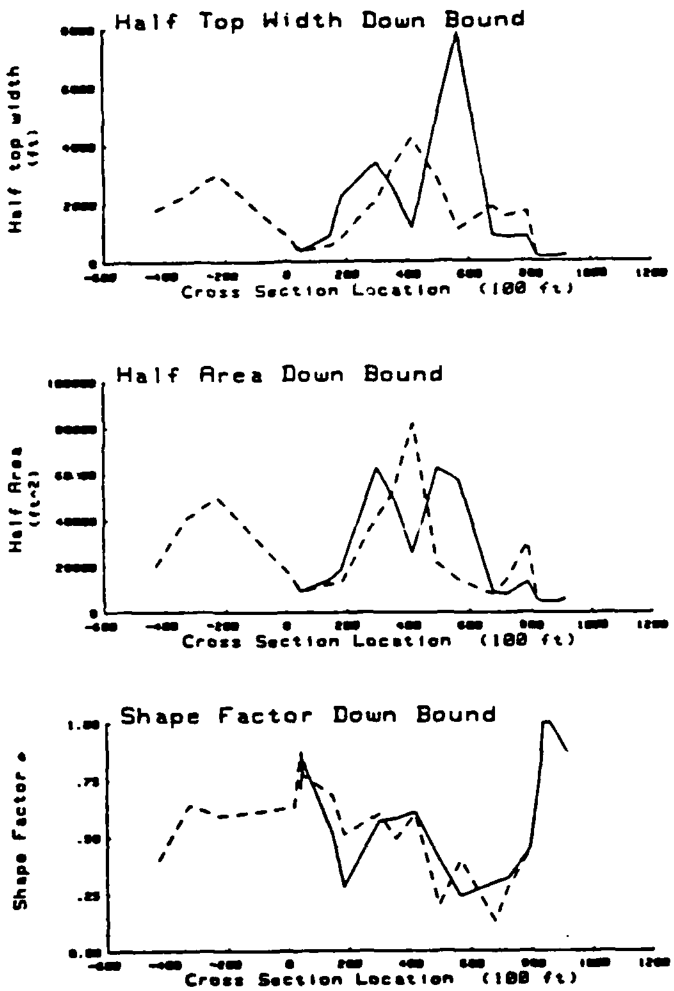


Figure 30 (cont.)

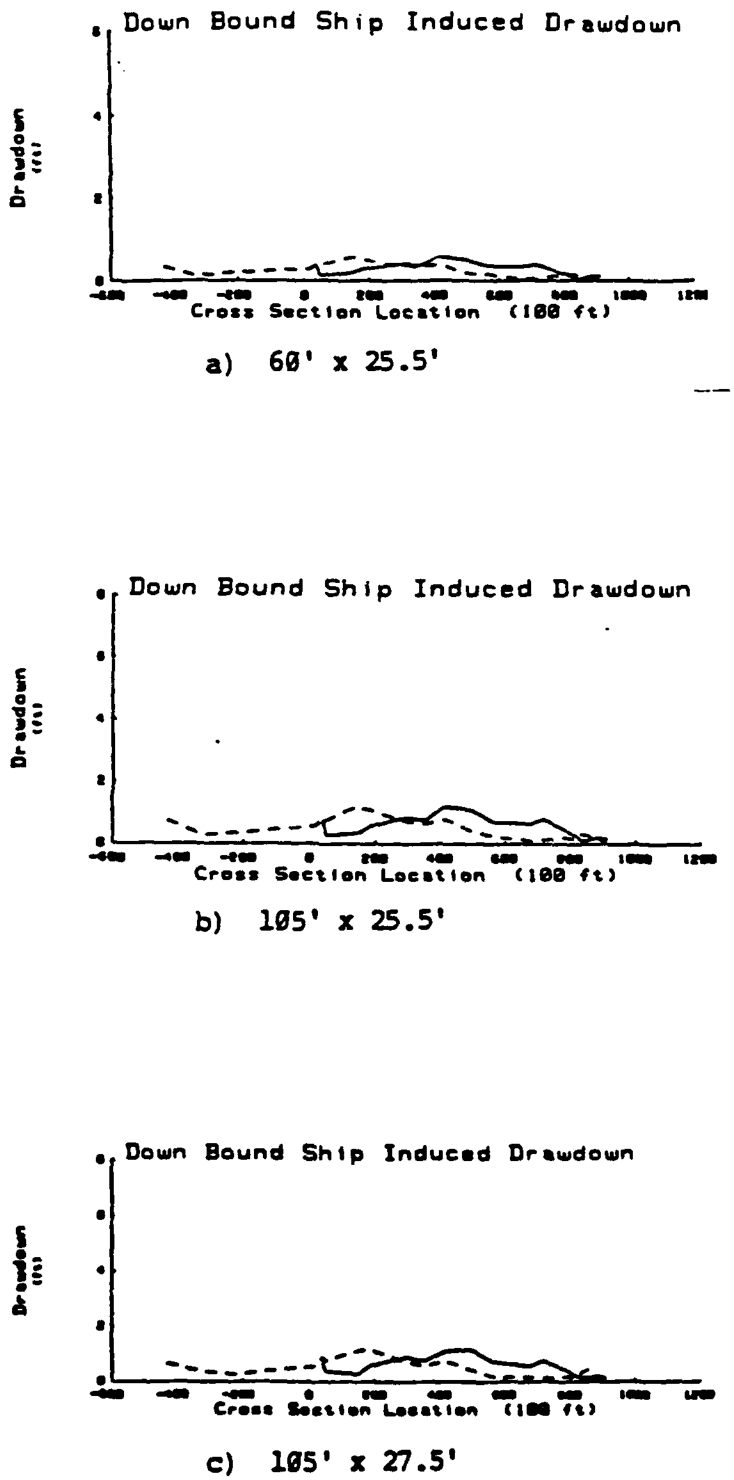
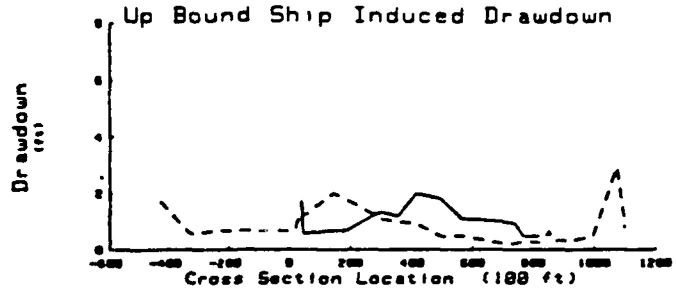
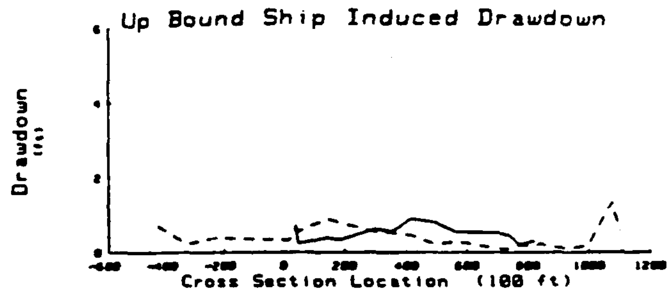


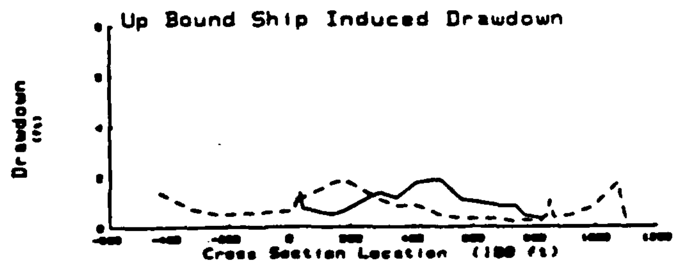
Figure 31 St. Marys River Drawdown Distribution



e) 105' x 25.5'

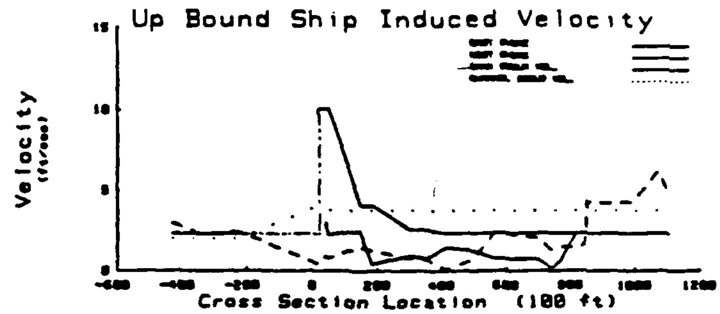


d) 60' x 25.5'

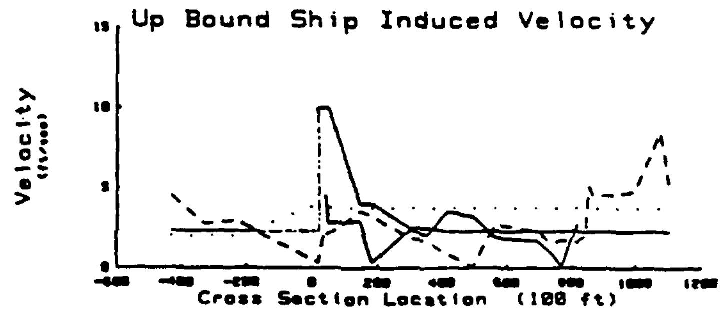


f) 105' x 27.5'

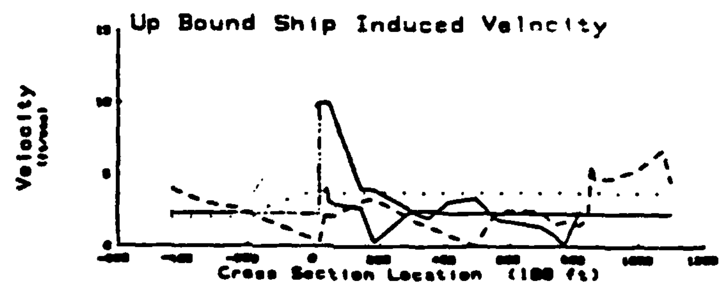
Figure 31 (cont)



a) 60' x 25.5'

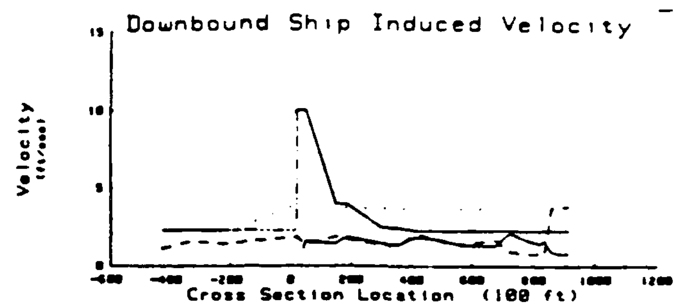


b) 105' x 25.5'

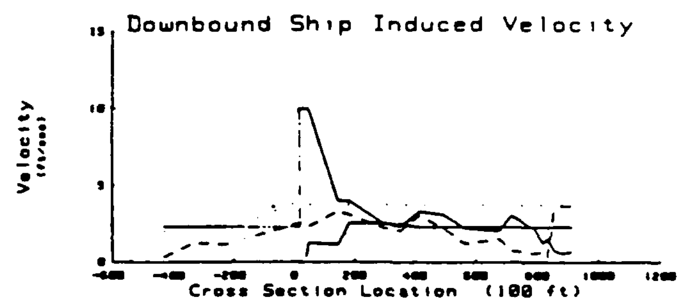


c) 105' x 27.5'

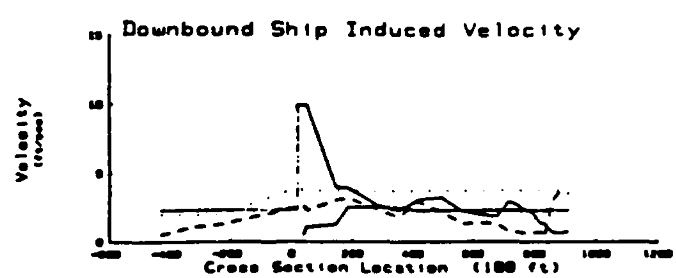
Figure 32 St. Marys River Ship Induced Velocity Distribution



d) 60' x 25.5'



e) 105' x 25.5'



f) 105' x 27.5'

Figure 32 (cont.)

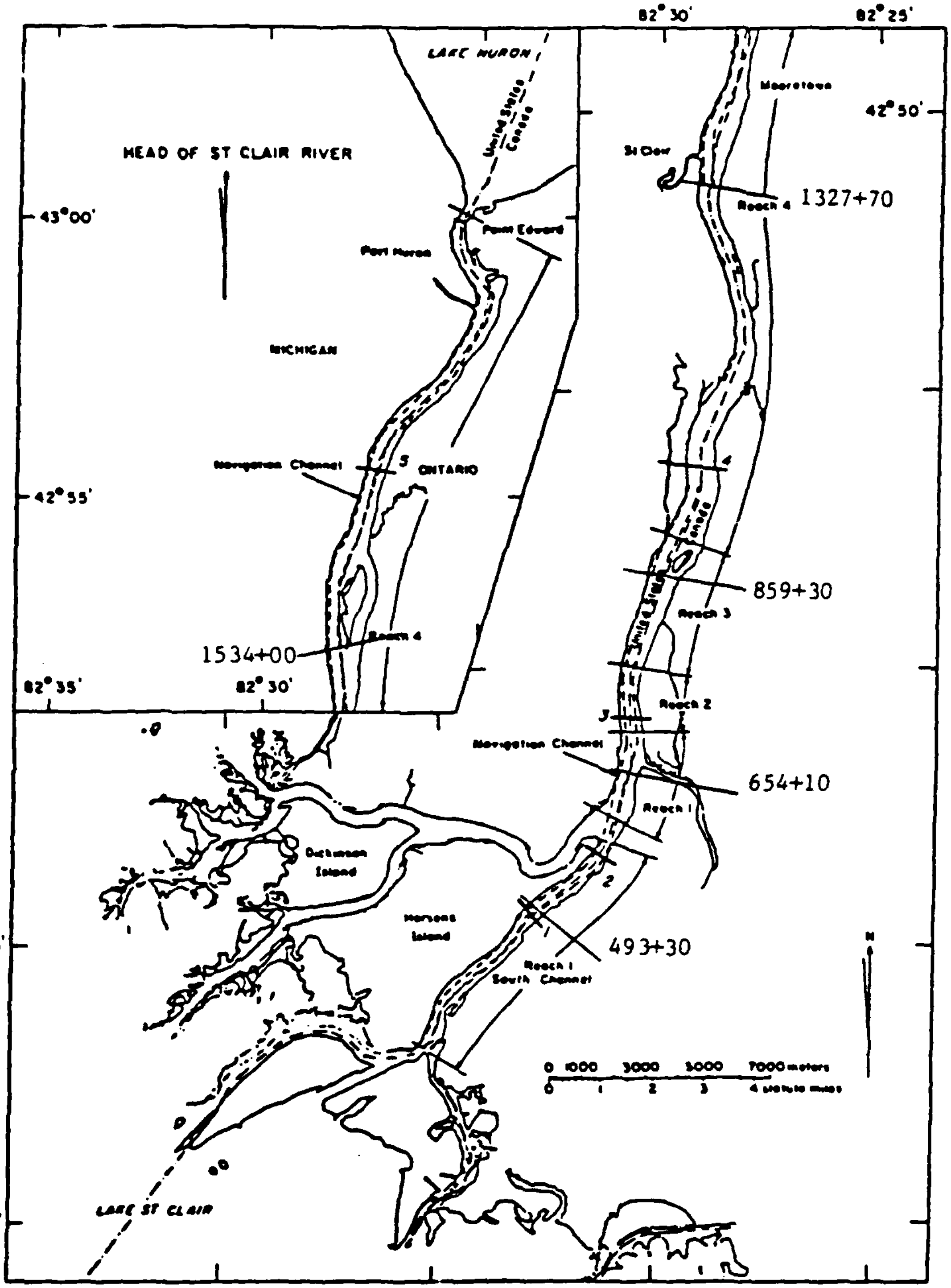


Figure 33 St. Clair River Reaches and Cross Sections

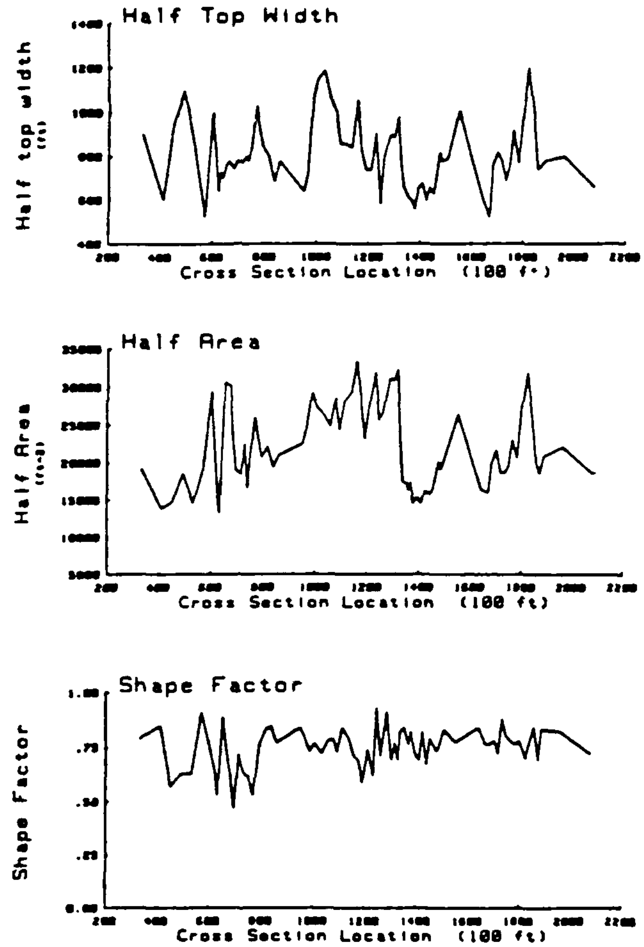
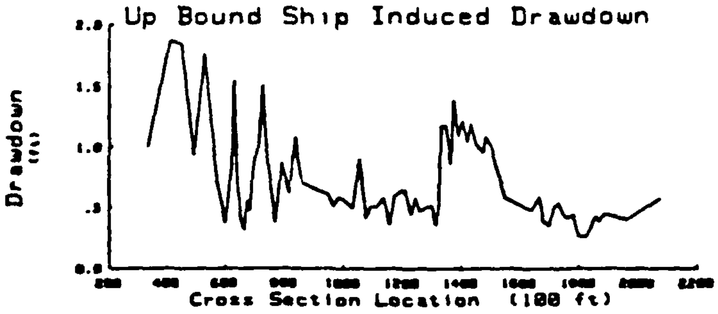
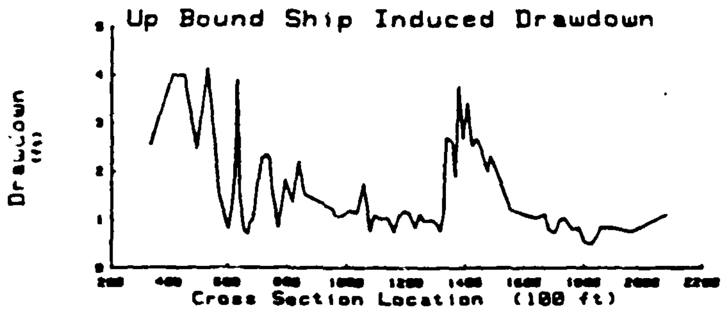


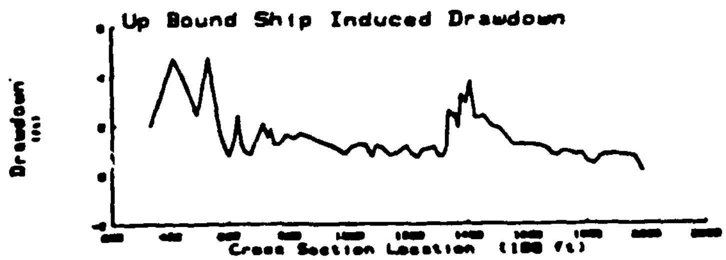
Figure 34 St. Clair River Geometry



a) 60' x 25.5'

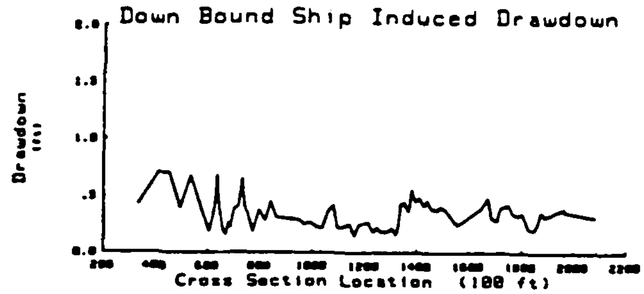


b) 105' x 25.5'

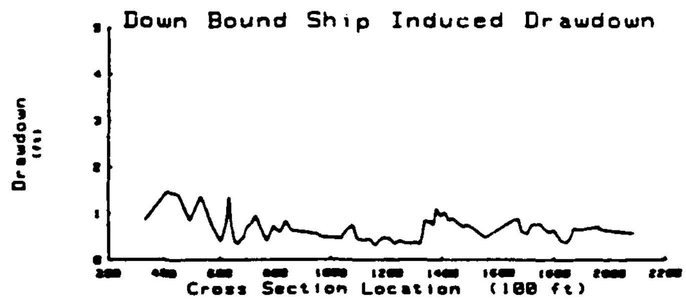


c) 105' x 27.5'

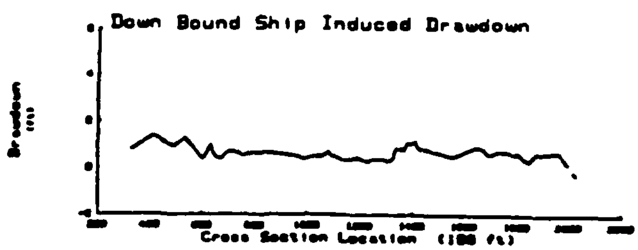
Figure 35 St. Clair River Drawdown Distribution



d) 60'x 25.5'

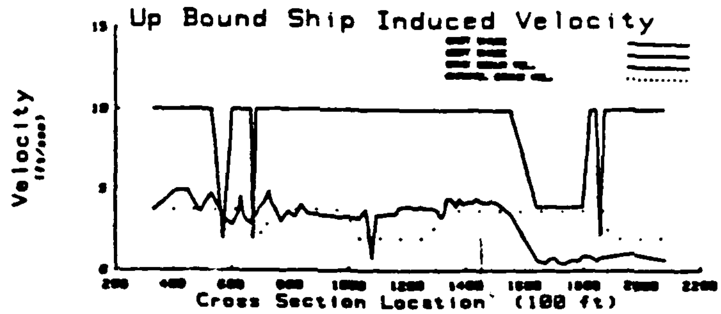


e) 105' x 25.5'

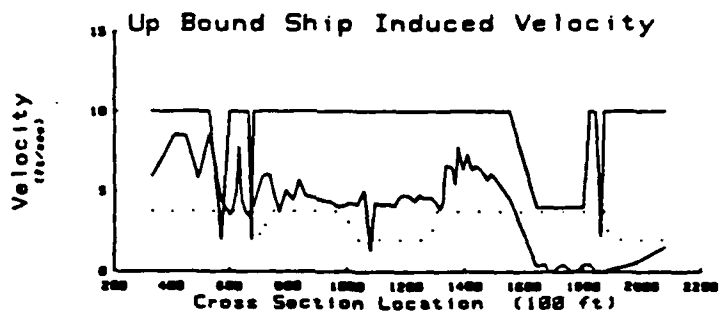


f) 105' x 27.5'

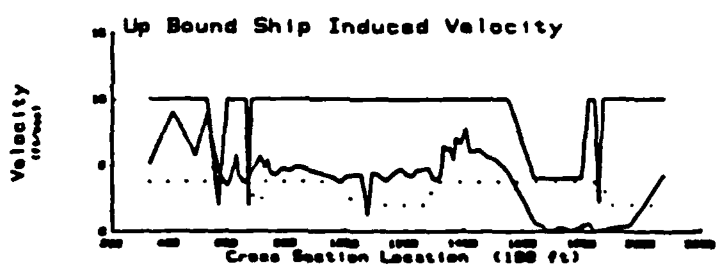
Figure 35 (cont.)



a) 60' x 25.5'

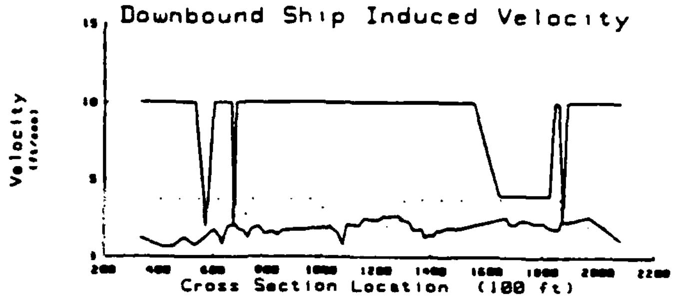


b) 105' x 25.5'

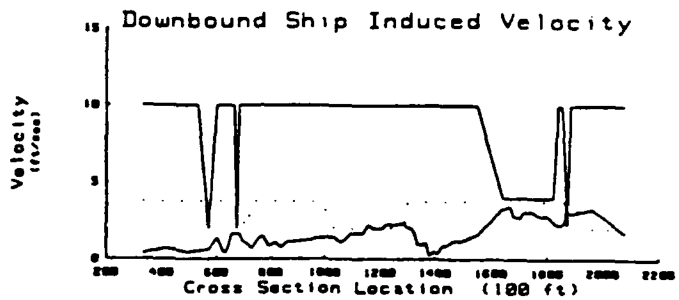


c) 105' x 27.5'

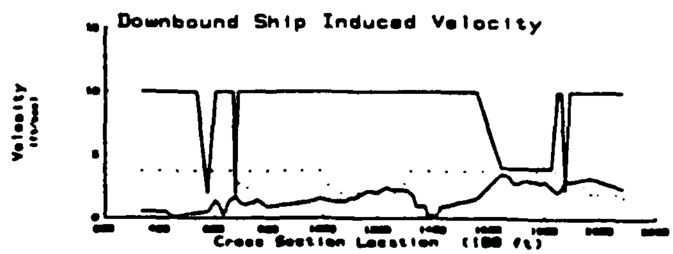
Figure 36 St. Clair River Ship Induced Velocity Distribution



d) 60' x 25.5'



e) 105' x 25.5'



f) 105' x 27.5'

Figure 36 (cont.)

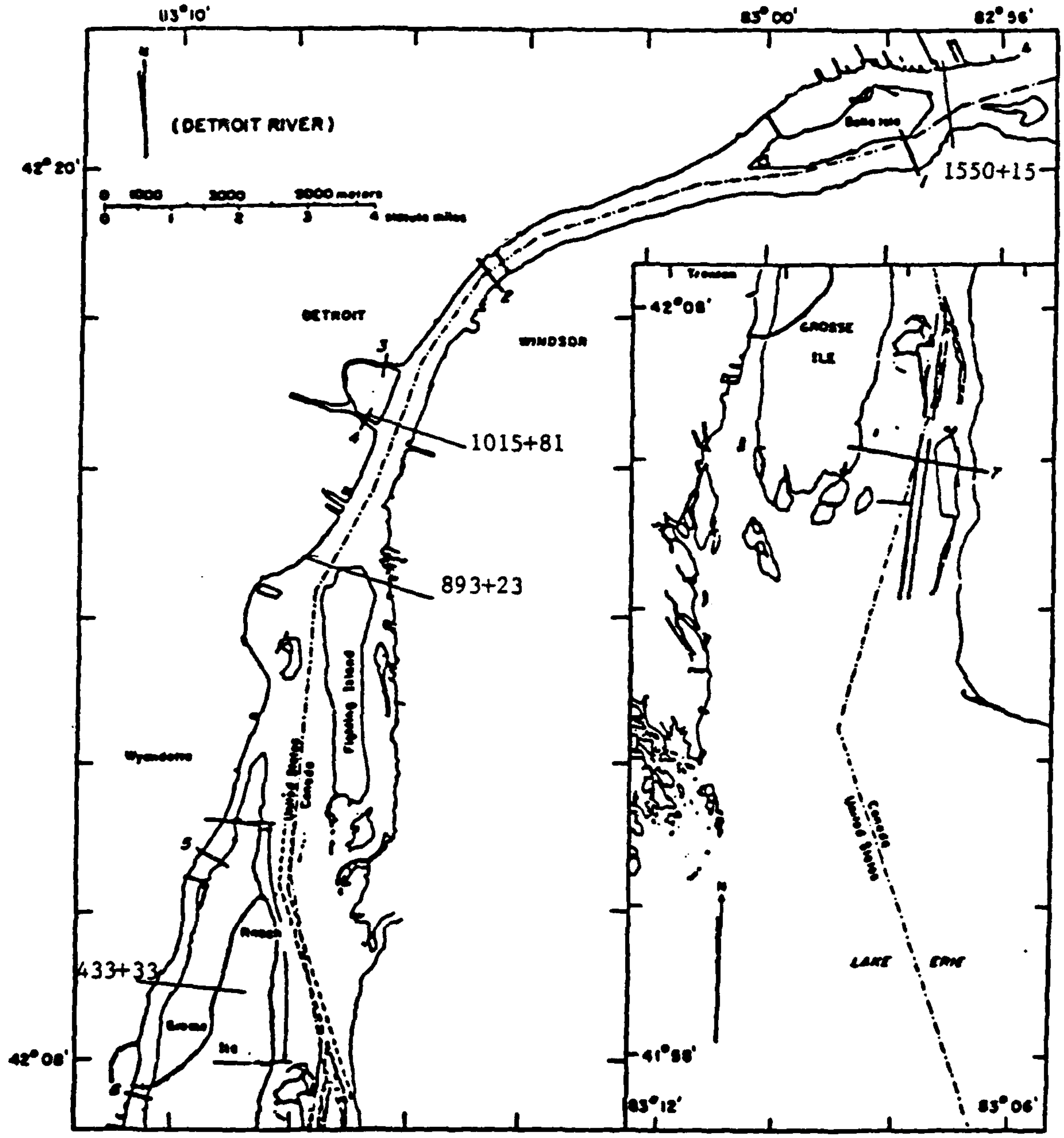


Figure 37 Detroit River Reaches and Cross Sections

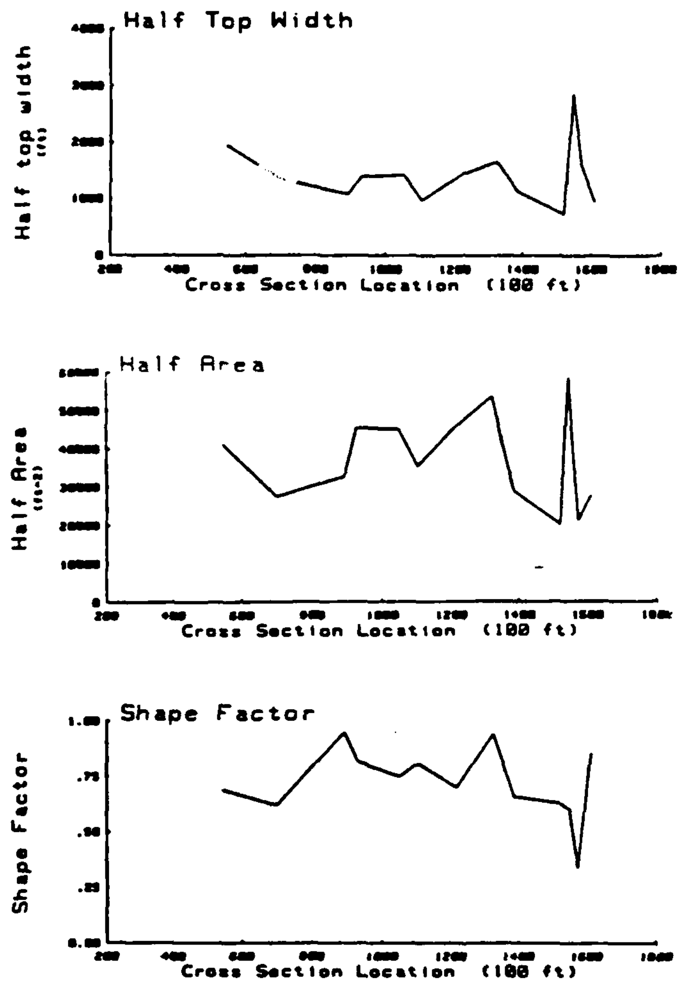


Figure 38 Detroit River Geometry

TRENTON CHANNEL

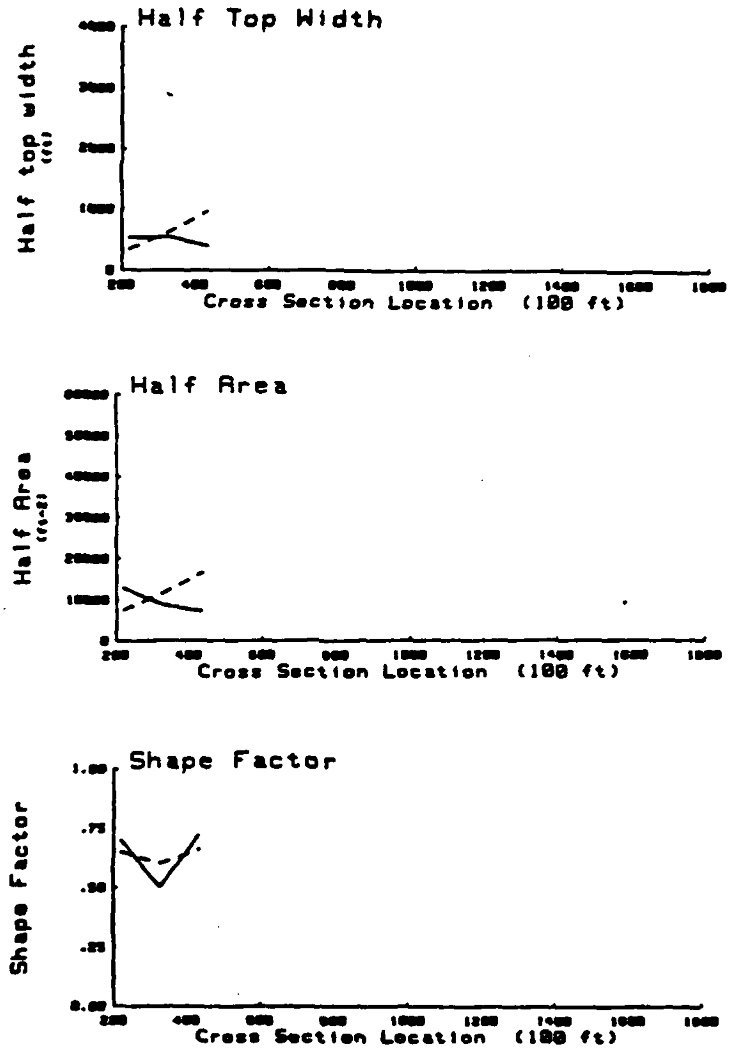
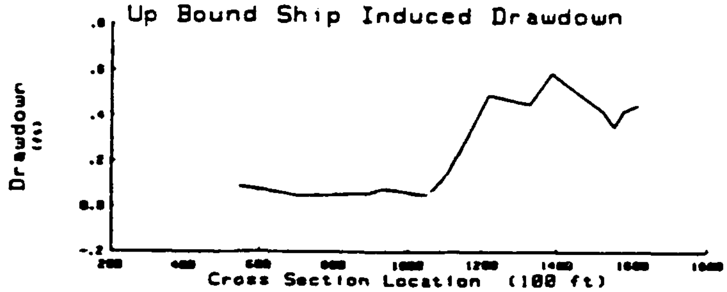
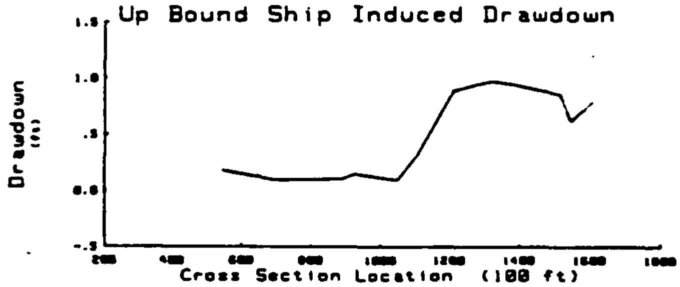


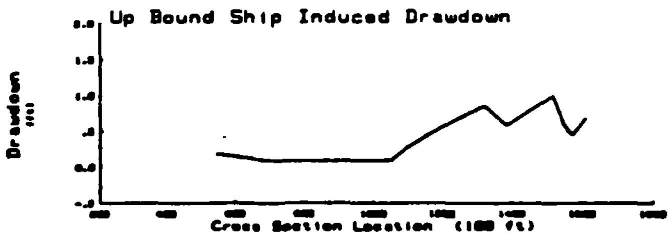
Figure 38 (cont.)



a) 60' x 25.5'

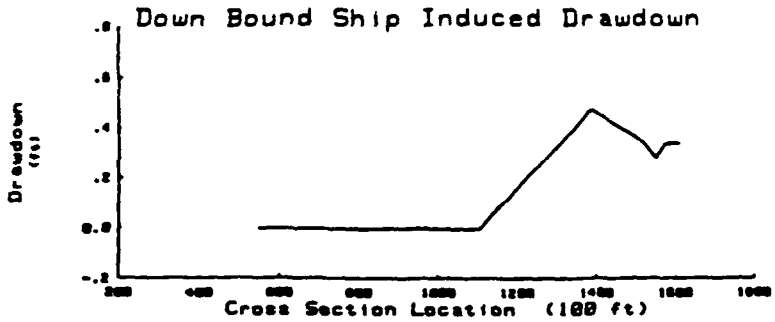


b) 105' x 25.5'

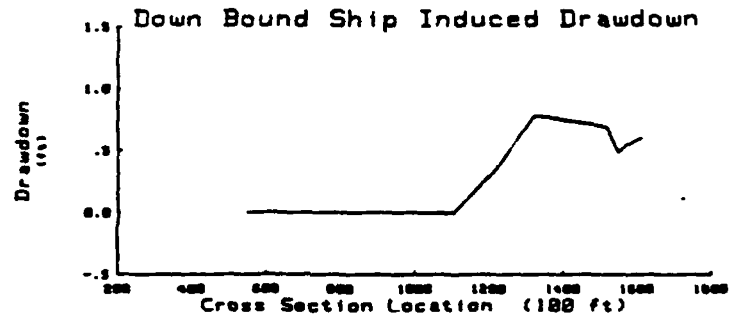


c) 105' x 27.5

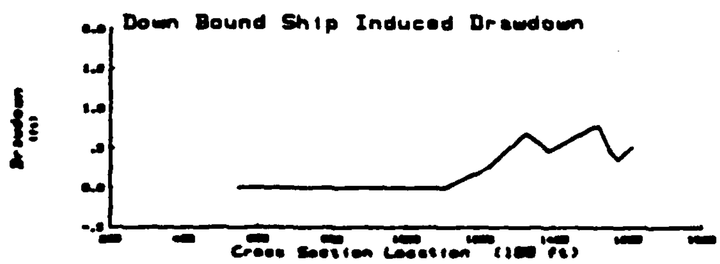
Figure 39 Detroit River Drawdown Distribution



d) 60' x 25.5'

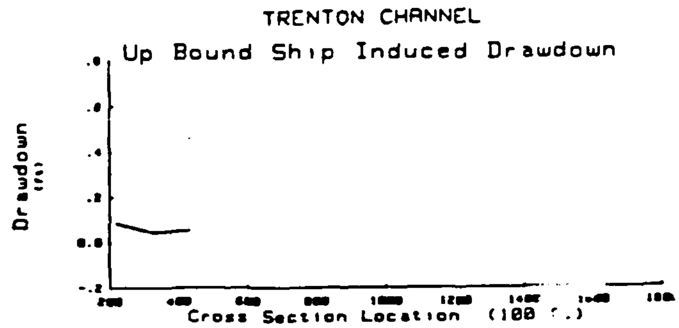


e) 105' x 25.5'

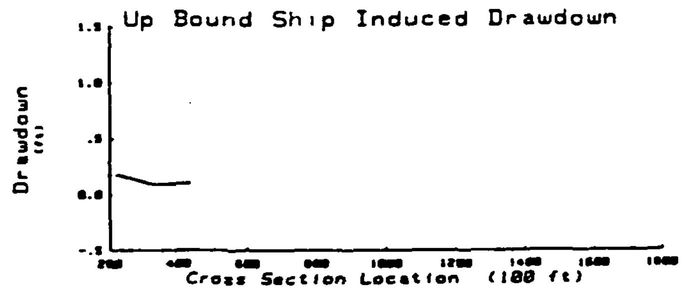


f) 105' x 27.5'

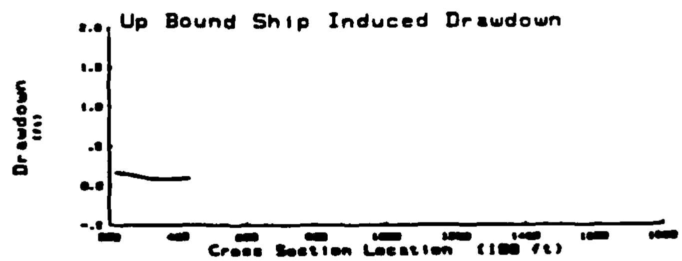
Figure 39 (cont.)



g) 60' x25.5'

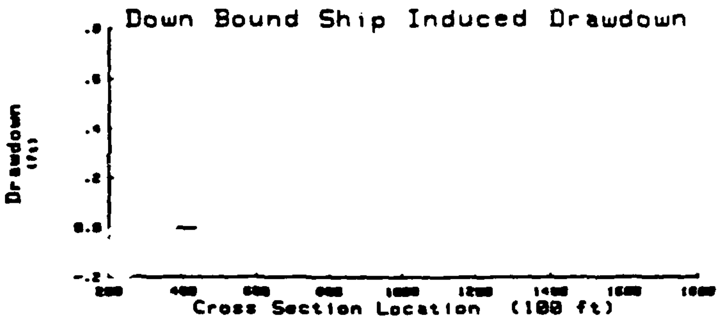


h) 105'x 25.5'

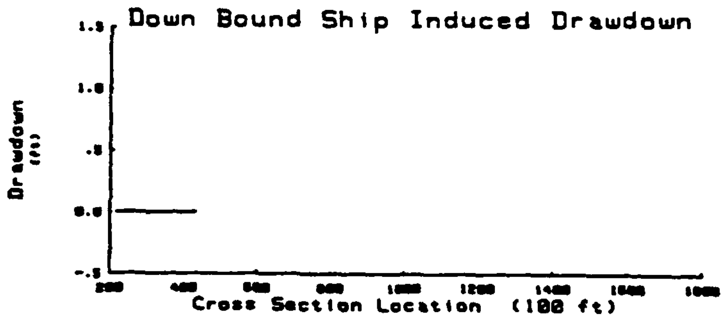


i) 105' x 27.5'

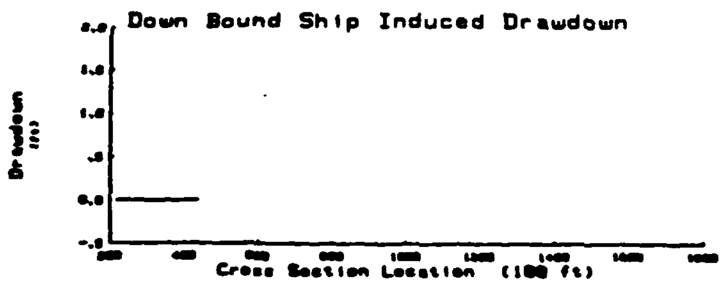
Figure 39 (cont.)



j) 60' x 25.5'

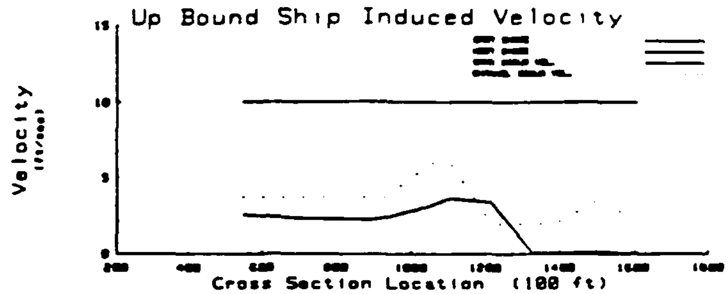


k) 105'.x 25.5'

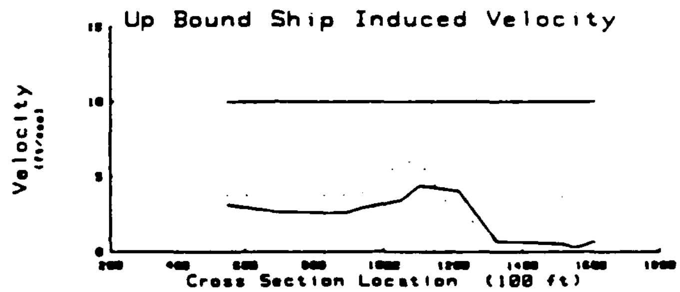


l) 105' x 27.5'

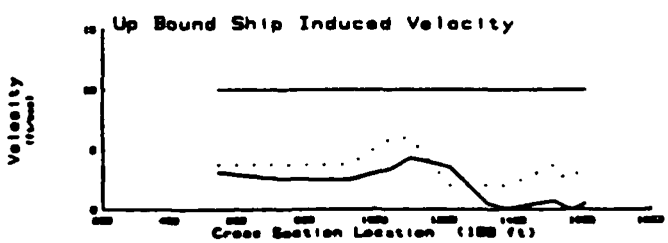
Figure 39 (cont.)



a) 60' x 25.5

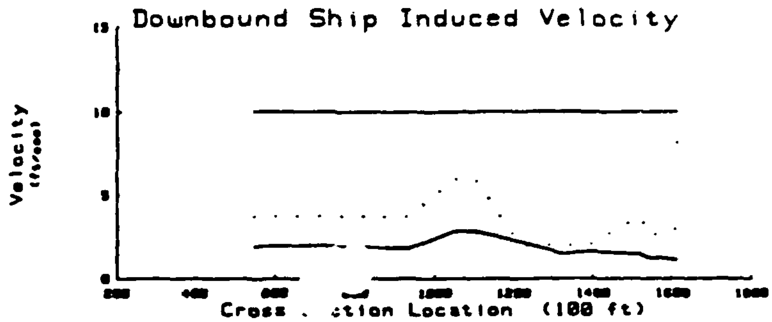


b) 105' x 25.5'

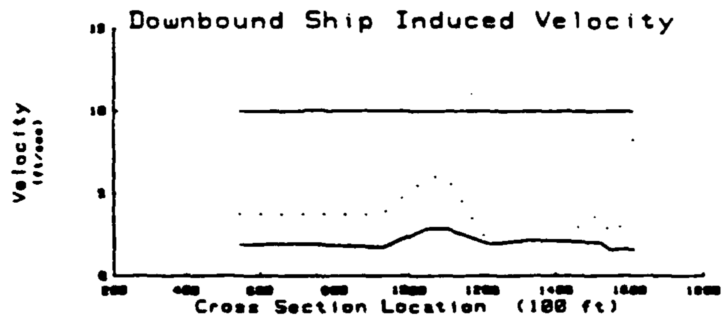


c) 105' x 27.5'

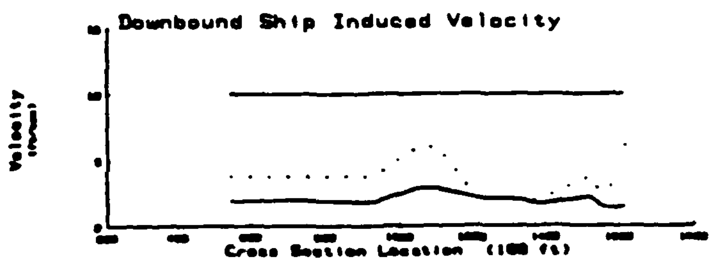
Figure 40 Detroit River Ship Induced Velocity Distribution



d) 60' x 25.5'

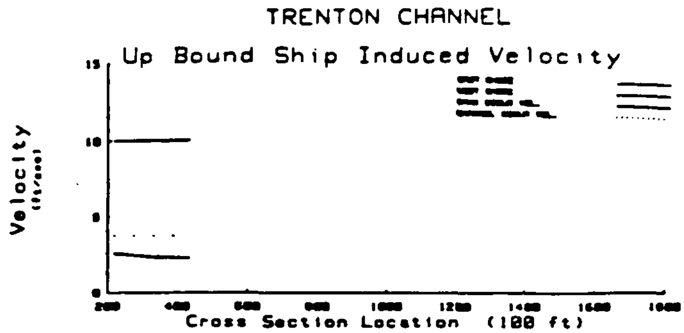


e) 105' x 25.5'

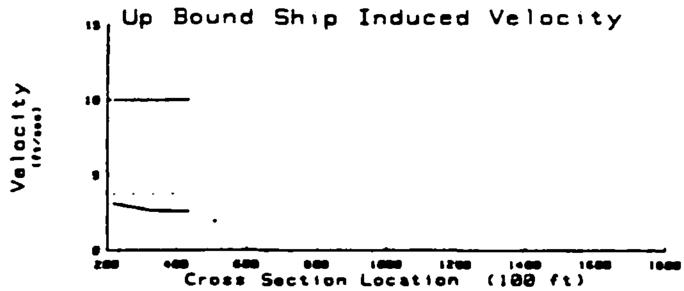


f) 105' x 27.5'

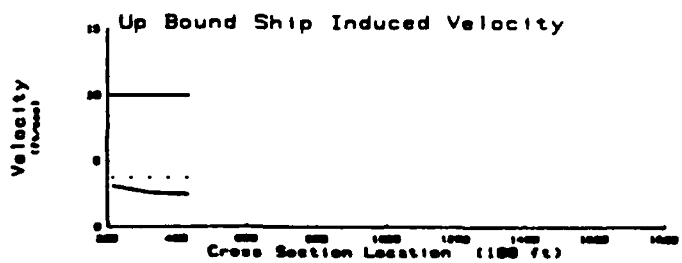
Figure 40 (cont.)



g) 60' x 25.5'

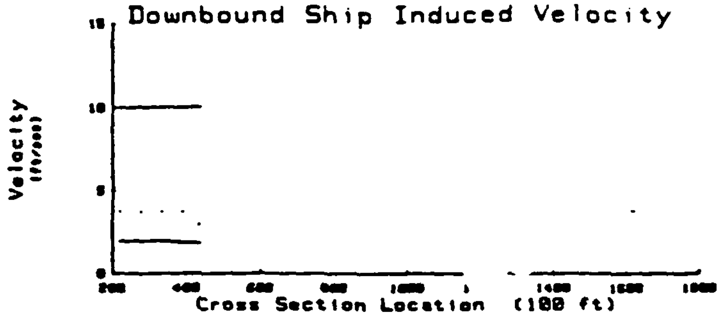


h) 105' x 25.5'

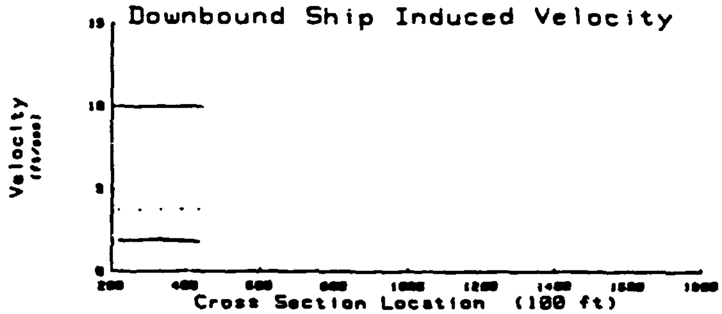


i) 105' x 27.5'

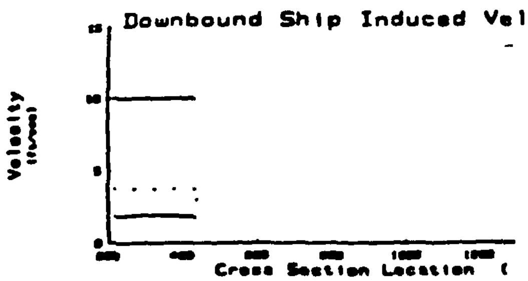
Figure 40 (cont.)



j) 60' x 25.5'



k) 105' x 25.5'



1) 105' x 27.5'

Figure 40 (cont.)

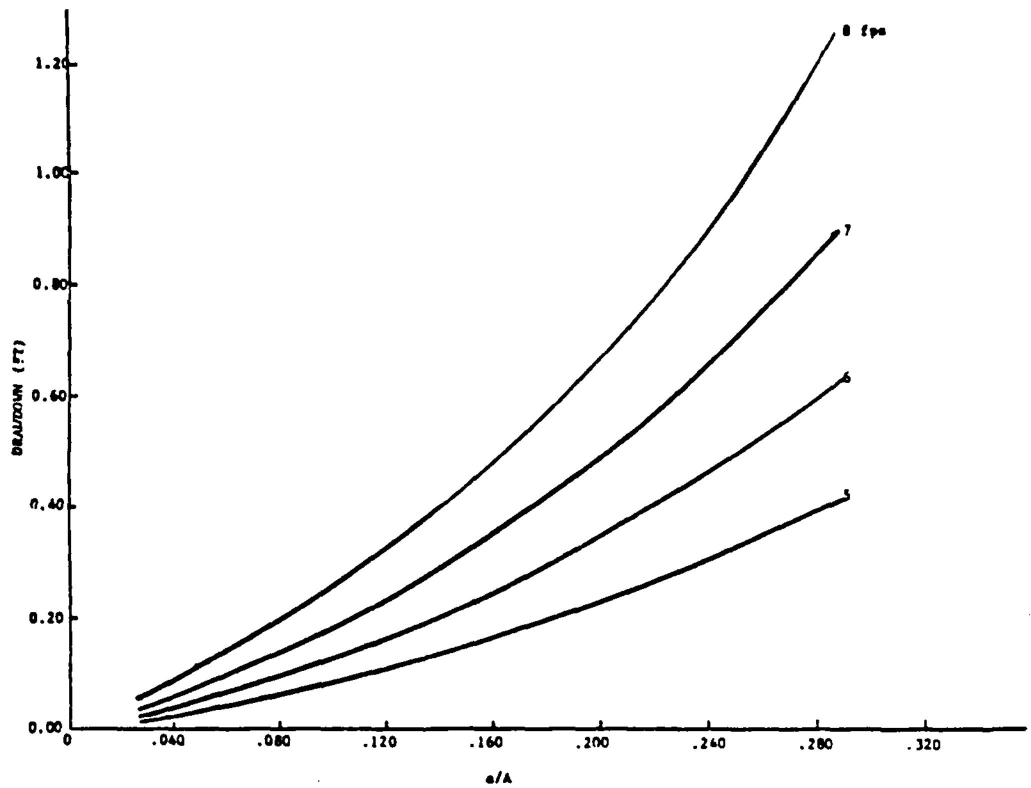


Figure 41 Drawdown in Harbor Areas

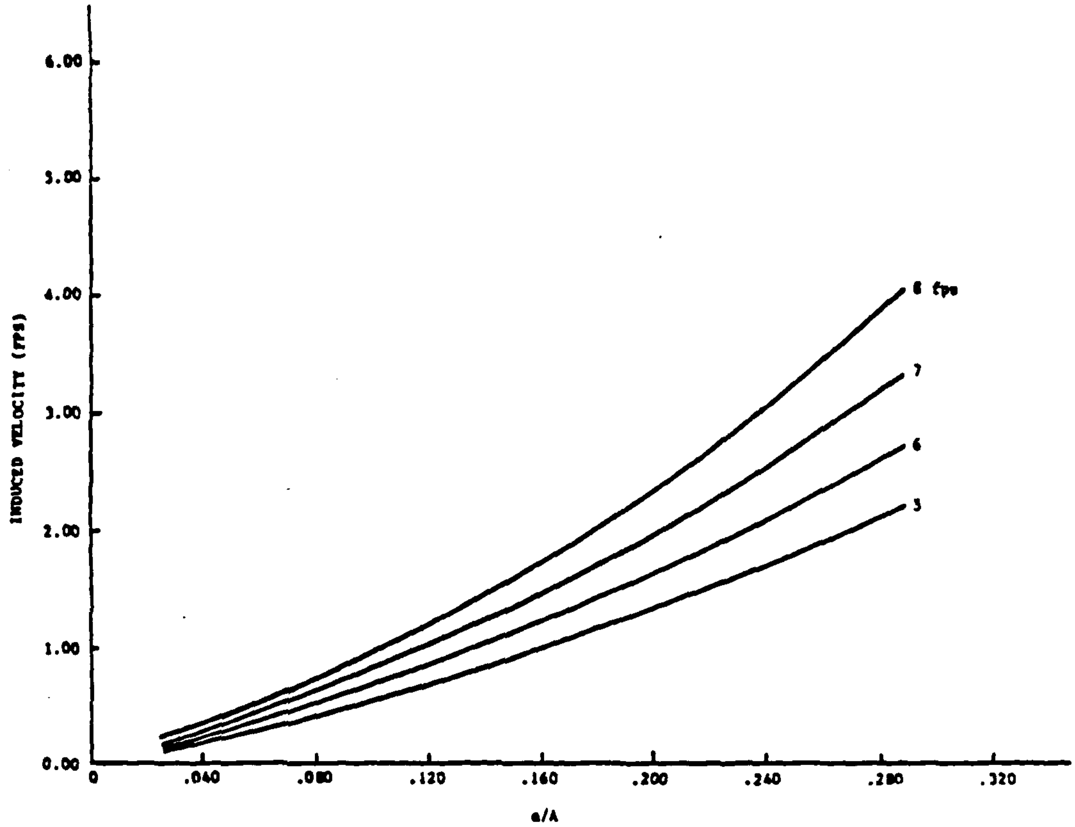


Figure 42 Ship Induced Velocity in Harbor Areas

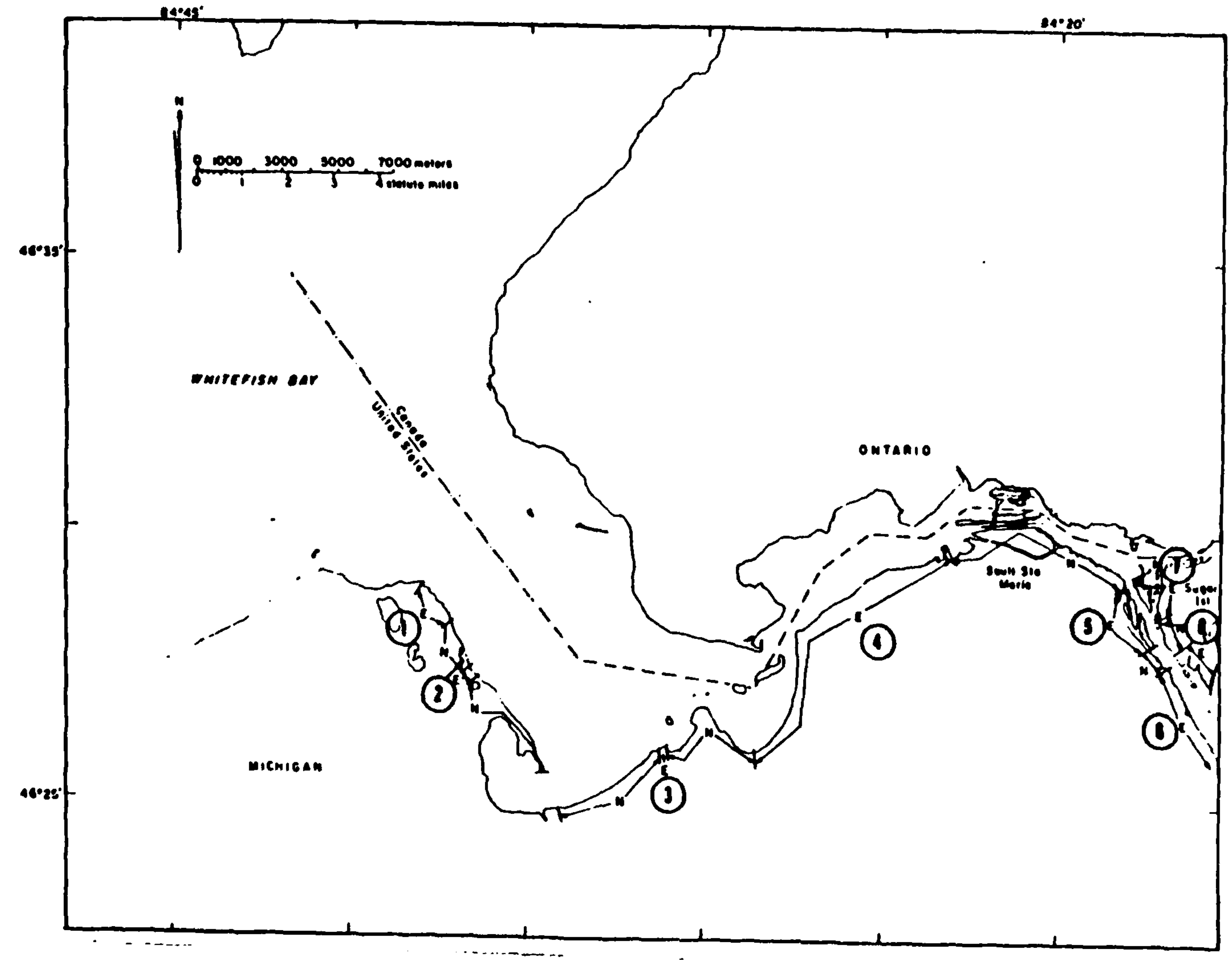


Figure 43 Potential Erosion Sites on the St. Marys River

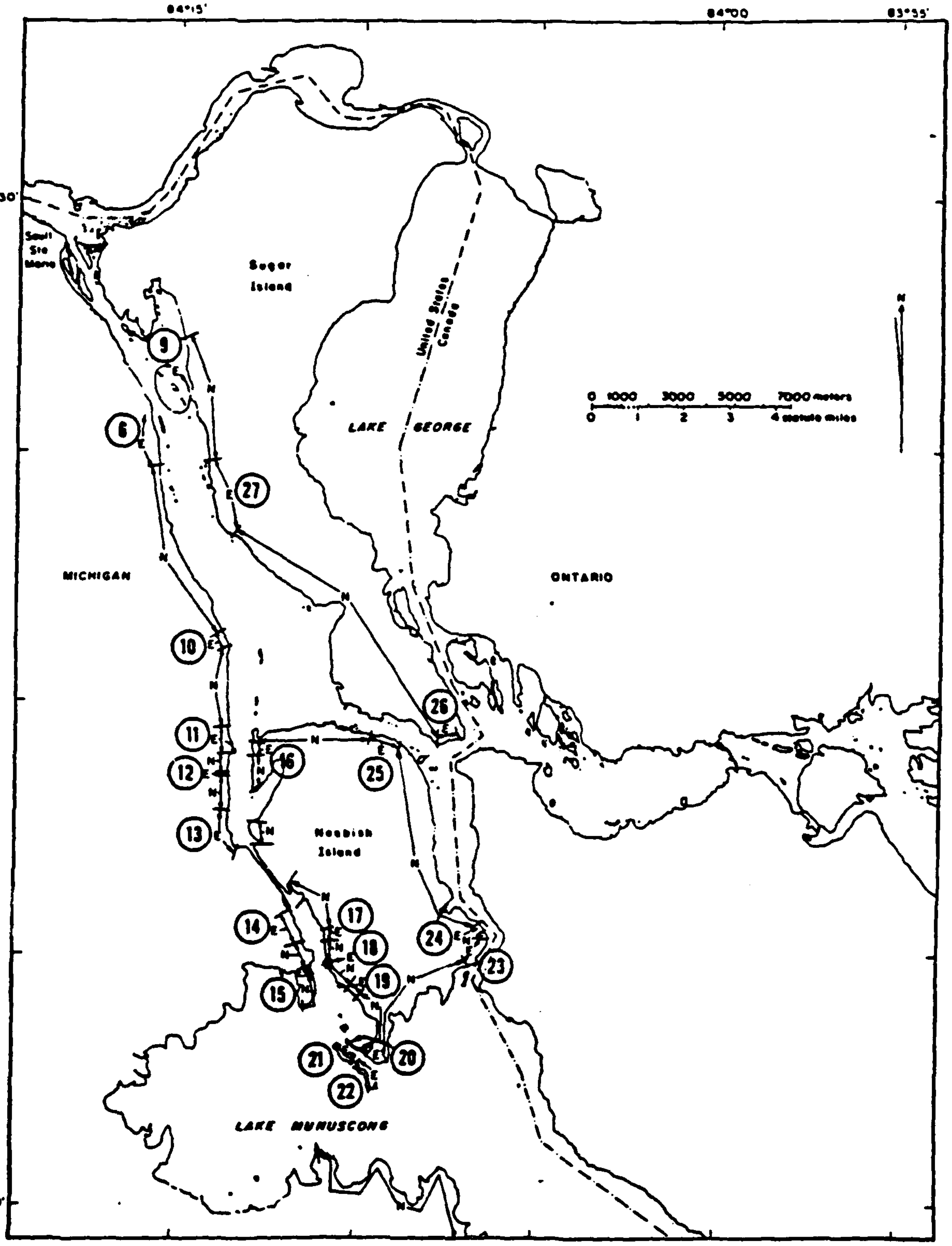


Figure 43 (cont.)

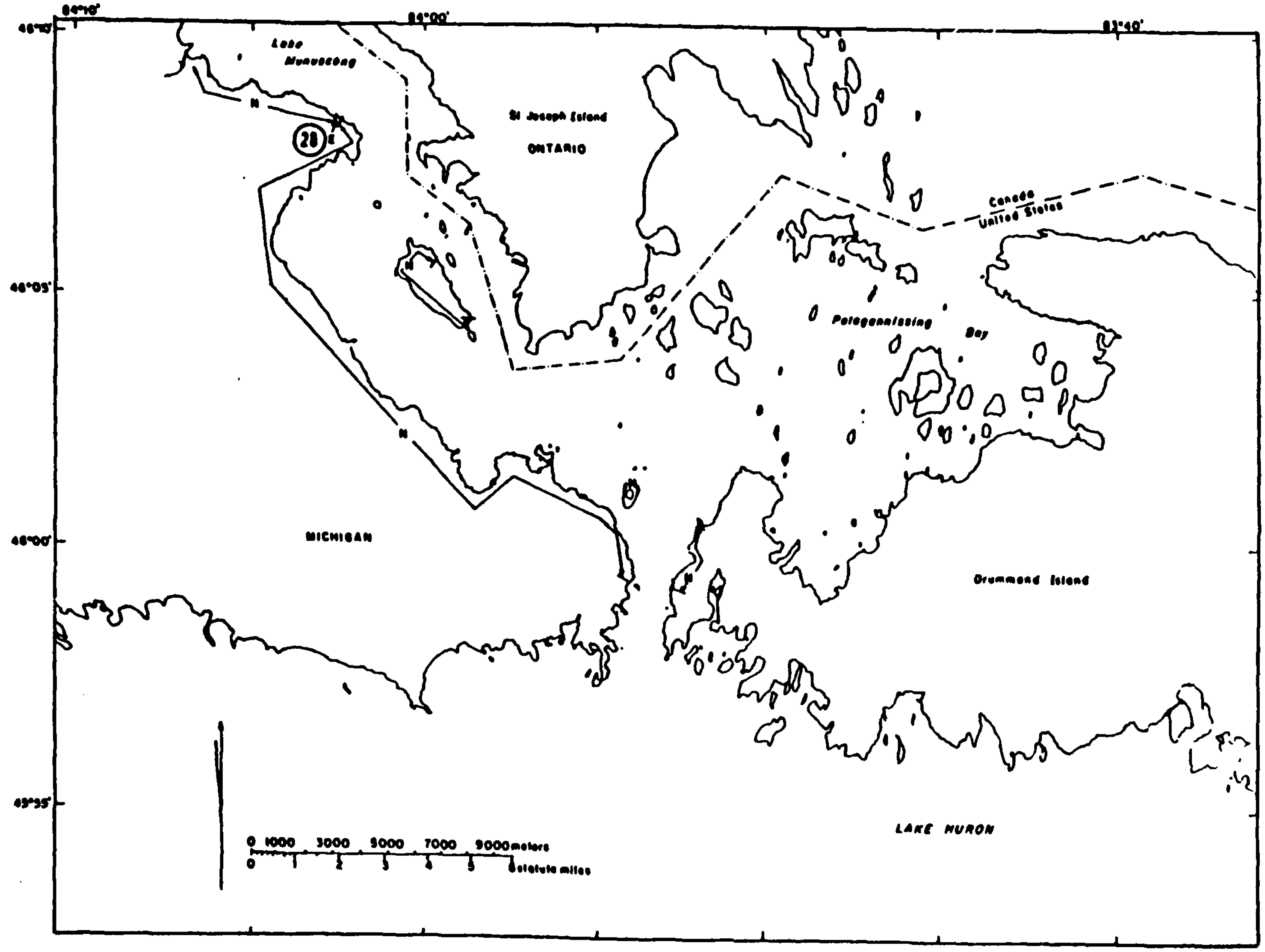


Figure 43 (cont.)

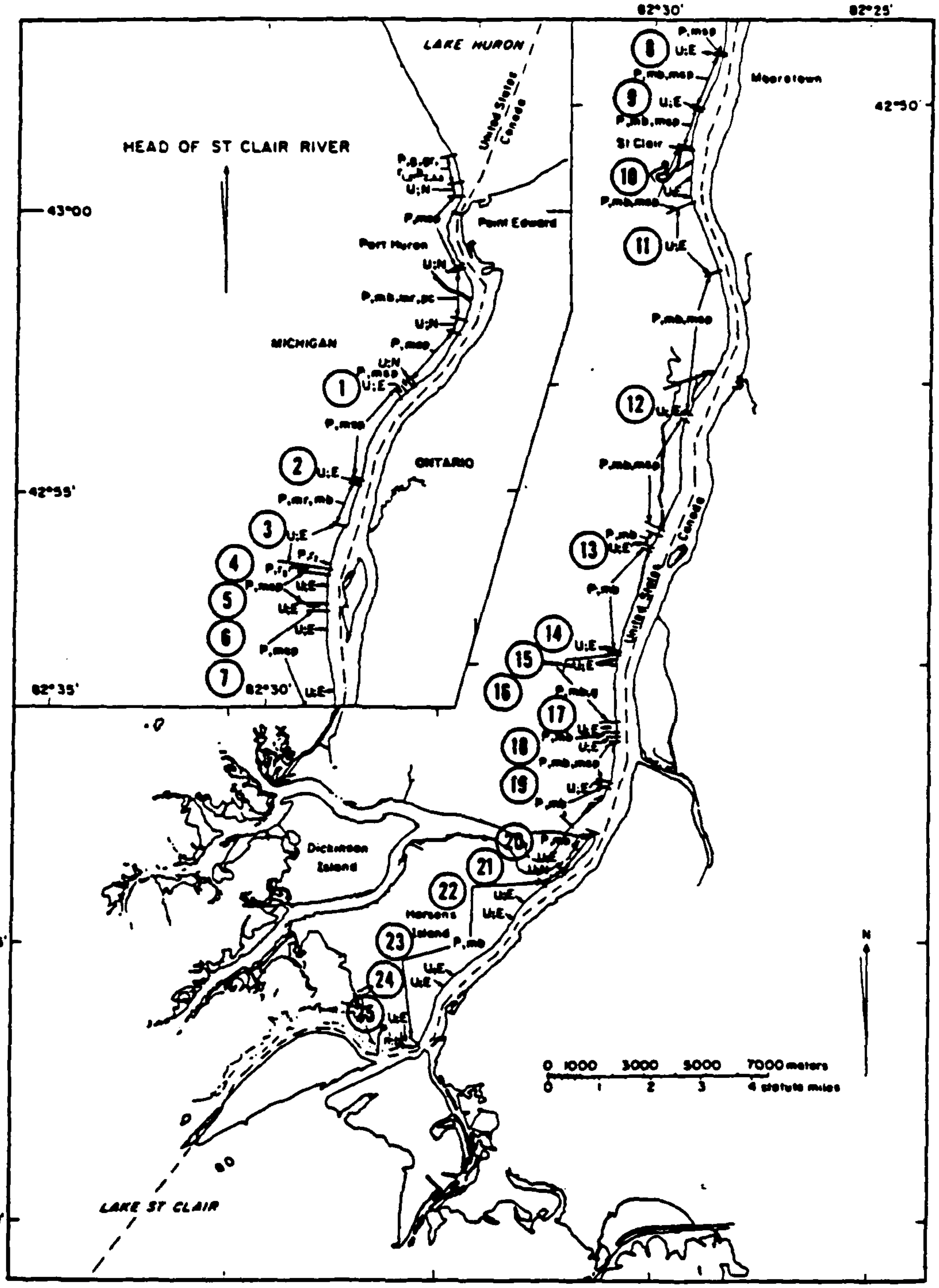


Figure 44 Potential Erosion Sites on the St. Clair River

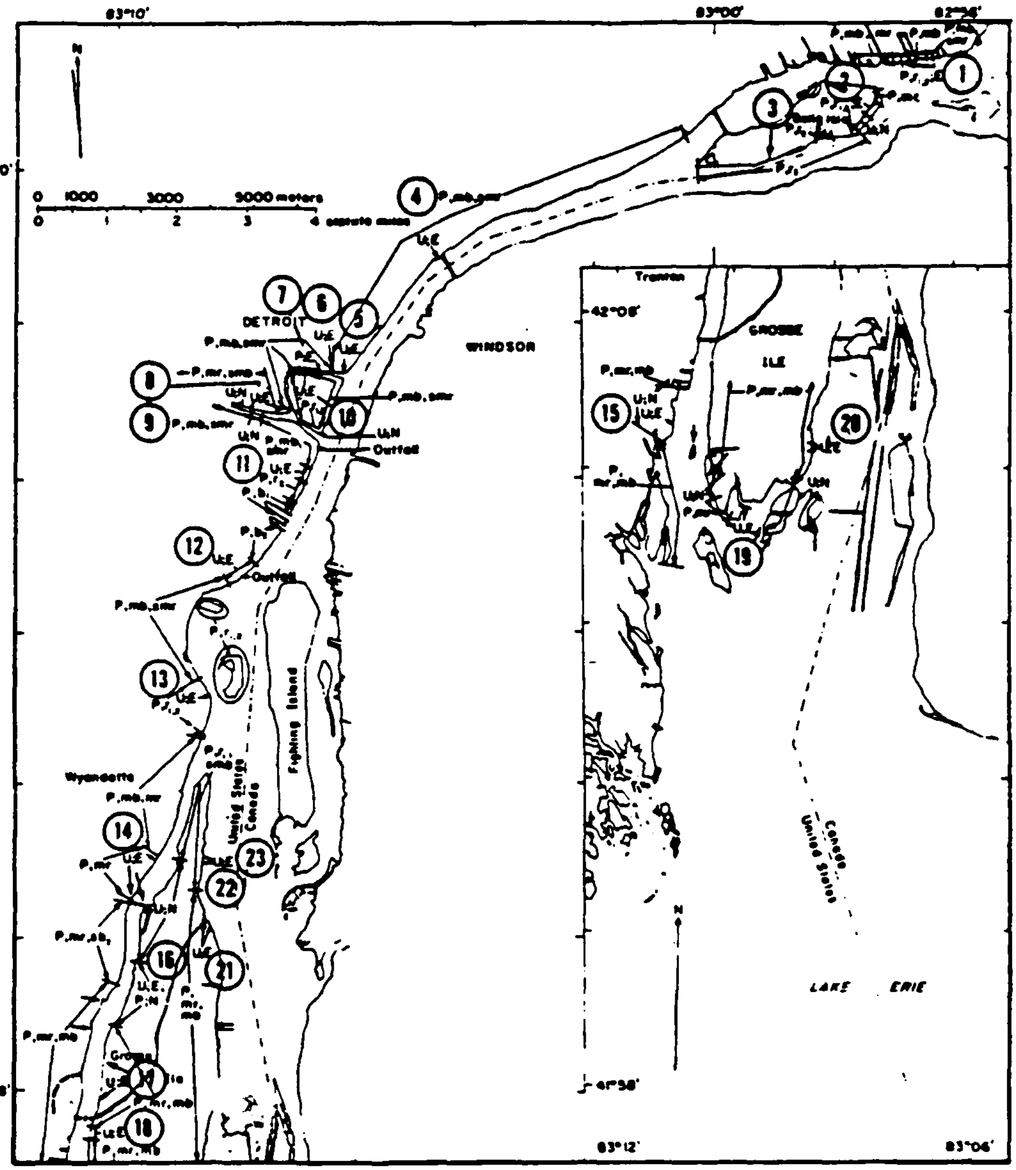


Figure 45 Potential Erosion Sites on the Detroit River

APPENDIX A

Channel Cross-Section Characteristics

VARIABLES INCLUDED:

- Cross-section number
- Water-level datums
- Topwidth
- Depth
- Area
- Shape factor
- Speed limits (up & down)
- Channel scour velocity
- Bank scour velocity

ST. MARYS RIVER

CROSS SECTION	DATUM	TOPWIDTH (ft)	DEPTH (ft)	AREA (ft^2)	SHAPE FACTOR
-430+84	LWD	3600	28.0	40000	.40
-430+84	LWD+1	3600	29.0	43600	.42
-430+84	LWD+2	3600	30.0	47200	.44
-330+84	LWD	4600	28.0	81800	.64
-330+84	LWD+1	4600	29.0	84400	.63
-330+84	LWD+2	4600	30.0	87000	.63
-230+84	LWD	6000	28.0	99400	.59
-230+84	LWD+1	6000	29.0	105400	.61
-230+84	LWD+2	6000	30.0	111400	.62
19+16A	LWD	1480	34.0	31550	.63
19+16A	LWD+1	1480	35.0	33188	.64
19+16A	LWD+2	1480	36.0	34520	.65
40+03A	LWD	746	32.5	20972	.87
40+03A	LWD+1	760	33.5	21754	.85
40+03A	LWD+2	764	34.5	22360	.85
40+03B	LWD	990	32.5	22688	.71
40+03B	LWD+1	1020	33.5	23622	.69
40+03B	LWD+2	1054	34.5	24556	.68
48+56A	LWD	740	31.0	17706	.77
48+56A	LWD+1	760	32.0	18500	.76
48+56A	LWD+2	780	33.0	19212	.75
48+56B	LWD	700	31.0	17924	.83
48+56B	LWD+1	720	32.0	18518	.80
48+56B	LWD+2	740	33.0	19074	.78
145+67A	LWD	1090	33.5	24804	.68
145+67A	LWD+1	1100	34.5	25898	.68
145+67A	LWD+2	1200	35.5	26874	.63
145+67B	LWD	1780	31.5	28710	.51
145+67B	LWD+1	1840	32.5	30390	.51
145+67B	LWD+2	1880	33.5	32030	.51
182+81A	LWD	1600	31.0	25204	.51
182+81A	LWD+1	1800	32.0	26938	.47
182+81A	LWD+2	1000	33.0	28674	.87
182+81B	LWD	4500	30.0	37346	.28
182+81B	LWD+1	4800	31.0	41224	.28
182+81B	LWD+2	4800	32.0	47652	.31
297+66A	LWD	4200	32.5	82398	.60
297+66A	LWD+1	4500	33.5	87614	.58
297+66A	LWD+2	4900	34.5	92828	.55
297+66B	LWD	6800	32.5	125580	.57
297+66B	LWD+1	7000	33.5	133506	.57
297+66B	LWD+2	7200	34.5	140182	.56
352+15A	LWD	6500	33.0	104520	.49
352+15A	LWD+1	6700	34.0	109714	.48
352+15A	LWD+2	6900	35.0	115326	.48
352+15B	LWD	5000	34.0	98910	.58
352+15B	LWD+1	5600	35.0	103898	.53
352+15B	LWD+2	5600	36.0	109092	.54
414+31A	LWD	8500	32.0	164364	.60
414+31A	LWD+1	8600	33.0	176072	.62
414+31A	LWD+2	9100	34.0	183312	.59
414+31B	LWD	2300	37.0	51604	.61
414+31B	LWD+1	2400	38.0	54376	.60
414+31B	LWD+2	2400	39.0	57766	.62

ST. MARYS RIVER

CROSS SECTION	DATUM	TOPWIDTH (ft)	DEPTH (ft)	AREA (ft^2)	SHAPE FACTOR
494+62AB	LWD	5700	38.5	42830	.20
494+62AB	LWD+1	5800	39.5	51520	.22
494+62AB	LWD+2	5900	40.5	57920	.24
494+62BB	LWD	9800	32.0	125120	.40
494+62BB	LWD+1	10200	33.0	136320	.40
494+62BB	LWD+2	10800	34.0	147200	.40
494+62AR	LWD	9200	33.0	96320	.32
494+62AR	LWD+1	9400	34.0	52480	.16
494+62AR	LWD+2	9500	35.0	116800	.35
494+62BR	LWD	6300	33.0	72000	.35
494+62BR	LWD+1	6600	34.0	80320	.36
494+62BR	LWD+2	7000	35.0	86720	.35
564+70AB	LWD	2200	32.0	28426	.40
564+70AB	LWD+1	3300	33.0	31656	.29
564+70AB	LWD+2	3300	34.0	35856	.32
564+70BB	LWD	15700	30.0	114994	.24
564+70BB	LWD+1	15800	31.0	135666	.28
564+70BB	LWD+2	15800	32.0	151818	.30
564+70AR	LWD	8800	30.0	54266	.21
564+70AR	LWD+1	9900	31.0	70740	.23
564+70AR	LWD+2	9900	32.0	79462	.25
564+70BR	LWD	9200	30.0	68156	.25
564+70BR	LWD+1	9200	31.0	75586	.27
564+70BR	LWD+2	9200	32.0	89798	.31
699+02A	LWD	2350	32.5	18788	.25
699+02A	LWD+1	2450	33.5	20960	.26
699+02A	LWD+2	2525	34.5	23990	.28
699+02B	LWD	900	32.0	22070	.77
699+02B	LWD+1	925	33.0	22878	.75
699+02B	LWD+2	925	34.0	23838	.76
740+30A	LWD	820	32.0	15592	.59
740+30A	LWD+1	820	33.0	16040	.59
740+30A	LWD+2	820	34.0	16870	.61
740+30B	LWD	890	32.5	23386	.81
740+30B	LWD+1	900	33.5	24024	.80
740+30B	LWD+2	900	34.5	25176	.81
769+43A	LWD	700	31.0	11216	.52
769+43A	LWD+1	750	32.0	11696	.49
769+43A	LWD+2	750	33.0	13334	.54
769+43B	LWD	4200	31.5	36470	.28
769+43B	LWD+1	4250	32.5	40314	.29
769+43B	LWD+2	4300	33.5	44392	.31
819+43A	LWD	1100	31.5	23198	.67
819+43A	LWD+1	1100	32.5	24162	.68
819+43A	LWD+2	1150	33.5	25432	.66
819+43B	LWD	1750	33.0	37564	.65
819+43B	LWD+1	2000	34.0	39188	.58
819+43B	LWD+2	2400	35.0	57818	.69
843+84A	LWD	1700	34.5	50470	.86
843+84A	LWD+1	1700	35.5	52452	.87
843+84A	LWD+2	1700	36.5	54282	.87
853+81A	LWD	3000	35.0	41676	.40
853+81A	LWD+1	3025	36.0	44572	.41
853+81A	LWD+2	3050	37.0	47618	.42
866+15A	LWD	5500	33.5	46120	.25
866+15A	LWD+1	5600	34.5	51792	.27
866+15A	LWD+2	5675	35.5	57912	.29

ST. MARYS RIVER

CROSS SECTION	DATUM	TOPWIDTH (ft)	DEPTH (ft)	AREA (ft^2)	SHAPE FACTOR
922+31A	LWD	3650	29.5	33706	.31
922+31A	LWD+1	3800	30.5	37260	.32
922+31A	LWD+2	4000	31.5	41320	.33
997+38A	LWD	1950	33.0	37582	.58
997+38A	LWD+1	2000	34.0	39900	.59
997+38A	LWD+2	2300	35.0	41210	.51
1075+37A	LWD	880	33.5	19628	.67
1075+37A	LWD+1	910	34.5	20518	.65
1075+37A	LWD+2	920	35.5	21260	.65
1101+32A	LWD	1700	33.5	35798	.63
1101+32A	LWD+1	1700	34.5	37468	.64
1101+32A	LWD+2	1700	35.5	39190	.65
676+31A	LWD	3775	31.5	15600	.13
676+31A	LWD+1	4000	32.5	19500	.15
676+31A	LWD+2	4100	33.5	19650	.14
676+31B	LWD	1800	33.0	18000	.30
676+31B	LWD+1	1825	34.0	19600	.32
676+31B	LWD+2	1900	35.0	21600	.32
717+49A	LWD	3100	31.5	27530	.28
717+49A	LWD+1	3150	32.5	31216	.30
717+49A	LWD+2	3300	33.5	34824	.32
717+49B	LWD	1650	29.5	15608	.32
717+49B	LWD+1	1675	30.5	17020	.33
717+49B	LWD+2	1675	31.5	18510	.35
788+71A	LWD	3450	40.0	60938	.44
788+71A	LWD+1	3600	41.0	64788	.44
788+71A	LWD+2	3625	42.0	68262	.45
788+71B	LWD	1700	35.0	26572	.45
788+71B	LWD+1	1750	36.0	27510	.44
788+71B	LWD+2	1750	37.0	29202	.45
820+34A	LWD	390	37.5	11258	.77
820+34A	LWD+1	400	38.5	11644	.76
820+34A	LWD+2	400	39.5	11892	.75
832+54A	LWD	300	31.0	9354	1.00
832+54A	LWD+1	300	32.0	9644	1.00
832+54A	LWD+2	300	33.0	9956	1.00
854+98A	LWD	310	30.5	9832	1.00
854+98A	LWD+1	310	31.5	10144	1.00
854+98A	LWD+2	310	32.5	10424	1.00
881+10A	LWD	290	32.0	8744	.94
881+10A	LWD+1	290	33.0	9026	.94
881+10A	LWD+2	290	34.0	9316	.94
909+97A	LWD	400	34.5	12038	.87
909+97A	LWD+1	400	35.5	12414	.87
909+97A	LWD+2	400	36.5	12764	.87

ST. MARYS RIVER

CROSS SECTION	UP LIMIT (fps)	DOWN LIMIT (fps)	CHAN. SCOUR VEL. (fps)	BANK SCOUR VEL. (fps)
-430+84	18	17.6	2	2.30
-330+84	18	17.6	2	2.30
-230+84	18	17.6	2	2.30
19+16A	12	14.7	4	10.00
40+03A	12	14.7	4	10.00
40+03B	12	14.7	4	10.00
48+56A	12	14.7	4	4.00
48+56B	12	14.7	4	4.00
145+67A	12	14.7	4	2.50
145+67B	12	14.7	4	2.50
182+81A	12	14.7	4	2.30
182+81B	12	14.7	4	2.30
297+66A	15	14.7	4	2.30
297+66B	15	14.7	4	2.30
352+15A	15	14.7	4	2.30
352+15B	15	14.7	4	2.30
414+31A	15	14.7	4	2.30
414+31B	15	14.7	4	2.30
494+62AB	-	14.7	4	2.30
494+62BB	-	14.7	4	2.30
494+62AR	18	-	4	2.30
494+62BR	18	-	4	2.30
564+70AB	-	14.7	4	2.30
564+70BB	-	14.7	4	2.30
564+70AR	18	-	4	2.30
564+70BR	18	-	4	2.30
699+02A	13	-	4	4.00
699+02B	13	-	4	4.00
740+30A	13	-	6	4.00
740+30B	13	-	6	4.00
769+43A	13	-	6	2.30
769+43B	13	-	6	2.30
819+43A	13	-	6	2.30
819+43B	13	-	6	2.30
843+84A	13	-	4	2.30
853+81A	13	-	2	2.30
866+15A	13	-	4	2.30
922+31A	13	-	4	2.30
997+38A	13	-	4	2.30
1075+37A	13	-	6	2.30
1101+32A	13	-	6	2.30
676+31A	-	14.7	4	2.30
676+31B	-	14.7	4	2.30
717+49A	-	14.7	4	2.30
717+49B	-	14.7	4	2.30
788+71A	-	14.7	4	2.30
788+71B	-	14.7	4	2.30
820+34A	-	14.7	6	10.00
832+54A	-	14.7	6	10.00
854+98A	-	14.7	6	10.00
881+10A	-	14.7	6	10.00
909+97A	-	14.7	4	4.00

ST. CLAIR RIVER

CROSS SECTION	DATUM	TOPWIDTH (ft)	DEPTH (ft)	AREA (ft^2)	SHAPE FACTOR
333+30A	LWD	1800	27.0	38300	.79
333+30A	LWD+1	1800	28.0	40200	.80
333+30A	LWD+2	1800	29.0	42100	.81
413+30A	LWD	1200	27.0	27600	.85
413+30A	LWD+1	1200	28.0	28800	.86
413+30A	LWD+2	1200	29.0	30000	.86
453+30A	LWD	1900	27.0	29400	.57
453+30A	LWD+1	1900	28.0	31200	.59
453+30A	LWD+2	1900	29.0	33000	.60
493+30A	LWD	2200	27.0	37200	.63
493+30A	LWD+1	2200	28.0	39400	.64
493+30A	LWD+2	2200	29.0	41600	.65
533+30A	LWD	1700	27.0	29000	.63
533+30A	LWD+1	1700	28.0	30600	.64
533+30A	LWD+2	1700	29.0	32200	.65
573+30W	LWD	1040	41.0	38792	.91
573+30W	LWD+1	1040	42.0	39832	.91
573+30W	LWD+2	1040	43.0	40872	.91
602+70	LWD	2000	39.0	58944	.76
602+70	LWD+1	2000	40.0	62944	.79
602+70	LWD+2	2000	41.0	66944	.82
612+50	LWD	1720	39.5	47462	.70
612+50	LWD+1	1720	40.5	50062	.72
612+50	LWD+2	1720	41.5	52662	.74
624+60	LWD	1280	40.5	32528	.63
624+60	LWD+1	1520	41.5	35488	.56
624+60	LWD+2	1560	42.5	38568	.58
633+50	LWD	1460	34.0	26416	.53
633+50	LWD+1	1520	35.0	29376	.55
633+50	LWD+2	1560	36.0	32496	.58
642+40	LWD	1480	42.5	41158	.69
642+40	LWD+1	1480	43.5	42598	.66
642+40	LWD+2	1480	44.5	44078	.67
654+20	LWD	1520	45.5	61436	.89
654+20	LWD+1	1520	46.5	62996	.89
654+20	LWD+2	1520	47.5	64556	.89
666+10	LWD	1560	51.5	60630	.76
666+10	LWD+1	1560	52.5	63800	.78
666+10	LWD+2	1560	53.5	66920	.80
675+20	LWD	1520	59.0	60528	.67
675+20	LWD+1	1560	60.0	63568	.68
675+20	LWD+2	1580	61.0	66648	.69
684+40	LWD	1480	53.0	46792	.60
684+40	LWD+1	1480	54.0	50072	.63
684+40	LWD+2	1480	55.0	53272	.65
696+60	LWD	1560	51.5	37888	.47
696+60	LWD+1	1600	52.5	41008	.49
696+60	LWD+2	1640	53.5	44248	.50
714+80	LWD	1540	33.0	36604	.72
714+80	LWD+1	1570	34.0	39724	.74
714+80	LWD+2	1580	35.0	42844	.77
730+00	LWD	1600	42.5	45022	.64
730+00	LWD+1	1660	43.5	46703	.65
730+00	LWD+2	1660	44.5	48382	.65

ST. CLAIR RIVER

CROSS SECTION	DATUM	TOPWIDTH (ft)	DEPTH (ft)	AREA (ft^2)	SHAPE FACTOR
740+00	LWD	1560	34.5	33208	.62
740+00	LWD+1	1560	35.5	38008	.69
740+00	LWD+2	1560	36.5	42808	.75
751+20	LWD	1680	40.5	42264	.62
751+20	LWD+1	1690	41.5	45624	.65
751+20	LWD+2	1700	42.5	48984	.68
769+40	LWD	2060	48.0	52014	.53
769+40	LWD+1	2060	49.0	54074	.54
769+40	LWD+2	2060	50.0	56134	.54
793+60	LWD	1700	32.0	41360	.76
793+60	LWD+1	1700	33.0	44720	.80
793+60	LWD+2	1700	34.0	48160	.83
817+40	LWD	1600	33.5	44228	.83
817+40	LWD+1	1600	34.5	47468	.86
817+40	LWD+2	1600	35.5	50708	.89
838+20	LWD	1370	33.0	38640	.85
838+20	LWD+1	1370	34.0	41360	.89
838+20	LWD+2	1370	35.0	44080	.92
859+30	LWD	1560	35.0	41888	.77
859+30	LWD+1	1560	36.0	45008	.80
859+30	LWD+2	1560	37.0	48128	.83
952+80	LWD	1280	42.0	45050	.84
952+80	LWD+1	1280	43.0	46330	.84
952+80	LWD+2	1280	44.0	47610	.85
968+30	LWD	1440	43.0	49360	.80
968+30	LWD+1	1480	44.0	52280	.80
968+30	LWD+2	1480	45.0	55240	.83
989+00	LWD	2100	38.0	58444	.73
989+00	LWD+1	2100	39.0	60524	.74
989+00	LWD+2	2100	40.0	62604	.75
1008+30	LWD	2300	31.0	54720	.77
1008+30	LWD+1	2340	32.0	59400	.79
1008+30	LWD+2	2340	33.0	64120	.83
1034+80	LWD	2380	31.0	52756	.72
1034+80	LWD+1	2380	32.0	57516	.76
1034+80	LWD+2	2380	33.0	62276	.79
1059+80	LWD	2110	30.0	49634	.78
1059+80	LWD+1	2120	31.0	51794	.79
1059+80	LWD+2	2120	32.0	53954	.80
1080+00	LWD	2000	36.0	57056	.79
1080+00	LWD+1	2080	37.0	61136	.79
1080+00	LWD+2	2140	38.0	65336	.80
1095+00	LWD	1720	39.0	48680	.73
1095+00	LWD+1	1720	40.0	52200	.76
1095+00	LWD+2	1720	41.0	55840	.79
1115+00	LWD	1720	39.0	56220	.84
1115+00	LWD+1	1720	40.0	59660	.87
1115+00	LWD+2	1720	41.0	63100	.89
1140+00	LWD	1680	44.0	58640	.79
1140+00	LWD+1	1680	45.0	62000	.82
1140+00	LWD+2	1680	46.0	65360	.85
1160+00	LWD	2120	44.5	66716	.71
1160+00	LWD+1	2120	45.5	70956	.74
1160+00	LWD+2	2120	46.5	75196	.76
1176+00	LWD	1660	50.0	57500	.69
1176+00	LWD+1	1660	51.0	60820	.72
1176+00	LWD+2	1660	52.0	64140	.74

ST. CLAIR RIVER

CROSS SECTION	DATUM	TOPWIDTH (ft)	DEPTH (ft)	AREA (ft^2)	SHAPE FACTOR
1192+00	LWD	1480	53.0	46254	.59
1192+00	LWD+1	1520	54.0	49264	.60
1192+00	LWD+2	1530	55.0	52304	.62
1212+00	LWD	1480	51.0	56228	.74
1212+00	LWD+1	1520	52.0	59228	.75
1212+00	LWD+2	[illegible]30	53.0	62268	.77
1231+70	LWD	[illegible]20	56.5	63772	.62
1231+70	LWD+1	1840	57.5	67452	.64
1231+70	LWD+2	1880	58.5	71172	.65
1247+00	LWD	1170	47.0	51096	.93
1247+00	LWD+1	1210	48.0	54296	.93
1247+00	LWD+2	1240	49.0	57576	.95
1261+60	LWD	1600	47.0	53132	.71
1261+60	LWD+1	1600	48.0	56332	.73
1261+60	LWD+2	1600	49.0	59532	.76
1286+60	LWD	1800	38.0	62150	.91
1286+60	LWD+1	1800	39.0	63960	.91
1286+60	LWD+2	1800	40.0	65770	.91
1302+50	LWD	1780	50.0	61584	.69
1302+50	LWD+1	1800	51.0	63414	.69
1302+50	LWD+2	1860	52.0	65334	.68
1317+30	LWD	1960	43.0	64604	.77
1317+30	LWD+1	1960	44.0	66564	.77
1317+30	LWD+2	1960	45.0	68524	.78
1327+70	LWD	1520	46.0	48076	.69
1327+70	LWD+1	1560	47.0	49616	.68
1327+70	LWD+2	1600	48.0	51196	.67
1337+70	LWD	1320	32.0	34642	.82
1337+70	LWD+1	1340	33.0	35782	.81
1337+70	LWD+2	1360	34.0	37102	.80
1353+30	LWD	1240	33.0	34416	.84
1353+30	LWD+1	1240	34.0	35656	.85
1353+30	LWD+2	1240	35.0	36896	.85
1358+68	LWD	1220	33.0	32452	.81
1358+68	LWD+1	1220	34.0	33692	.81
1358+68	LWD+2	1220	35.0	34932	.82
1369+20	LWD	1200	38.0	34490	.76
1369+20	LWD+1	1200	39.0	35670	.76
1369+20	LWD+2	1200	40.0	36850	.77
1380+20	LWD	1120	31.5	28906	.82
1380+20	LWD+1	1120	32.5	30026	.82
1380+20	LWD+2	1120	33.5	31146	.83
1395+10	LWD	1320	32.5	30716	.72
1395+10	LWD+1	1330	33.5	32076	.72
1395+10	LWD+2	1340	34.5	33436	.72
1410+30	LWD	1360	31.0	28906	.69
1410+30	LWD+1	1390	32.0	30266	.68
1410+30	LWD+2	1400	33.0	31626	.68
1425+20	LWD	1200	33.0	32302	.82
1425+20	LWD+1	1200	34.0	33502	.82
1425+20	LWD+2	1200	35.0	34702	.83
1439+30	LWD	1320	35.5	31396	.67
1439+30	LWD+1	1340	36.5	32716	.67
1439+30	LWD+2	1340	37.5	34036	.68
1454+40	LWD	1260	33.0	32654	.79
1454+40	LWD+1	1260	34.0	33914	.79
1454+40	LWD+2	1260	35.0	35174	.80

ST. CLAIR RIVER

CROSS SECTION	DATUM	TOPWIDTH (ft)	DEPTH (ft)	AREA (ft^2)	SHAPE FACTOR
1479+30	LWD	1640	33.5	40150	.73
1479+30	LWD+1	1640	34.5	41690	.74
1479+30	LWD+2	1640	35.5	43330	.74
1488+00	LWD	1560	32.5	38114	.75
1488+00	LWD+1	1640	33.5	39254	.71
1488+00	LWD+2	1680	34.5	40434	.70
1509+50W	LWD	1580	32.5	42792	.83
1509+50W	LWD+1	1580	33.5	44372	.84
1509+50W	LWD+2	1580	34.5	45952	.84
1554+70	LWD	2020	34.0	52754	.77
1554+70	LWD+1	2020	35.0	54754	.77
1554+70	LWD+2	2020	36.0	56754	.78
1644+30	LWD	1220	32.0	32604	.84
1644+30	LWD+1	1260	33.0	33864	.81
1644+30	LWD+2	1300	34.0	35104	.79
1671+90	LWD	1040	40.0	31774	.76
1671+90	LWD+1	1050	41.0	32814	.76
1671+90	LWD+2	1060	42.0	33854	.76
1684+20	LWD	1520	34.5	39698	.76
1684+20	LWD+1	1520	35.5	41218	.76
1684+20	LWD+2	1520	36.5	42738	.77
1704+30	LWD	1640	34.0	43320	.78
1704+30	LWD+1	1640	35.0	44960	.78
1704+30	LWD+2	1640	36.0	46600	.79
1719+50	LWD	1560	33.0	37132	.72
1719+50	LWD+1	1580	34.0	38572	.72
1719+50	LWD+2	1610	35.0	40052	.71
1734+90	LWD	1380	30.5	37156	.88
1734+90	LWD+1	1380	31.5	38456	.88
1734+90	LWD+2	1380	32.5	39856	.89
1750+30	LWD	1520	32.0	38868	.80
1750+30	LWD+1	1520	33.0	40388	.81
1750+30	LWD+2	1520	34.0	41908	.81
1765+00	LWD	1840	32.0	46038	.78
1765+00	LWD+1	1840	33.0	47878	.79
1765+00	LWD+2	1840	34.0	49718	.79
1784+60	LWD	1540	35.0	41056	.76
1784+60	LWD+1	1540	36.0	42596	.77
1784+60	LWD+2	1540	37.0	44136	.77
1801+00	LWD	1920	36.0	53736	.78
1801+00	LWD+1	1920	37.0	55656	.78
1801+00	LWD+2	1920	38.0	57576	.79
1824+80	LWD	2400	38.0	63850	.70
1824+80	LWD+1	2400	39.0	66250	.71
1824+80	LWD+2	2400	40.0	68650	.72
1845+00	LWD	2000	32.5	51320	.79
1845+00	LWD+1	2000	33.5	53320	.80
1845+00	LWD+2	2000	34.5	55320	.80
1859+80	LWD	1480	32.0	39774	.84
1859+80	LWD+1	1480	33.0	41254	.84
1859+80	LWD+2	1480	34.0	42734	.85
1874+00	LWD	1520	35.5	37000	.69
1874+00	LWD+1	1560	36.5	38520	.68
1874+00	LWD+2	1560	37.5	40080	.69
1889+60	LWD	1560	32.0	41584	.83
1889+60	LWD+1	1560	33.0	43144	.84
1889+60	LWD+2	1560	34.0	44704	.84

ST. CLAIR RIVER

CROSS SECTION	DATUM	TOPWIDTH (ft)	DEPTH (ft)	AREA (ft^2)	SHAPE FACTOR
1964+10	LWD	1600	33.5	44076	.82
1964+10	LWD+1	1600	34.5	45676	.83
1964+10	LWD+2	1600	35.5	47276	.83
2079+70	LWD	1320	39.0	37132	.72
2079+70	LWD+1	1320	40.0	38452	.73
2079+70	LWD+2	1320	41.0	29772	.73

ST. CLAIR RIVER

CROSS SECTION	UP LIMIT (fps)	DOWN LIMIT (fps)	CHAN. SCOUR VEL. (fps)	BANK SCOUR VEL. (fps)
333+30A	18	17.6	4	10.00
413+30A	18	17.6	4	10.00
453+30A	18	17.6	4	10.00
493+30A	18	17.6	4	10.00
533+30A	18	17.6	4	10.00
573+30W	18	17.6	4	2.00
602+70	18	17.6	4	10.00
612+50	18	17.6	4	10.00
624+60	18	17.6	4	10.00
633+50	18	17.6	4	10.00
642+40	18	17.6	4	10.00
654+20	18	17.6	4	10.00
666+10	18	17.6	4	10.00
675+20	18	17.6	3	2.00
684+40	18	17.6	3	10.00
696+60	18	17.6	2	10.00
714+80	18	17.6	2	10.00
730+00	18	17.6	4	10.00
740+00	18	17.6	4	10.00
751+20	18	17.6	4	10.00
769+40	18	17.6	4	10.00
793+60	18	17.6	4	10.00
817+40	18	17.6	4	10.00
838+20	18	17.6	4	10.00
859+30	18	17.6	4	10.00
952+80	18	17.6	4	10.00
968+30	18	17.6	4	10.00
989+00	18	17.6	4	10.00
1008+30	18	17.6	3	10.00
1034+80	18	17.6	2	10.00
1059+80	18	17.6	2	10.00
1080+00	18	17.6	2	10.00
1095+00	18	17.6	2	10.00
1115+00	18	17.6	2	10.00
1140+00	18	17.6	2	10.00
1160+00	18	17.6	2	10.00
1176+00	18	17.6	2	10.00
1192+00	18	17.6	2	10.00
1212+00	18	17.6	2	10.00
1231+70	18	17.6	2	10.00
1247+00	18	17.6	2	10.00
1261+60	18	17.6	2	10.00
1286+60	18	17.6	2	10.00
1302+50	18	17.6	4	10.00
1317+30	18	17.6	4	10.00
1327+70	18	17.6	4	10.00
1337+70	18	17.6	4	10.00
1353+30	18	17.6	4	10.00
1358+68	18	17.6	4	10.00
1369+20	18	17.6	4	10.00
1380+20	18	17.6	4	10.00
1395+10	18	17.6	4	10.00
1410+30	18	17.6	4	10.00
1425+20	18	17.6	4	10.00
1439+30	18	17.6	4	10.00
1454+40	18	17.6	4	10.00
1479+30	18	17.6	4	10.00
1488+00	18	17.6	4	10.00

ST. CLAIR RIVER

CROSS SECTION	UP LIMIT (fps)	DOWN LIMIT (fps)	CHAN. SCOUR VEL. (fps)	BANK SCOUR VEL. (fps)
1509+50W	18	17.6	4	10.00
1554+70	18	17.6	4	10.00
1644+30	13	17.6	4	4.00
1671+90	13	17.6	4	4.00
1684+20	13	17.6	4	4.00
1704+30	13	17.6	4	4.00
1719+50	13	17.6	4	4.00
1734+90	13	17.6	4	4.00
1750+30	13	17.6	4	4.00
1765+00	13	17.6	4	4.00
1784+60	13	17.6	4	4.00
1801+00	13	17.6	4	4.00
1824+80	13	17.6	4	10.00
1845+00	13	17.6	4	10.00
1859+80	13	17.6	4	2.25
1874+00	13	17.6	4	10.00
1889+60	13	17.6	2	10.00
1964+10	13	17.6	2	10.00
2079+70	13	17.6	2	10.00

DETROIT RIVER

CROSS SECTION	DATUM	TOPWIDTH (ft)	DEPTH (ft)	AREA (ft^2)	SHAPE FACTOR
219+19A	LWD	690	34.0	15138	.65
219+19A	LWD+1	690	35.0	15900	.66
219+19A	LWD+2	690	36.0	16612	.67
219+19B	LWD	1064	34.5	25654	.70
219+19B	LWD+1	1064	35.5	26854	.71
219+19B	LWD+2	1064	36.5	28202	.73
328+79A	LWD	1256	31.0	23492	.60
328+79A	LWD+1	1270	32.0	24932	.61
328+79A	[illegible]	1284	33.0	26060	.62
328+79B	[illegible]	1100	31.7	17510	.50
328+79B	LWD+1	1150	32.7	18762	.50
328+79B	LWD+2	1190	33.7	25904	.65
433+33A	LWD	1930	26.0	32954	.66
433+33A	LWD+1	1960	27.0	35170	.66
433+33A	LWD+2	1980	28.0	37016	.67
433+33B	LWD	810	24.5	14318	.72
433+33B	LWD+1	820	25.5	15454	.74
433+33B	LWD+2	820	26.5	16164	.74
548+10A	LWD	3900	30.5	82256	.69
548+10A	LWD+1	4000	31.5	86358	.69
548+10A	LWD+2	4800	32.5	91486	.59
700+00A	LWD	2700	33.0	54940	.62
700+00A	LWD+1	2700	34.0	59874	.65
700+00A	LWD+2	2700	35.0	61968	.66
700+00B	LWD	6900	32.5	81496	.36
700+00B	LWD+1	6900	33.5	91366	.40
700+00B	LWD+2	6900	34.5	92562	.39
893+23A	LWD	2160	32.0	65488	.95
893+23A	LWD+1	2160	33.0	67348	.94
893+23A	LWD+2	2200	34.0	69022	.92
930+25A	LWD	2800	39.5	90902	.82
930+25A	LWD+1	2850	40.5	93358	.81
930+25A	LWD+2	2850	41.5	95970	.81
1051+81A	LWD	2880	41.5	90196	.75
1051+81A	LWD+1	2880	42.5	92768	.76
1051+81A	LWD+2	2920	43.5	94696	.75
1104+70A	LWD	1960	44.5	70864	.81
1104+70A	LWD+1	1960	45.5	72488	.81
1104+70A	LWD+2	1960	46.5	74548	.82
1217+22A	LWD	2840	46.0	91288	.70
1217+22A	LWD+1	2840	47.0	93636	.70
1217+22A	LWD+2	2840	48.0	96592	.71
1326+11A	LWD	3308	34.5	106852	.94
1326+11A	LWD+1	3308	35.5	110514	.94
1326+11A	LWD+2	3308	36.5	114618	.96
1387+02A	LWD	2260	38.5	57778	.66
1387+02A	LWD+1	2260	39.5	59604	.67
1387+02A	LWD+2	2260	40.5	61918	.68
1520+66A	LWD	1440	44.0	40000	.63
1520+66A	LWD+1	1440	45.0	40964	.63
1520+66A	LWD+2	1440	46.0	42368	.64
1550+15A	LWD	5700	34.0	116226	.60
1550+15A	LWD+1	5700	35.0	120754	.61
1550+15A	LWD+2	5700	36.0	126604	.62

DETROIT RIVER

CROSS SECTION	DATUM	TOPWIDTH (ft)	DEPTH (ft)	AREA (ft^2)	SHAPE FACTOR
1573+89A	LWD	3160	39.5	42272	.34
1573+89A	LWD+1	3160	40.5	46310	.36
1573+89A	LWD+2	3160	41.5	49086	.37
1611+77A	LWD	1900	34.0	54916	.85
1611+77A	LWD+1	1900	35.0	57254	.86
1611+77A	LWD+2	1900	36.0	59086	.87

DETROIT RIVER

CROSS SECTION	UP LIMIT (fps)	DOWN LIMIT (fps)	CHAN. SCOUR VEL. (fps)	BANK SCOUR VEL. (fps)
219+19A	3	2.9	4	10.00
219+19B	3	2.9	4	10.00
328+79A	3	2.9	4	10.00
328+79B	3	2.9	4	10.00
433+33A	3	2.9	6	10.00
433+33B	3	2.9	6	10.00
548+10A	18	17.6	2	10.00
700+00A	18	20.5	2	10.00
700+00B	18	20	2	10.00
893+23A	18	20.5	4	10.00
930+25A	18	20.5	3	10.00
1051+81A	18	20.5	3	10.00
1104+70A	18	20.5	3	10.00
1217+22A	18	20.5	3	10.00
1326+11A	18	20.5	4	10.00
1387+02A	18	20.5	4	10.00
1520+66A	18	20.5	2	10.00
1550+15A	18	20.5	4	10.00
1573+89A	18	20.5	2	10.00
1611+77A	18	20.5	4	10.00

Appendix B

Detailed Ship Effects Figures

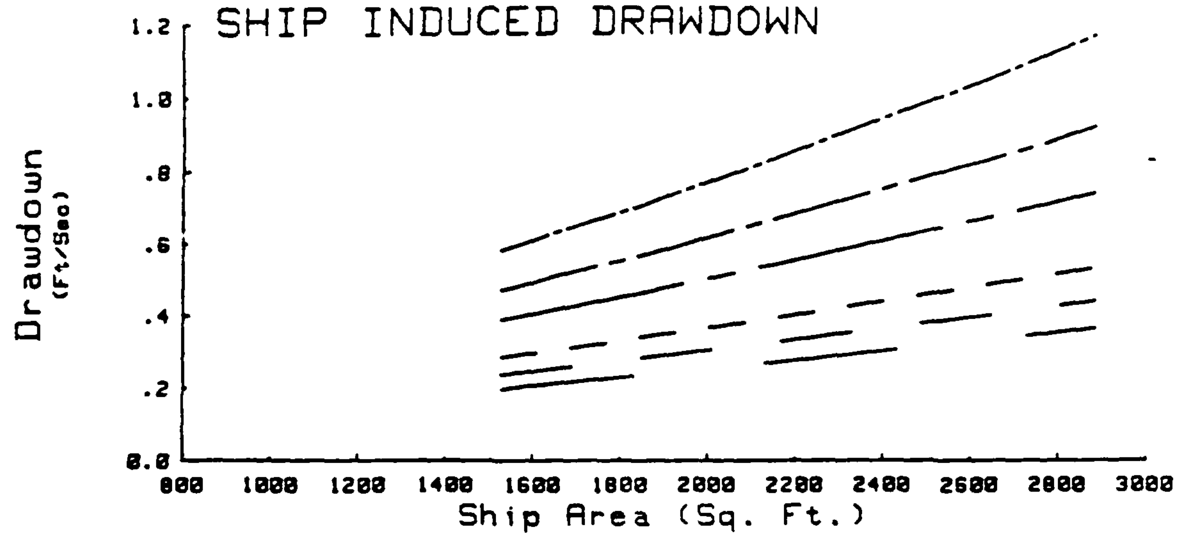
KEY:

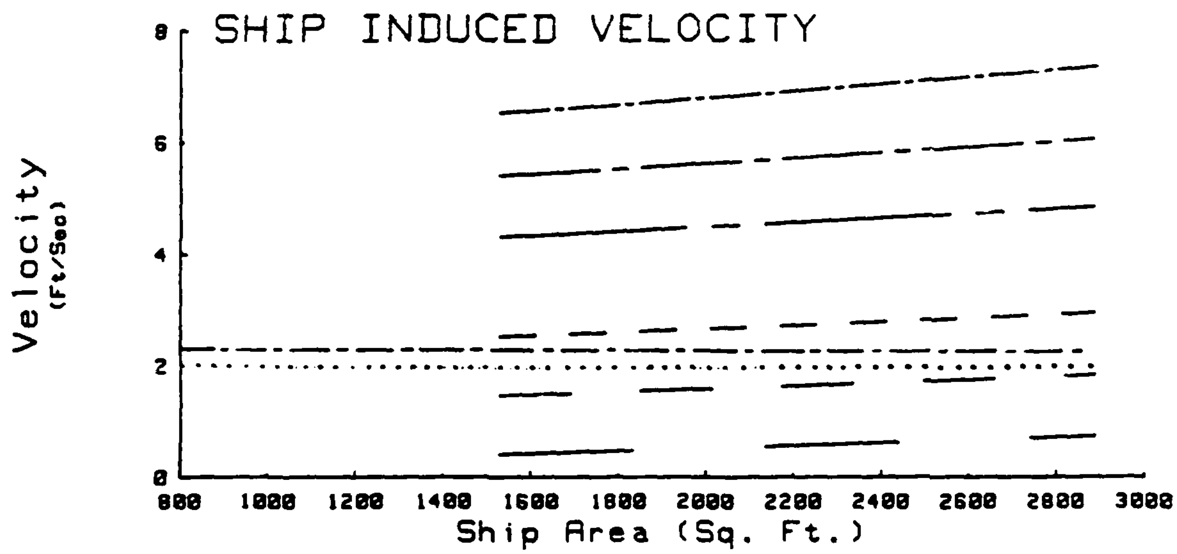
DOWN BOUND AT SPEED
DOWN BOUND AT SPEED+1
DOWN BOUND AT SPEED+2
UP BOUND AT SPEED
UP BOUND AT SPEED+1
UP BOUND AT SPEED+2

Median Vessel Dimensions By Class

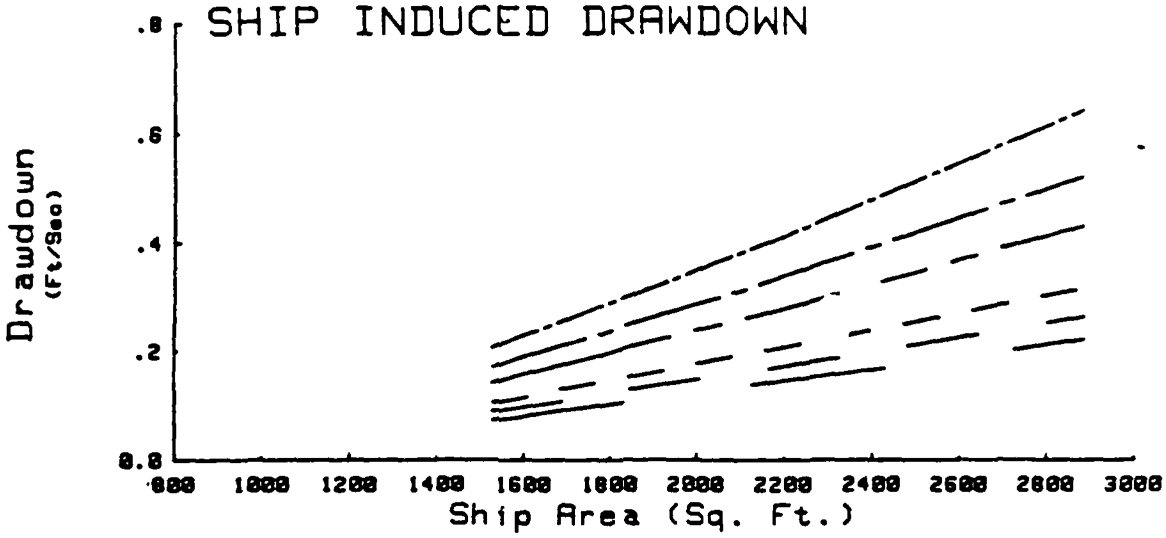
Class	Length (ft)	Beam (ft)	Draft (ft)	Area (ft)
5	627	60	25.5	1530
		60	26.5	1590
		60	27.5	1650
6	676	70	25.5	1785
		70	26.5	1855
		70	27.5	1925
7	728	60	25.5	1530
		60	26.5	1590
		60	27.5	1650
8	728	70	25.5	1785
		70	26.5	1855
		70	27.5	1925
10	1000	105	25.5	2677.5
		105	26.5	2782.5
		105	27.5	2887.5

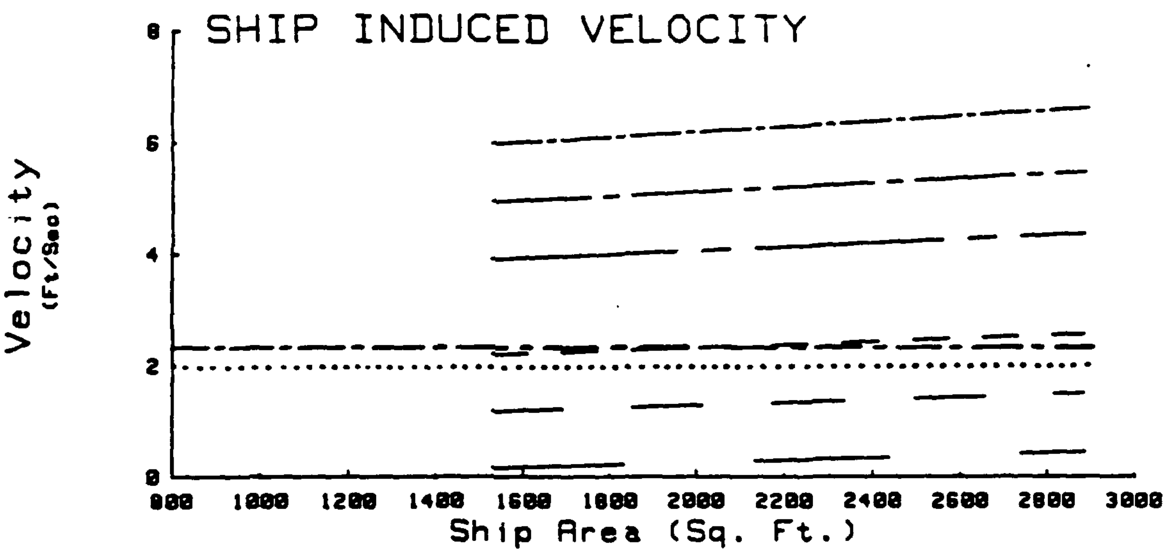
ST. MARYS RIVER
-230+84 AT LWD+0



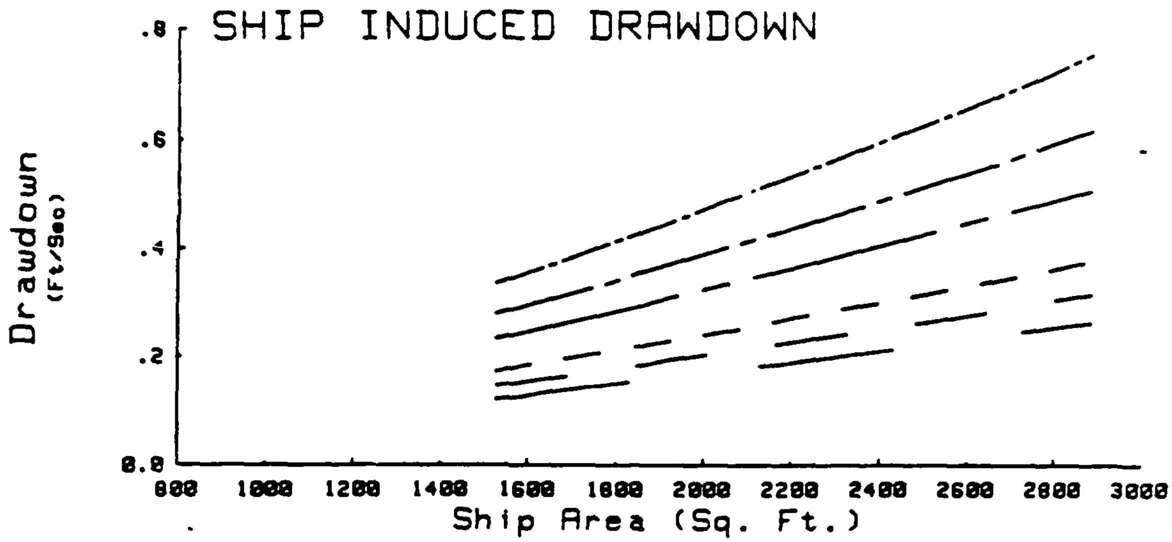


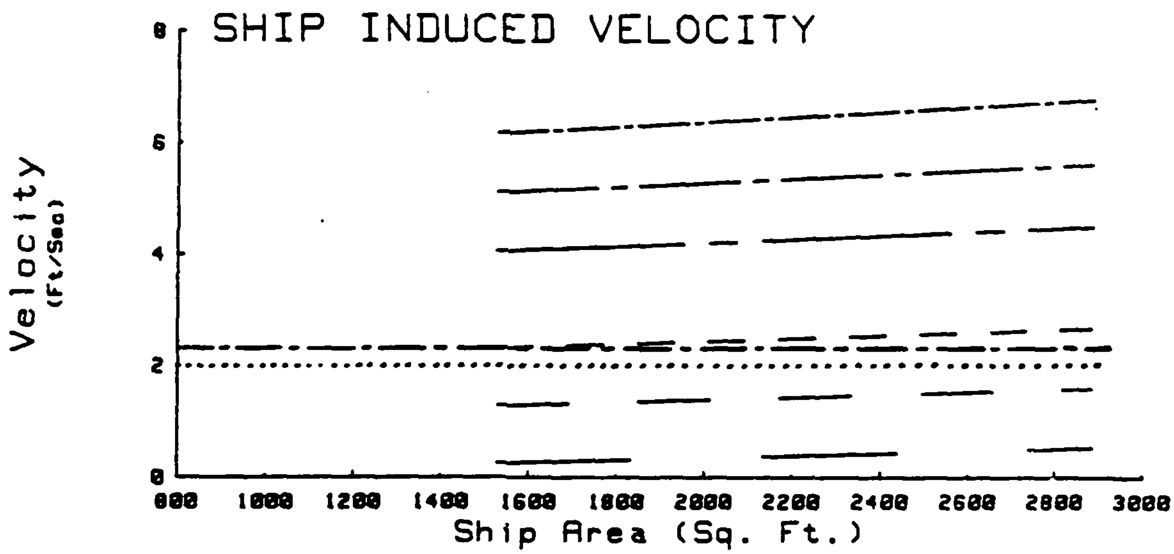
ST. MARYS RIVER
-230+84 AT LWD+1



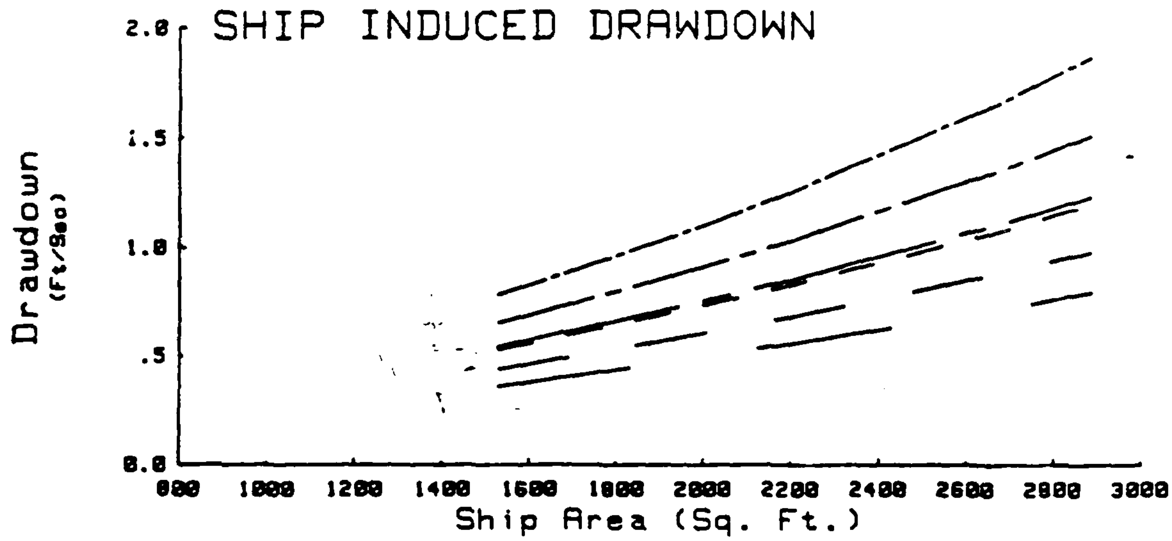


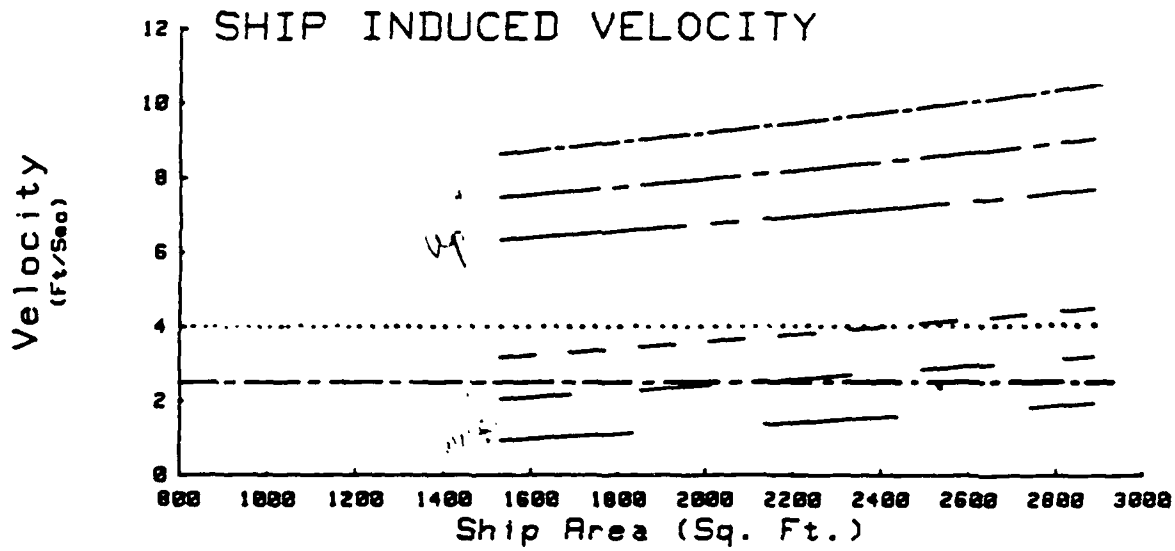
ST. MARYS RIVER
-230+84 AT LWD+2



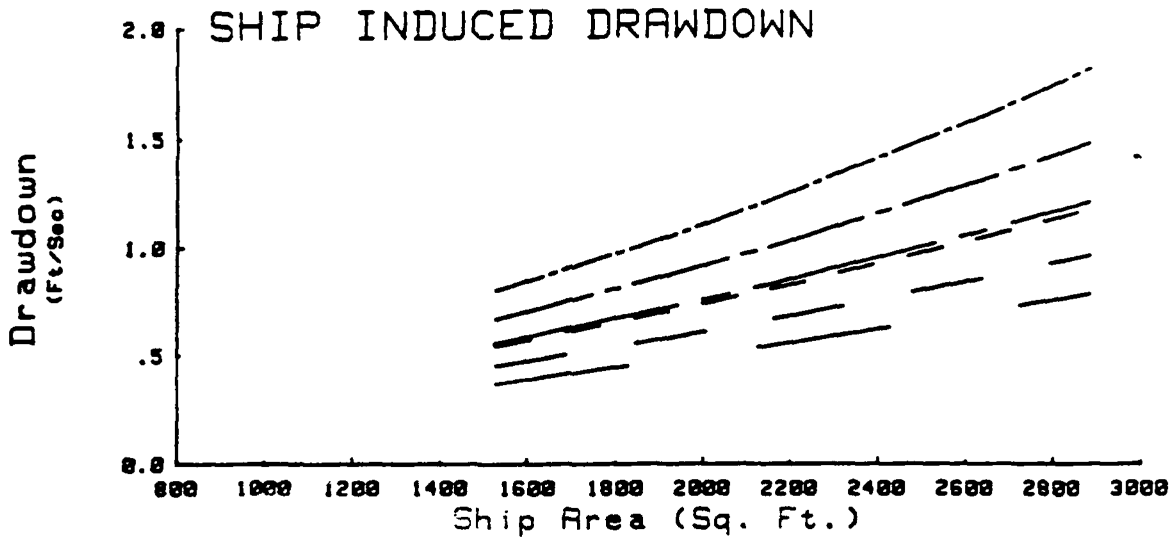


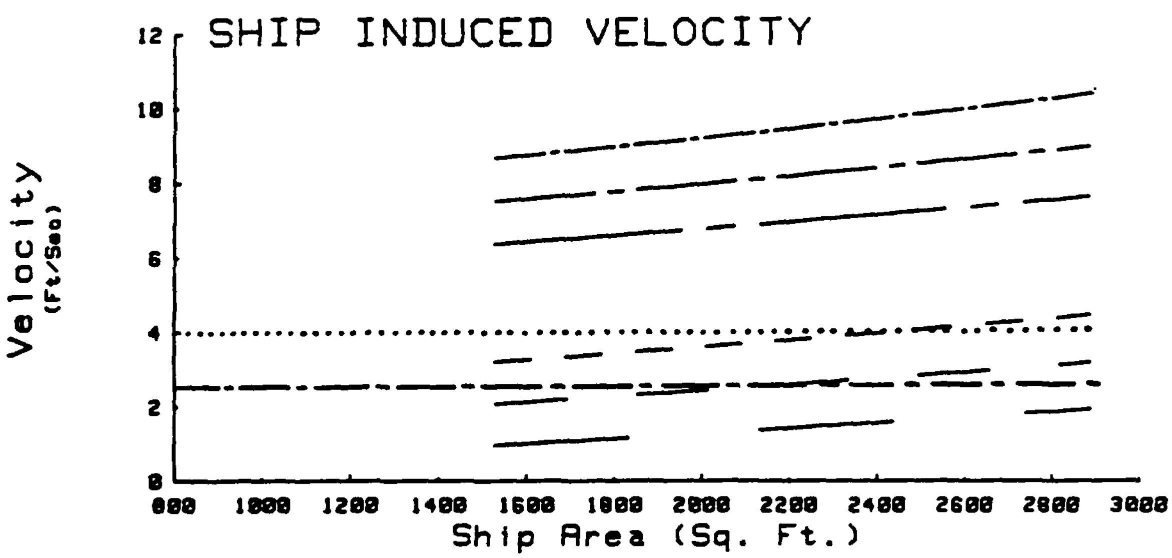
ST. MARYS RIVER
145+67W AT LWD+0



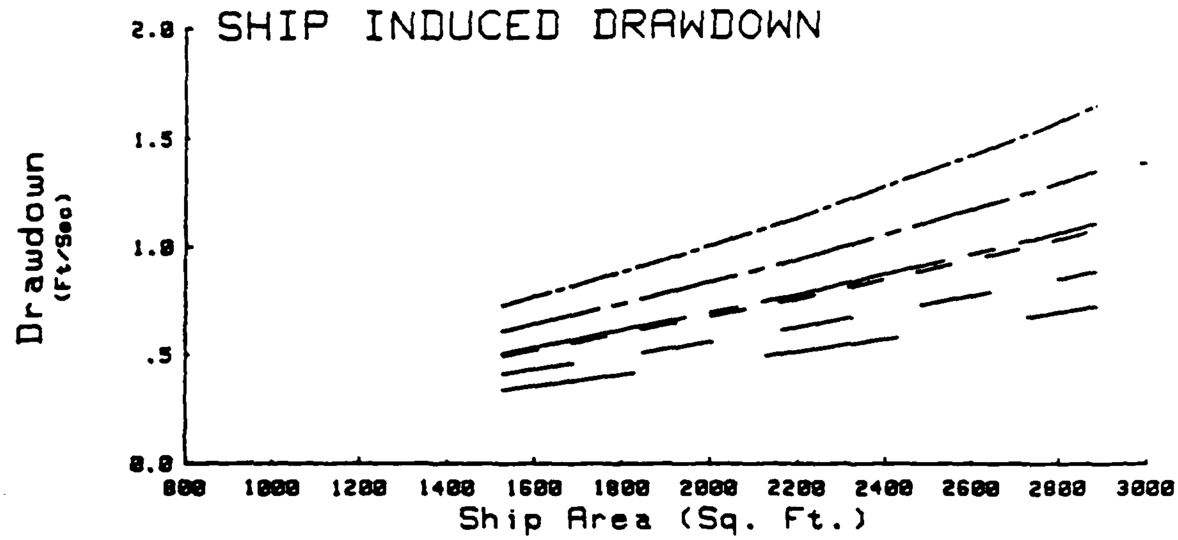


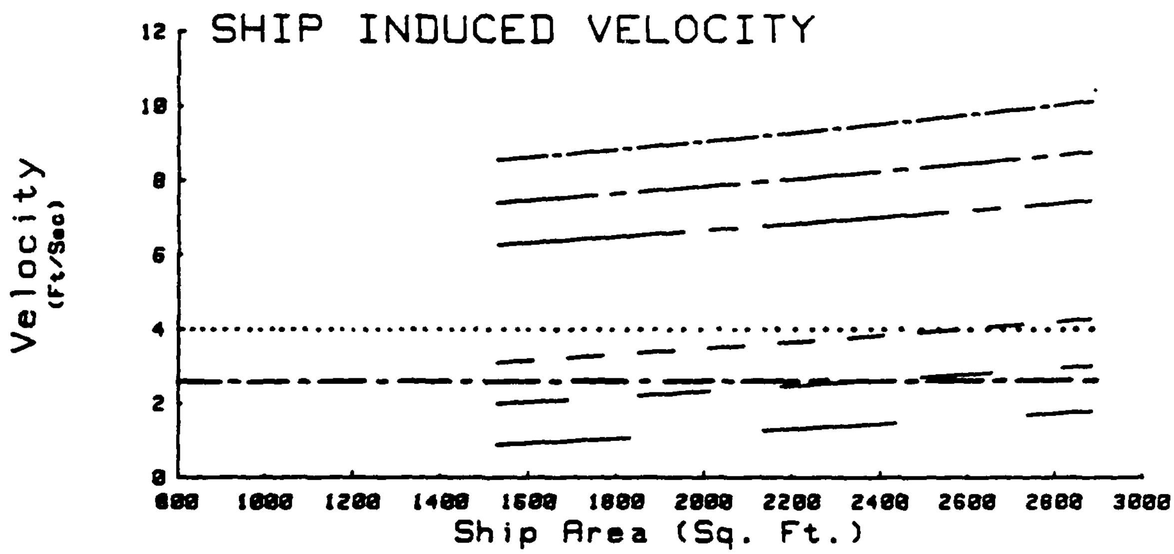
ST. MARYS RIVER
145+67W AT LWD+1



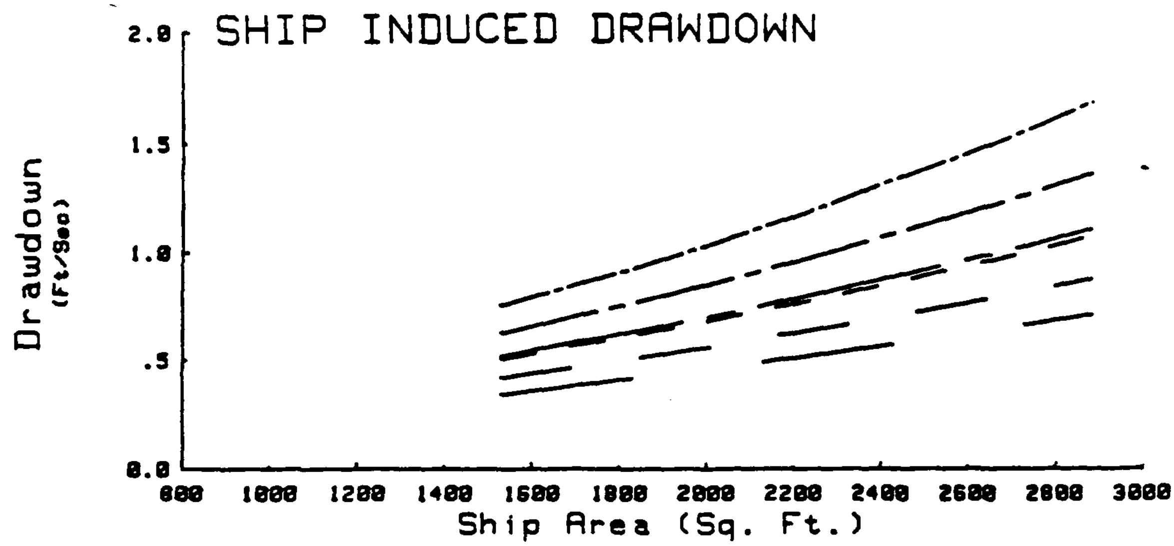


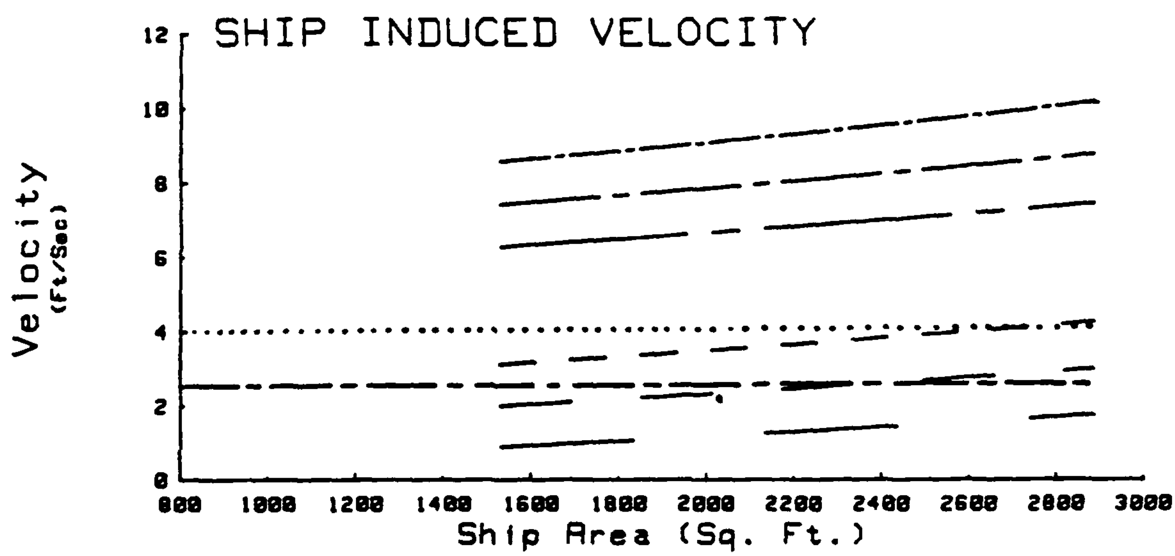
ST. MARYS RIVER
145+67W AT LWD+2



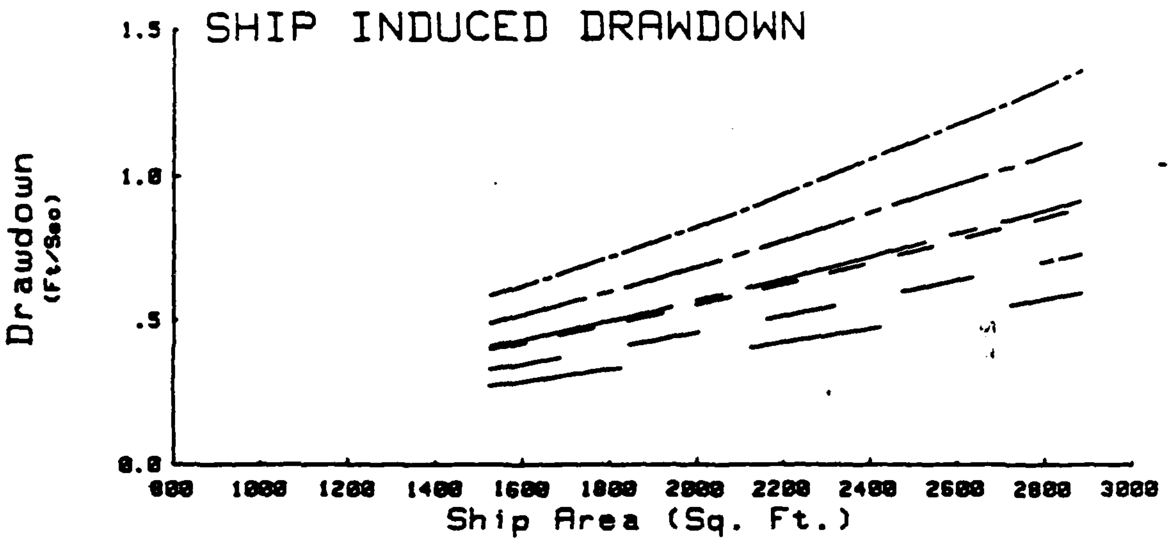


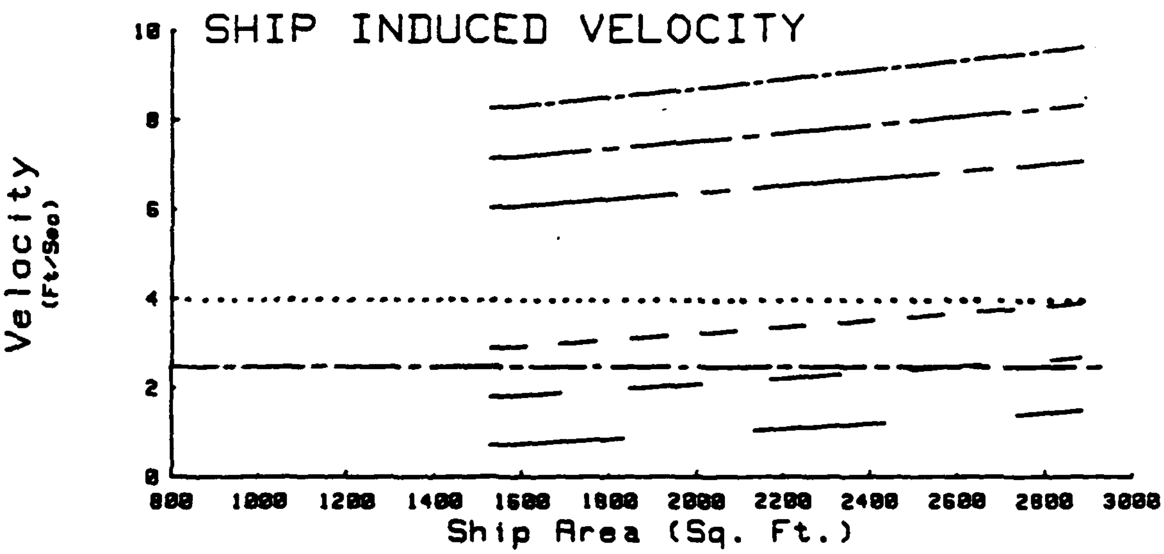
ST. MARYS RIVER
145+67E AT LWD+0



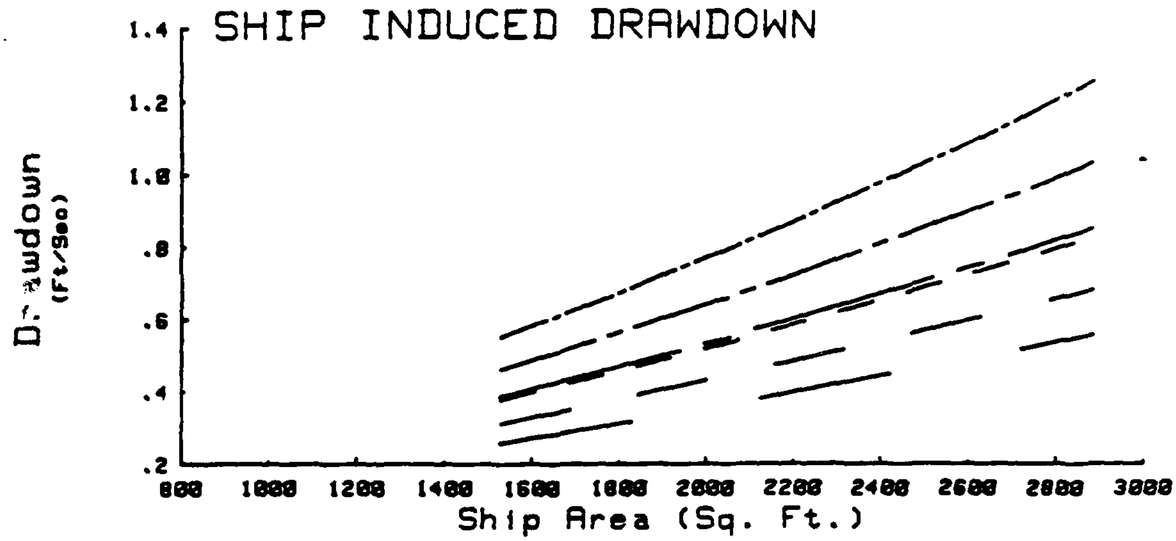


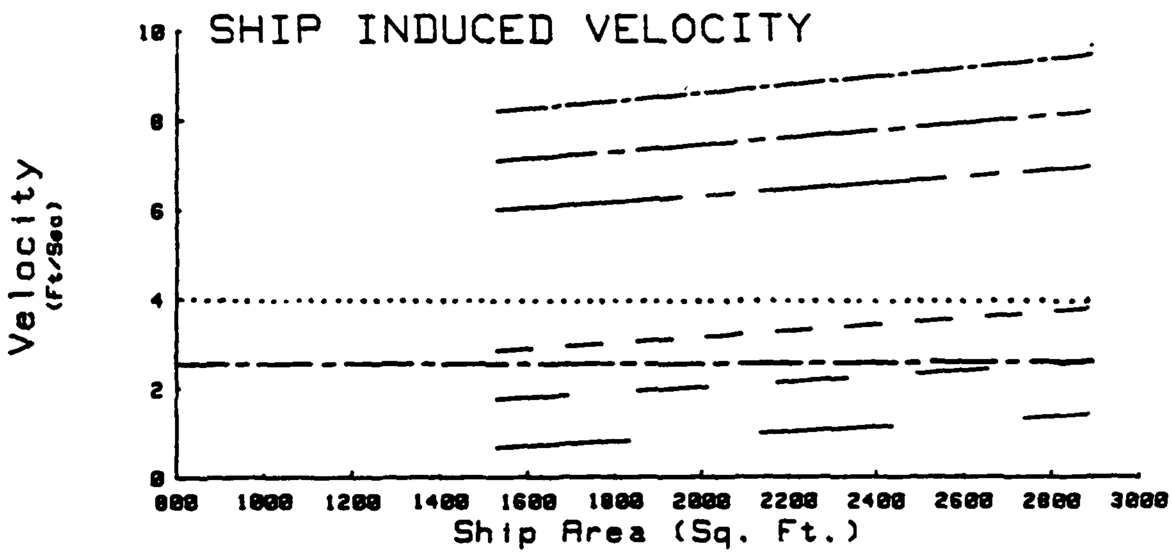
ST. MARYS RIVER
145+67E AT LWD+1



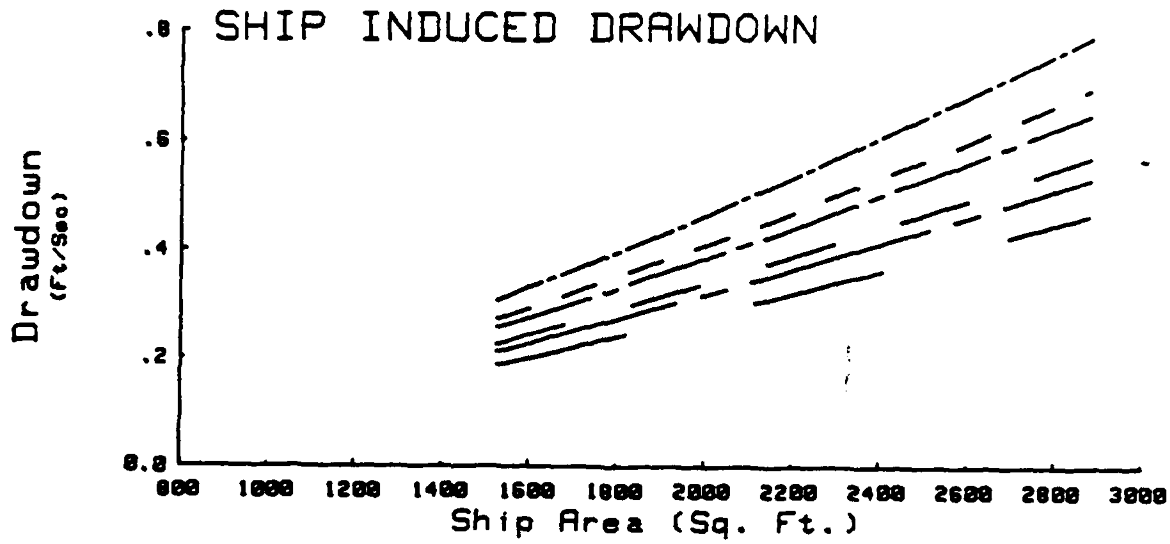


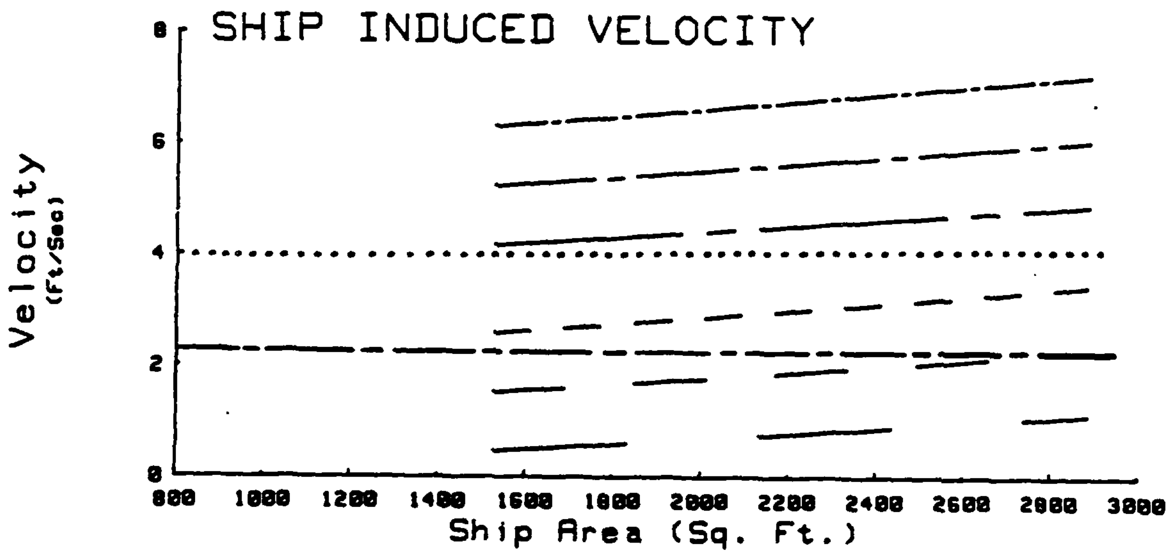
ST. MARYS RIVER
145+67E AT LWD+2



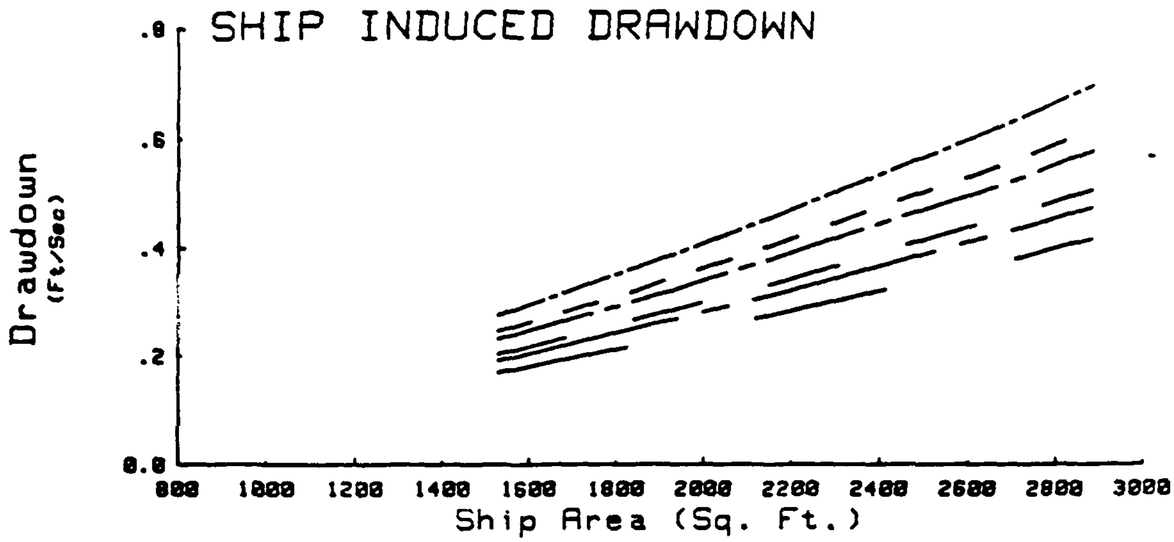


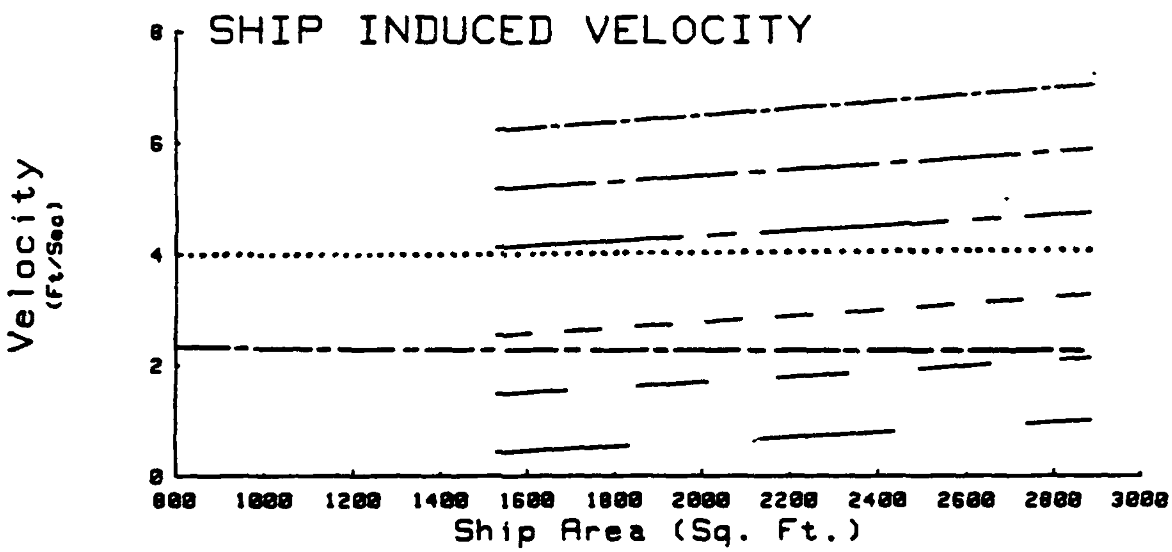
ST. MARYS RIVER
182+81E AT LWD+0



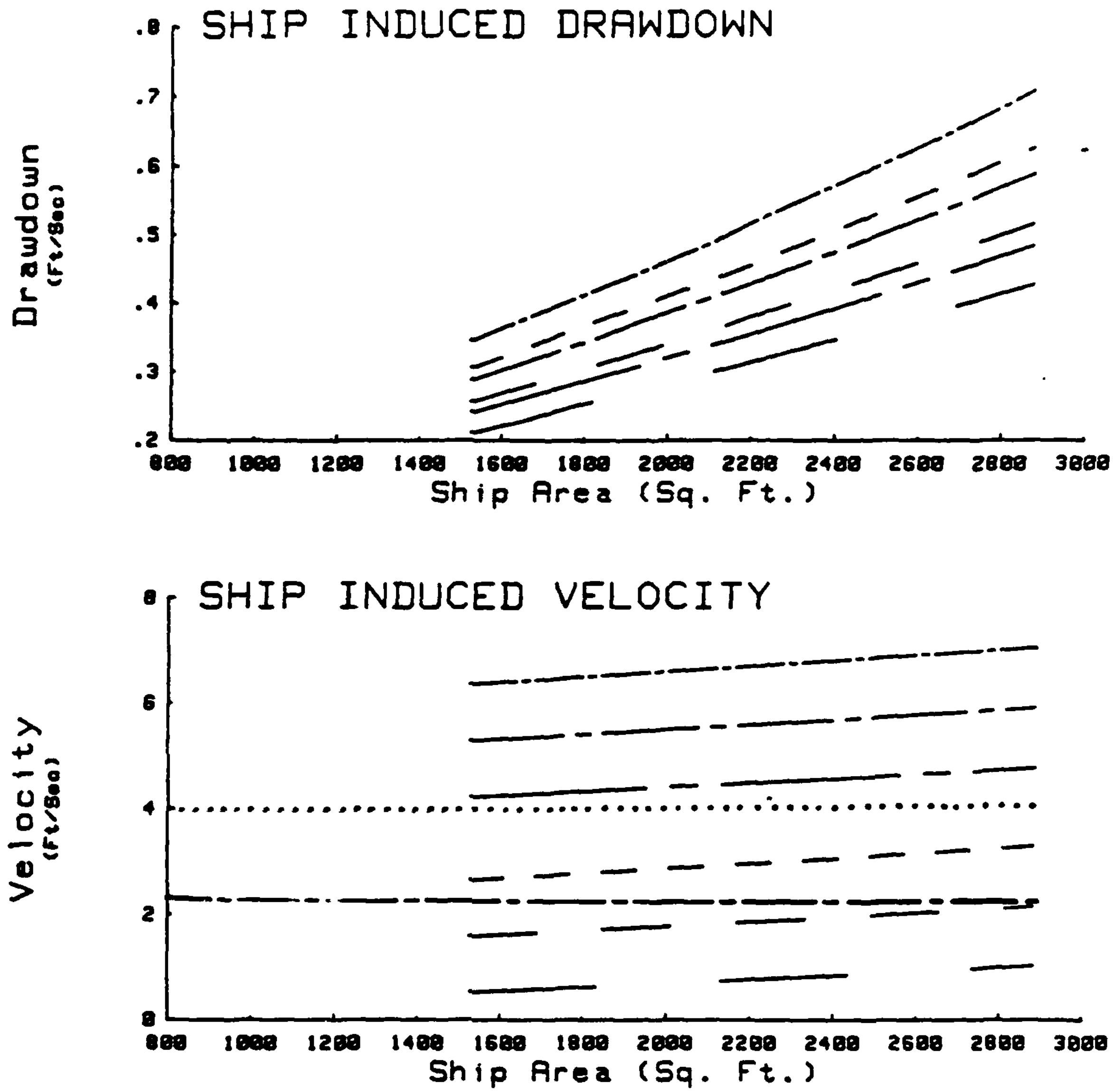


ST. MARYS RIVER
182+81E AT LWD+1

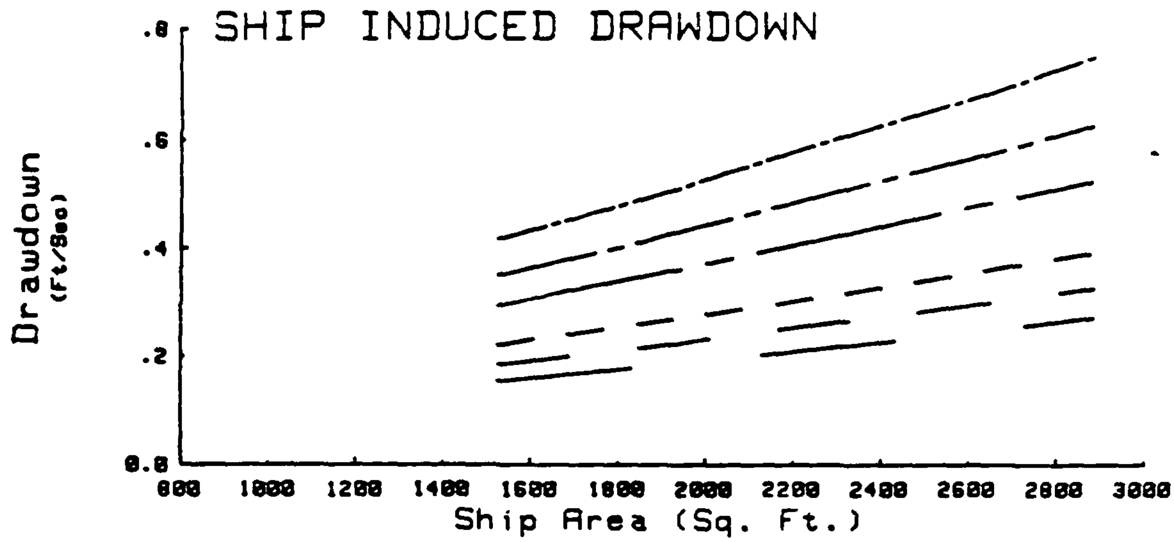


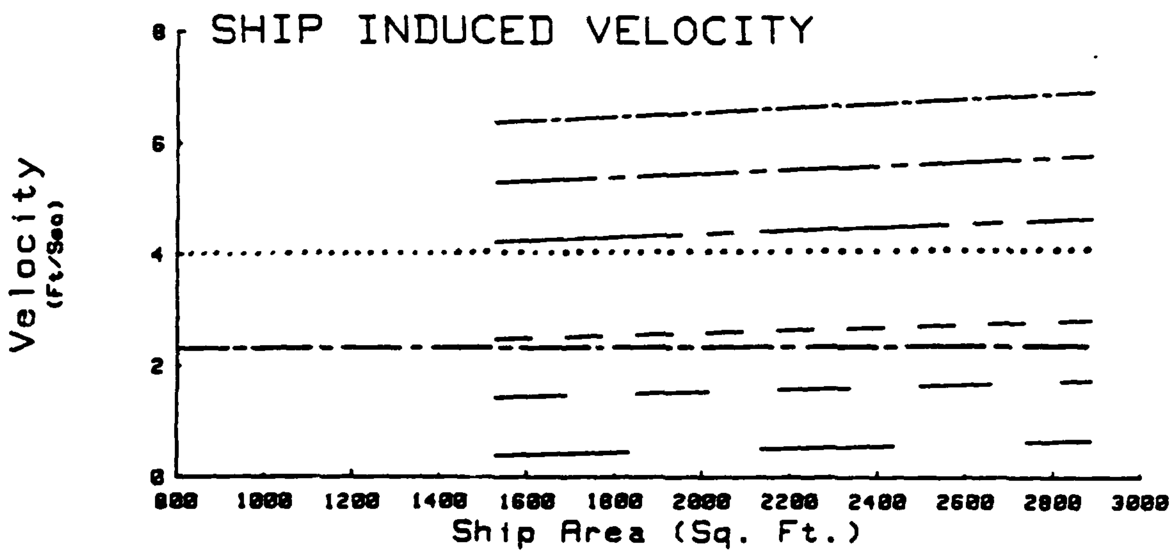


ST. MARYS RIVER
182+81E AT LWD+2

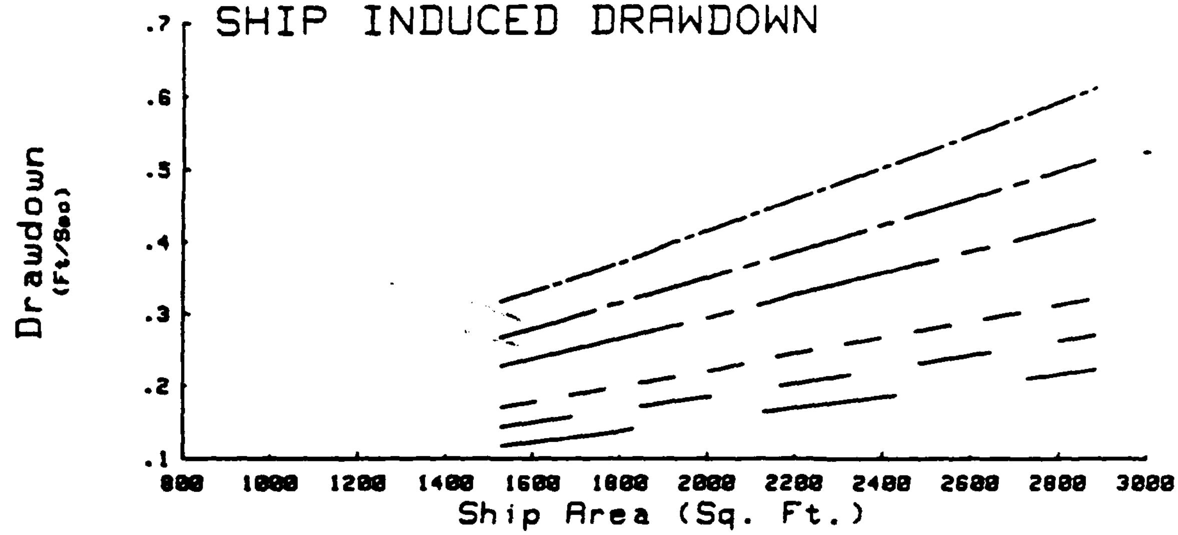


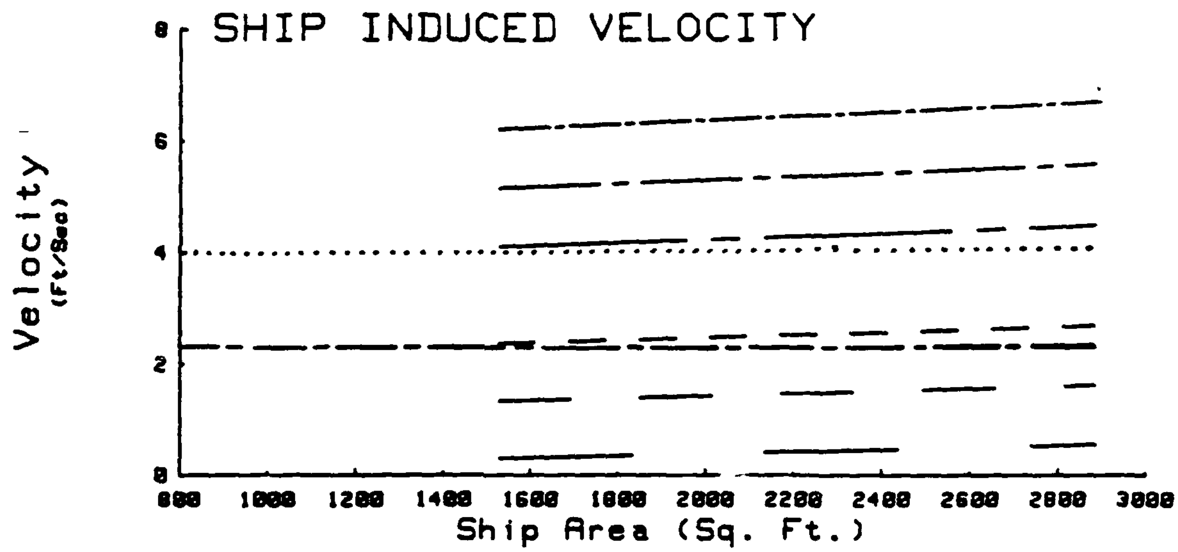
ST. MARYS RIVER
297+66W AT LWD+0



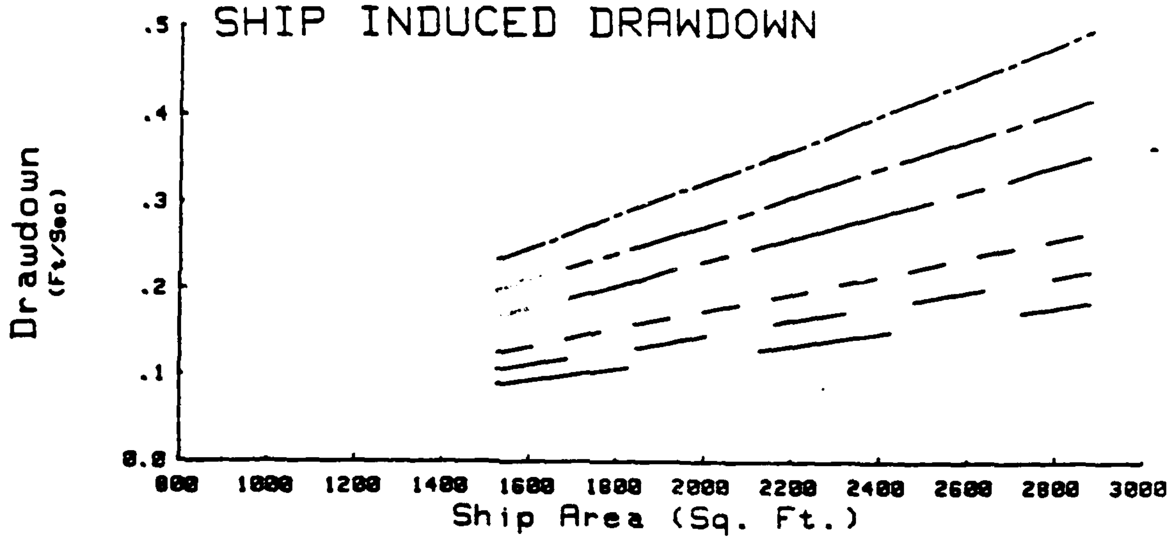


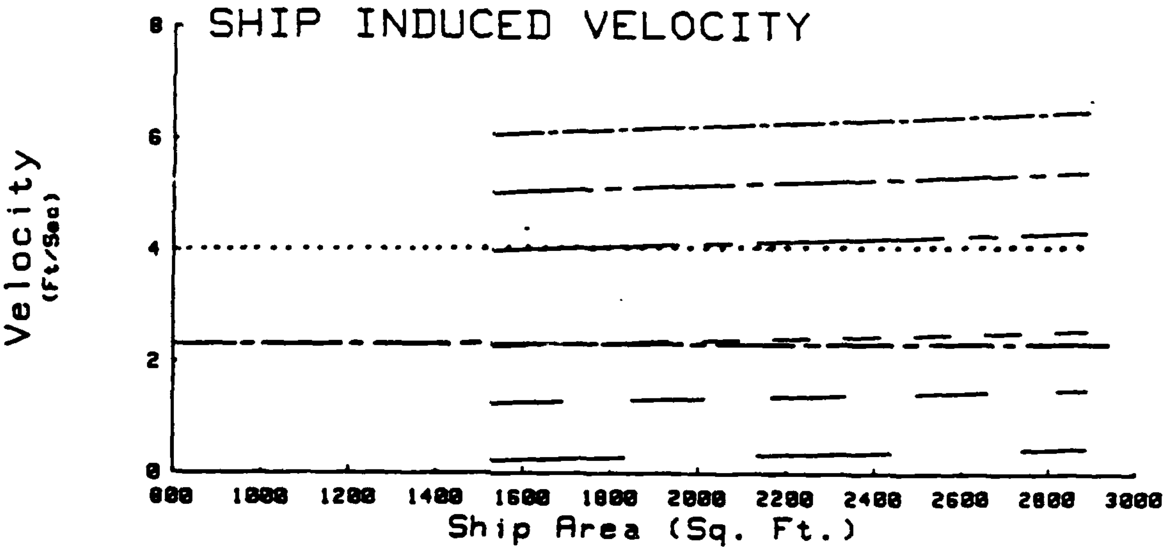
ST. MARYS RIVER
297+66W AT LWD+1



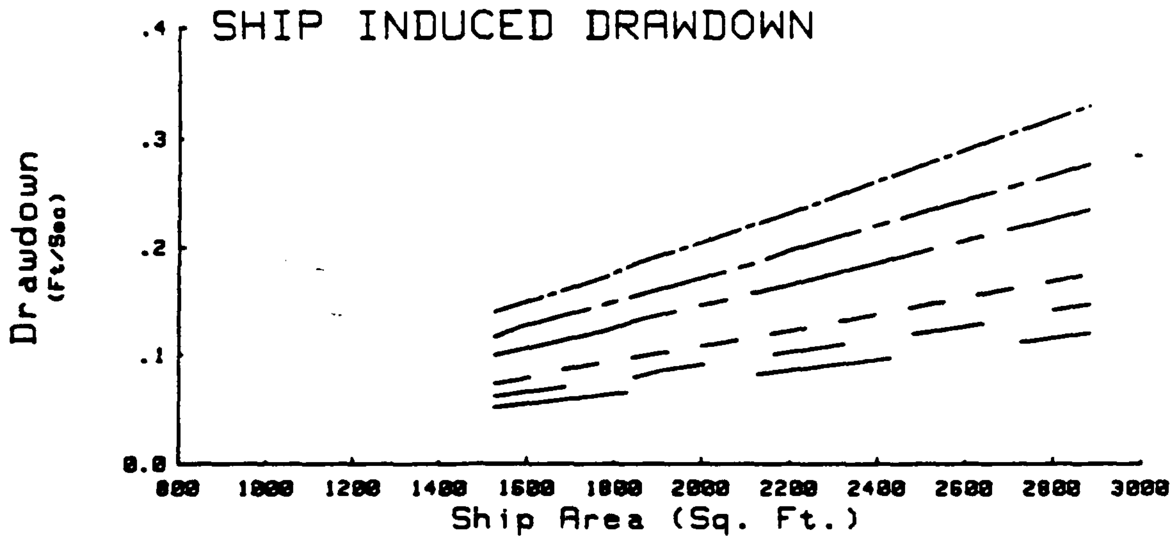


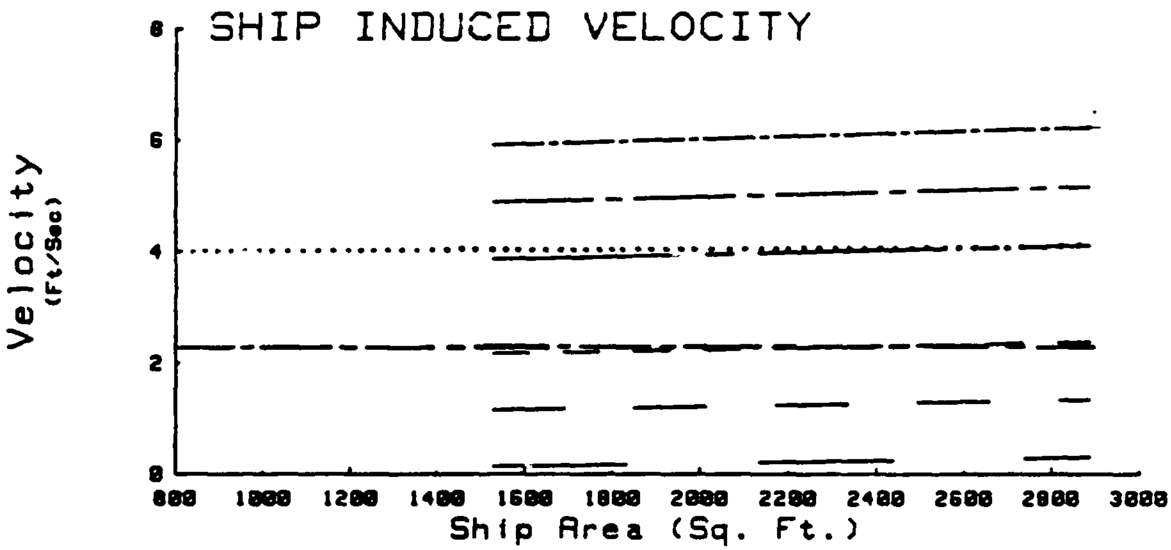
ST. MARYS RIVER
297+66W AT LWD+2



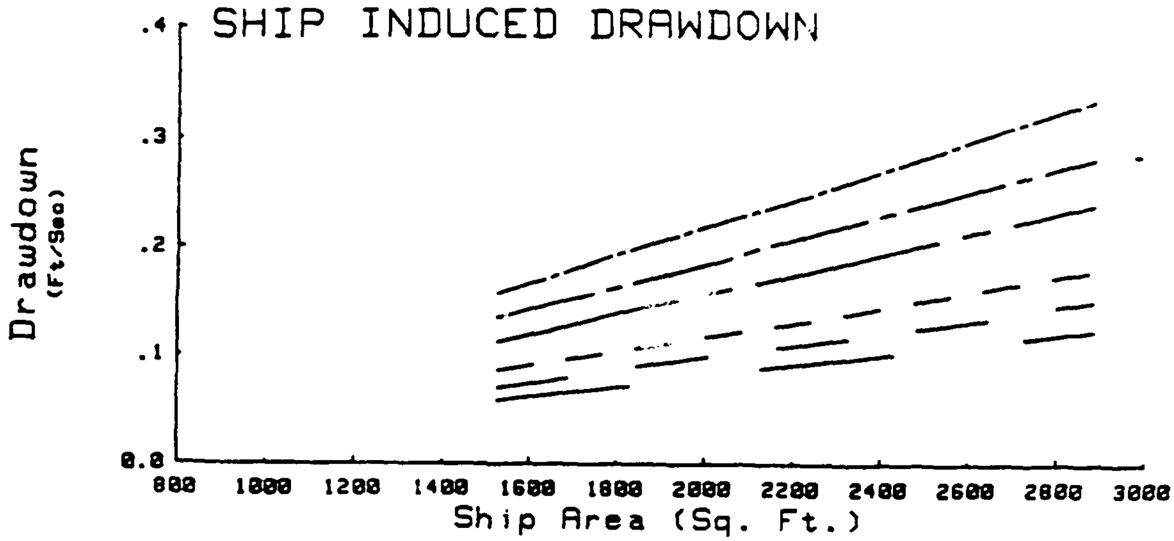


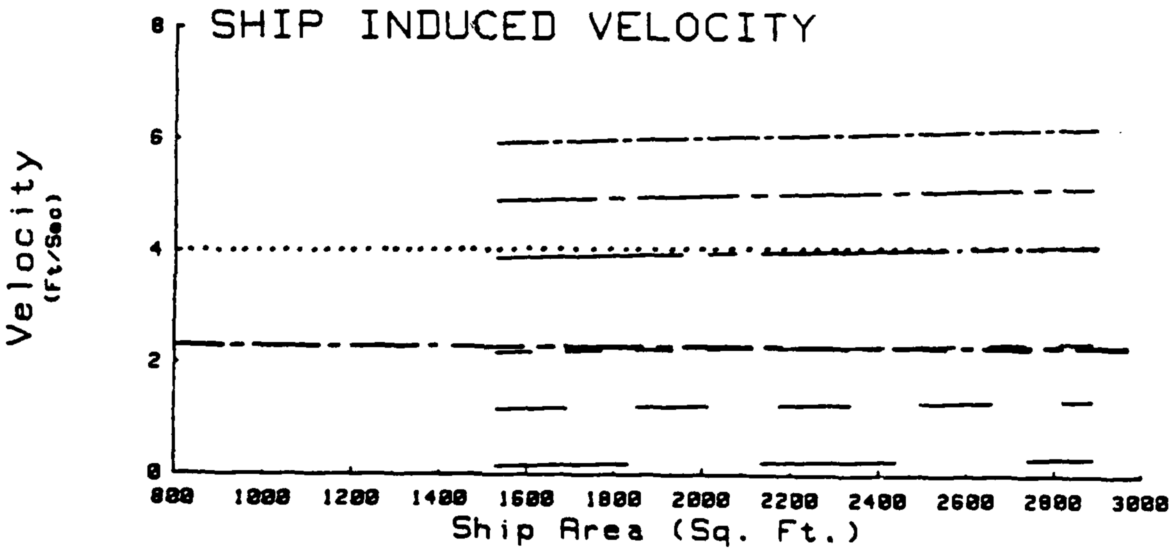
ST. MARYS RIVER
297+66E AT LWD+0



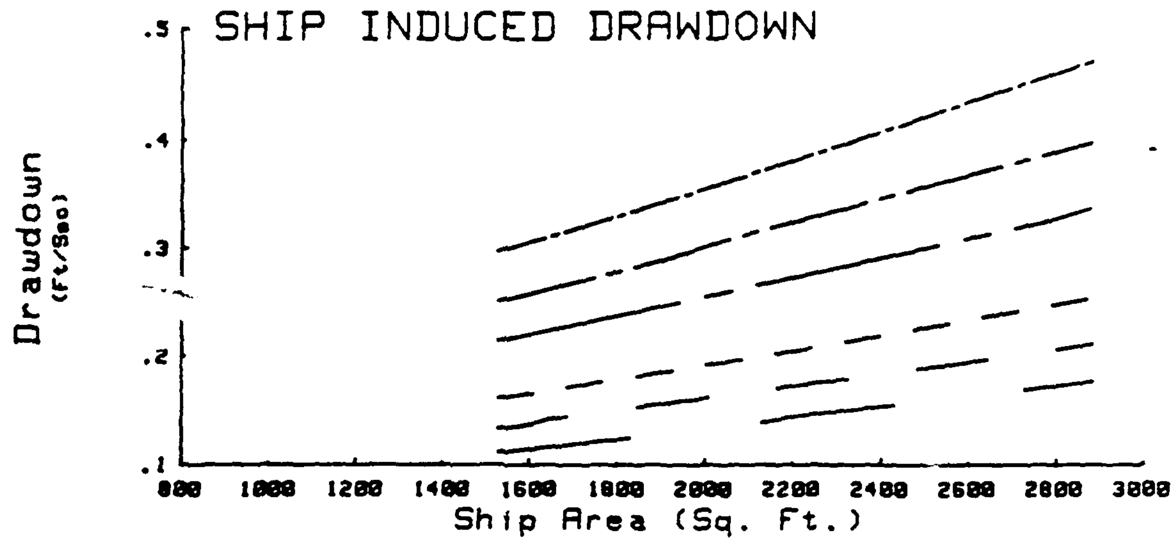


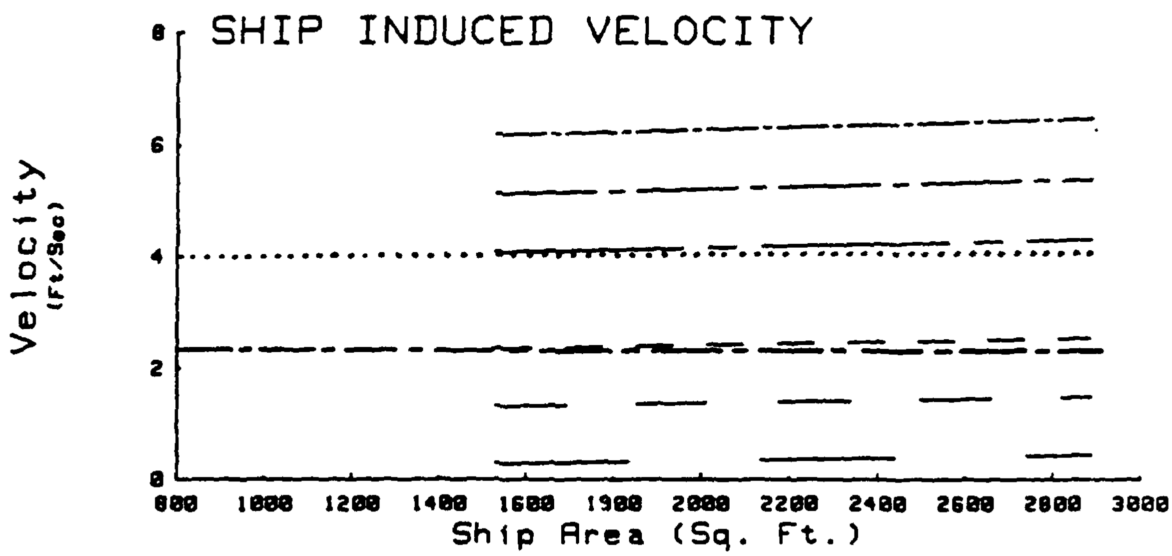
ST. MARYS RIVER
297+66E AT LWD+1



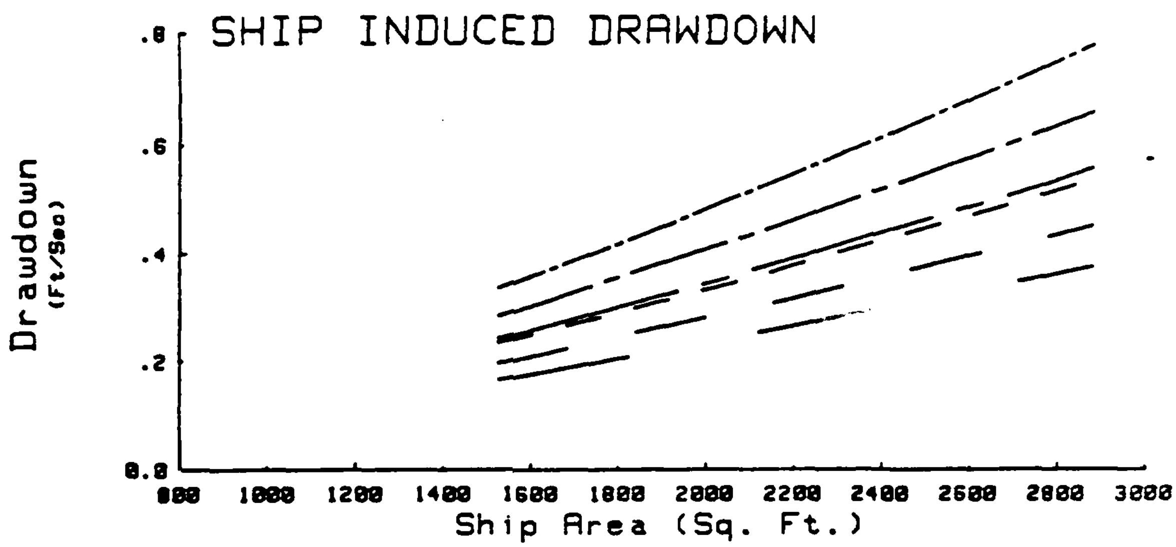


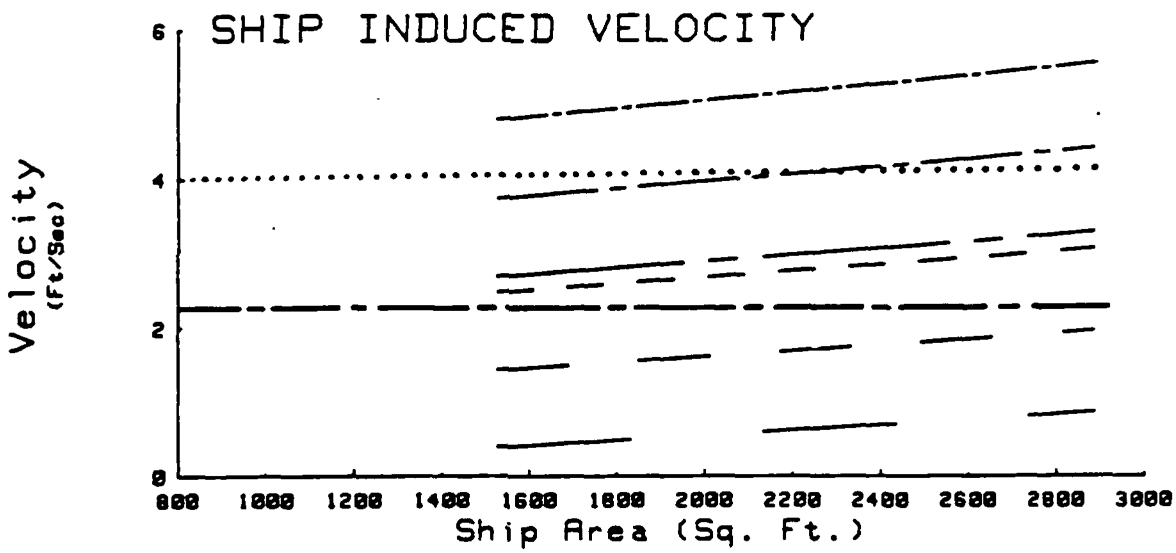
ST. MARYS RIVER
297+66E AT LWD+2



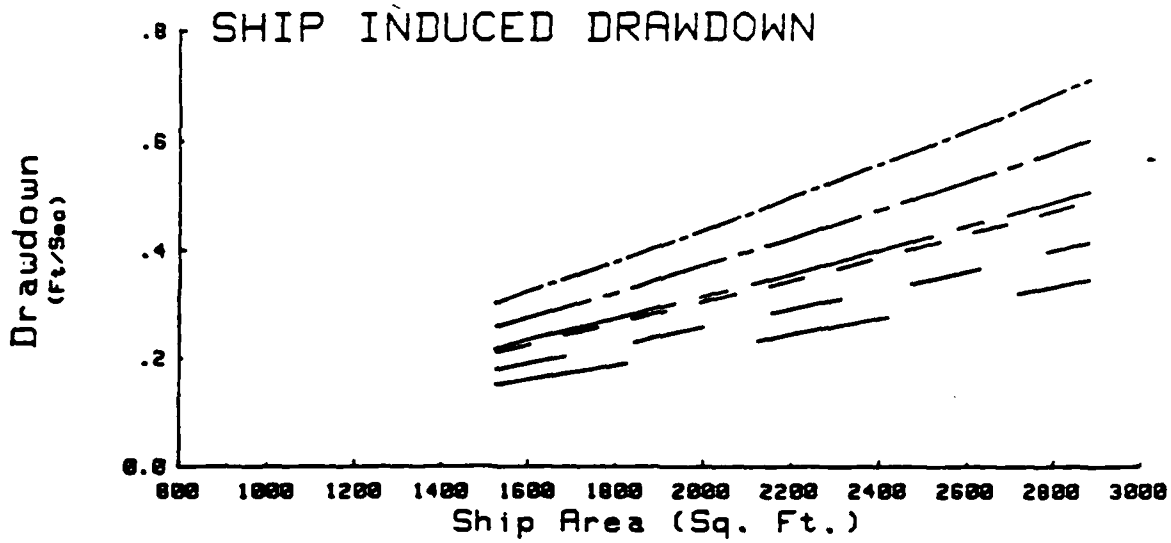


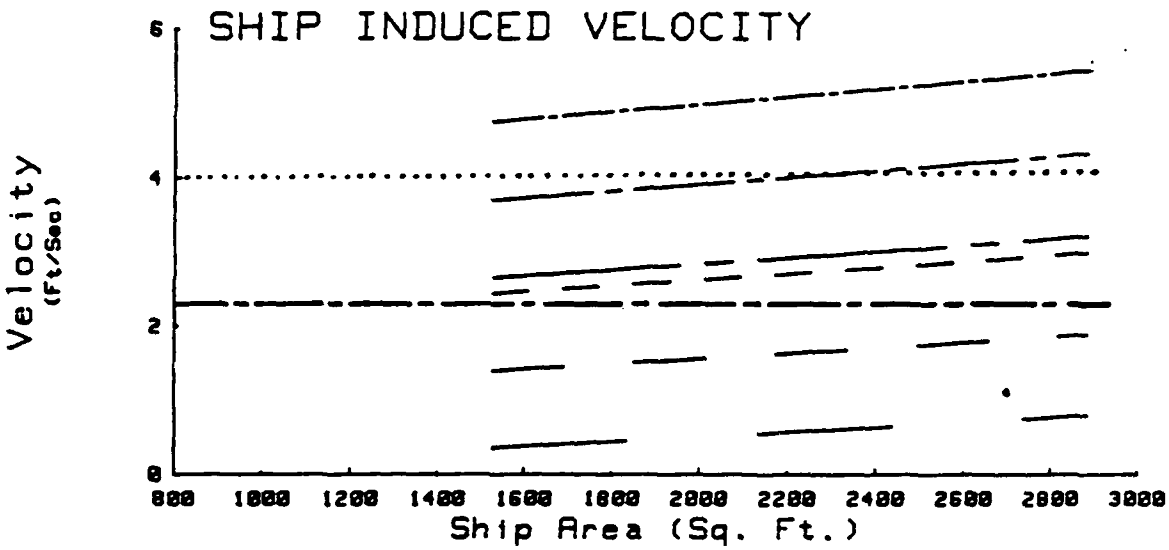
ST. MARYS RIVER
414+31E AT LWD+0



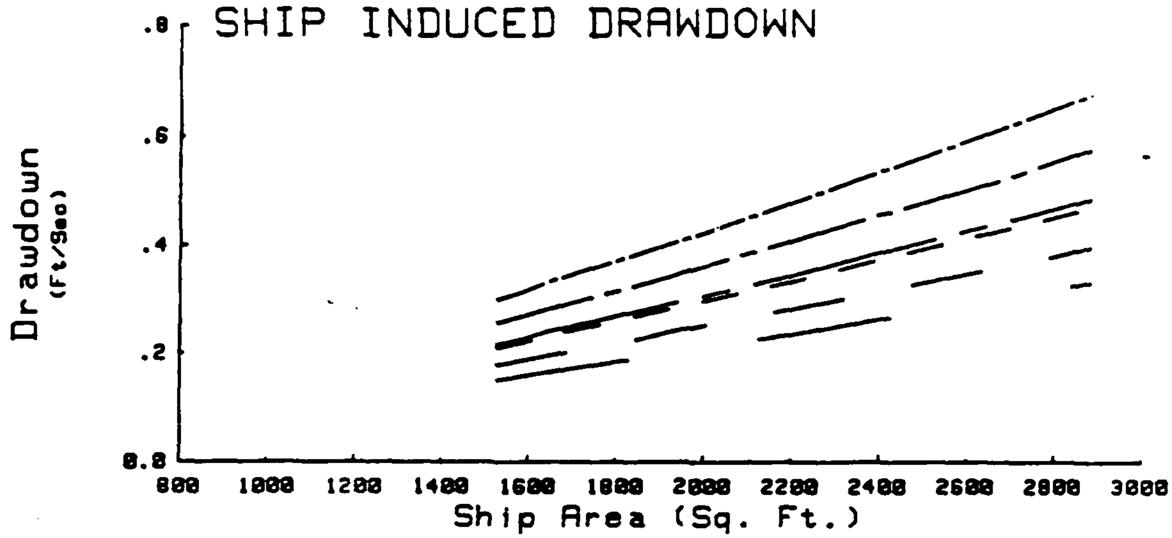


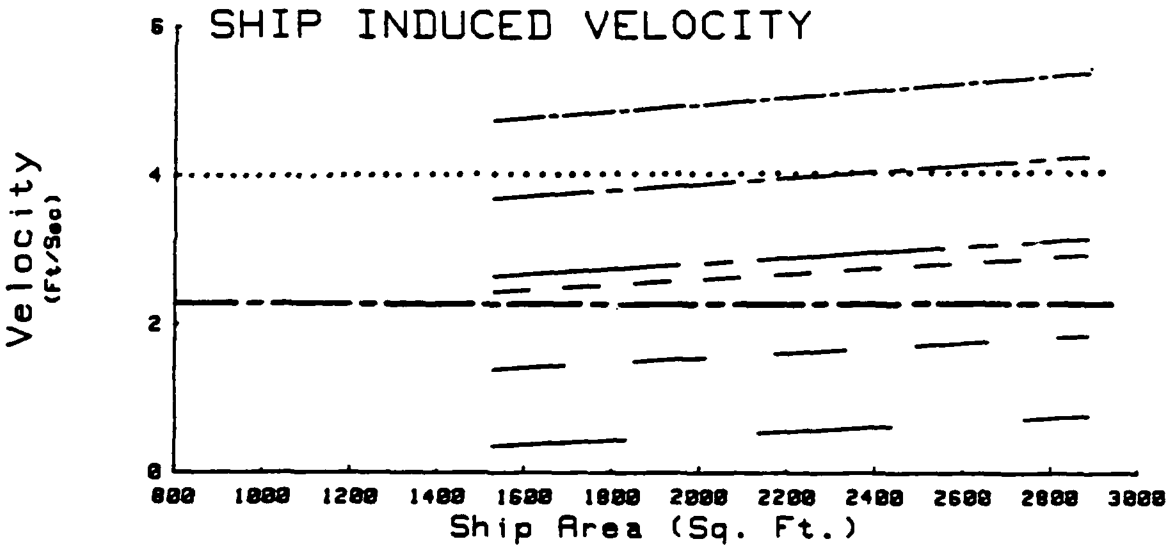
ST. MARYS RIVER
414+31E AT LWD+1





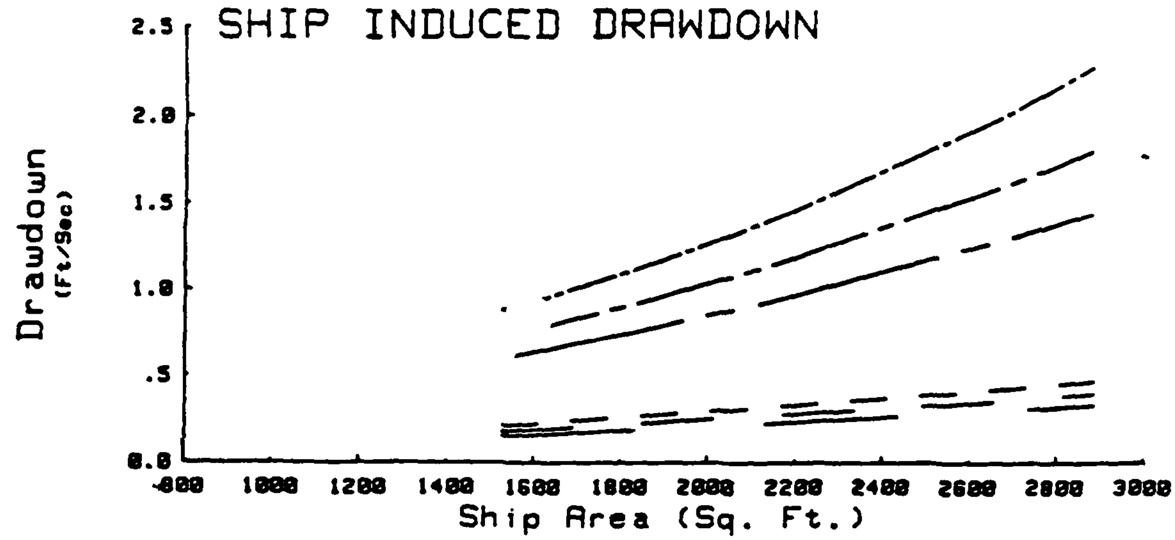
ST. MARYS RIVER
414+31E AT LWD+2

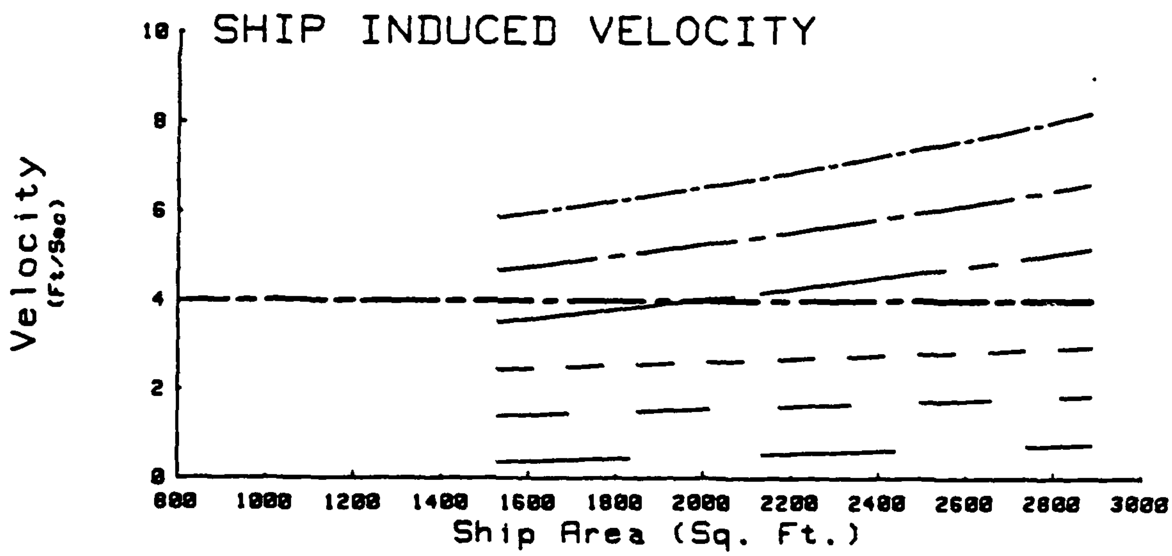




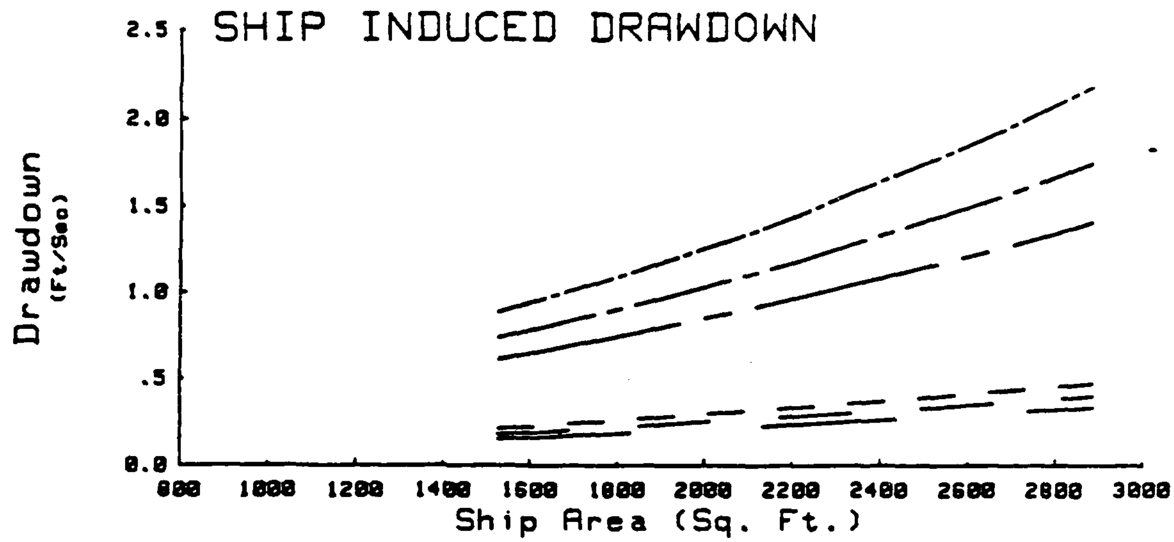
ST. MARYS RIVER

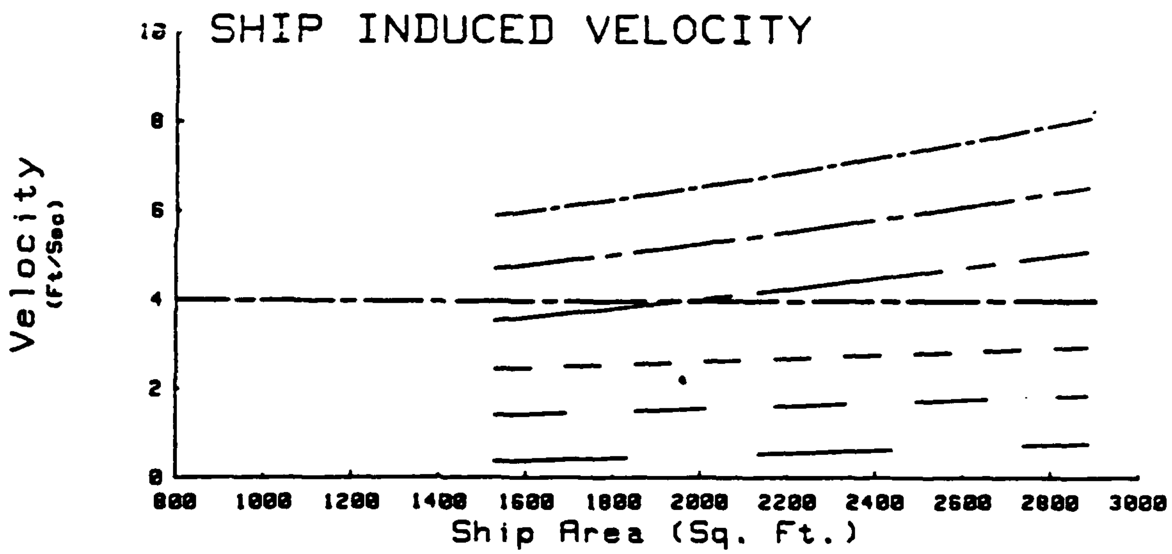
699+02E AT LWD+0





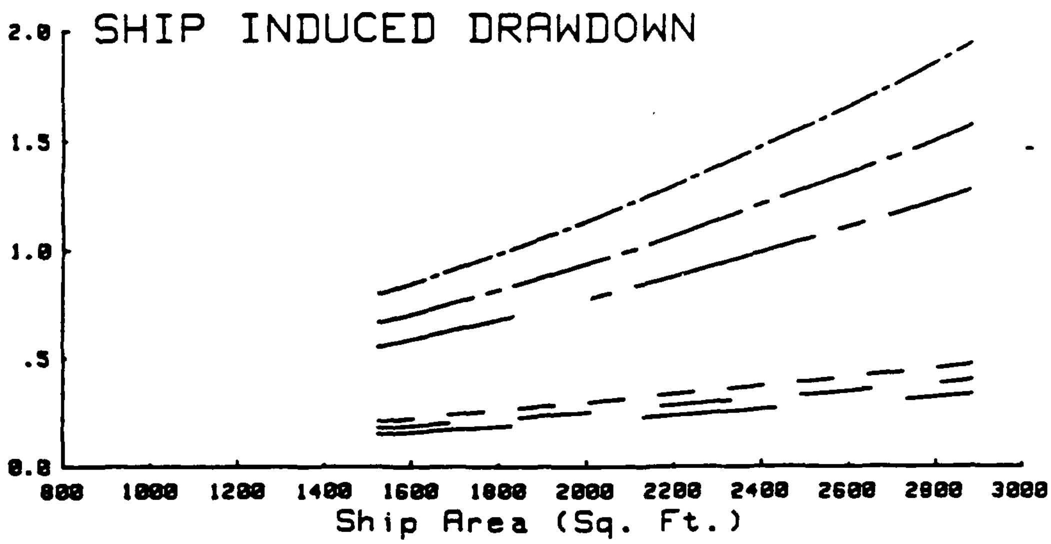
ST. MARYS RIVER
699+02E AT LWD+1

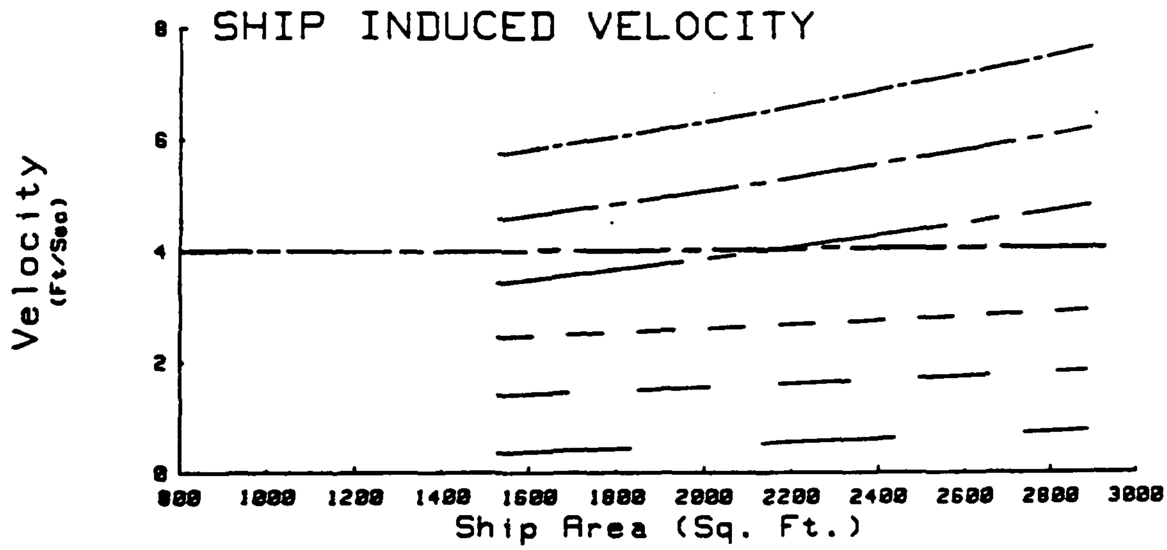




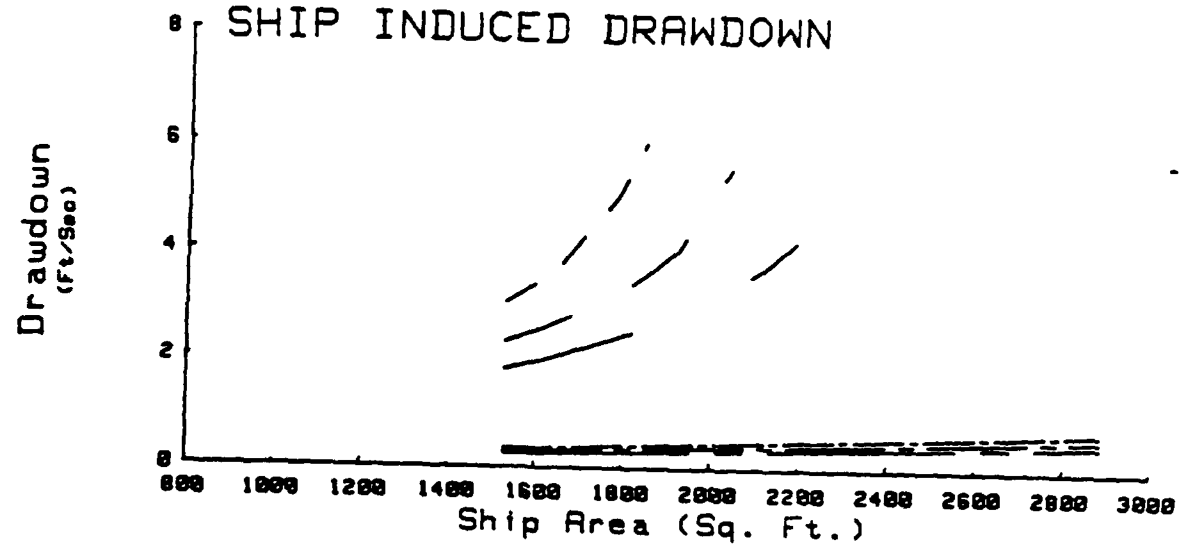
ST. MARYS RIVER

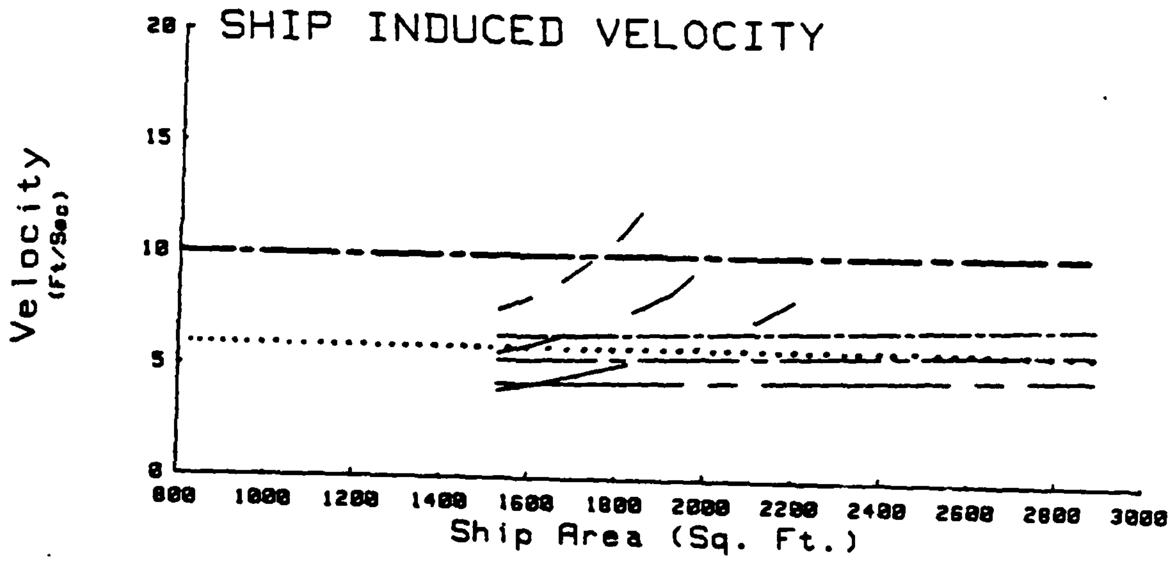
699+02E AT LWD+2



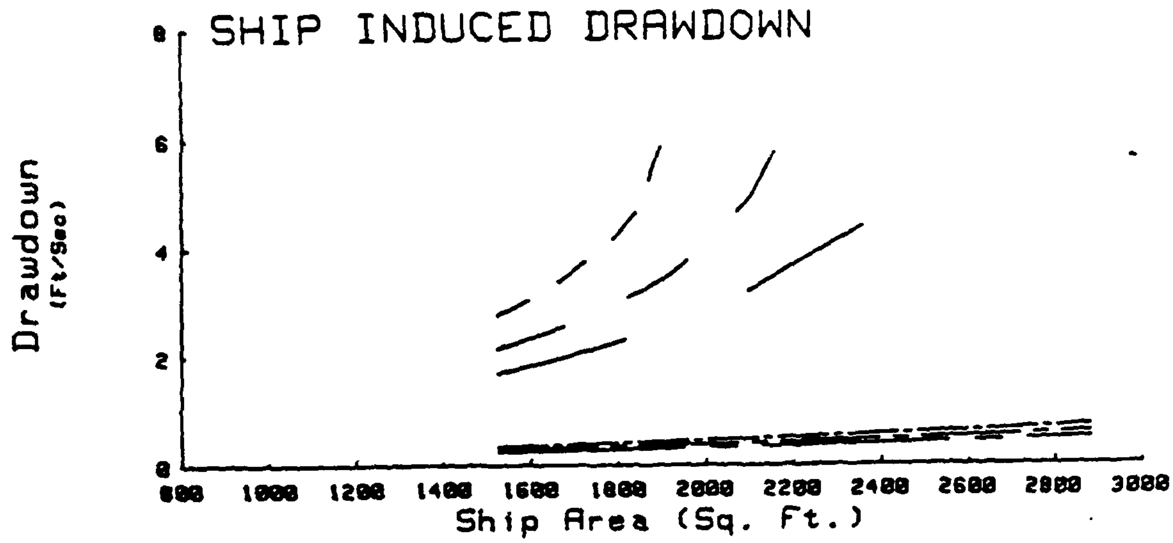


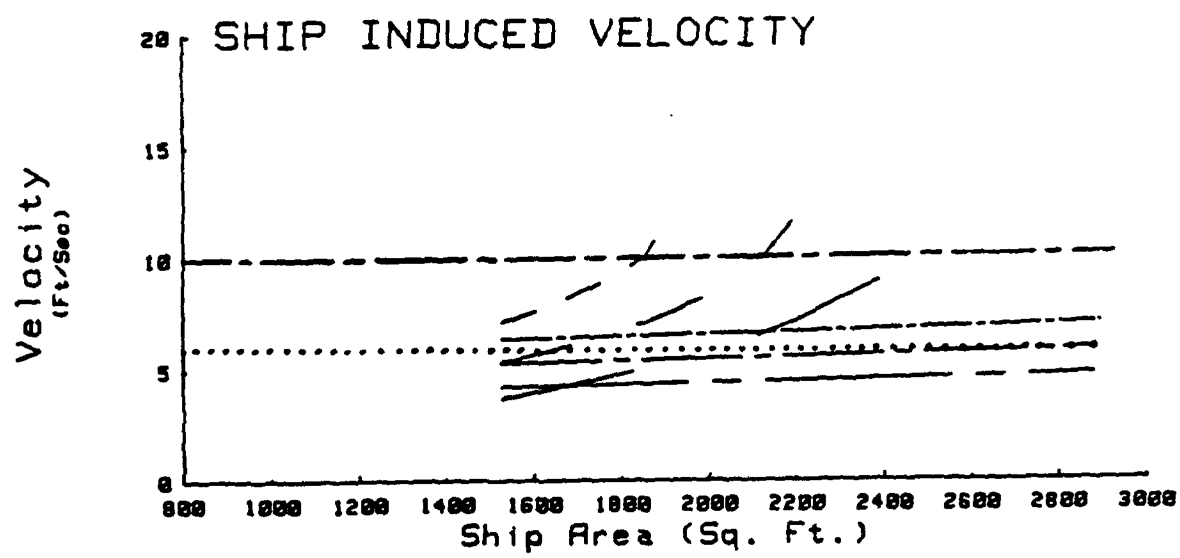
ST. MARYS RIVER
881+10 AT LWD+0



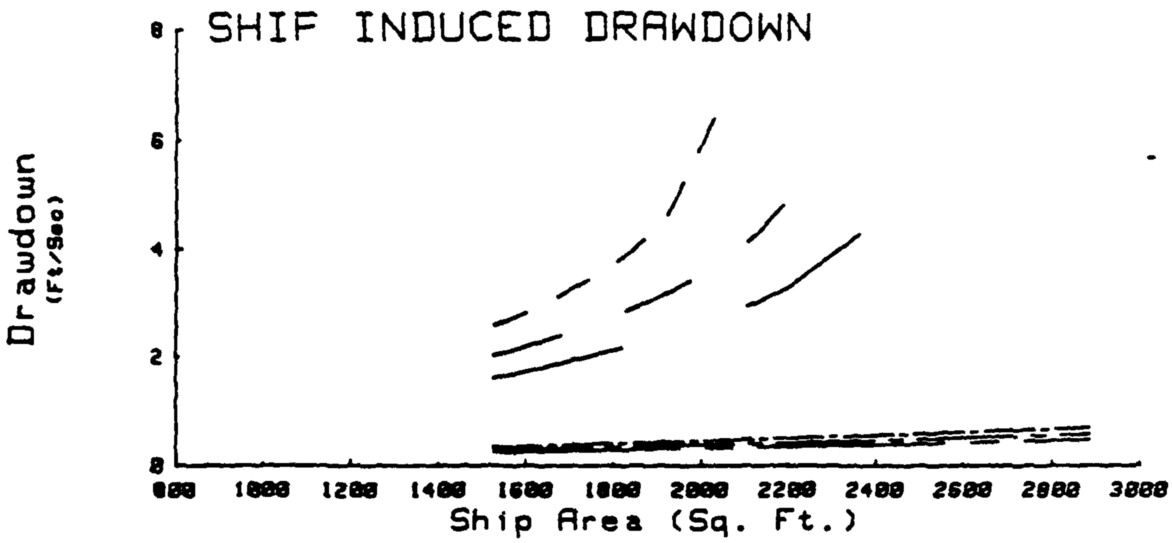


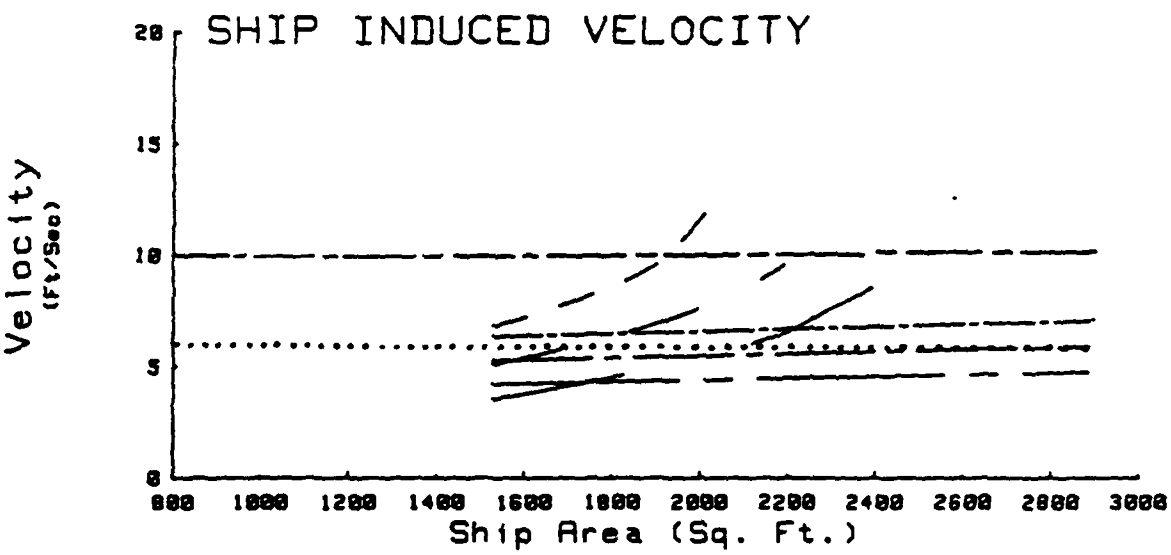
ST. MARYS RIVER
881+10 AT LWD+1



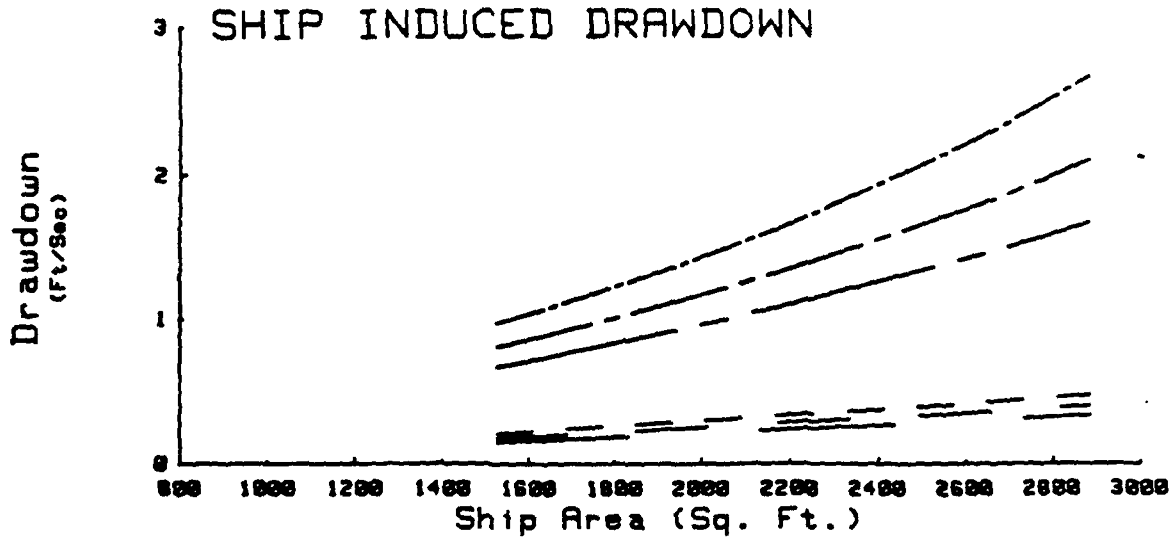


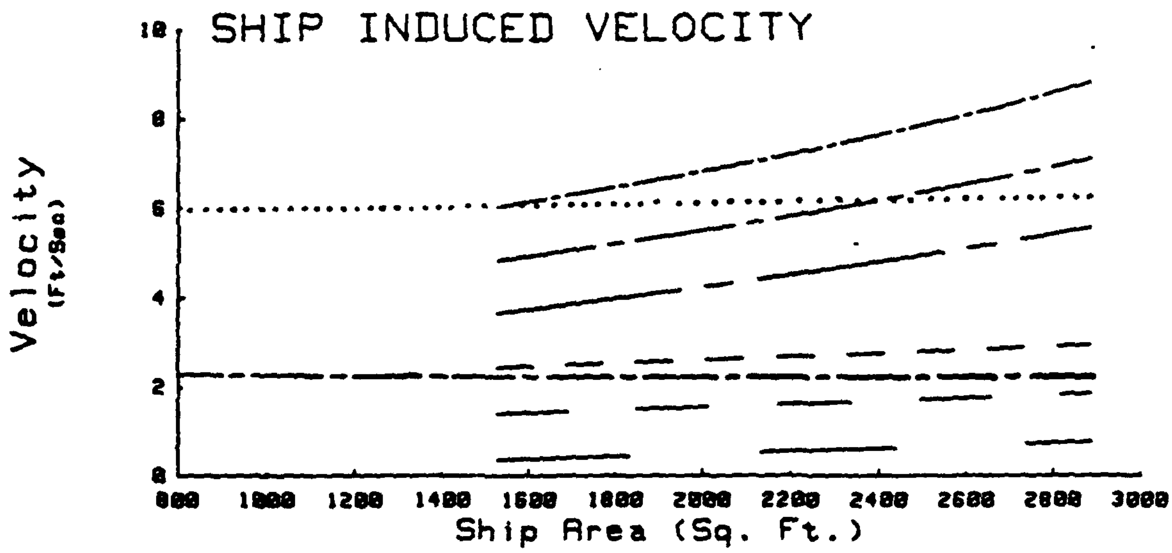
ST. MARYS RIVER
881+10 AT LWD+2



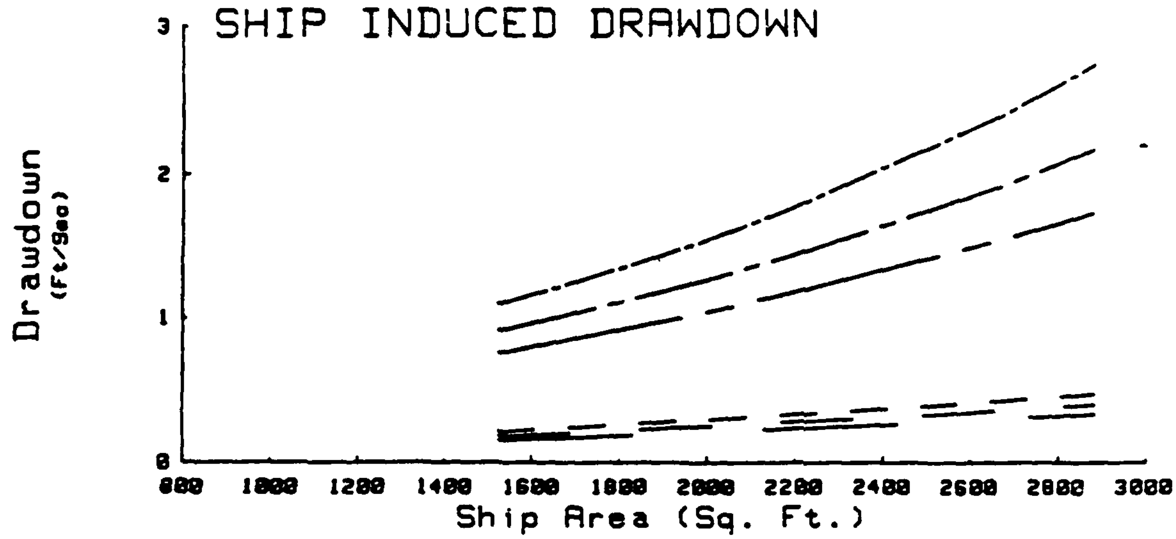


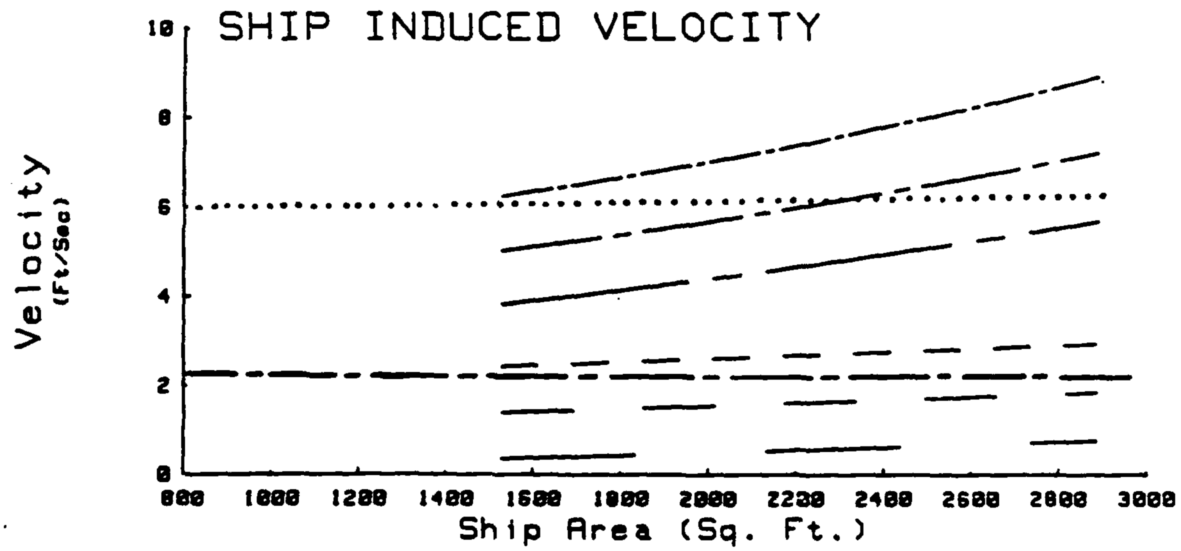
ST. MARYS RIVER
1075+37 AT LWD+0



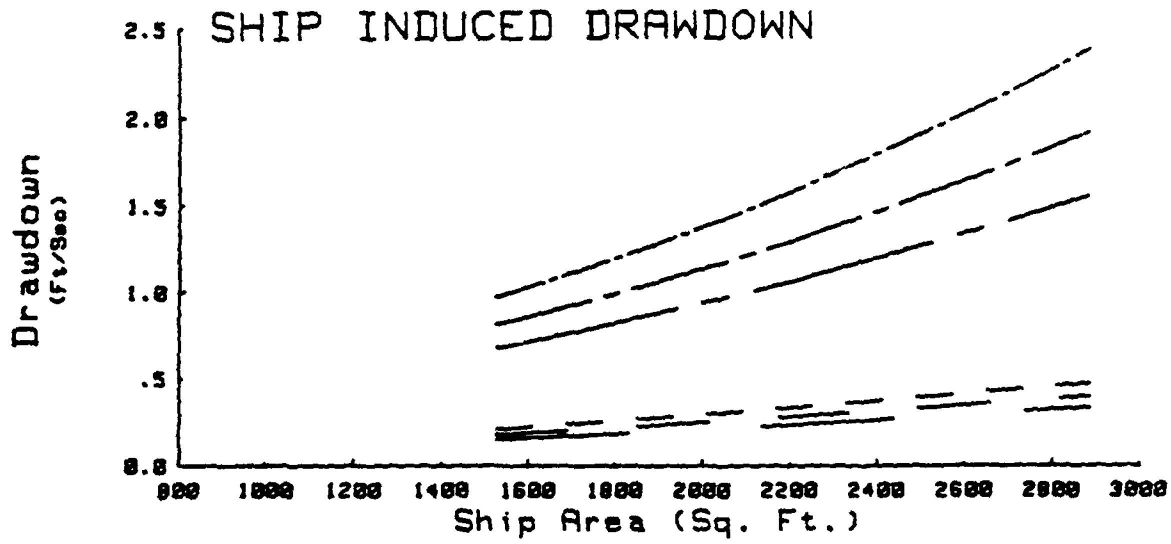


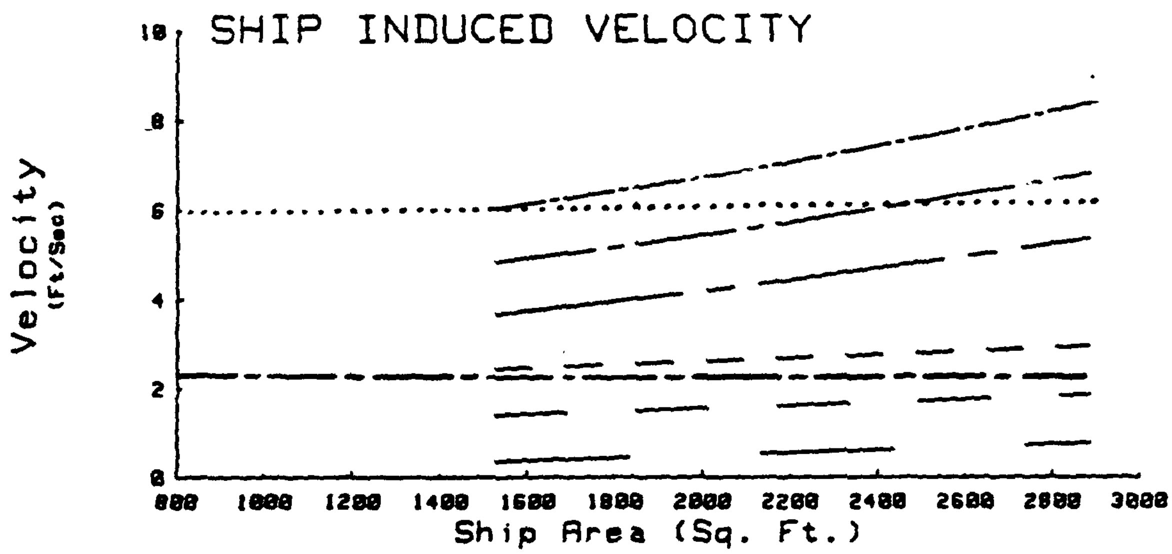
ST. MARYS RIVER
1075+37 AT LWD+1



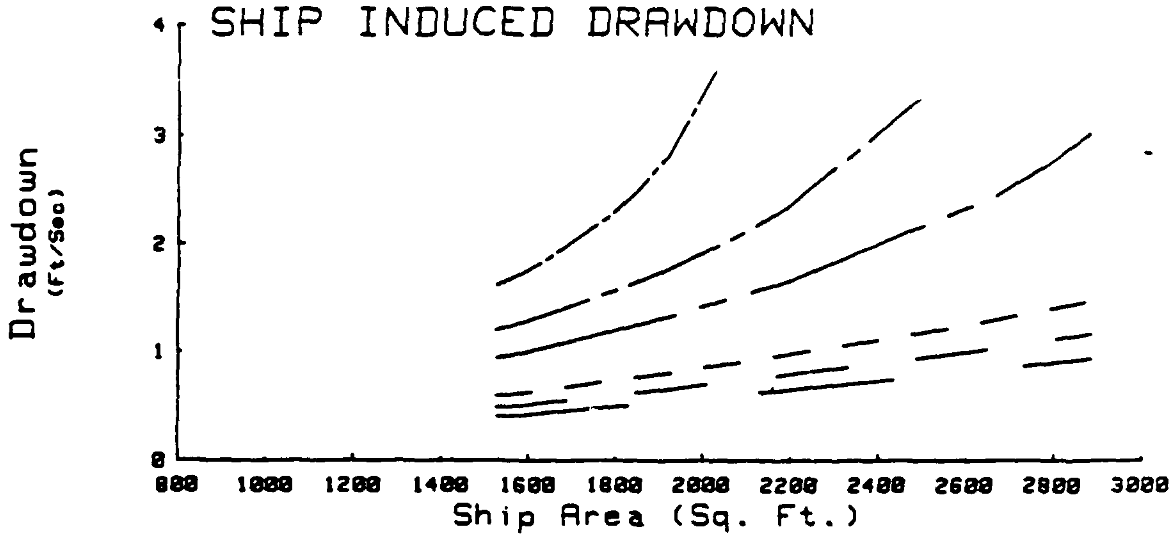


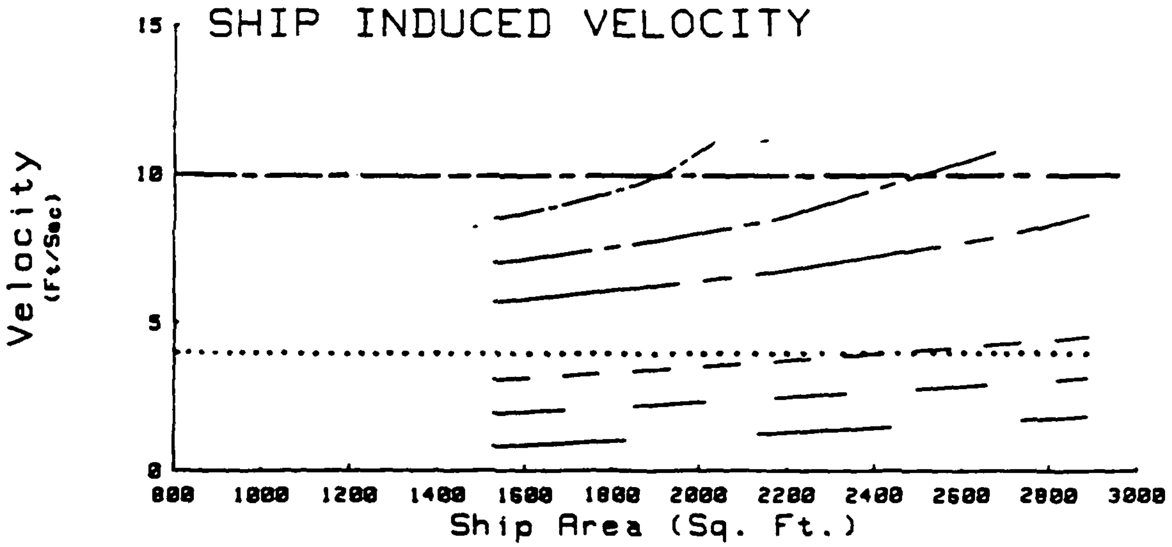
ST. MARYS RIVER
1075+37 AT LWD+2



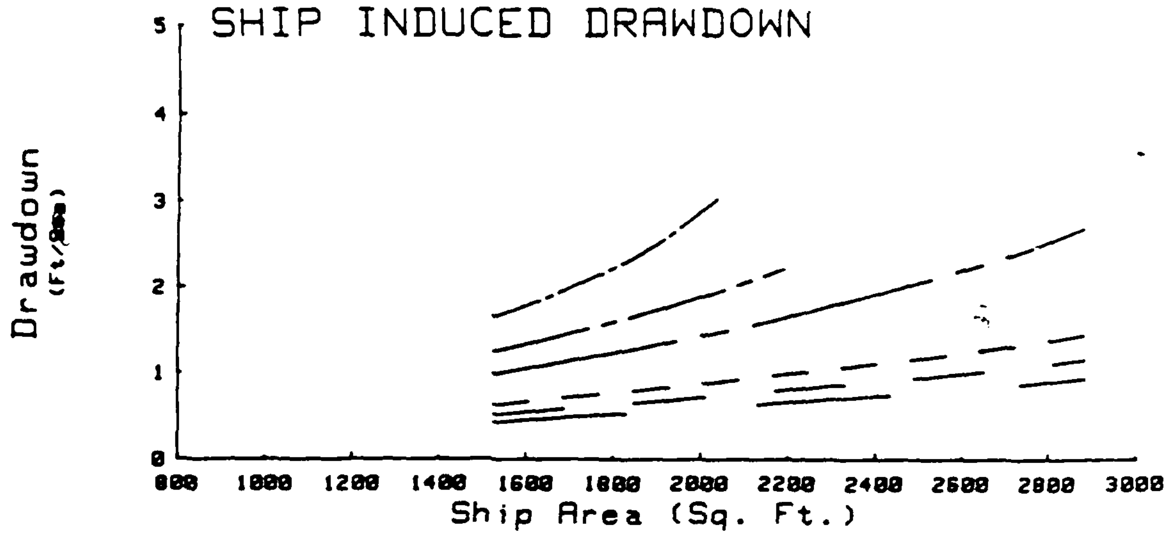


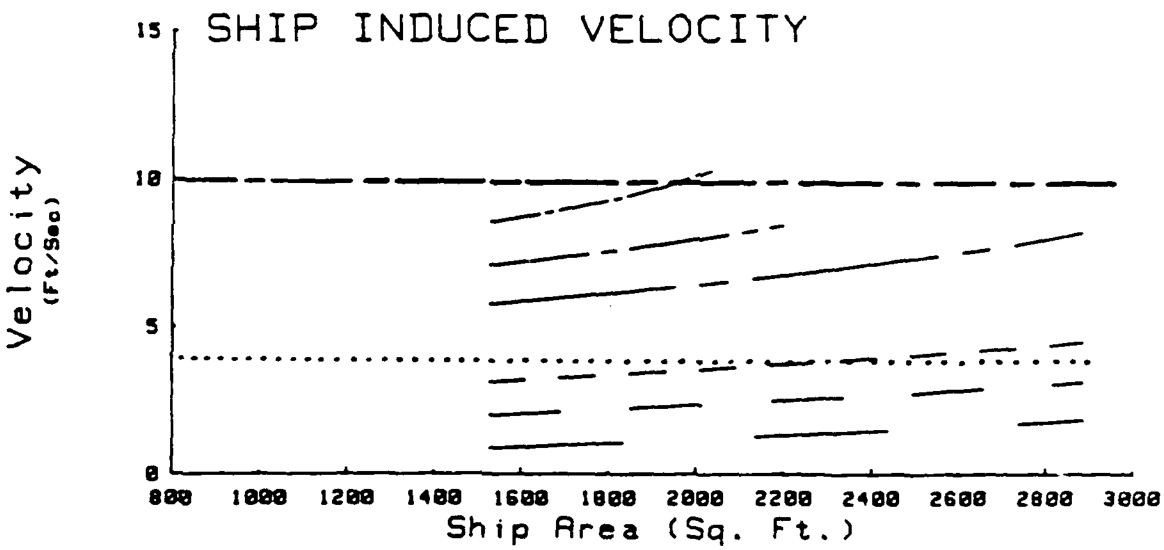
ST. CLAIR RIVER
493+30 AT LWD+0



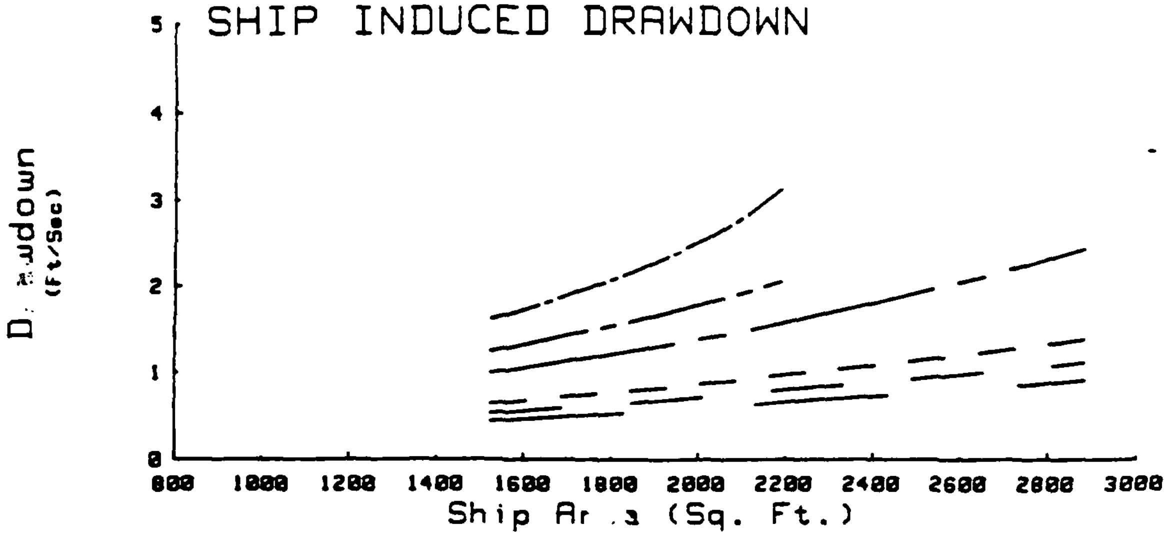


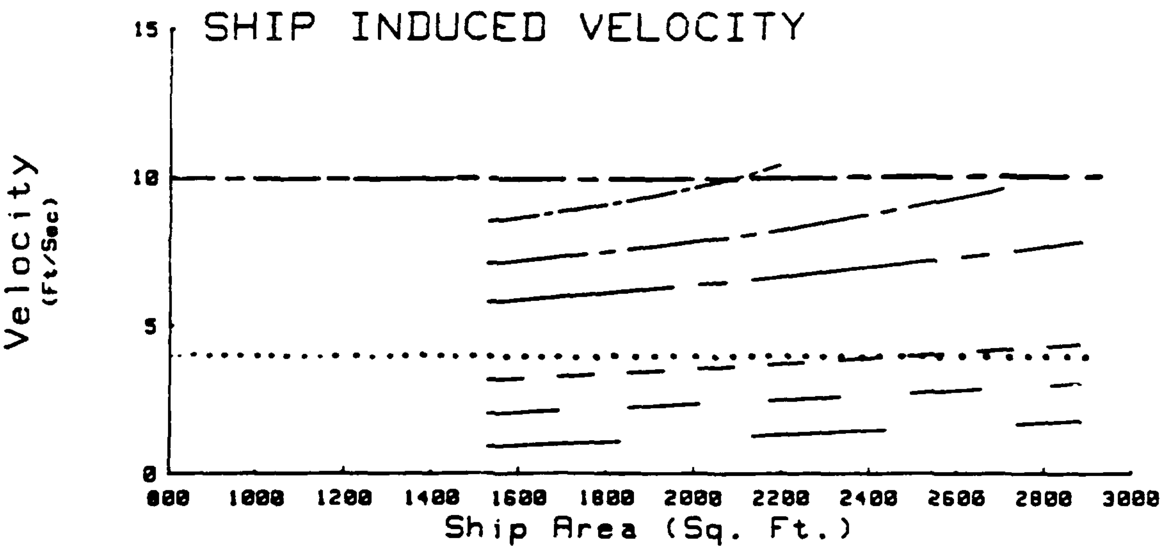
ST. CLAIR RIVER
493+30 AT LWD+1



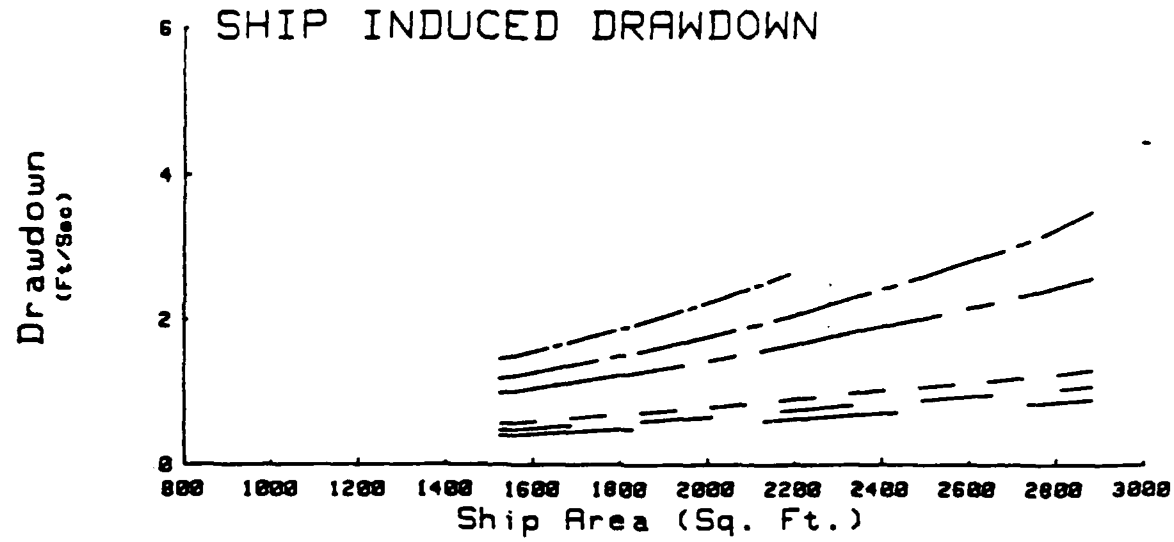


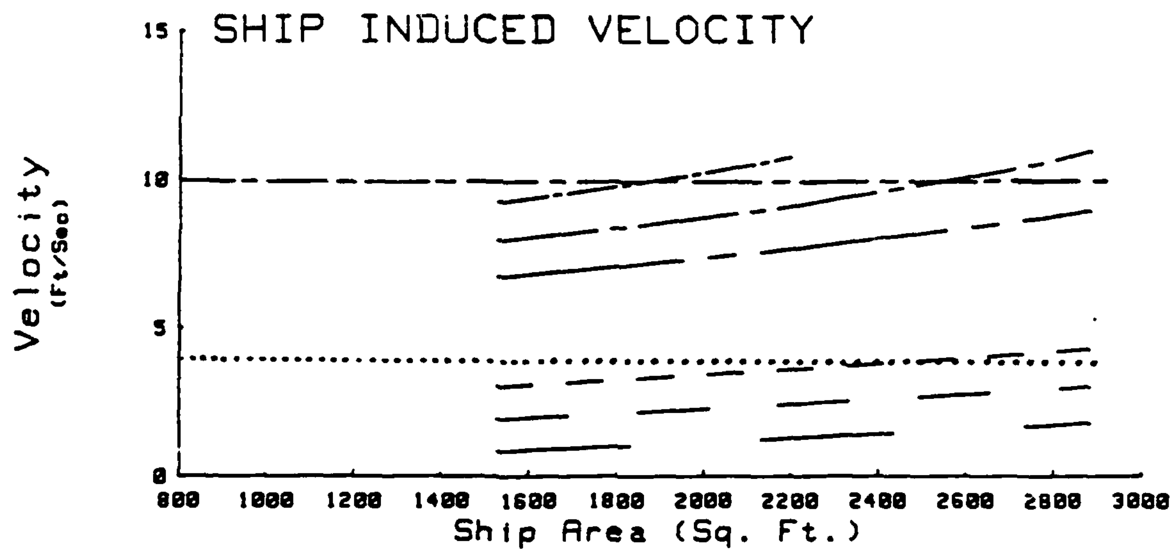
ST. CLAIR RIVER
493+30 AT LWD+2



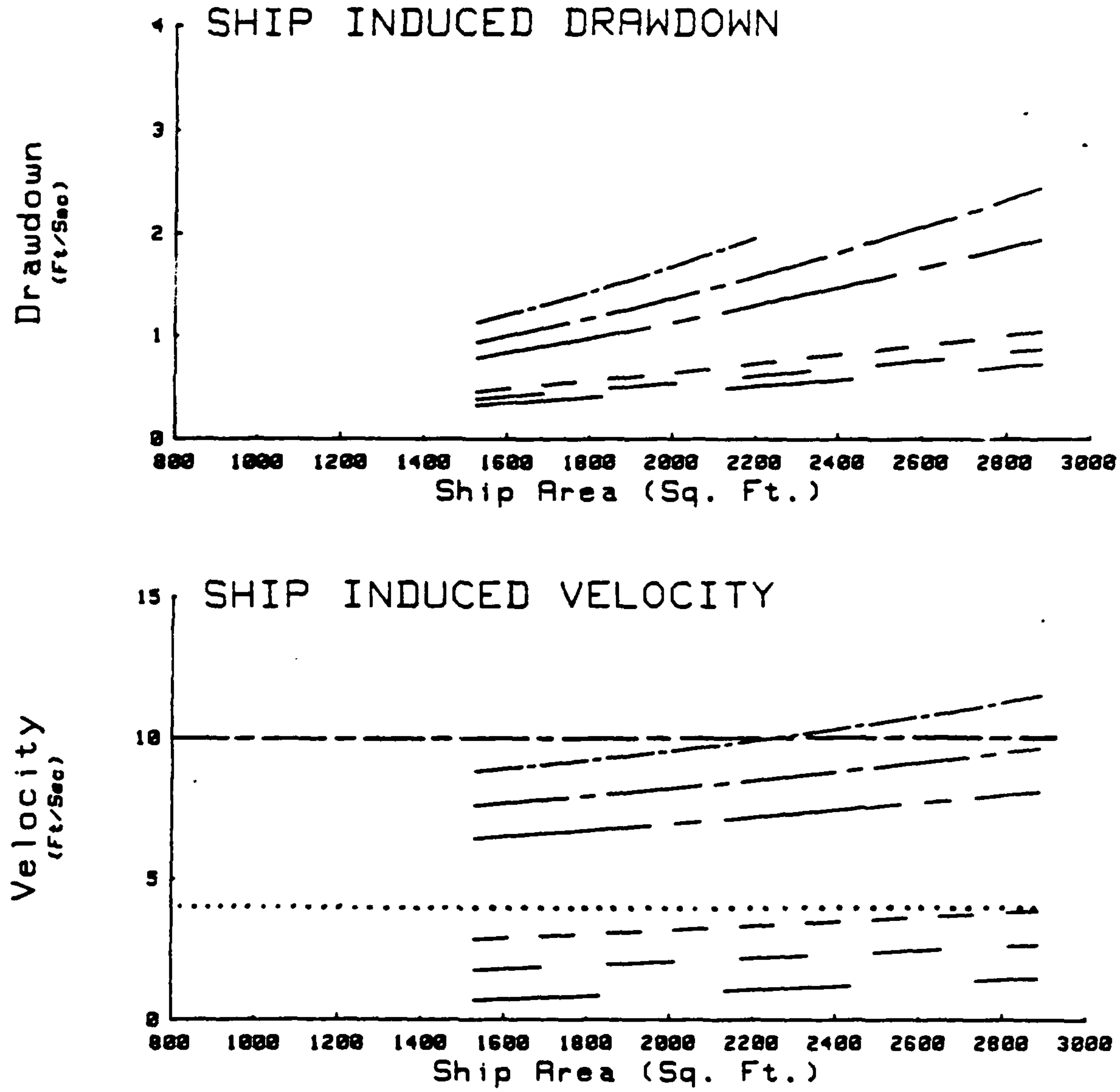


ST. CLAIR RIVER
1358+68 AT LWD+0

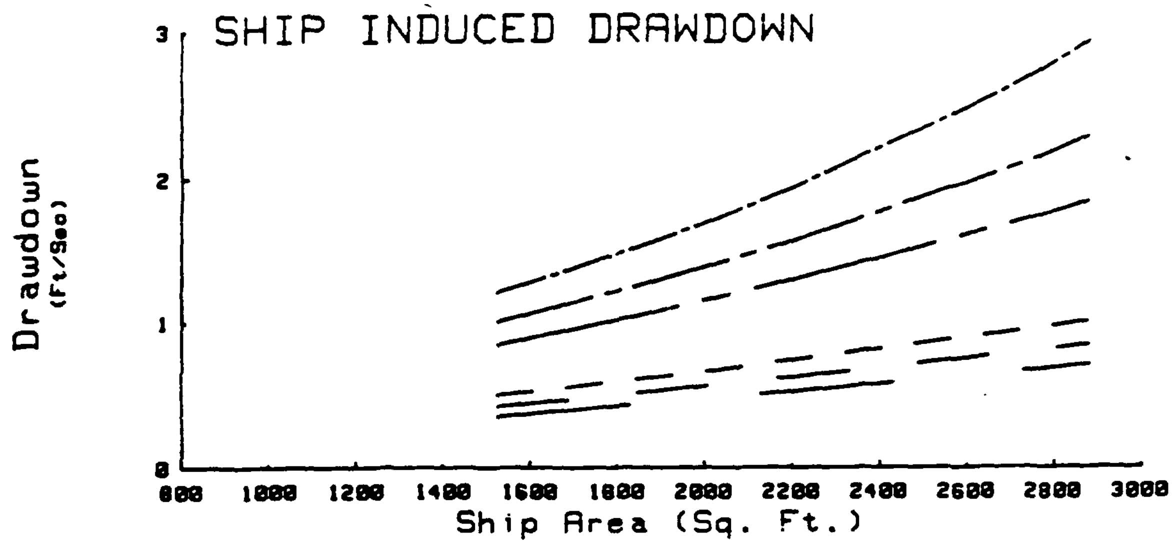


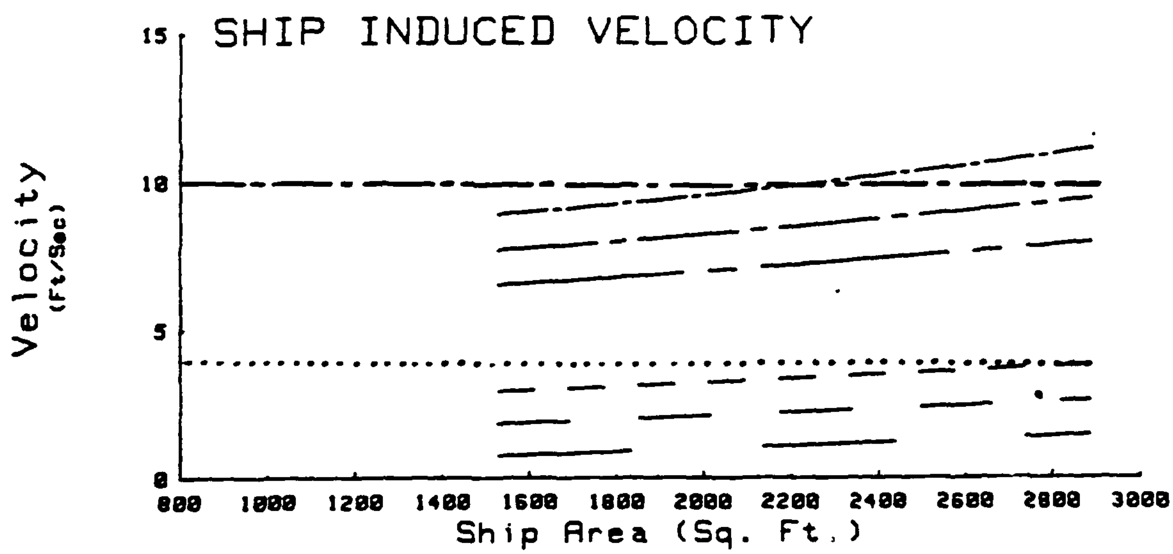


ST. CLAIR RIVER
1358+68 AT LWD+1

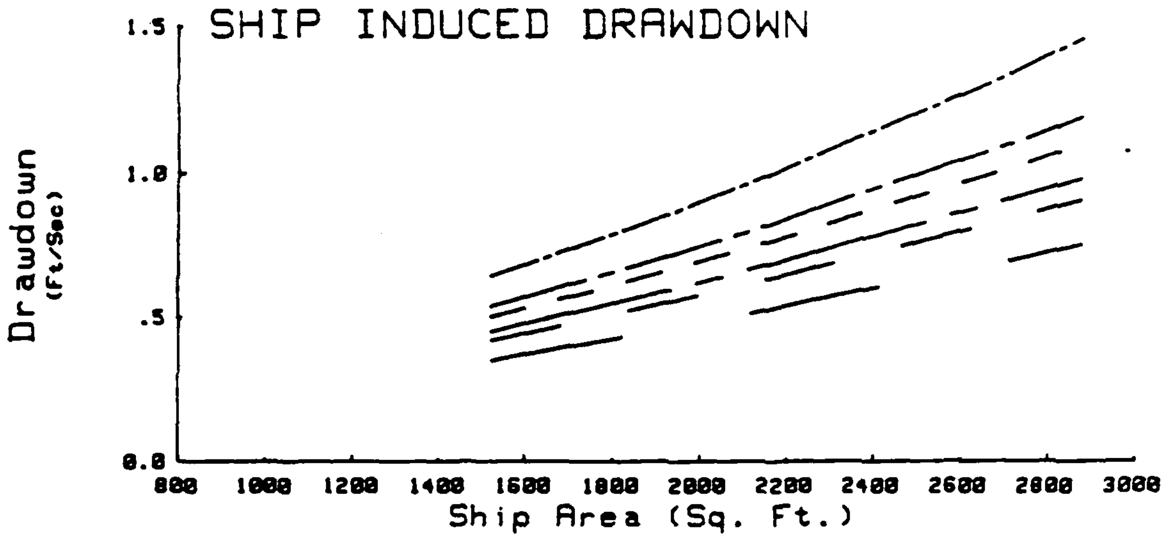


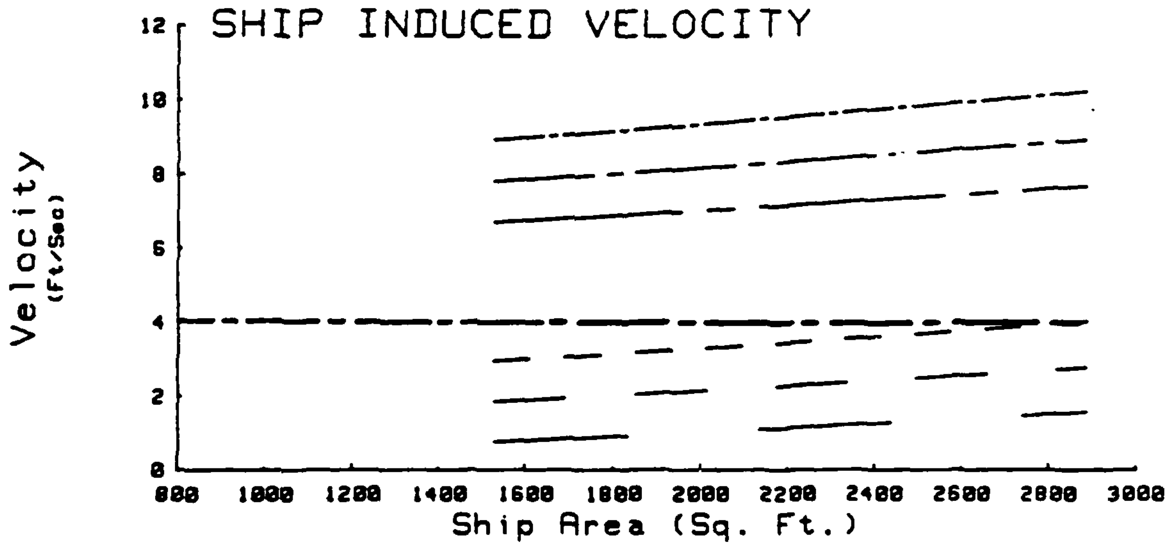
ST. CLAIR RIVER
1358+68 AT LWD+2



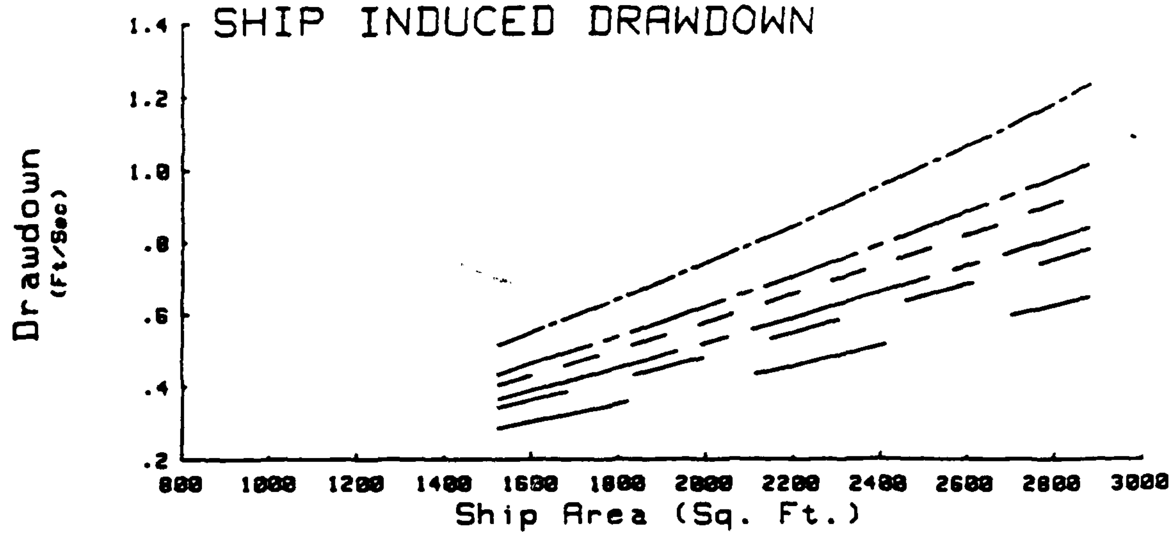


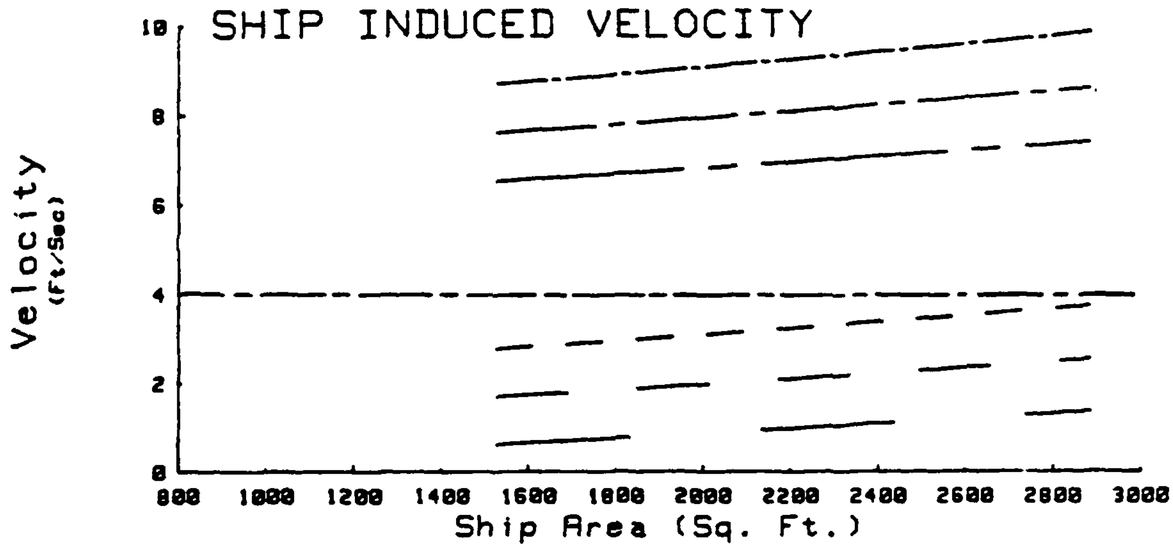
ST. CLAIR RIVER
1750+30 AT LWD+0



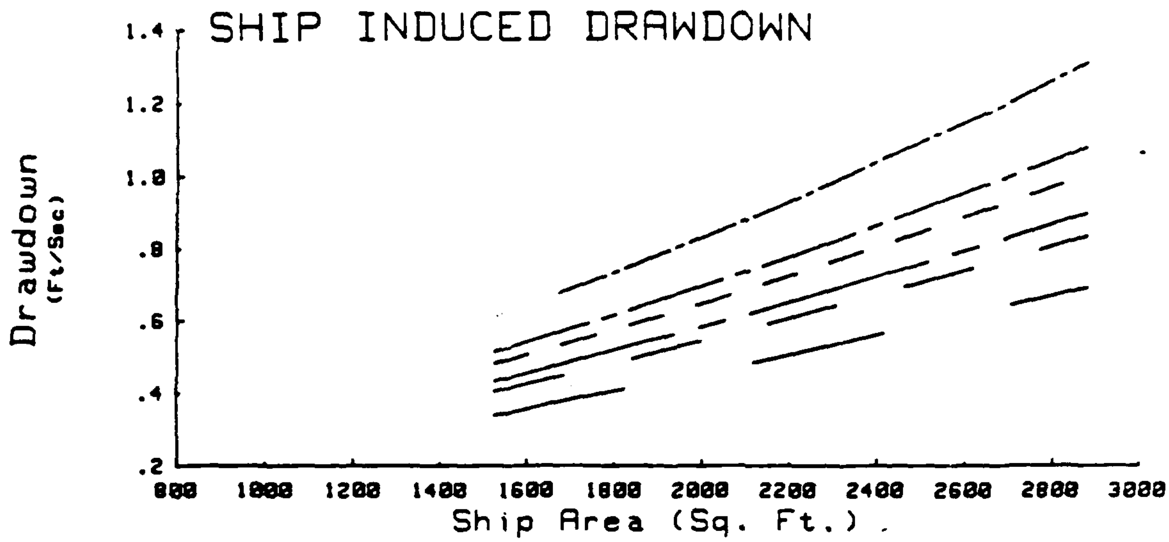


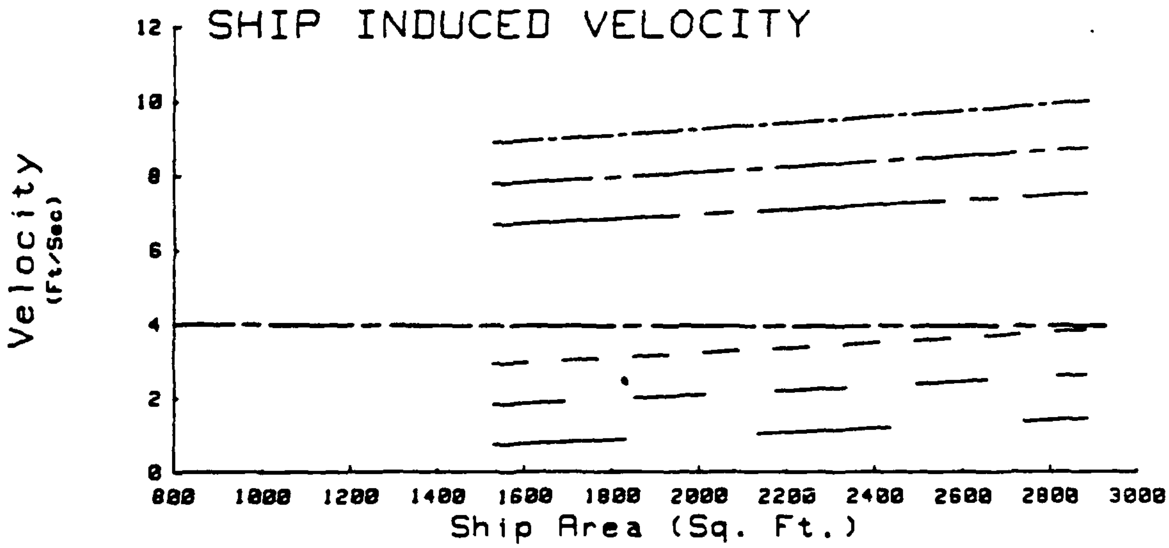
ST. CLAIR RIVER
1750+30 AT LWD+1



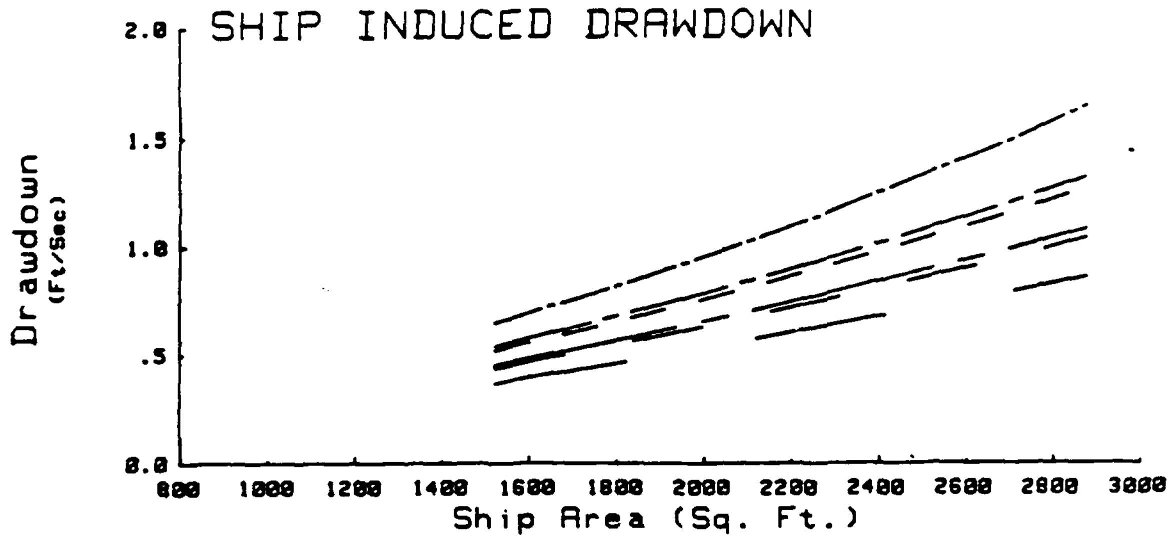


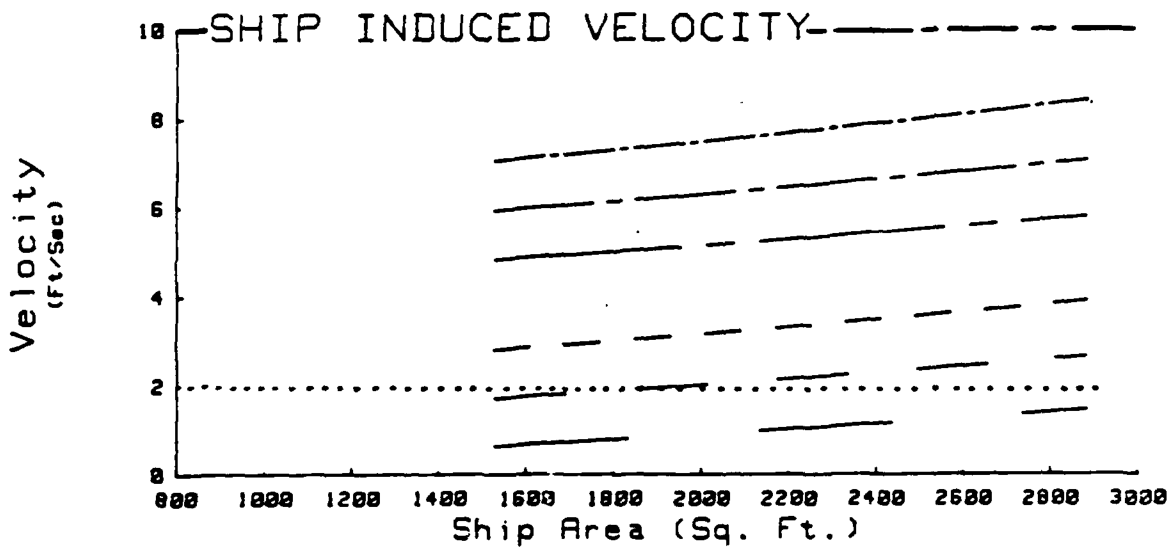
ST. CLAIR RIVER
1750+30 AT LWD+2



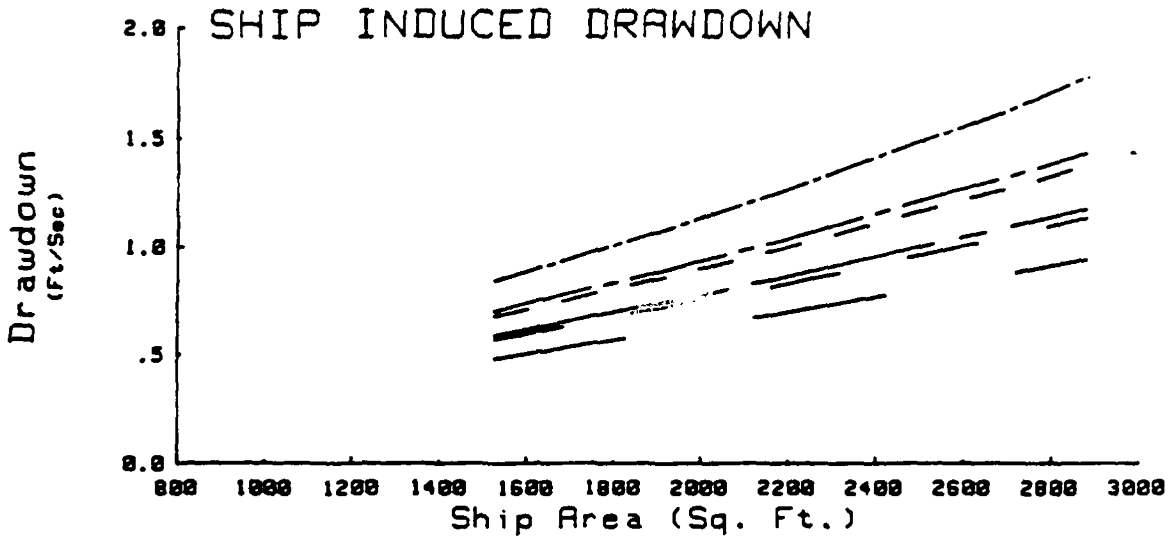


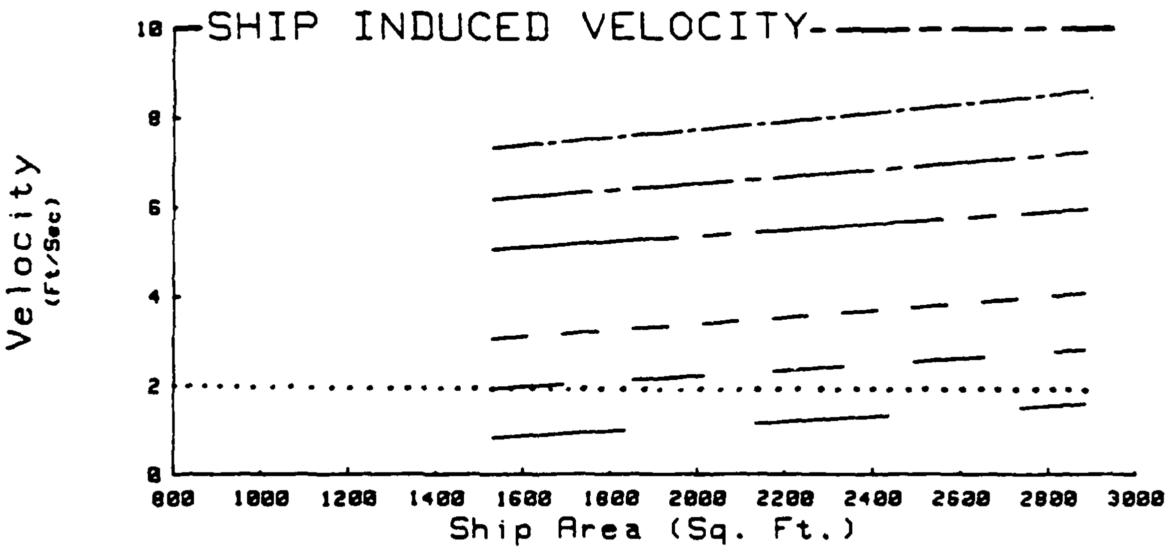
DETROIT RIVER
700+00 AT LWD+0



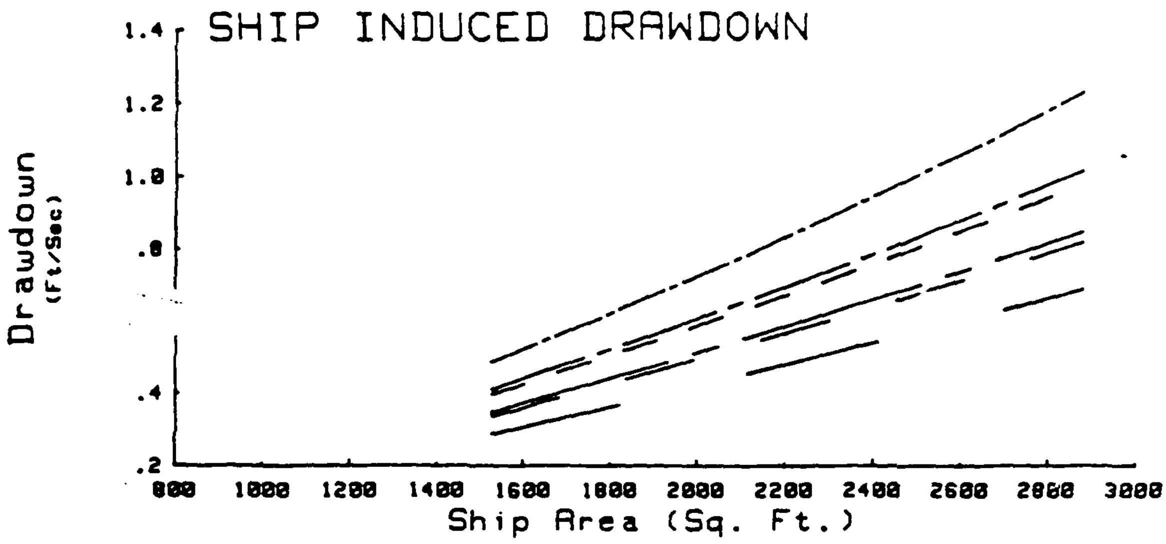


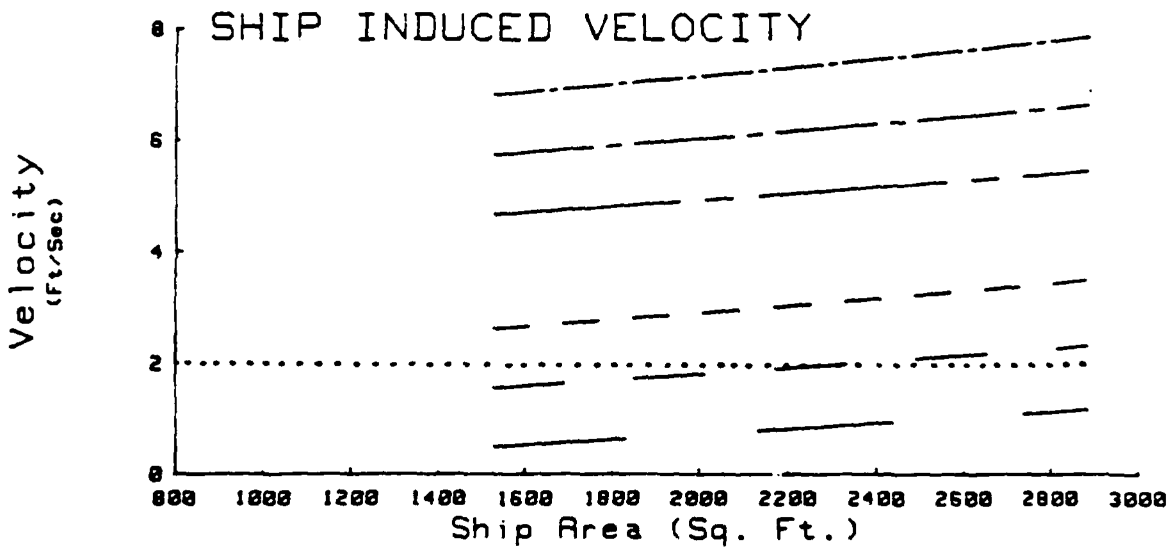
DETROIT RIVER
700+00 AT LWD+1



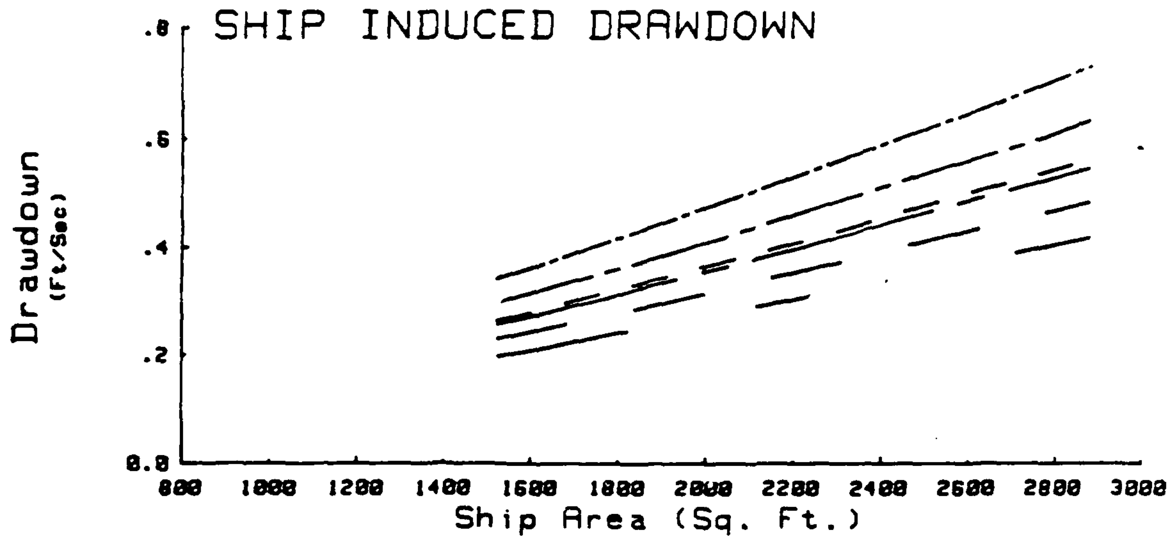


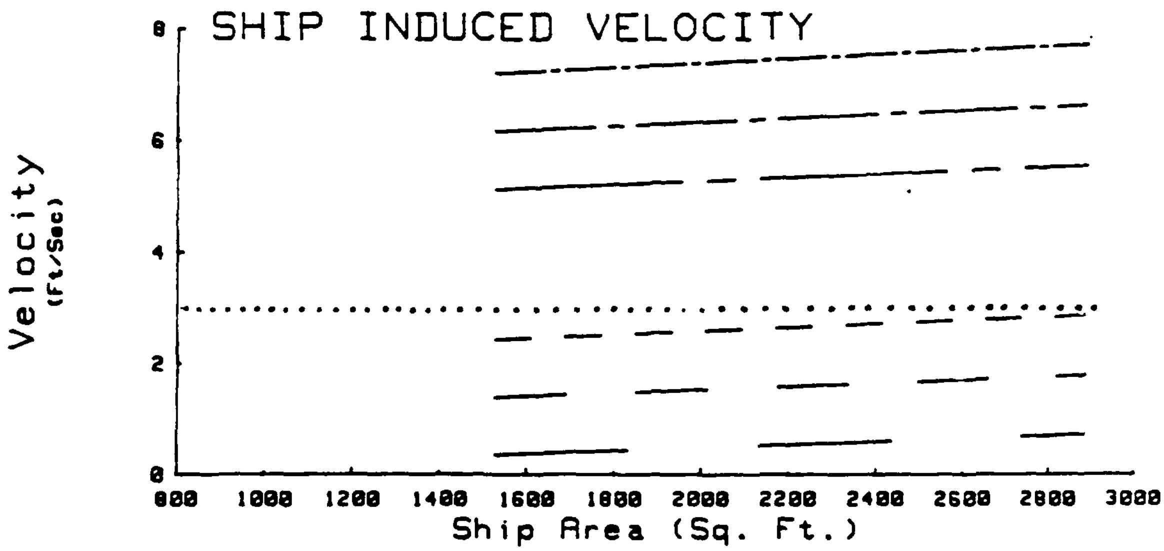
DETROIT RIVER
700+00 AT LWD+2





DETROIT RIVER
1217+22 AT LWD+0





DETROIT RIVER
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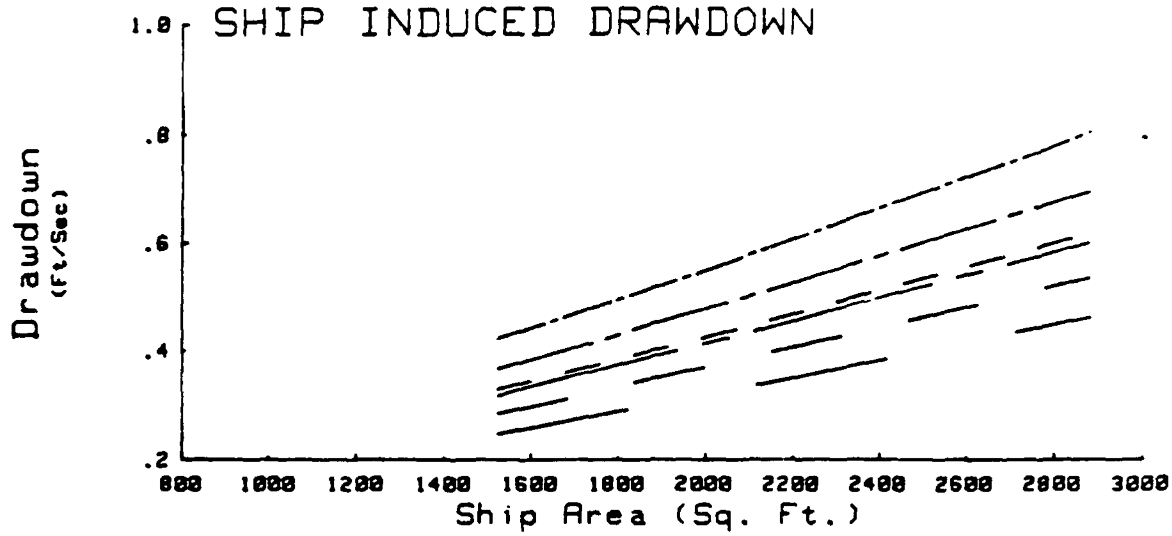

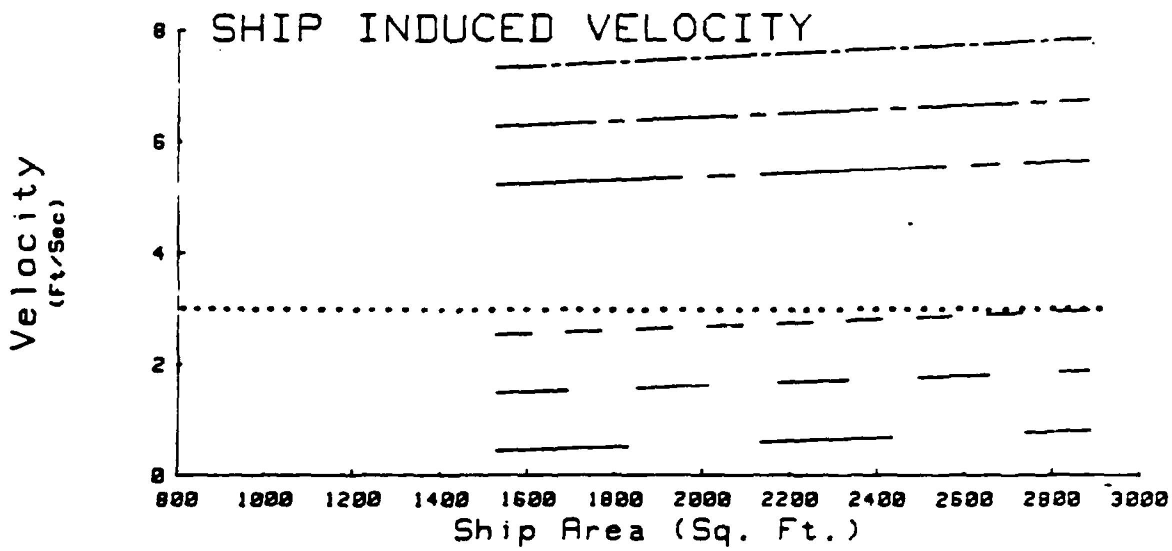

DETROIT RIVER
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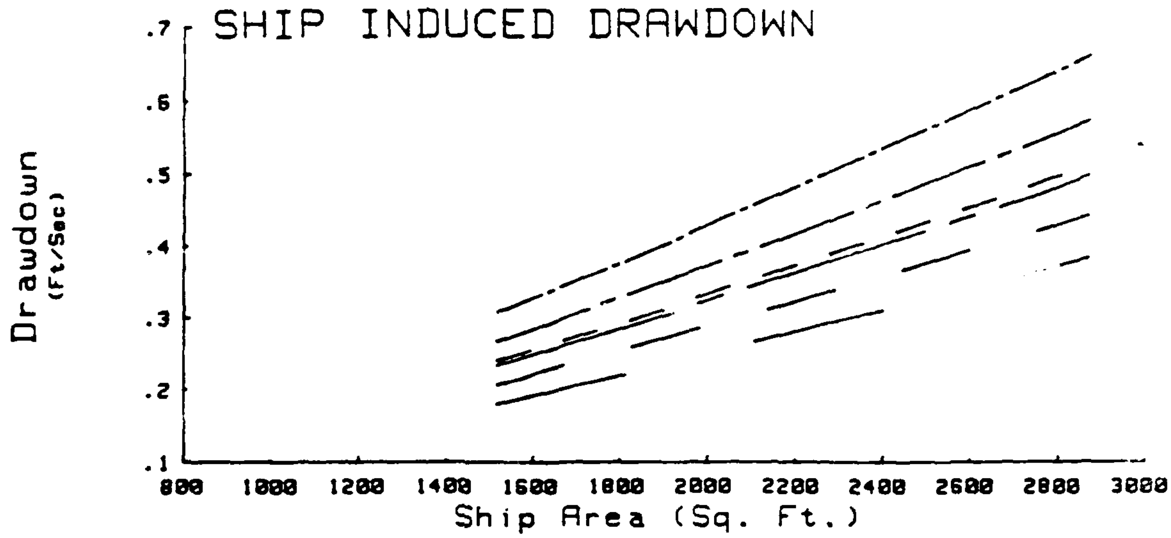

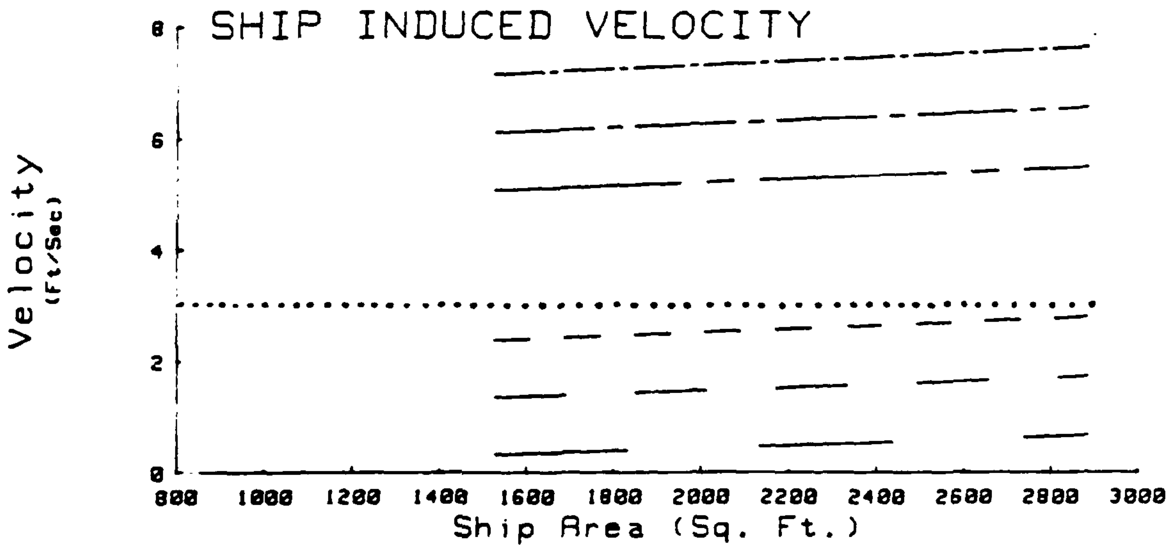

DETROIT RIVER
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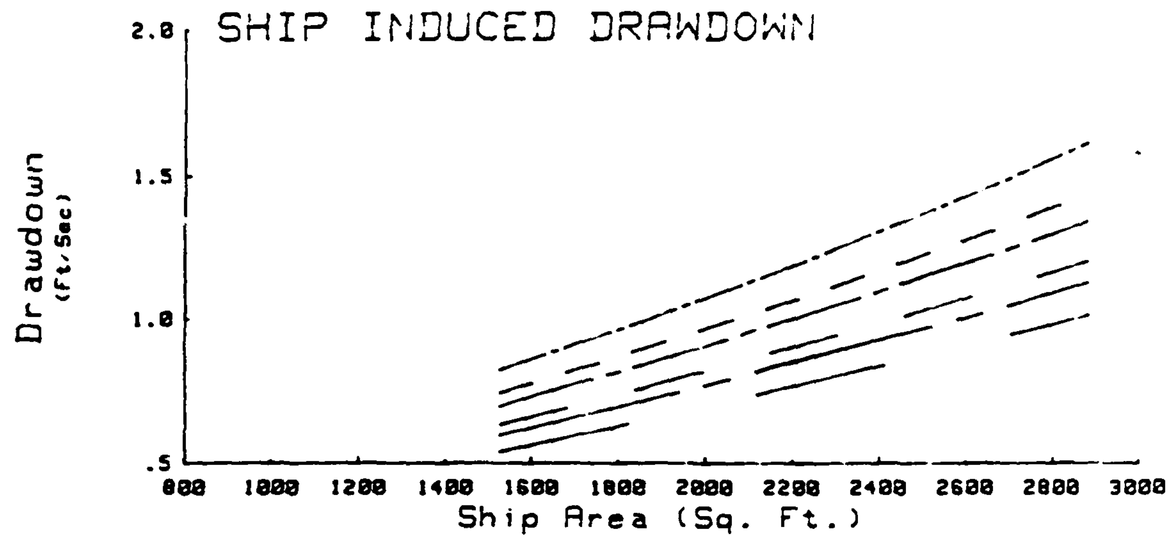
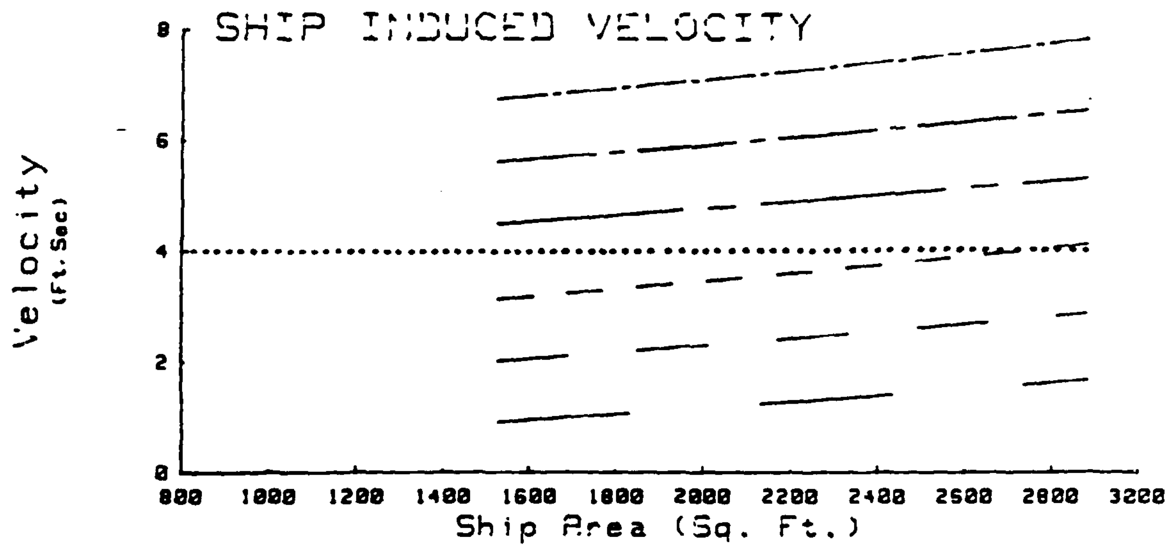
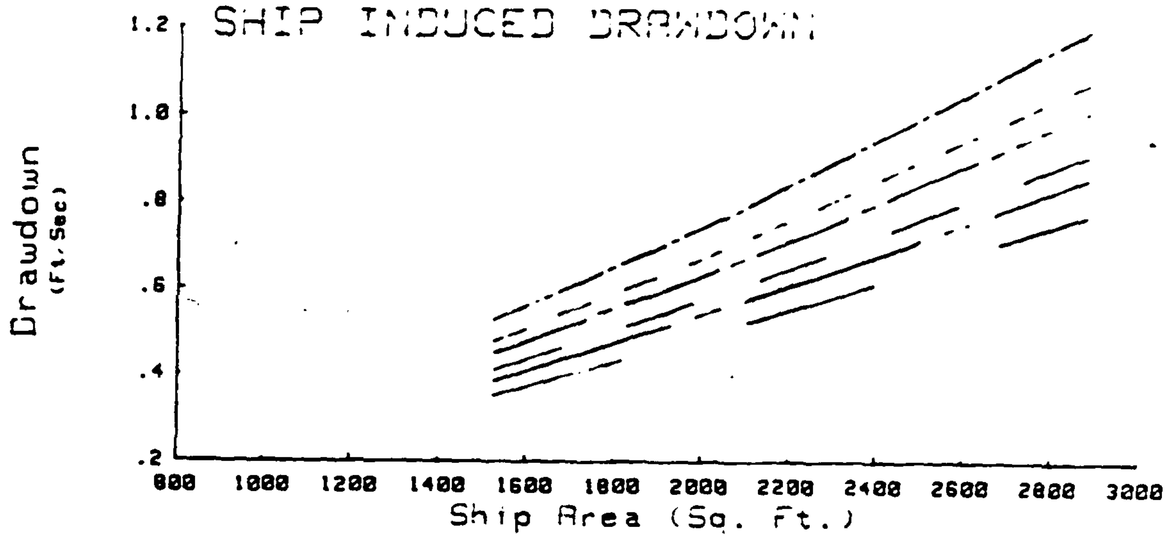
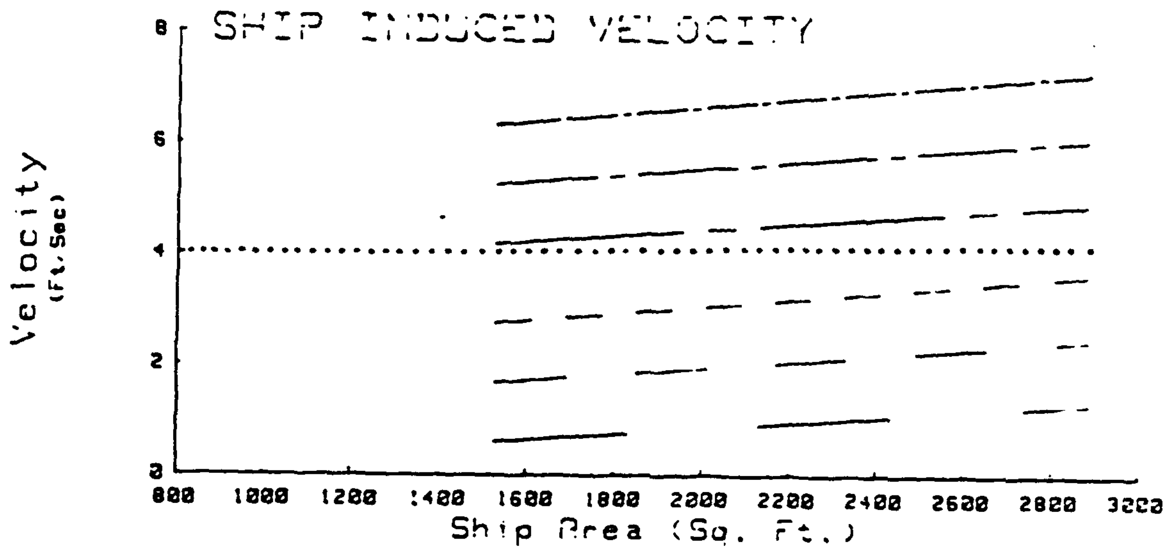




DETROIT RIVER
1387+02 AT LWD+1





DETROIT RIVER
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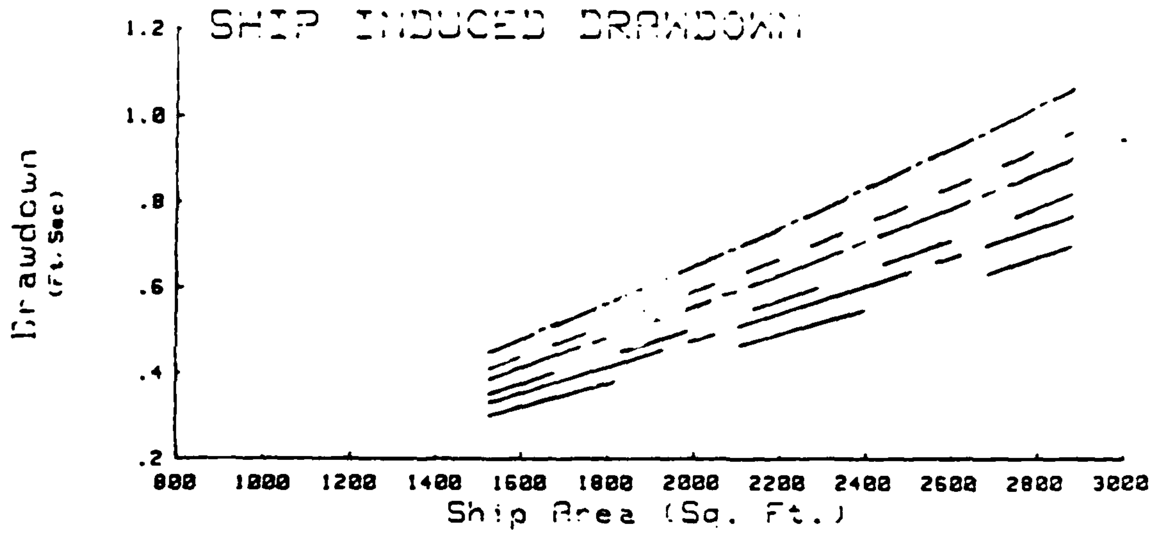
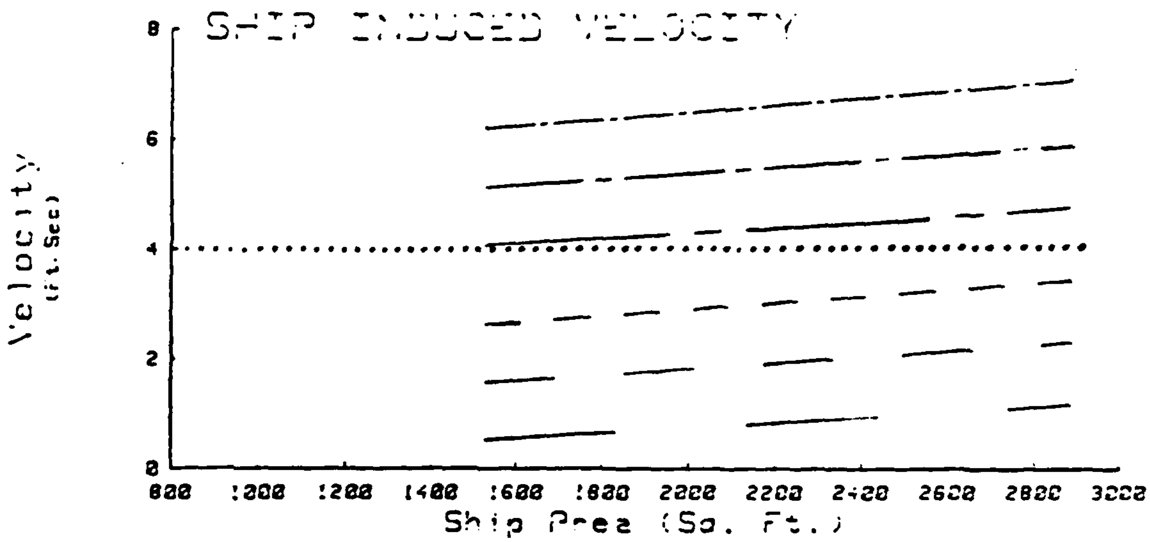
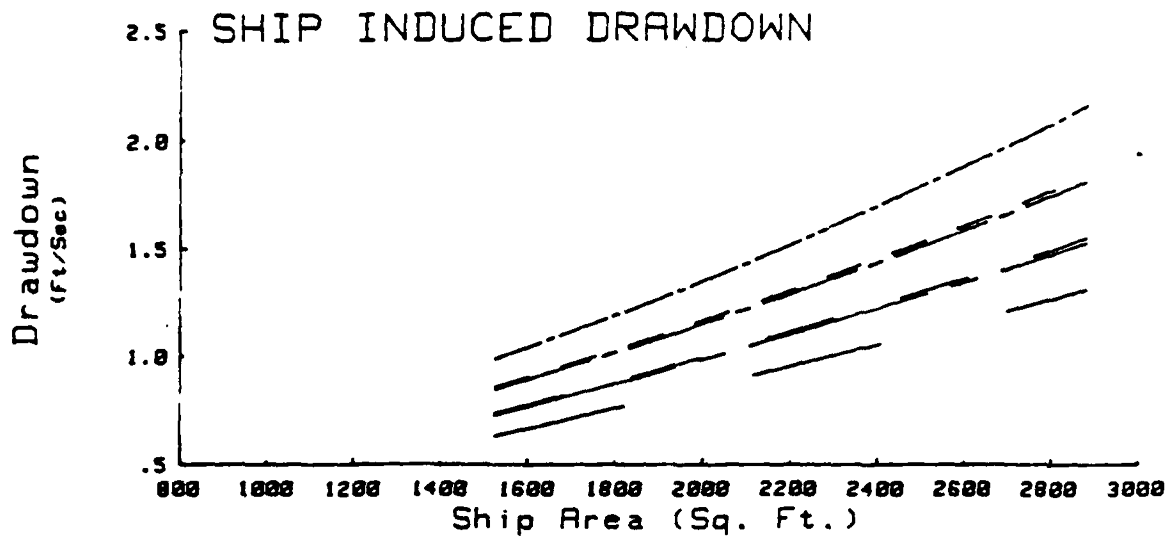
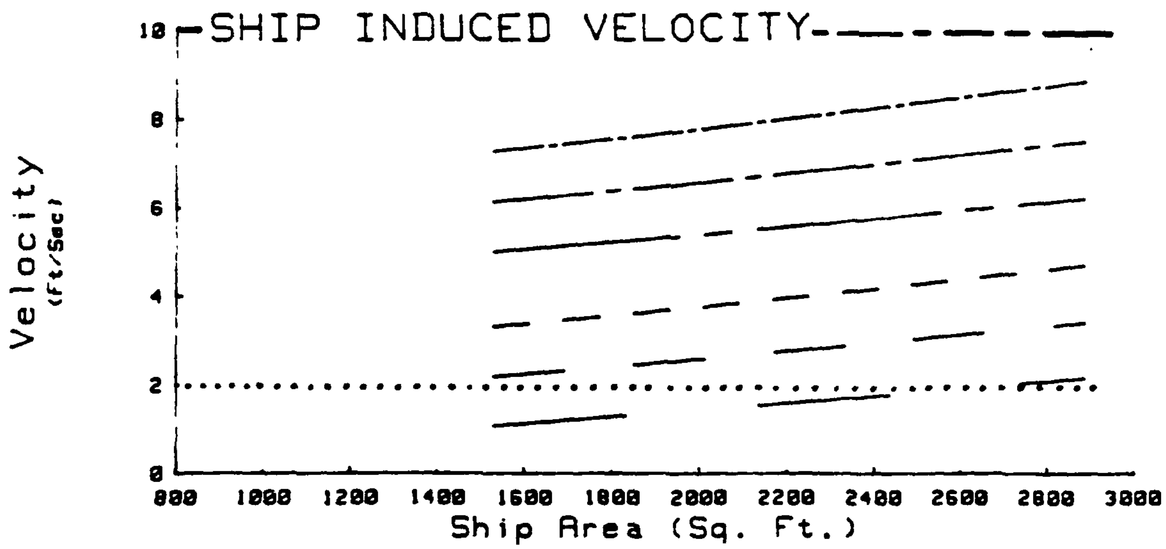


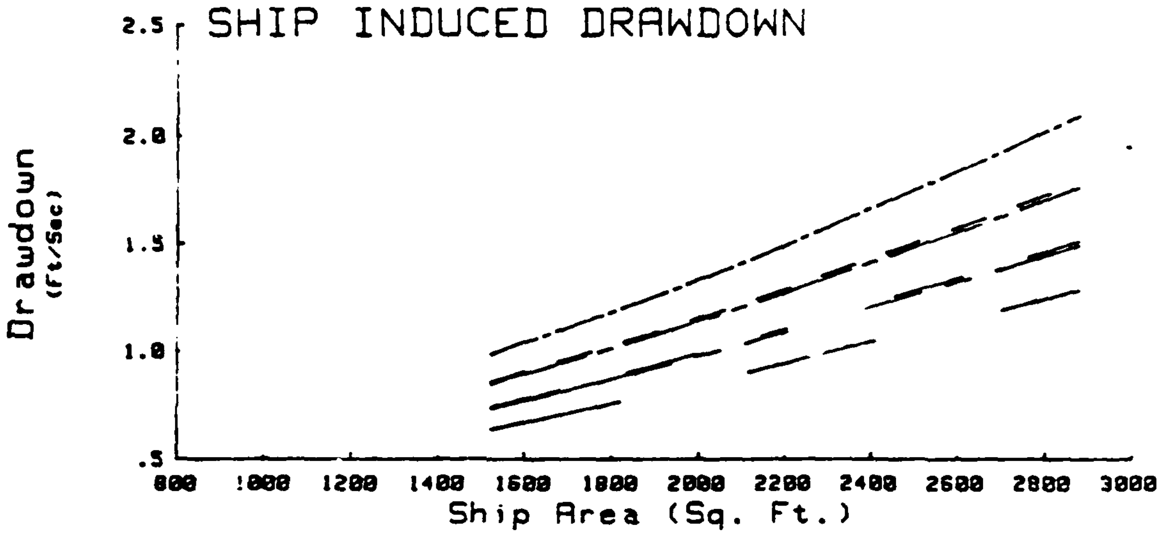


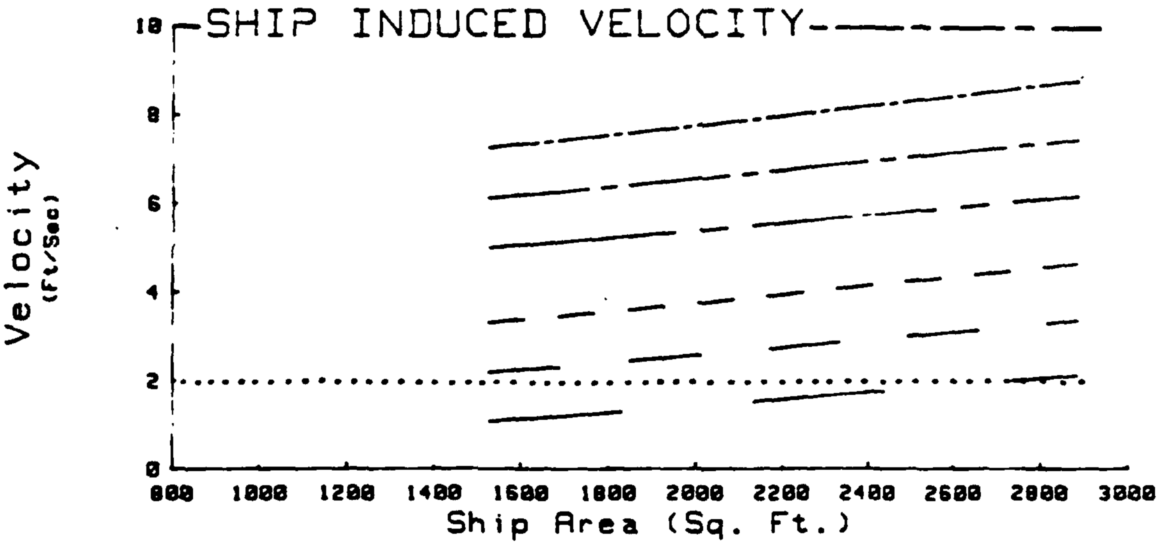
DETROIT RIVER
1520+66 AT LWD+0





DETROIT RIVER
1520+66 AT LWD+1





DETROIT RIVER
1520+66 AT LWD+2