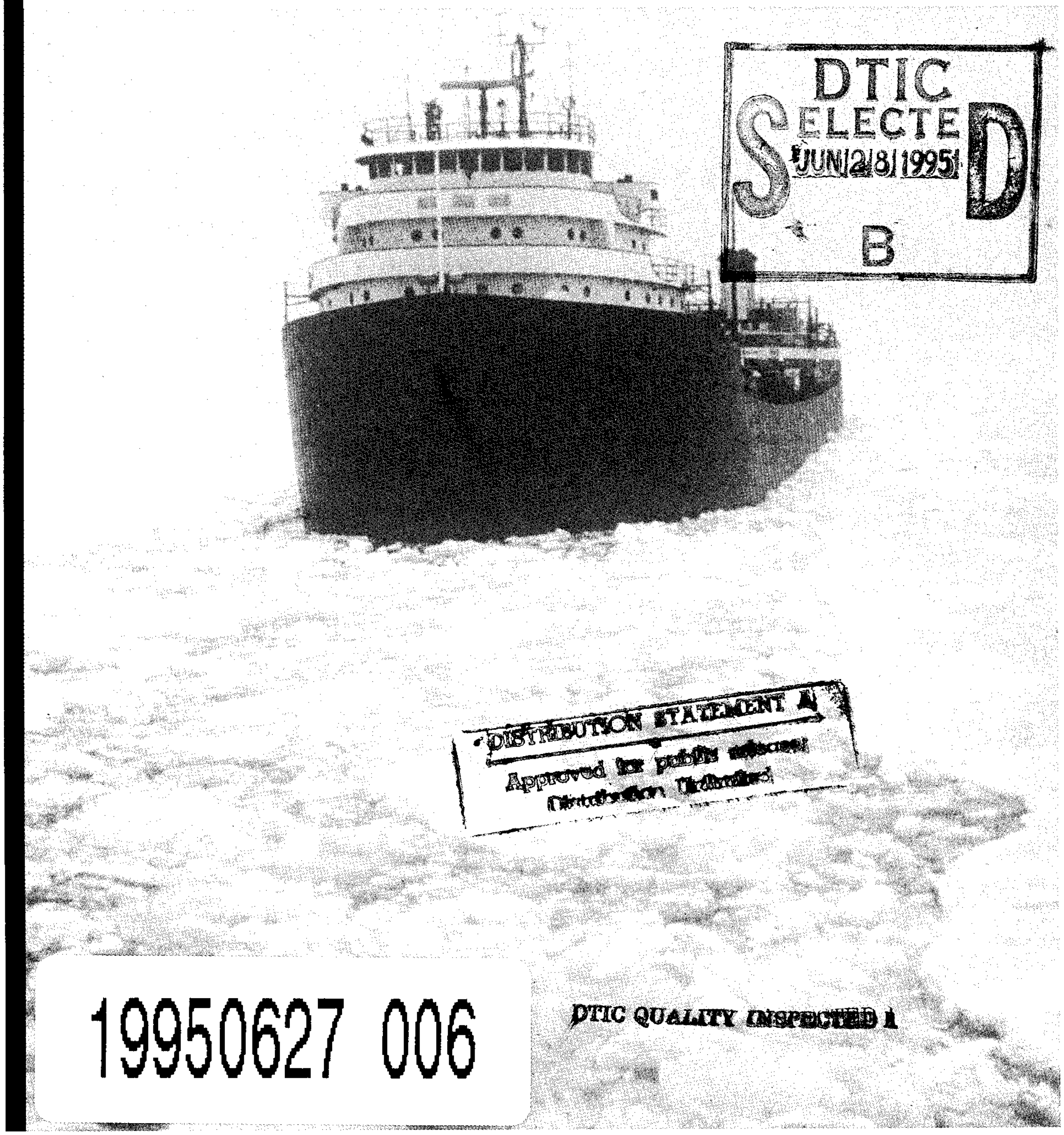
CRREL REPORT 95-10

Winter Navigation on the Great Lakes

A Review of Environmental Studies

James L. Wuebben, Editor

May 1995



Abstract

In 1970, Congress authorized a three-part Great Lakes–St. Lawrence Seaway Navigation Season Extension Program. It authorized a winter navigation demonstration program, a detailed survey study of season extension feasibility and a study of insurance rates for shippers. This report provides a review of numerous environmental and engineering studies conducted as part of the demonstration and feasibility portions of the program, as well as many environmental studies conducted after the completion of the original program. Topics include sediment transport, shoreline erosion, shore structure damage, oil and hazardous substance spills, biological effects, ship-induced vibrations and ice control systems.

Cover: The John G. Munsun *in the St. Marys River.*

For conversion of SI units to non-SI units of measurement consult ASTM Standard E380-93, *Standard Practice for Use of the International System of Units,* published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

CRREL Report 95-10

US Army Corps of Engineers
Cold Regions Research &
Engineering Laboratory

Winter Navigation on the Great Lakes

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May 1995

Prepared for
U.S. ARMY ENGINEER DISTRICT, DETROIT

PREFACE

This report was edited by James L. Wuebben, Research Hydraulic Engineer, Ice Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory. The following CRREL researchers wrote the various sections of the report:

- Introduction
  - Stephen L. DenHartog, formerly of the Ice Engineering Research Division
- Sediment Transport, Shoreline Erosion and Shore Structure Damage
  - James L. Wuebben, Ice Engineering Research Division
- Oil and Hazardous Substance Spills
  - Steven F. Daly, Ice Engineering Research Division
- Biological Effects
  - James L. Wuebben, Ice Engineering Research Division
- Vibrations Caused by Ship Traffic
  - F. Donald Haynes, Ice Engineering Research Division
- Bubbler Systems
  - George D. Ashton, Deputy Director for Research and Engineering
- Ice Control Structures
  - Russell E. Perham, formerly of the Ice Engineering Research Division
- Ice Control at Locks
  - John H. Rand, Programs and Resources Directorate.

This report was prepared for the U.S. Army Engineer District, Detroit, under Intra-Army Reimbursable Order NCE-IA-860127. This literature review summarizes selected investigations conducted under the Great Lakes–St. Lawrence Seaway Winter Navigation Demonstration Program, the Navigation Season Extension Feasibility Program and the Extended Season Navigation program under Operation and Maintenance Authority. It is not meant to be an all-inclusive, state-of-the-art review of the engineering, physical and environmental effects of navigation in winter but rather a comprehensive review of work conducted on the Great Lakes system in support of the season extension programs. While the sections on ice control might be better classified as reviews of engineering projects rather than environmental studies, they have been included because of their bearing on flow hydraulics, ice characteristics and shipping operations. The review primarily covers those reports specifically identified by the District for inclusion, but these have been supplemented with additional information when necessary for completeness.

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JAMES L. WUEBBEN, EDITOR

INTRODUCTION

In 1970, Congress authorized a three-part Great Lakes–St. Lawrence Seaway Navigation Season Extension Program in the Rivers and Harbors Act of 1970 (PL91-611) and subsequent amendments. It authorized a demonstration program, a detailed survey study of season extension feasibility and a study of ways to provide reasonable insurance rates to shippers. Since that time, there has been a series of investigations conducted by the U.S. Army Corps of Engineers on extending the navigation season on the Great Lakes and St. Lawrence Seaway system. From 1970 to 1979, with an expenditure of about $21 million, a large number of environmental and engineering studies and demonstrations were completed by the U.S. Army Corps of Engineers (COE), U.S. Coast Guard (USCG), St. Lawrence Seaway Development Corporation (SLSDC), U.S. Fish and Wildlife Service (FWS), National Oceanic and Atmospheric Administration (NOAA), Maritime Administration (MARAD), Environmental Protection Agency (EPA) and others.

The demonstration program was administered by a Winter Navigation Board, which in turn set up seven working groups as follows: Ice Information, Ice Navigation, Ice Engineering, Ice Control, Ice Management, Economic Evaluation, and Environmental Evaluation. Primary organizational responsibility was handled by the Detroit District, COE. Under the demonstration portion of the program, the working groups, for example, developed ice cover reporting and prediction schemes, conducted studies of fish habitat and winter shore damage, determined future needs for icebreakers and harbor improvements, and found methods to overcome lockage delays due to ice.

Concurrently a survey study was undertaken to determine how long a season extension was feasible and whether it would be the same for all reaches of the waterway. It soon became clear that there are three reaches with different problems that had to be considered separately:

- The St. Lawrence River section of the St. Lawrence Seaway and the Welland Canal from Tidewater to Lake Erie;
- The Detroit and St. Clair River portion; and
- The upper lakes including the St. Marys River and the locks at Sault Ste. Marie.

Six time extensions were considered, ranging from the status quo (with closure of the Sault Locks and the St. Lawrence Seaway from late December to early April) to year-round navigation on the entire system (except for a one-month closure on the Seaway). An interim feasibility report was completed in 1977 recommending season extension to 31 January ±2 weeks on the upper Great Lakes only. This would require very few engineering measures. The final recommendation of the final demonstration and survey reports (WNB 1979, USACE 1979a) was that, from an engineering and economic standpoint, year-round navigation was feasible on the upper two reaches, and a two-month closure (from 7 January to 7 March) would be necessary on the lower reach. The recommended plan projected a total investment cost of $451 million with a 4.0 benefit-to-cost ratio. The Office of Management and Budget, in response to the 1977 interim feasibility report, recommended that, since the Corps already had authority to operate the locks and maintain navigation, limited extension be considered under operation and maintenance authority. Consequently the Detroit District addressed operation of the locks at Sault Ste. Marie, Michigan, to 8 January ±1 week in an October 1979 environmental impact statement

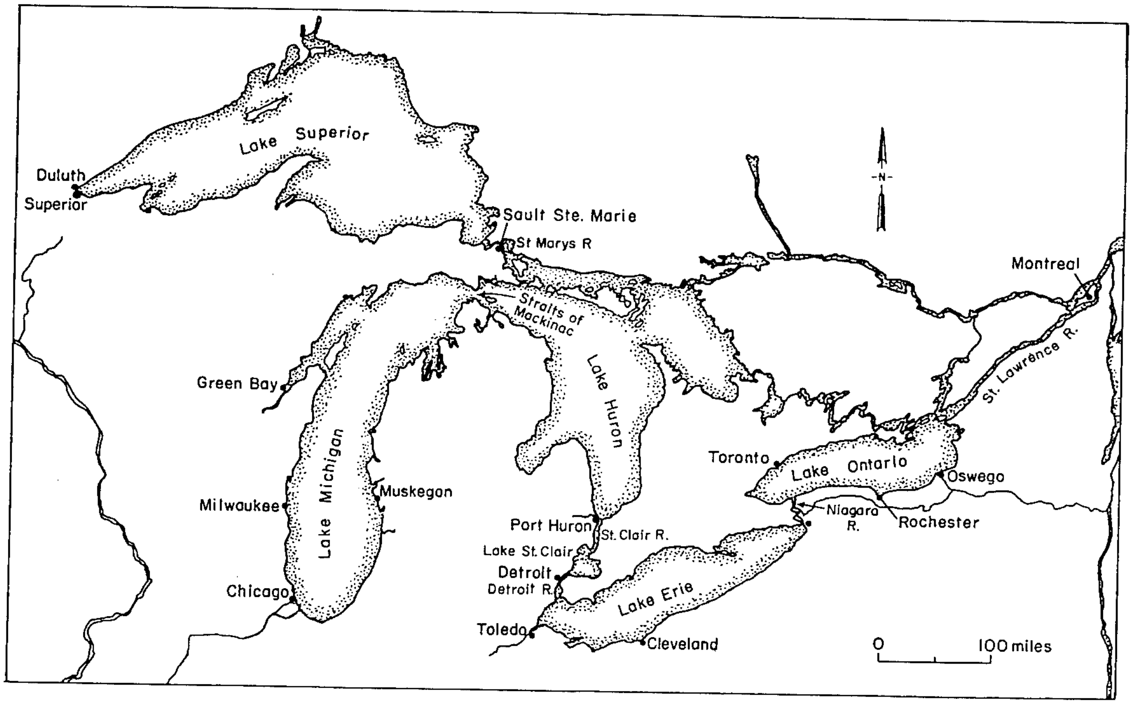

Figure 1. The Great Lakes Region.

(EIS) and is now operating the locks up to 8 January ±1 week. In 1981 the District began considering operating the locks to as late as 31 January ±2 weeks. Studies have been conducted since that time in preparation of an EIS for that proposal. A draft EIS was completed in 1988 (USACE 1988). The St. Lawrence Seaway is currently being operated under traditional season guidelines.

This report provides a review of numerous environmental and engineering studies conducted under the Extended Season Navigation Programs, including many environmental studies conducted after the publication of the 1979 Final Survey Report under Operation and Maintenance Authority. These later studies were undertaken to support the preparation of environmental impact statements for extended operation of the lock facilities at Sault Ste Marie, Michigan, to 8 January ±1 week and subsequently 31 January ±2 weeks. The Survey Study and Demonstration Program covered all U.S. portions of the Great Lakes–St. Lawrence Seaway System shown in Figure 1. Most environmental analyses, however, were conducted on the St. Lawrence, Detroit, St. Clair and St. Marys Rivers, especially the St. Marys, where the confined waterways were considered to present the greatest potential for damage. The 8 January ±1 week and 31 January ± 2 weeks program concerned the upper Great Lakes only.

Topics covered in this report include sediment transport, shoreline erosion, shore structure damage, oil and hazardous substance spills, biological effects, ship-induced vibrations, bubbler systems, ice booms and ice control at locks. For the most part the reports covered are those selected by the Detroit District for inclusion, but additional materials have been included as necessary for completeness. In many cases the studies of a particular topic extended over several years, with the more recent reports including information published in prior years. In those instances, emphasis was placed on the final, comprehensive versions. More detailed and extensive reviews of methods for dealing with river and lake ice problems can be found in Ashton (1986) and USACE (1982).

SEDIMENT TRANSPORT, SHORELINE EROSION AND SHORE STRUCTURE DAMAGE

In this section, reports dealing with the effects of extended season navigation on sediment transport, shoreline erosion and shore structure damage are reviewed. As a starting point the physical effects of vessel passage on river hydraulics are reviewed in some detail since they form a common basis for potential damage mechanisms discussed in later sections dealing with specific impacts.

Physical effects of commercial navigation in ice

Vessel passage through confined waterways may result in changes in the pattern and magnitude of water motion due to ship-generated waves, propeller wash, and drawdown and surge. A confined waterway is defined as one in which the shoreline or bottom is close enough to influence ship-generated water movements. These changes in the flow of water can, if large enough, cause the movement of particulate materials, leading to erosion of the shoreline and the channel bed, damage to shoreline structures, increases in turbidity and other chemical and biological effects. In addition to these mechanisms, which occur year-round, additional effects during navigation in ice might occur due to direct movement of ice in contact with vessels, by disruption of stable natural ice covers, and through interaction of vessel-induced hydraulic effects with the ice cover. The size and significance of these potential mechanisms depend on a number of local conditions, such as the bathymetry, water levels, surficial soil conditions, ice conditions, shore and shore structure composition and geometry, and presence of other natural agents such as water currents or waves.

Ship waves

The generation of water waves during vessel passage is the mode of action most often associated with ship-induced effects in the nearshore zone. When a ship sails in ice-free open water, a system of diverging and transverse waves develop. Diverging waves are those that form the familiar V-shaped wave pattern starting at the bow of a ship, while transverse waves form a less noticeable wave train that follows the vessel and is oriented normal to the sailing line.

Due to the decay of the waves as they propagate away from the ship and the interaction between these dissimilar wave sets, the generated wave heights are a strong function of position. The location of maximum wave heights, referred to as cusps, occur where the crests of the two wave types intersect so that they reinforce each other. The wave heights at these cusp locations decrease inversely proportionally to about the cube root of the distance from the disturbance.

The height of ship-generated waves is primarily a function of vessel speed (Gates and Herbich 1977). Figure 2 was developed by Ashton (1974a) from data presented by Sorenson (1973) for waves generated by boats with displacements from 3 to 343 tons. These data were derived from measurements in the Oakland Estuary (California) in a water depth of about 35 ft for various ship speeds. Although this figure ignores depth and draft effects, there is remarkably little scatter. The figure serves to show the strong relation between the maximum wave height 100 ft from the sailing line $H_{\max,100}$ and ship velocity V. 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 or hull geometry due to the small variations caused by factors other than vessel speed. Ofuya also cited the results of wave data collection at three sites on the St. Clair River and one each on the Detroit and St. Lawrence Rivers. For gauges located in 5–25 ft of water, very few waves were measured in excess of 0.6 ft, and then only when the speed limit was significantly exceeded. Further data on ship-generated, open-water waves on the Great Lakes connecting channels are presented in the report by USACE-SLSA (1972).

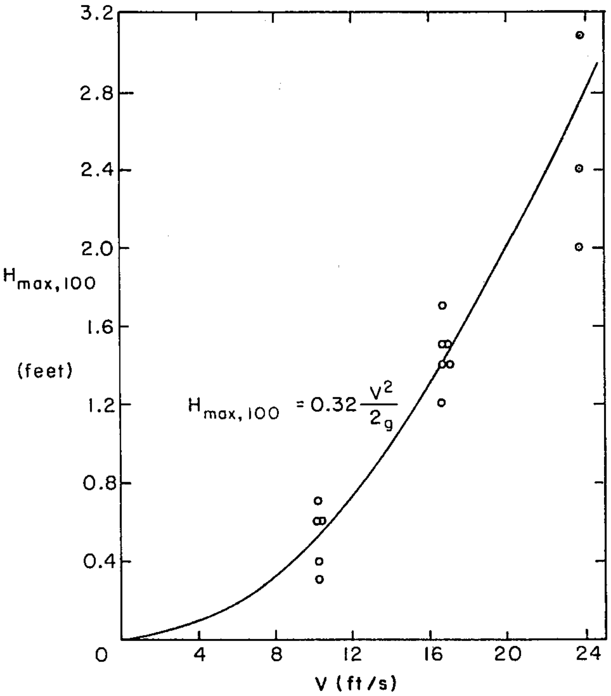

Figure 2. Maximum wave heights 100 ft from the sailing line for a variety of hull forms. (From Ashton 1974.)

Wuebben et al. (1984) analyzed the variation in ship-generated waves with vessel size on the St. Marys, St. Clair and Detroit Rivers. For the 44 shoreline sites considered, the waves generated by a 1000-ft vessel traveling at existing speed limits were calculated to be no more than about 0.5 ft in amplitude at the shoreline. Although equations are available for predicting ship-generated wave heights and their subsequent decay in open water, none adequately address situations involving shallow water or confined or irregularly shaped channels accompanied by complex flow distributions such as those found in the Great Lakes connecting channels. Without site-specific field data to calibrate and check the calculated values, any projections made must be considered approximate. The available theories do, however, clearly show that vessel speed is by far the most important variable controlling the magnitude of ship waves generated, followed by the distance to the shoreline, which governs their decay.

During winter ice conditions, the short-period waves generated by vessel passage are effectively damped by the ice cover. As part of a study of the effects of winter navigation on shoreline erosion and structure damage (USACE 1974), continuous measurements of water level variations during ship passage were collected at several locations on the St. Marys River during periods with and without an ice cover. These data clearly showed both wind- and ship-generated waves during open-water periods, but during periods with ice covers no waves were detectable.

Figure 3 from Carter et al. (1981) shows the effect of an ice cover on the height of waves encountering an ice cover. Relative wave amplitude is defined as the height of a wave passing under the ice divided by the height of that same wave under open-water conditions. Based on data given in USACE (1974) and Ofuya (1970), the wave period for ships on the Great Lakes connecting channels is on the order of 2–4 s. Thus, according to Figure 3, these ship-generated waves would be drastically attenuated during navigation in ice relative to their open-water heights (a 3-ft, 3-s wave would be reduced to 0.3 ft by a 1.5-ft-thick ice cover). Further, since these waves decay rapidly (even in open water) as they propagate from the ship, these waves are considered to be insignificant and will not be addressed further.

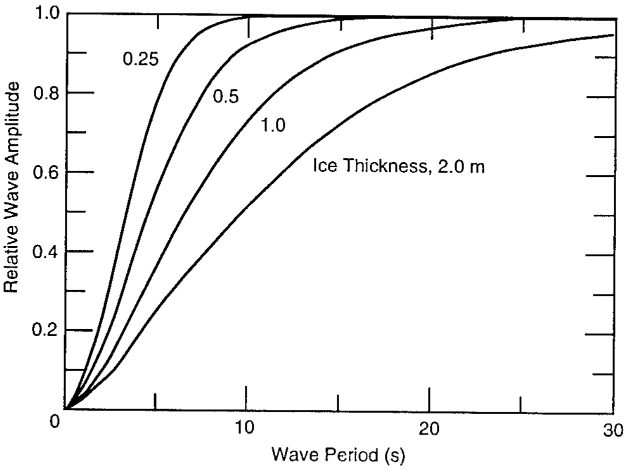

Figure 3. Damping of waves at an ice edge. The water depth is 10 m. (From Carter et al. 1981.)

Propeller wash

During vessel passage the bottom and sides of a channel may be subjected to a propeller-driven water jet. There has been very little study of sediment transport or other effects due to prop wash, and there were no data available for the Great Lakes–St. Lawrence Seaway area. Most previous studies of the damage potential of winter navigation were focused on shoreline and nearshore effects. As a result, prop wash effects were typically disregarded since they are normally limited to areas very close to the vessel track.

In a study of the effect of vessel size on ship-related damage, Wuebben (1983a) selected empirical relations based on their ability to deal with the variation in propeller jet velocity for locations with limited depth or lateral confinement. Lacking any calibration data from the Great Lakes system, he was unable to provide site-specific, quantitative predictions, but he did conclude that fully loaded commercial vessels are easily capable of scouring the channel bed throughout the dredged portions of the connecting channels. He also found that vessel speed was by far the most important factor determining the magnitude of prop wash, followed by cross-sectional area and hull geometry. For confined channels, hydraulic interaction with the channel boundaries requires a higher propeller thrust to maintain open-water speed, increasing the damage potential.

Hochstein and Adams (1985b, 1986) modified their existing prop wash numerical model for application to the St. Marys River by incorporating appropriate ship and site characteristics and transferring other necessary information from earlier studies on the Kanawha and Ohio Rivers in West Virginia and Ohio. They concluded that the effects of prop wash could not be effectively separated from backwater (drawdown) influences, so they considered both simultaneously. Through a combination of basic theory and empiricism, they provided a quasi-two-dimensional prediction of vessel effects. The "quasi" prefix is used since the two-dimensional predictions are premised on empirically assumed distributions of ambient and ship-affected velocities. Without collecting appropriate field data (which they recommend), the performance of these assumed distributions in the complex, dredged channel portions of the river cannot be accurately assessed. However, the model has been verified against all available Great Lakes connecting channel data.*

In their reports Hochstein and Adams have accounted for the effects of ice in terms of the added propeller thrust required to maintain speed. This was accomplished by assuming that the propeller jet velocity for a ship in ice increased as the square of its equivalent open-water velocity. In their comparison of the effects of prop wash for various sizes of vessels traveling at existing speed limits, they often found that the maximum effects of lower-class vessels reached a maximum when their available horsepower was insufficient to maintain speed. Thus, the largest and most high-powered vessels could induce substantially larger propeller-induced effects than size alone might indicate. Quantitative, site-specific predictions of ship-induced velocity distributions across selected river cross sections were provided.

Drawdown and surge

When a vessel is in motion, even in deep water, the water level in the vicinity of the ship is lowered and the ship with it (called vessel squat). For the same ship this effect increases as the vessel speed increases or as the water depth decreases. When a ship enters a confined water, there is a considerable change in flow patterns about the hull. 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, which increases vessel squat. In a channel that is restricted laterally, this effect is further exaggerated.

There is, however, another problem associated with the water level drop caused by the movement of a ship in confined waterways. The water level drop becomes, in effect, a trough extending from the ship to the shore and moves along the channel at the same velocity as the ship. As the ship size or speed increases, this moving trough deepens. For the restricted sections of the Great Lakes channels, this effect might most easily be envisioned as a channel constriction such as a bridge pier.

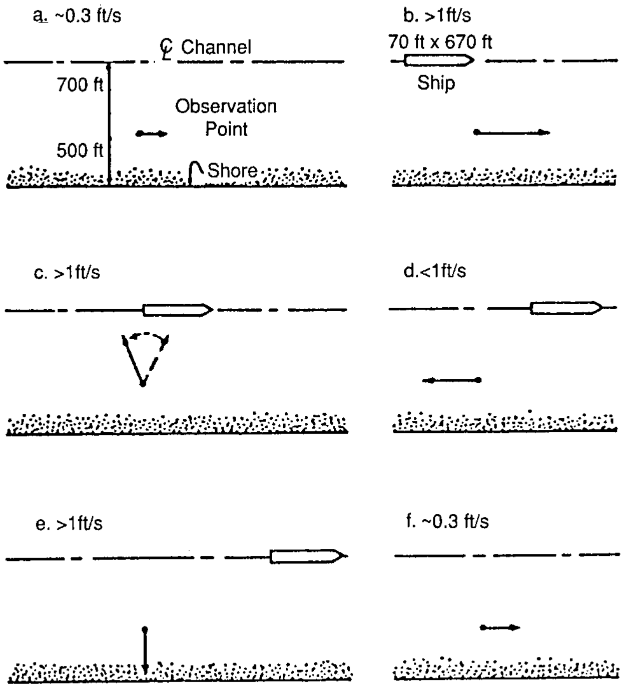

Figure 4. Ship-induced water movements. (From Wuebben et al. 1978a.)

The phenomenon of nearshore drawdown and surge 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 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. To analyze the mechanics of sediment motion during vessel passage, two-dimensional, near-bottom velocity measurements were collected at a number of locations along the St. Marys, St. Clair and Detroit Rivers during periods with and without ice (Alger 1977a, 1978, 1979a, Wuebben et al. 1978a).

An example of these measurements (from Wuebben et al. 1978a) is presented in Figure 4 to illustrate the magnitude and complexity of the situation. The figure presents water velocities under the ice cover during the passage of a 670-ft ore carrier near Six Mile Point on the St. Marys River. The observation point was located in about 10 ft of water, and there was an ambient velocity

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* Personal communications, Don Williams, Detroit District, COE.

of about 0.3 ft/s. The direction of the near-bottom water motion rotated 360° during the event, with velocities in all directions significantly greater than the ambient downstream current. Numerous other data sets for the variation of water level and velocity are available in the reports by Alger (1977a,b, 1978, 1979a,b). Nearshore drawdowns of up to 3 ft have been measured on the connecting channels (USACE 1974, Wuebben 1978), but the highest recorded values have been for large vessels approaching or exceeding the speed limits. A field study of drawdown and surge on the St. Lawrence Seaway (Normandeau Associates 1979) documented no drawdown events greater than 2 in. and felt that no reasonable correlation with vessel parameters was possible.

Ice effects

In a study of the effects of winter navigation on shoreline erosion and dock damage (USACE 1974), continuous recordings of water level fluctuations were collected at various sites along the St. Marys River. While the ship- and wind-generated waves were well defined in the open-water recordings, they were undetectable for periods with ice cover, indicating total damping. In contrast, ship-generated drawdown and surge were undamped and apparently even enhanced.

From data at an individual site, the authors were able to get a reasonable correlation between measured drawdown values and an estimate of the drag force on a ship hull (USACE 1974). At one site on the mainland shore of Lake Nicolet, ship passages were monitored during open-water conditions, early ice (0.3–0.5 ft) and mid-winter ice (1–1.3 ft). Although a comparison of the drawdown and surge among these three conditions is somewhat limited by the relatively few data points (22) and the scatter inherent in making such measurements, their parameterization technique indicates that a drawdown of 0.4 ft during open-water conditions might be increased by about 40% during periods with ice. The data did not indicate any clear difference with increasing ice thickness.

Hodek et al. (1986) also examined the effect of ice on the magnitude of drawdown. Although the flexure and cracking of an ice cover would dissipate some energy, they felt that the primary effect of an ice cover would be to decrease the area available for flow and thus increase the magnitude of drawdown. On that basis, smaller cross sections would be more severely affected by ice since the same thickness of ice would constitute a larger percentage of the water area in more-confined channel reaches. The numerical model accompanying their report accounts for both a change in vessel effects with the presence of ice and with increasing ice thickness. For one example given, a 1-ft open-water drawdown would be increased as much as 33% for 18 in. of ice. For the same ice condition, the percentage increase in drawdown would increase as ship speed increased.

Analysis of drawdown

Most analytical and predictive work on drawdown in the Great Lakes connecting channels has employed a one-dimensional approach. Although a multi-dimensional treatment would provide more detail, especially in regard to water velocities, there are insufficient data to calibrate or validate an expanded treatment. Fortunately field data (Wuebben et al. 1978a) show that the magnitude of drawdown is relatively constant over most of the channel cross section during vessel passage and that a one-dimensional treatment predicts this value within acceptable accuracy (Alger 1977a, Wuebben 1983a, Hodek et al. 1986).

If the channel cross section is not symmetrical or the ship passes closer to one shore, the one-dimensional results can be improved by assuming that no water crosses the sailing line so that the section may be split into separate pieces for calculation (Wuebben 1983a, Hodek et al. 1986). For highly non-uniform flow distributions or complex channel shapes, empirical cross-section shape factors can also be included, but these are highly site specific and cannot be reliably transferred elsewhere (Wuebben 1983a). The distribution of velocities and sediment transport potential across a river cross section cannot be directly considered, however. Previous work has generally used the existing field database to develop shore and shore structure damage criteria that can be empirically correlated to one-dimensional modeling (Wuebben 1981b, 1983a, Wuebben et al. 1984, Hodek et al. 1986).

Wuebben (1981b, 1983a) and Wuebben et al. (1984) developed such a one-dimensional treatment to allow an assessment of vessel size on drawdown and resulting sediment transport potential. For the long, parallel mid-body commercial vessels common on the Great Lakes, vessel length is relatively insignificant in determining drawdown. A sensitivity analysis demonstrated that ship velocity is by far the most important variable controlling the magnitude of drawdown. As shown in Figure 5, a change in vessel speed of 2 ft/s would

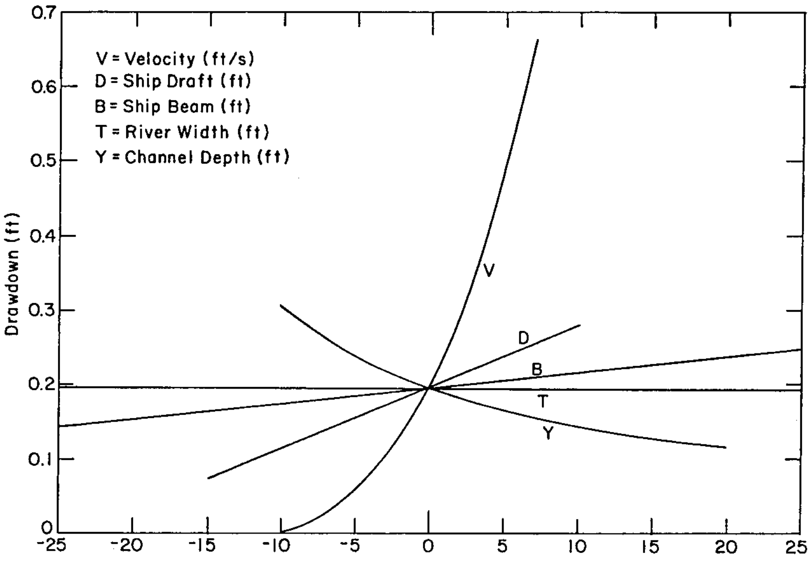

Figure 5. Effects on drawdown due to changes in variables from a basic case.

be more significant than a 10-ft change in vessel beam, vessel draft or channel depth. The basic case in Figure 5 is 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 corresponds to the central point on Figure 5.

Vessel speed and water velocity are of equal importance in the calculations, but due to its greater range of variation, vessel speed is more significant in practical applications. An increase in vessel draft is more significant than an equal increase in beam simply because it geometrically adds more cross-sectional area to the ship. Similarly, an increase in water depth (with discharge unchanged) would more than offset the corresponding increase in allowable draft since the increase in flow area across the river is much larger than the change in the wetted area of the ship. The net effect is a decrease in the blockage of the channel.

Hodek et al. (1986) and Alger and Hodek (1986) further refined the one-dimensional approach and developed an interactive, user-friendly program that could be run on a desktop computer system. This model allows rapid computation and comparison of various scenarios of fleet mix and site characteristics. The database for ship effects was considerably expanded by monitoring hydraulic conditions at five new sites on the St. Marys River in addition to those documented under previous studies. New topics such as vessel-generated turbidity, an estimate of the surge (increase in water level) that often follows the drawdown phase, and an estimate of shore structure damage potential for basic structural categories were included. They also found that drawdown is very sensitive to the position of a vessel within the channel. The capability to predict the magnitude of the surge that follows the drawdown phase is important in evaluating whether an onshore bluff will be attacked or whether nearshore flooding during high-water periods will be exacerbated, whereas the values of turbidity are significant in the potential for biological impacts.

Hochstein and Adams (1985b) adapted a model that considers drawdown and the effects of propeller wash to the St. Marys River. A subsequent report (Hochstein and Adams 1986) added treatment of ship-generated waves. Their model is attractive for assessing environmental effects in that it makes quantitative predictions of the distribution of water velocity, suspended solids and bed load across a river cross section based on prop wash, waves and drawdown. The numerical formulation they employed is a quasi-two-dimensional treatment in that it conducts hydraulic calculations in one dimension and then superimposes assumed distributions for the cross-channel variations of both ambient and ship-influenced flow variables. While in simple channel shapes this approach may provide useful additional detail, extension to the complex channel shapes and flow distributions present in the St. Marys River is uncertain. However, the Hochstein and Adams model should provide an improved basis for comparison of various vessel frequency scenarios. This model was subsequently modified by personnel from the Detroit District to allow input of measured ambient velocity distributions, but the hydraulic calculations remain one dimensional. Treating ship effects in two dimensions is important due to significant variation in ship-induced water velocities across a river cross section. This variation must be accounted for in predicting magnitudes of sediment transport, turbidity and impacts on biological systems.

Data from a prior study on the Kanawha River in West Virginia (Hochstein and Adams 1985a) were compared with predicted values, but the results are not presented in two-dimensional form. Further, no information is given on river or ship characteristics or the location of the sampling points, so the feasibility of transferring velocity distributions and parameter values developed there to a Great Lakes connecting channel is unclear. Lacking a complete, two-dimensional set of field data on the variation of ship-induced water velocities and sediment movement on the St. Marys River (which they strongly recommended obtaining), the performance of the model cannot be definitely assessed. It was, however, calibrated against the available data on ship-generated drawdown and waves. The model was also applied to channels in Duluth–Superior Harbor* and resulted in predictions of sediment suspension of the same order of magnitude as the field data of Stortz and Sydor (1980).

In summary, the major hydraulic effects of vessel passage during periods of ice include propeller wash and drawdown and surge. Ship-induced waves were found to be quickly damped by an ice cover and thus unimportant. In contrast, propeller wash and drawdown can be increased due to the need for greater thrust to overcome the resistance of ice and the reduction of open cross-sectional area by the ice. Several models have been developed for or adapted to the Great Lakes connecting channels for predicting vessel-induced drawdown, providing both one-dimensional and two-dimensional predictions. The two-dimensional approach also considers ship waves and propeller wash effects. These models provide a capability to develop system-wide predictions of vessel effects, not only for existing navigation scenarios but more importantly for scenarios considered for possible future implementation where field documentation is not possible.

Sediment transport and shoreline erosion

The potential for shore damage due to drawdown is a direct function of the ship-induced change in hydraulic conditions that can initiate sediment transport or increase transport rates. For sediment transport to occur, near-bottom or nearshore water velocities must overcome a sediment particle's resistance to motion. Three modes of transport of granular bottom sediments have been observed during vessel passage (Wuebben et al. 1978a). They are

- Bed load, which is typified by a pattern of slowly migrating sand ripples on the riverbed;
- Saltation load, the movement of individual grains in a series of small arcs beginning and ending at the riverbed; and
- Explosive liquefaction, in which bottom sediment is rapidly suspended due to a rapid change in the soil pore-water pressure gradient.

Bed load is the most commonly observed transport mode, with a progression to saltation and liquefaction for events with larger, faster ships.

For the cohesive sediments that are widely distributed in the Great Lakes system, disrupted sediments typically go directly into suspension, where they can remain for extended periods. Hodek et al. (1986) and Liston and McNabb (1986) made field measurements of turbidity and light extinction profiles under both ambient and ship-influenced conditions on the St. Marys River. According to Hodek et al. (1986), during open-water periods, turbidity develops due to wind-driven waves acting on clay bluffs and the nearshore riverbed. For waves on the order of 6 in. or more in height, they observed that a high level of turbidity may develop, extending from the shore to the navigation channel, and no increase in turbidity could be detected during ship passage during periods of wind-driven waves. In the absence of wind-driven waves, they stated that nearshore turbidity develops with the passage of each vessel. This topic is discussed further in the section dealing with biological effects.

As discussed previously, a drawdown and surge event can cause water movements in all directions, so that sediment transported in one direction may be offset during an opposing current.

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* Personal communication, Don Williams, Detroit District, COE.

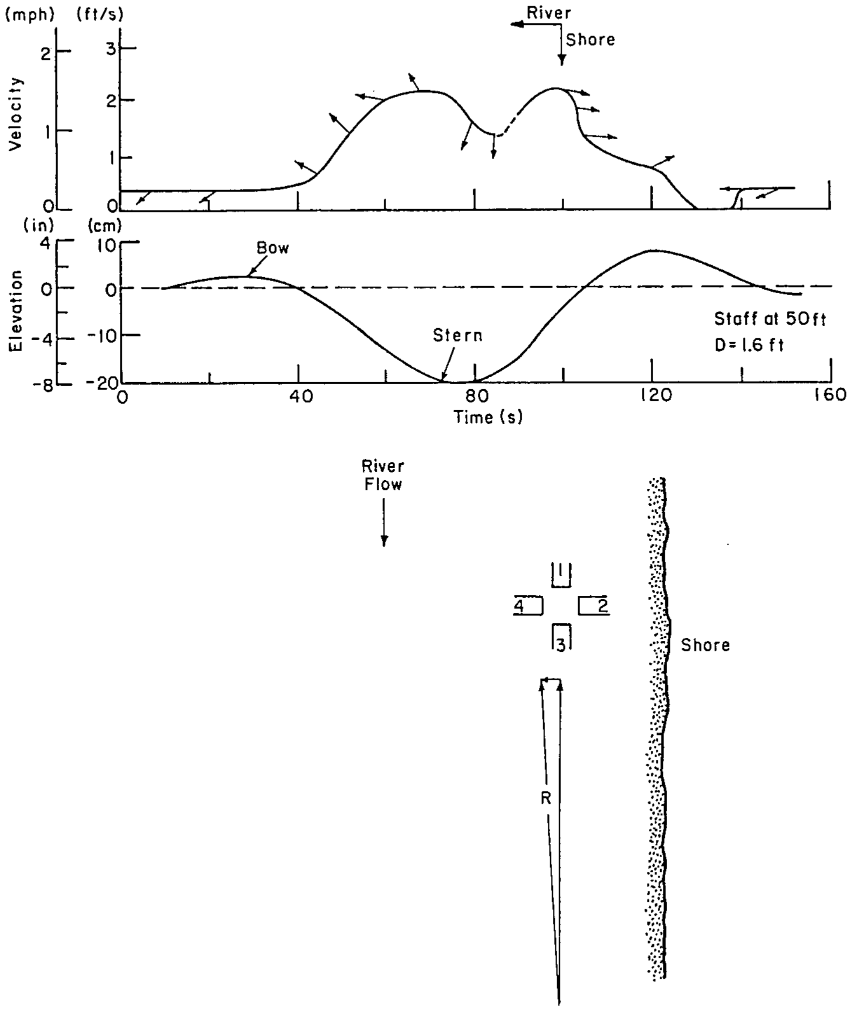

Figure 6. Velocity, water surface elevation and sediment movement measurements during vessel passage. (After Alger 1978.)

However, natural currents, a sloping bottom and the intensity and duration of vessel-generated currents can combine to cause net transport in almost any direction. Figure 6 shows velocity and stage measurements for a vessel passing Nine Mile Point on the St. Marys River at 10 mph (Alger 1978). In the velocity graph the axes define the magnitude of water velocity with time, while the direction of water movement at any particular time is indicated by the superimposed arrow.

Sediment transport was also measured during that event using an array of four traps oriented in 90° increments. The traps had been set for a 20-minute period prior to vessel passage, and no sediment was collected in any of the traps. On a different date the traps were set during a period with wind-driven waves of about 1-ft amplitude, and all traps collected some sediment. There were no wind waves during the vessel passage presented in Figure 6, so that all transport should be ship induced. The direction of net transport has been found to be sensitive to the characteristics of a specific site, the vessel direction and the magnitude of the drawdown event. In this case the net transport was primarily upstream and slightly offshore, as indicated by the vector *R* in Figure 6.

Further data on sediment transport during vessel passage can be found in Alger (1978, 1979a,b) and Hodek et al. (1986). The data analysis by Hodek et al. showed that downbound ships caused much less sediment transport than upbound vessels at comparable drawdowns. It also showed that upbound vessels creating a drawdown of 6 in. or less cause relatively little disturbance. For data indicating net transport, 83% of upbound ships and 70% of downbound ships caused net offshore movement.

Damage criteria

A major problem in setting damage criteria is in defining levels of ship-induced effects that are either undesirable or unacceptable. It cannot be realistically required that ships cause no sediment motion, even if it were possible to accurately predict the transient, ship-induced threshold of motion in the large, irregularly shaped channels considered. Small sediment dislocations should not necessarily be considered damaging, particularly since natural currents, waves, recreational boating and other factors are often more significant.

At the other extreme, ships may cause large water-level fluctuations and currents that would cause unacceptable levels of sediment transport, shoreline erosion and structural damage, as well as affecting recreation and personal safety. Between these extremes the increase in significance of ship effects is gradual, so it is difficult to define a precise threshold where the effects become unacceptable. Any criterion must consider site-specific conditions of shoreline geometry and composition, vessel speeds and water levels. Predictions of vessel effects are most often premised on existing speed limits, but if these limits are not observed, these effects can be severely underestimated. Since drawdown increases as the square of ship velocity, ship effects can increase rapidly for small increments above those speed limits. In contrast, properly developed and enforced speed limits could effectively eliminate ship-induced damages.

The water level is another important variable in determining vessel effects, and it cannot be totally controlled. As shown in Figure 7 for a typical shore profile on the St. Marys River, both natural and ship-induced hydraulic forces are free to act on the low bluff on the waters edge during a high-water period. This bluff is frequently considered to be the shoreline by many property owners. If the water level were lower, the water would not act directly against this "shore" but on the mildly sloping beach below. Persistent erosive forces might eventually erode back to the bluff, but in the interim the rate of material loss would be less since the mild sloping beach would dissipate the energy more efficiently.

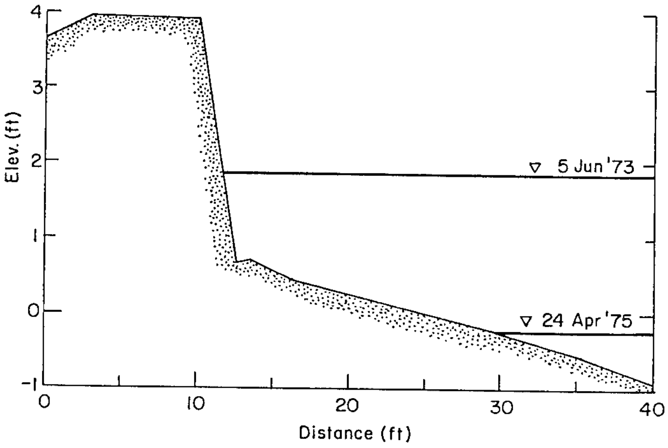

Figure 7. Relation of water level to a shore profile on the St. Marys River. (From Wuebben 1983a.)

In addition to the lack of predictability for ship waves discussed earlier, there is almost no information available to examine their ability to cause sediment movement. Wuebben et al. (1984) assumed that ship waves were similar to wind-driven gravity waves, so that coastal sediment transport theory could be applied. This assumption is reasonable in deep water, but the validity of its extension to shallow nearshore zones is uncertain. Wuebben then used information presented in the Shore Protection Manual (USACERC 1984) to propose a nearshore wave height of 0.5 ft as a criterion for the onset of sediment motion. Depending on the depth of nearshore water, lower wave heights could indeed cause transport, but due to the oscillatory nature of water movement in waves, motion does not necessarily imply erosion. In addition, the criterion assumes a sand bed system, and no information was found to deal with the cohesive sediments that are widespread in the Great Lakes system. Since cohesive sediments and materials larger than sand are more resistant to erosion, any error would be on the conservative side, and predictions could be tempered with engineering judgment. While this criterion is somewhat arbitrary, it did provide a useful tool for locating potential damage sites. However, for winter navigation, ship-generated waves are of negligible importance because they are nearly immediately damped by ice.

Hochstein and Adams (1985b) adapted a model that considers both drawdown and the effects of propeller wash to the St. Marys River. They noted that bottom disturbance is a function of distance from the propeller axis to the bottom and that disturbances are greatest in channel bends and reaches where crosswinds force vessels to crab their sailing line. Using a combination of basic theory and empiricism, their model produces two-dimensional distributions of water velocities. It was then assumed that sediment transport equations developed for gravity-driven flows could be applied to these calculated velocity distributions. This assumption may not be strictly correct but definitely necessary given the state of the art.

For two sites on the St. Marys River, they predicted velocities, bed loads and suspended sediment concentrations for several vessel classes. They did not attempt to discriminate between events causing or not causing a level of unacceptable transport, but they did compare vessel effects in terms of kinetic energy density (one-half of the square of net ship-induced velocity). It is not clear how the kinetic energy of individual ship passages can be summed to provide a season-long estimate of the potential for sediment movement, but it is used here to compare the cumulative effects of different fleet mixes and navigation season durations.

In general, they found downbound vessel passage to be more damaging, since ships are typically loaded passing downbound and light passing upbound. In comparing the relative effects of ships in open water, a continuous broken ice cover and sheet ice, they concluded that propeller wash effects also increase in that order since increasing propeller thrust would be required to maintain speed. They also concluded that the newer, 1000-ft vessels had a potential for damage four to nine times higher than smaller existing vessels due to higher horsepower, twin propellers and greater possible draft. The lower number represents open-water sailing, the latter with a solid ice sheet.

In developing a damage criterion for vessel-induced drawdown, Wuebben et al. (1984) adapted non-scouring velocity criteria from the open-channel-flow literature for the various classes of soils found in the Great Lakes connecting channels. Since drawdown is the ship effect that can be predicted with the best accuracy, these scour criteria were then correlated to field data on the maximum ship-induced velocities caused by given levels of drawdown. This allowed the use of a one-dimensional drawdown model to compare the significance of various channel, vessel size and speed scenarios and to predict reaches along the river where the erosion potential was high.

Hodek et al. (1986) based their damage criteria on the level of drawdown and velocity disturbance, the magnitude of surge, soil conditions and shore geometry. They also indicated that the development of shorefast, grounded ice would serve as a barrier to shoreline damage. In developing their criteria, they used data on ship-induced velocities as well as the results of 34 measurements of directional sediment transport. This allowed quantitative prediction of net transport and direction for sand-sized materials, but their actual damage criteria were largely qualitative in nature. Their basis for prediction of cohesive sediment transport is unclear. They classified the potential for damage into three categories. None to light refers to inconsequential movement, moderate damage implies light transport as bedload, while severe damage is defined as a condition where sediment is suspended and soils sustaining shallow-rooted organics may be displaced. As mentioned earlier, they found little sediment transport for drawdown events less than 6 in. in magnitude and concluded that damage could be effectively minimized by controlling vessel speed to prevent larger events.

Field studies of shoreline recession

The first field study of shore damage in connection with winter navigation on the Great Lakes was conducted by the Detroit District on the St. Marys River beginning in 1972 (USACE 1974). In that study they measured waves and water level fluctuations at four sites and repeatedly surveyed shoreline profiles at 12 sites. They observed no gouging of shorelines due to ice shoving and instead felt that the shore ice formations served as protection against damage.

During a survey period from November 1972 to March 1973 they noted little or no change in the measured shore profiles. A subsequent June survey indicated some erosion at most sites, with a maximum recession of about 2.5 ft for two sites on Lake Nicolet but more typically 0.5 ft or less. They observed that waves generated by small craft, particularly cruisers, were generally higher and apparently more damaging than those generated by commercial vessels. Sites found to be experiencing significant erosion were near Mission Point, Frechette Point, Six Mile Point, Nine Mile Point, the north shore of Neebish Island and upstream of Johnson's Point.

Their conclusions were that erosion of the shorelines occurs during the traditional navigation season but is minor during the extended season period. Further, they concluded that less than 5000 ft of shoreline is subject to significant erosion and that high water levels (which occurred during the study) are the most significant cause of erosion.

A follow-up study by the consulting firm of Dalton, Dalton, Little and Newport, Inc. (1975)

concluded that about 26,000 ft of shoreline along the St. Marys River was subject to significant erosion due to all causes. Of this, about 12,000 ft had been protected in some way, leaving 14,000 ft unprotected. Based on data collected by the Detroit District, they concluded that waves due to wind and small boats were far more significant than waves generated by large ships. They recommended that eroding shorelines should be structurally protected to prevent erosion due to natural causes. They concluded that control of vessel speed was not important since they considered the significance of large ship waves to be minor.

Subsequently the U.S. Army Cold Regions Research and Engineering Laboratory began a series of studies of the influence of ship passage on sediment transport and shoreline erosion extending over several years (Alger 1977a,b, 1978, 1979a, 1980, 1981, Gatto 1978, 1980a,b, 1982, Hodek et al. 1986, Wuebben 1978, 1981a,b,c, 1983a,b, Wuebben et al. 1978a,b, 1984). These studies ranged from field documentation to numerical modeling of the physical effects of vessel passage on shoreline and shore structure stability.

The reports by Alger provide data from repeated surveys of shore profiles from 1977 to 1981 along the St. Marys, St. Clair and Detroit Rivers. Ten sites received detailed monitoring over a period of years, with multiple profiles at each site. Supplementary observations included documentation of ice conditions and water levels and velocities during ship passage. The maximum recorded shoreline recession documented over a one-year interval was somewhat less than 4 ft, and for the full period from 1976 to 1981 the maximum recession was about 8 ft for a site on the St. Marys River, but most sites showed little or no change over the full period of study. Although he found that large vessel passage can produce large hydraulic effects and cause sediment transport, based on these studies, Alger found no evidence of an increased potential for ship-induced erosion due to the presence of ice.

On the St. Marys River, Wuebben (1981a,c, 1983b) reported the results of shore and shore structure monitoring during two winter periods with essentially no commercial shipping. During the period from 15 January to 24 March 1980 there were only eight passages (all by icebreakers), and from 31 December 1980 to 24 March 1981 there were nine passages (all icebreakers except for one tanker). Under the program, shoreline profiles were repeatedly surveyed throughout the two winters to detect any change due to natural agents.

Three river areas monitored during years with winter navigation were selected for detailed observation during the closed period. One site experiencing minor erosion over the course of several years showed no measurable change during the entire period bracketing both closed seasons. A second site previously exhibiting bluff recession on the order of 1.5 ft per year continued to recede at about the same rate through the period of study. Of the total bluff recession recorded at this site from 1976 to 1981, the maximum recession was 8 ft, with an average of about 5 ft.

The third site, despite an apparent potential for damage, had not experienced meaningful erosion during previous years of winter navigation. During the 1980 closed season, however, significant shoreline recession was noted at five of seven profiles at the site (0.5–2 ft). Over the 1980-81 closed season, this site again showed little change, suggesting that the temporary increase in erosion may have been due to the relatively high water levels during 1979-80, which allowed water forces to act directly on the low bluffs at the water's edge. The shore at one of the profile locations had been structurally protected during the study period. During the 1980-81 closed period no further changes were noted. The data collected during extended season navigation (Alger 1977a,b, 1978, 1979a) and the limited observations during periods closed to navigation do not provide evidence of increased erosion due to navigation in ice on the St. Marys River.

Gatto (1978, 1980a,b, 1982) reviewed the shoreline characteristics and historic shoreline recession rates for the St. Marys, St. Clair and Detroit Rivers. Most of this information has been incorporated into the final 1982 report. The specific objectives were to document bank conditions and erosion sites along the rivers, to monitor and compare the amounts of winter and summer bank recession and change, and to estimate the amount of recession that occurred prior to winter navigation. An analysis of historical air photos showed that bank recession was active prior to winter navigation along the St. Marys, St. Clair and Detroit Rivers and was active without winter navigation on the St. Lawrence River.

An extensive field program was conducted to inventory shoreline characteristics in terms of soil types, shore geometry and the presence and type of vegetation and shore protection structures (Gatto 1982). Three hundred and forty-five miles of river shoreline were observed and photographed at least twice yearly from 1977 through

1980, with any visible signs of recent erosion noted. Banks were found to be eroding along 21.5 miles (6.2%). The erosion along approximately 15 of the 21.5 miles (70%) was occurring along reaches not bordering winter navigation channels. The results of the twice-yearly surveys did not conclusively indicate whether or not winter bank erosion was more or less than that occurring during the summer. Along most of the reaches, the degree of erosion appeared to remain the same over the winter and summer.

On the St. Lawrence Seaway a study was conducted to determine the nature and extent, if any, of shoreline erosion during the winter season to serve as a database in the event that the navigation season was extended there (Palm 1977a,b, Palm and Cutter 1978). They developed a classification system to define the potential for shoreline erodibility based on soil type, slope, vegetation and potential for ice action. They estimated that 28.6 miles of shoreline could be impacted by an extended navigation season, or 7% of the shoreline length evaluated. Of 8250 ft considered to have a potential for high impact, 6200 ft was classed as highly erodible. They also monitored 12 shoreline sites to document any ongoing erosion. Although some slumping of bluffs was noted, no general recession of the shore profiles was evident during the winter season.

In summary, although various analyses of vessel effects have concluded that there is a potential for shoreline erosion, field surveys and reviews of historical records have not supported that conclusion. For the most part, erosion rates due to any cause have been minor, and a comparison of erosion rates during years with and without winter navigation shows no appreciable difference. Both one- and two-dimensional models have been developed to examine sediment transport caused by drawdown and surge, and the two-dimensional treatment also considers propeller-induced transport. All of these models have a strong empirical component due to the complexities of vessel effects and their interaction with details of the river channel geometry and flow.

Shore structure damage

Damage to shore structures can occur due to water currents, water level fluctuations or ice action, either alone or in combination with vessel traffic. Since ship effects extend over a limited area surrounding the ship, the potential for vessel-related damage is primarily limited to areas near the shipping tracks, such as the connecting channels and harbors. Further, structures designed for commercial use are typically able to withstand forces in excess of those generated by the above mechanisms. This leaves privately owned structures, such as docks, boathouses, boat hoists, etc., as the structures most likely to experience damage. The majority of these private structures are of lightweight construction sufficient to serve their summertime function but not necessarily engineered to withstand the load potential of winter ice.

Ice conditions within the Great Lakes system, even without winter shipping, have always subjected these small structures to forces capable of damage, but over time, construction techniques evolved to provide structures that were generally competent to withstand the local ice conditions. The degree to which the shore structures of the Great Lakes system may be damaged by ice varies greatly according to the manner of ice action. Winter navigation, by disrupting the normal ice cover characteristics, may aggravate any natural ice-related damage. Ice effects on structures typically fall into one of the following categories:

- Static ice forces, which arise from a structure in contact with an ice sheet subject to thermal expansion and contraction or steady wind or water drag forces;
- Dynamic horizontal ice forces, which arise from ice sheets or floes that move against a structure due to water currents or wind; or
- Vertical ice forces, which arise from a change in water level and require the adhesion of floating ice to structures.

For small structures within the connecting channels, dynamic horizontal and vertical forces are typically the critical modes of ice action.

Dynamic horizontal ice forces

Depending on the size and strength of an ice floe, the horizontal force exerted on a structure may depend on the strength of an ice sheet and its failure mode (bending, crushing or shear) or the magnitude of the force driving the ice sheet (wind or water current). With a vertical pile or structure face, failure of the ice sheet usually occurs by crushing. Current Association of State Highway Transportation Officials standards employ a crushing strength of ice of 400 psi, while the Canadian bridge design code provides for "effective ice strength" values ranging from 100 to 400 psi. Thus, if there is sufficient driving force for the ice sheet, a pile subjected to horizontal ice loads would have to be strong indeed.

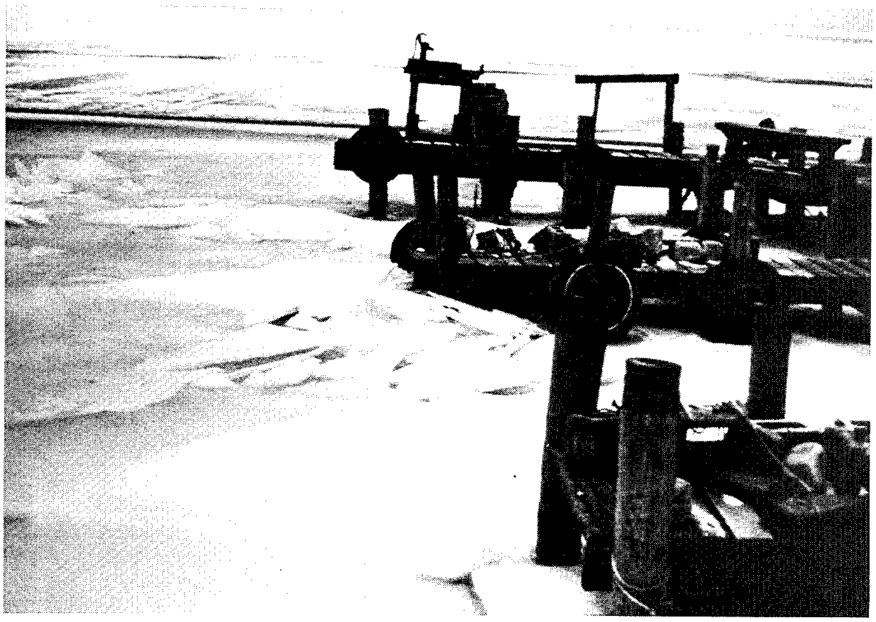

Figure 8. Horizontal movement of ice against rocks in early winter.

Figure 9. Spring breakup on the St. Marys River. Note the large floating ice masses in the foreground.

Damage due to horizontal forces can occur naturally during the unstable early ice period (Fig. 8) or during ice cover breakup events (Fig. 9). Ships do not typically transfer forces to a structure through the ice, unless they come very close to shore, since any forces imparted to the ice cover are rapidly distributed through the ice, rendering point loads quite small. Further, small privately owned structures are often contained within a band of shore-fast ice that can provide effective protection (Hodek et al. 1986). Rather, they may break up or dislodge ice, allowing it to be moved by natural water currents, waves or winds against a structure. Since the St. Clair River is typically ice-free over much of its length, ship passage through the natural ice arch on Lake Huron has

Figure 10. Series of finger piers damaged by ice jacking.

the potential to cause damage if it destroys the arch, causing an ice run. However, this arch has also been disrupted naturally during periods with high winds. Vessels could also influence horizontal ice loading if they generate significant drawdown and surge, since the associated water movements can exert drag forces on the underside of an ice cover, leading to horizontal forces on an ice-bound structure.

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 setup, 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 the structures, these fluctuations can exert large vertical forces through the floating ice cover. For the confined channel areas of the Great Lakes, the drawdown and surge generated by vessel passage can be a major factor.

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 friction 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 of the soil. Figure 10 shows a series of finger piers damaged by ice jacking.

With moderate water level fluctuations of sufficient frequency, cracks in the ice sheet around structures may not refreeze, and a permanently open, active crack may result (Fig. 11). This crack may serve as a vertical force release mechanism. One method of structure protection that takes advantage of this concept is to surround a structure with pile clusters, as in Figure 12, that resist uplift and force an active crack to form around it. If the crack passes through a dock, if the water level fluctuations are large or infrequent, this protective mechanism is lost (Fig. 13).

If piles resist uplifting, continuing water level fluctuations may cause the ice to break around the pile, and an accumulation of ice rubble may develop. These accumulations can develop to the point where they damage the horizontal members of a dock. Docks can also be damaged if the

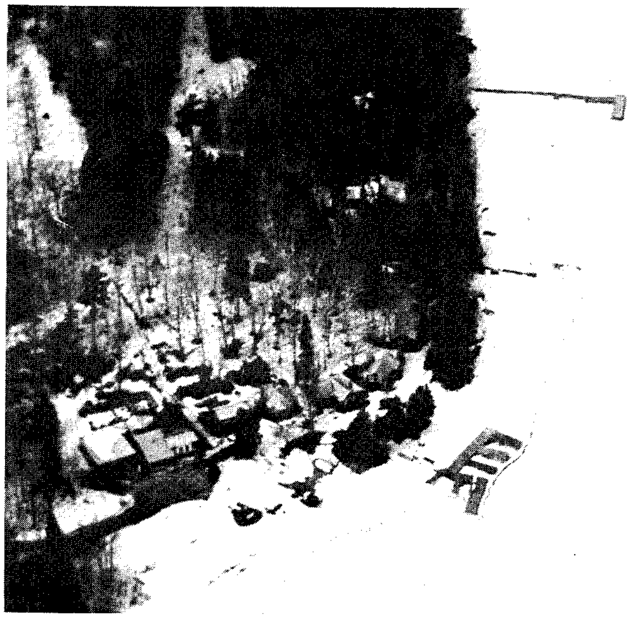

Figure 11. Aerial view of Johnson's Point, showing active crack offshore of structures.

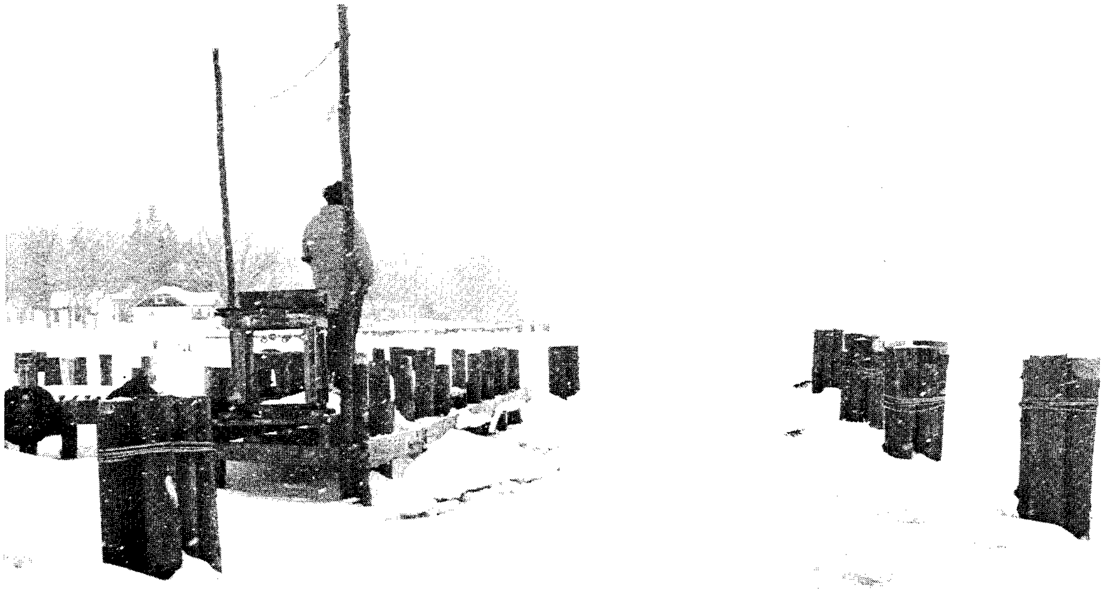

Figure 12. Private dock on the St. Marys River with protective pile clusters.

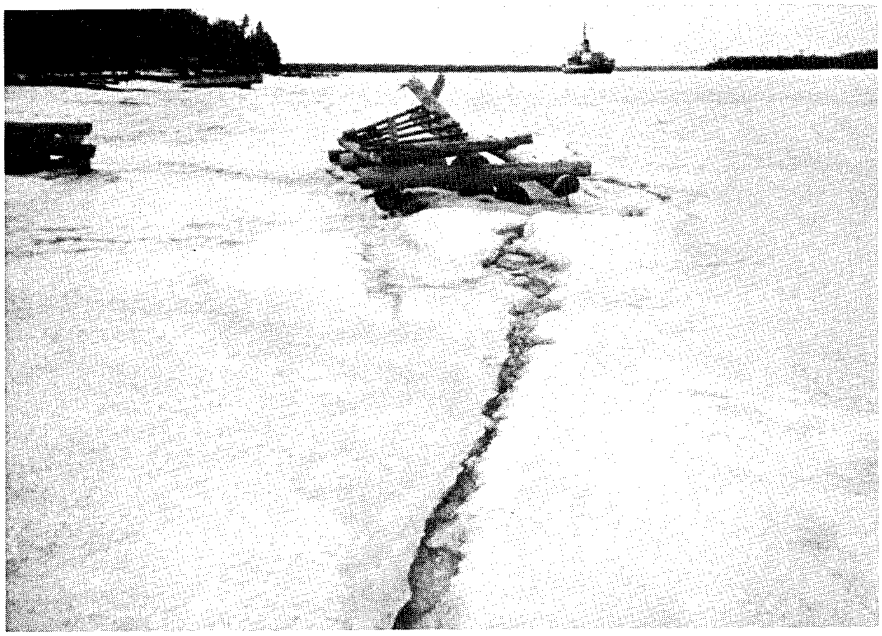

Figure 13. Active crack passing through a damaged dock.

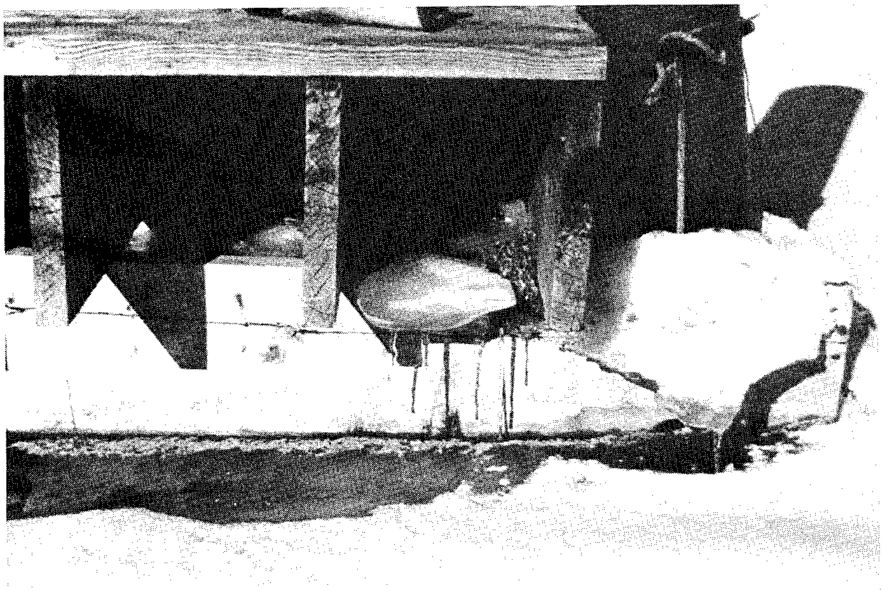

Figure 14. Horizontal member of dock in contact with the ice cover.

water level is high enough so that the ice surface contacts the cross members; then the ice can act directly on the superstructure, as shown in Figure 14. Further discussion of the modes of ice action on structures and illustrative photographs can be found in Wuebben (1983b).

Wuebben (1981b,1983a) and Wuebben et al. (1984) evaluated the effects of vessel passage on shore structure damage in terms of vessel size. He discounted propeller wash as a damage mechanism due to its remoteness from most private shore structures, and ship waves were considered insignificant during periods with an ice cover because they are efficiently damped by ice. This left drawdown as the major vessel effect contributing to shore structure damage and then only for periods with ice. His criterion for the onset of damage potential was a drawdown in excess of 1 ft, but actual damage estimates would have to be augmented by an analysis of structural integrity on a site-by-site basis. The 1-ft criterion was only meant to define river areas where reasonably well built structures could be exposed to damaging ship effects and to compare the damage potential of various fleet mixes.

In forming their estimate of the potential for vessel-related structural damage, Hodek et al. (1986) considered both vertical and horizontal dynamic loadings. For the areas of St. Marys River considered in the report, they felt that dynamic horizontal loadings would be small for cases with a continuous ice sheet (such as those that commonly occur during the extended season). If vessel passage were sufficient to break the ice cover into individual pans (as documented in USACE 1974), the potential for damage by horizontal forces would increase. For vertical ice forces, they felt that gravity structures, such as rock-filled timber cribs, would not be damaged by vertical forces. The rest of their analysis was limited to uplift forces on vertical piles. They concluded that all piles, unless properly engineered and installed, will be subjected to tensile loads in excess of their capacity and will eventually move upward.

Field studies of structure damage

The first field study of shore structure damage during winter navigation was conducted by the Detroit District on the St. Marys River beginning in 1972 (USACE 1974). They selected several docks in two reaches of the river for monitoring: near Six Mile Point on Lake Nicolet and Johnson's Point on Neebish Island. Some of the docks monitored were pile supported, while others were constructed with rock-filled timber cribs or steel piling. Monitoring was limited to visual observations and photographs. Their conclusions were that water level fluctuations and ice floes can cause structural damage and that navigation in ice can be a contributing factor.

The pile-supported portions of structures were found to be the most susceptible to damage, but even timber crib structures were not immune. Jacking of finger piers due to vertical ice forces induced by natural water level fluctuations and drawdown was common, and several structures were damaged as the result of differential ice movements along active cracks that passed through them. Water levels were high enough that some structures were damaged by ice in contact with the horizontal members of the superstructure. Some structures were observed to sustain damage during icebreaking operations when the ice cover was so violently disrupted that chunks of ice were thrown against them. While most damage was minor, three of the docking structures monitored had portions substantially destroyed, and a boat house was so severely damaged during the opening of navigation in March that it later collapsed.

In that study (USACE 1974) arrays of survey stakes were laid out at six sites to monitor ice movement in the offshore direction. At one site the ice was found to have moved as much as 30 ft offshore over a period of 40 days, but typical ice movements were on the order of 10 ft or less. Some lateral movement was also observed at three sites. In connection with some of their recordings of water level fluctuations, they also measured the relative motion of the ice sheets on either side of an active crack. These data indicated that the offshore ice sheet could move at least several tenths of a foot offshore during vessel passage (apparently in response to the drawdown-induced movement of water) and that the ice cover did not fully return to its original horizontal position when the water returned to its prior elevation.

It is postulated here that this mechanism results in a gradual horizontal jacking of the ice cover towards the navigation channel, since the water in the open shore crack can partially or totally refreeze before the next ship passage. Starting from this new position the next event will leave the offshore ice sheet slightly farther from its original location. Repeated cyclings of this backing process could lead to the large horizontal motions recorded over the winter season and lead to increased ice volumes in the vessel track. If the crack were to pass through a structure, this horizontal jacking could incrementally pull the structures apart.

A follow-up study by the consulting firm of Dalton, Dalton, Little and Newport, Inc. (1975) concluded that although ship passage during ice-covered conditions can contribute to structure damage, a major factor is the inadequate design and construction of many structures on the river. They concluded that control of vessel speed was not important since they considered ship-generated waves to be of minimal importance. Instead, they recommended improved structural design to withstand natural forces and consideration of removable, floating structures.

Carey (1980) reviewed the potential for winter-navigation-related shore structure damage on the St. Marys, St. Clair and Detroit Rivers using aerial photos, Corps of Engineers permit data and site visits. He estimated the total value of private shoreline structures at that time to be on the order of $18 million (1976 dollars). A probabilistic approach was employed that consisted of characterizing the ice conditions, on a reach-by-reach basis, that occur naturally and under several schemes of winter navigation. On the basis of these ice conditions and the channel characteristics within each reach, two probability estimates were made: the probability of the occurrence of ice damage and its probable severity. Damage values were calculated in terms of replacement cost. Although the results of this study are hard to summarize since they provide maximum potential damage costs as a function of various levels of probability, it was concluded that there was a 90% probability that the annual ice damage costs for the three rivers should not exceed $1.275 million without navigation, $2.28 million with the traditional season (navigation to December 15th) and $3.05 million with year-round navigation. If damage mitigation measures were implemented, it was felt that these year-round damages could be reduced to $1.65 million.

On the St. Marys River, Wuebben (1981a,c, 1983b) reported the results of shore structure monitoring during two winter periods with essentially no commercial shipping. During the period from 15 January to 24 March 1980 there were only eight passages (all by icebreakers), and from 31 December 1980 to 24 March 1981 there were nine passages (all icebreakers except for one tanker). Under the program, docks were repeatedly observed and photographed throughout the two winters, and four river areas were selected for detailed monitoring based on a high potential for damage during years with winter navigation. At these sites, points on the structures were repeatedly surveyed to document any displacement of their components.

Visits immediately following the close of navigation showed some damage due to both horizontal and vertical forces, but their condition at that time was used as a basis for future comparisons. No structural displacements were measured in either closed season, except for one dock that was documented to have had piles uplifted a maximum of 5 in. following the passage of a convoy of one tanker and four icebreakers on 3 March 1981. Apparently the natural water level variations were not sufficient to cause noticeable damage during either period. Hodek et al. (1986) noted that very slow water level variations due to long-term seasonal changes may result in such low loading rates that plastic deformation within the ice or at the ice/structure interface can occur. This will result in very low vertical forces being applied to the structure.

In addition, ice conditions were monitored at several sites. In contrast to periods with navigation in ice, active, shore-parallel cracks were largely absent. During the 1979-80 closed period one site had a grounded crack only during a survey in late January, and a second site showed an active crack only during a survey in late February. During the 1980-81 field season, no active cracks were observed. Arrays of pins were set in the ice across active cracks evident at the close of the navigation season, but no measurable changes in the relative locations of these pins were detected during the closed season, except near the dock experiencing uplift in March. At this location the shore parallel crack opened 1.5 in., but no lateral movement was noted. Apparently the water level fluctuations during these two field seasons were not large or frequent enough to develop the continuous, open, shore-parallel cracks evident during all previous field seasons with navigation in ice.

On the St. Lawrence Seaway a study was conducted to determine the nature and extent of any damage to shore structures during the winter season to serve as a database in the event that the navigation season was extended there (Palm 1977a,b, Palm and Cutter 1978). As part of that study they inventoried 5675 structures within the U.S. portion of the seaway and categorized them according to function, type of construction, historical and cultural significance, and potential for damage due to ice.

Damage potential criteria were based on the distance from the navigation channel, the presence of sharp turns and the conditions of an individual structure. Structures closer than 300 yards from the channel or near turns sharper than 10° were considered susceptible to damage. Structure types included both shore protection measures and facilities for recreational boating. Overall they determined that 3247 should not be impacted, 135 might require minor additional maintenance, 177 could be subject to moderate damage and 54 could be severely impacted. Of 26 historic or culturally significant structures, 4 were considered susceptible to damage.

They also conducted repeated surveys of 18 structures to check for any vertical or horizontal displacement. During the first winter season 6 of the 12 docks monitored were determined to have been displaced vertically and/or horizontally, but most displacements were on the order of 0.1 ft with a maximum of 0.2 ft. Although it was stated that the measurements were accurate to 0.001 ft, the reported displacements may actually reflect only the true accuracy of the survey. It is particularly interesting to note that all recorded vertical displacements indicated that the structures were sinking as the winter progressed. This is contrary to the typically reported lifting or "jacking" of pile structures by vertical ice forces.

During 1978, their second winter season, 8 of the 18 structures monitored during the first season showed vertical and/or horizontal displacements in excess of 0.1 ft at one or more locations. Of six additional structures monitored during the second season only, five exhibited measurable movement. Structures not experiencing damage were supported by concrete or substantial timber cribs. Of the docks experiencing displacement, one was pile supported and the remainder were timber cribs. For the survey points monitored on these docks, 109 displacements in excess of 0.1 ft were recorded. For events with vertical displacement, 13 were up and 19 were down. For horizontal motion events, 6 displacements were onshore and 20 were offshore; 26 were upriver and 22 were downriver. The maximum vertical displacements were about 0.6 ft and occurred in both directions. The maximum horizontal displacement was 0.9 ft onshore and 1.8 ft downstream. One incident of total destruction was cited, but no description of cause was provided.

In summary, there is a documented potential for shore structure damage due to vessel passage in ice. While little or no damage was observed during periods without winter navigation, extensive damage or complete destruction of a number of structures was documented on the St. Marys River during the demonstration program. Because it is necessary to consider details of construction techniques, ice conditions, ship passage characteristics and site layouts, quantitatively predicting damage for the thousands of privately owned structures on the Great Lakes connecting channels is a nearly impossible task. The most comprehensive analysis conducted so far relied on probabilistic estimates of damages based on broad categories of structure types, their values and ice conditions in the general area. Lightly constructed, pile-supported structures were found to be most susceptible to damage. More substantial pile structures or other designs (such as timber cribs) were found to be more resistant but not immune to damage. Improved structure designs and proper control of vessel speed could minimize damages.

Summary

Although various analyses of vessel effects have concluded that there is a potential for shoreline erosion, field surveys and reviews of historical records have not supported that conclusion. For the most part, erosion rates due to any cause have been minor, and a comparison of erosion rates during years with and without winter navigation shows no clear trend. High water levels, however, have been associated with periods of increased shoreline recession. There is a definite potential for sediment transport during vessel passage, and it appears that this material is often transported offshore towards the channel. Since ambient sediment transport in the connecting channels is quite low, this would constitute a permanent (though apparently small) net loss of soil from the nearshore zone. The transport could also have biological ramifications through increases in suspended solids and turbidity; these topics will be discussed later.

Information from periods without navigation revealed little or no ice-related damage to even poorly constructed structures. There was a documented potential for damage to private shore structures due to vessel passage in ice, particularly the light-duty pile-supported docks constructed by recreational boaters. Because there are thousands of these structures on the connecting channels, the previous damage estimates have run into millions of dollars. Well-designed structures were found to be significantly more resistant to damage but not immune. However, numerous studies cited in the text have pointed out the strong relation between the magnitude of vessel effects and vessel speeds. Speed limits developed with regard to sediment transport and dock damage could essentially eliminate measurable damage. In most cases existing limits were found adequate.

OIL AND HAZARDOUS SUBSTANCE SPILLS

Spills of oil or hazardous substances from transiting vessels during the season extension program represent a potential adverse impact to the environment. Because of the combination of cold weather and ice, spills in winter present additional difficulties in tracking, recovery and mitigation. Because of this, the potential for spills during extended season navigation has been extensively analyzed during the past 15 years. This analysis was undertaken even though actual spills were unknown during the demonstration program; indeed, spills in general are quite rare in the Great Lakes at any time of year. In addition, the general operational assessment is that spills in winter are unlikely for the following reasons:

- When vessel traffic continues through an extended season, tracks are established by preceding ships, so the risk of collision or grounding is less.
- Vessels moving through ice are not able to move at high rates of speed; they are not able to move out of their tracks with ease; and when they do start to get out of the track, it is relatively easy to stop them because of the friction effect of ice.
- There are fewer vessels operating and they generally operate with an escort when they are in difficult waters.
- With lake waters covered or largely covered by ice, the effects of wind and waves are considerably reduced, and ice between ships tends to serve as a buffer to keep vessels away from danger.

Even with the excellent record of low spill occurrence and the positive operational assessment given above, nearly all aspects of potential spills associated with the extended season navigation have been addressed in a series of reports. Ironically the excellent record of spills has been the greatest hindrance to the advancement of knowledge on tracking and forecasting spills in ice, the development of recovery techniques and the assessment of spill impacts. Given this, the Coast Guard, in cooperation with many local, state and federal agencies, has a number of contingency plans, with equipment and personnel in place, to respond to potential spills. The ability to forecast spill movement in the connecting channels during winter conditions was greatly improved recently, with the development of a comprehensive computer model that can quickly and accurately forecast spill movement (Shen et al. 1986).

The following section is a summary of the work done to assess the potential of spills, the probable impacts and the response capabilities. In each case only a summary is given; the original reports contain more information and greater detail.

Spill scenarios

Spills from vessels can be divided into spills due to accidents, operational spills and spills during loading and unloading. An operational spill occurs during a transfer of fuel or as a result of a malfunction of a fueling system. An accidental spill would be the "result of collision with ice, other vessel or obstacle, grounding or accidental spillage in transfer operations" (USCG 1973) and is thought most likely to occur from a "vessel ill-equipped to navigate ice identified as the older ships in the Great Lakes fleet" (USCG 1973). Hull damage caused by ice crushing a drifting or moored and swinging ship against a large landbound ice sheet is also a possibility (Shulze et al. 1982). However, due to double-hulled construction, the presence of a forward cofferdam in the bow, and the aft location of the fuel tanks, it is thought that substantial damage to the hull must occur before a spill would occur (Shulze et al. 1982).

A tabulation of spills from ships is available for the St. Marys River and Whitefish Bay for the years 1974–1979 (Shulze et al. 1982) and the St. Clair River, Lake St. Clair and the Detroit River for the years 1974–1981 (Shulze and Horne 1982). There were no ship spills resulting from accidents in the St. Marys River or Whitefish Bay during this period. There were three spills that resulted from collisions on the Detroit River during the period covered. The average spill amount was 8 gal., and 84% of the spill material was recovered. There were no spills on the St. Clair River or Lake St. Clair due to accidents during the study period. A summary of all spills reported for the entire period is provided in Table 1.

Table 1. Summary of oil spills on the Great Lakes connecting channels.

		Operational spills		*Accidental spills*	
River system	*Study period*	*Number*	*Avg. amount (gal.)*	*Number*	*Avg. amount (gal.)*
St. Marys	1974–1979	11	81	0	0
St. Clair River and Lake St. Clair	1974–1981	7	15	0	0
Detroit River	1974–1981	34	67	3	8

Identification of probable spill materials

The frequency and amount of substances shipped through the St. Lawrence Seaway Development Corporation (SLSDC) locks in 1977 (Nicholson and Dixon 1979) and the St. Clair–Detroit River System (SCDRS) for the period 1974–1979 (Shulze and Horne 1982) have been tabulated.

By far the largest amount of potential spill material is oil and petroleum products. The majority of this is residual fuel oil (also called number 6 and Bunker C) on all the systems studied. Also, refined fuels, mostly gasoline and fuel oil, are extensively transported. Residual fuel oil is not thought likely to spill in winter because of its high viscosity. At low ambient air temperatures, residual fuel is nearly solid (Shulze and Horne 1982), with the consistency of toothpaste (USCG 1973).

The potentially hazardous substances shipped are approximately 10% of the volume of petroleum products on the Detroit River and 32% of the volume of petroleum products on the St. Clair River. Approximately 85% of the potentially hazardous substances on the St. Clair and 70% on the Detroit River are basic chemicals and chemical products (Shulze and Horne 1982). In many cases these are a bulk cargo and are not likely to spill, and many are not necessarily hazardous if they are released in the water. Potentially toxic chemicals such as insecticides and disinfectants make up only 0.4% of the chemicals shipped.

Determination of spill probabilities

The probability of a spill on the St. Marys River and the SCDRS has been calculated for various options of the Extended Season Navigation Program (Schulze and Horne 1982, Schulze et al. 1982). The probability of a spill is determined by summing the product of the probability of an accident and the probability of a spill, given that an accident has occurred, for all the possible accidents. The accidents assumed to be possible were grounding, collision, collision with ice and, for the SCDRS, grounding in ice. For each river system the probability for each type of accident was determined by compiling the accident record and the number of vessel transits. The probability of a spill given an accident was determined by examining the records from tank ships for all of the Great Lakes. It was felt that tank ships represented the principal threat for a spill.

The probability of a spill during the extended season was quite low in all cases. Generally the probability was an order of magnitude less than the probability of a spill in the normal season, in part due to the lower frequency of shipping. However, it was found that there was an increased risk of a spill per transit during the extended season period of 1.5–3 times the normal season. In Lake St. Clair it was found to be five times the normal risk. This increased risk was largely due to operating in ice.

The likely spill size in the extended season was determined by summing the products of the average spill size resulting from an accident and the probability of a spill from each accident type. It was found that the likely additional discharge of oil during the extended season is small and, for the St Marys River, generally less than an operational spill during the normal season. Because of the limitation of data that are available, it was not possible to compute an expected value of spill size for the SCDRS.

Identification of spill impacts

To date, the potential impacts of an oil or hazardous substance spill associated with extending the navigation season have been discussed (USACE 1979a, Baca et al. 1986). Actual data describing impacts of spills in the Great Lakes are scarce, reflecting the relatively minor nature of spills in the Great Lakes.

The general effects of a spill on an aquatic environment could vary by impact and degree. These include:

- Direct kill of organisms through coating and asphyxiation;
- Direct kill through contact poisoning of organisms;
- Direct kill through exposure to water-soluble toxic components of oil at some distance in space and time from the accident;
- Destruction of the generally more sensitive species;
- Destruction of the generally more sensitive juvenile forms of organisms;
- Incorporation of sublethal amounts of oil and oil products into organisms, resulting in reduced resistance to infection and other stresses (the principle cause of death in birds surviving the immediate exposure to oil);
- Destruction of food values through the incorporation of oil and oil products into fisheries resources; and

- Incorporation of carcinogens into aquatic food chain and human food resources.

Oil and greases could have a devastating effect upon waterfowl as well as upon life within the water; the problems for waterfowl are compounded by low water temperatures. Therefore, of the living resources, waterfowl appear to be potentially the most vulnerable to the effects of an oil spillage. However, few waterfowl are present during the extended season navigation period except on the Detroit River (Davis and Erwin 1982).

The specific impacts of spills on the freshwater environment have been summarized based on laboratory and field studies and on observations during four actual spills (Baca et al. 1986). None of the observed spills were in the Great Lakes. The impacts were summarized as follows:

- Algae. Phytoplankton was relatively unaffected by spilled oil except in certain laboratory cultures and in exposures to certain components of oils. Filamentous and benthic algae showed some impacts but were generally resistant or recovered quickly. Blue-green algae frequently increased following spills.
- Macrophyte vegetation. Submerged species or the submerged portions of emergent species were generally not impacted. However, emergent species or those at the edge of the water (typically marsh) were affected or killed by surface oiling.
- Invertebrates. Results of laboratory studies established toxicity levels, but impacts in real spills have been minimal or short-lived. The most impacted groups have been insects moving at the air/water interface.
- Fish. Toxicity studies have established levels, and field experience shows serious impacts caused by spills in some cases. Larvae and fry have generally been more sensitive than adults. Tainting of flesh in adults is another impact. Oiling of lines and gear and impacts on ice fishing are other factors to consider relative to fisheries.
- Birds. Historically the most noticeable impacts have been on this group. Toxic effects can be through ingestion, absorption or transfer to eggs and chicks. Surficial oiling has been most deleterious, causing problems with heat regulation and buoyancy.
- Mammals. Similar to birds, impacts are related to surface oiling, which causes a loss in insulative properties of the fur. Mortality can also be caused by ingestion.

Existing contingency plans

A comprehensive review of the existing contingency plans has been published (Nicholson and Dixon 1979). The contingency plans for cleaning up oil spills in the Great Lakes exist on the international (joint Canada–United States), national, regional, subregional and state levels. The U.S. plan was developed by the Council on Environmental Quality, the regional and subregional plans by the U.S. Coast Guard, and the state plans by the individual state agencies responsible for natural resources. Generally all the plans detailed the five cleanup phases of discovery and notification; evaluation and initiation of action; containment and countermeasures; cleanup, mitigation and disposal; and documentation and cost recovery (Nicholson and Dixon 1979). However, very few of the plans contained any winter cleanup information, the exceptions being the Coast Guard subregional plan for Sault Ste. Marie and the New York plan.

Response capabilities and recovery techniques

The Coast Guard has developed a number of contingency plans for spill cleanup and containment. The response time is said to be on the order of a few hours, and equipment is available for various types of oil spills. A good description of the organizational structure of the response capabilities for the Great Lakes is available (USACE 1979a). However, the presence of ice and cold weather may seriously hamper all major phases of oil spill mitigation. As no major spill has resulted from winter navigation, there is no practical experience available to guide us in assessing the extent to which cold weather and ice will seriously interfere with recovery operations. The only recourse at this point seems to be to gather all information on oil spill recovery from other locations (such as the Arctic) and through laboratory and controlled field experiments, and suggest how this may be relevant to the season extension program.

Several good summaries of techniques of wintertime oil recovery are available (USCG 1973, Nicholson and Dixon 1979, USACE 1979a). These summaries divide the techniques into responses for spills in water, on ice or under ice. Generally spills in water are handled if possible with the same techniques as during the open-water season, with the acknowledgment that access may be difficult and that floating ice may interfere with operations. Absorbing agents, skimming by vacuum, skimming by pumping or burning, and herding agents have been proposed. Oil spills on ice are rare. Burning has been proposed, and if the ice is strong enough, scraping by large machinery may be possible. Little is known about the behavior of oil beneath ice; this type of spill would probably be the most difficult to deal with. It is known that the oil collects in pockets beneath the ice; pumping the oil out of these pockets, driving out the oil with compressed air, and deploying booms through the ice (if it is thin) or under the ice (if thick) have been suggested.

Alaska Clean Seas, a nonprofit organization sponsored by 15 oil companies, is devoted to oil spill response in most offshore areas of Alaska. This organization has sponsored research and development of better oil spill cleanup equipment and techniques, much of it for use in ice-covered waters. In addition, it provides manuals, training and equipment for oil spill containment, disposal and mitigation. This organization could be a resource in improving the response capabilities and recovery techniques in the Great Lakes during the extended season navigation periods.

Modeling oil and hazardous substance spills

The ability to model and forecast the transport of oil and hazardous substance spills is necessary to speed up response to spills and to adequately and expeditiously deploy existing equipment. The ability to model oil and hazardous substance spills depends intimately on the understanding of the many processes that affect spills. These processes include advection by wind and water currents; weathering of the material by evaporation and dissolution; mechanical spreading of the material by viscous, tension and gravity forces; and interaction of the material with the shoreline. In addition the ability to model movement in open-water and ice-covered conditions can significantly improve response and deployment in winter. A recent development in modeling (Shen et al. 1986) has provided a state-of-the-art model that incorporates the above considerations. The model is specifically developed for the St. Marys River, the St. Clair River, Lake St. Clair and the Detroit River. Available on mainframe or desktop computer, the model should be valuable for real-time response to a spill or to provide planning capabilities for spill response.

BIOLOGICAL EFFECTS

This section reviews the available documentation on the potential ecological effects of extended season navigation on the Great Lakes system. Most of the work has centered on the St. Marys River, where an ice cover is normally present in winter, effects on the river ice regime due to winter navigation have been most apparent and the potential for damage would seem the greatest. Further, significant navigation already occurs in winter on the St. Clair and Detroit Rivers independent of any season-extension activities. Virtually all of the studies have taken place since 1979, and only one of those years included navigation on the St. Marys River significantly beyond the traditional season. Data in other years were collected to provide baseline information for comparison. Topics considered include water quality, benthic invertebrates, aquatic plants, fish, waterfowl and raptorial birds.

Water quality

Liston and McNabb (1986) collected baseline water quality data at seven stations in both shipping and non-shipping channels along the St. Marys River during periods without winter navigation. Variables considered include temperature, pH, dissolved oxygen, turbidity and sedimentation rates.

Temperature, pH and dissolved oxygen were not considered subject to impact by winter navigation. Turbidity was a more significant concern because of the biological importance of water clarity and light penetration for photosynthesis. Further, turbidity can directly impact invertebrates and fish by fouling gill mechanisms, which in turn can affect circulation, respiration, excretion and salt balance. Turbidity levels sufficient to harm invertebrates and fish were not expected to occur on the St. Marys River, with or without extended season shipping, especially considering the rapid flushing rates in the river. Lake Nicolet, for example, undergoes about 1.3 volume exchanges daily. From their studies, however, Liston and McNabb concluded that slight increases in turbidity can limit the outer depth limits of submerged macrophyte growth and affect species composition.

Turbidity was generally lower during periods of winter ice than for open-water conditions. Winter means were between 0.5 and 2.3 NTU, while summer means ranged from 1.3 to 45.5 NTU with no vessel traffic.* During open water, ambient turbidities generally decreased from shallow zones out to the navigation channel and increased with distance downriver due to tributary inputs and broad expanses of shallow water subject to wind-driven wave action. Turbidity measurements during open-water vessel passages showed no values in excess of 11.8 NTU at any of their sites, which is within the range of natural variation. Winter sedimentation rates without the presence of navigation ranged from 53 to 2400 mg/day·m^2, with a median value of about 962. The mean particle size from all samples was estimated to be between 50 and 60 µm.

Sletten (1986) conducted a two-year study of the water quality effects of extended season operations on the SCDRS. Included were documentation of background water quality, sedimentation rate data and water quality variations with time during vessel passages. The background water quality information was primarily summarized from existing databases supplemented by a limited amount of data collection. The primary emphasis in the analysis of these data was to locate extreme values of total suspended solids and turbidity for comparison with vessel passage events. Other variables examined were pH, temperature and dissolved oxygen. Average turbidities were found to vary from 8.7 JTU in the winter to 7.3 in the summer, but temporal variations within a season were large. Mean values of suspended solids, pH and dissolved oxygen did not vary significantly between seasons.

Baseline sedimentation rate data were also collected by Sletten (1986) at two sites on each river in shallow, off-channel areas. Samplers were typically placed at each site monthly from December or January through March in both years. All samplers were collected simultaneously the following April, and the amount of sedimentation between deployment of each sampler could be estimated incrementally. Most stations indicated a trend of increasing sedimentation rates with time from January through March, but no explanations were given. Average rates during the entire sampling period ranged from 94 to 483 mg/day·m^2, with a median of 310 and a maximum measurement of 850 at one site during 8 March to 9 April 1985.

Ship passages were monitored at two sites, one on each river. The Detroit River site had 24 passages sampled, equally split between field trips in August 1983 and April, August and December 1984. The St. Clair River site had 18 passages sampled, evenly split between the three 1984 field trips. April and December were considered winter, while the August trips constituted summer. Water samples were collected at intervals following the passage of the bow for periods of 30 or 60 minutes, providing a time record of water quality variations. Although levels of turbidity and suspended solids were found to vary following vessel passage, all maximum values recorded were significantly less than natural variations in background levels. No significant correlations between ship size, speed or season of passage, and measured changes in water quality parameters were detected.

Possible reasons cited for the lack of any correlations were that none exist, that correlations exist but are too complex for analysis, and that the samplers were not located properly. However, Sletten used linear regression with single ship variables (draft, displacement or speed) to examine correlation. Correlation on this basis would require equal effects for large and small ships if they traveled at the same speed, or equal effects for a single ship traveling at different speeds. A lumped parameter reflecting both ship speed and size would be more appropriate. Further, the data show that the elapsed time from ship passage to the maximum recorded parameter values ranged as high as 60 minutes, which was the maximum period of sample collection. While vessel passage effects can persist for a relatively long time, it is curious that maximum values were often found as much as an hour after the event, probably indicating other causes. Hodek et al. (1986) found that spatial variations in turbidity were large, even under ambient conditions on the St. Marys River, and that the maximum levels of ship-generated turbidity were near the shoreline. Sletten's sampling was conducted at the edge of the navigation channel, where Hodek's observations showed

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* In the discussions that follow, turbidities are expressed in both Jackson Turbidity Units (JTU) and Nephelometric Turbidity Units (NTU) in order to retain the units employed by the authors of the reports under review. Although these units are roughly equivalent, turbidity readings are influenced to some degree by the measurement technique and the characteristics of the material in suspension. For the purposes of this report, however, it should be possible to consider these units equivalent.

the least change and where fluctuations due to other causes would be more significant.

A study by Gleason et al. (n.d.) examined sedimentation rates on the St. Marys River by placing nine samplers at three locations: one in a channel closed to winter navigation and two along active channels. Sedimentation data were collected between 7 and 27 March. The samplers were left in place during breakup, but five were lost and only two retained usable samples. Their analysis of the data at one site indicated an increase in sedimentation with vessel traffic, although rates were low (averaging 1.3 mg/day in their 18.5-cm^2 sampler area). A second site showed no relation between sedimentation rates and vessel passage, perhaps due to high natural turbidity. The third site, which had the highest sedimentation average at 11.1 mg/day, showed a correlation with vessel passage. Further, sedimentation rates were found to decrease with increasing distance from the channel.

They concluded that winter navigation can increase sedimentation rates over ambient conditions, but that natural sedimentation during spring breakup also causes sedimentation rates equaling or exceeding those due to navigation. They cited sedimentation rates on a channel with significant navigation being 50 times greater than at their control site, but the large difference in site conditions (and thus natural sedimentation rates) makes the comparison of questionable validity. The authors did not find significant spawning areas in the St. Marys, nor did they demonstrate or discuss the effects of sedimentation rates on coregonine eggs.

Hodek et al. (1986) conducted a field investigation of ship-generated turbidity on the St. Marys River. They provided the results of 95 measurements of turbidity and 85 light extinction profiles under both ambient and ship-influenced conditions. Unfortunately there were no vessel passages during sampling periods with an ice cover. Ambient turbidities during open-water conditions were typically in the range of 5–30 JTU, although numerous points were higher and the maximum reading was 380. Measurements during open-water vessel passages typically ranged from 6 to 30 JTU, with a maximum of 53. This information has been incorporated into the database of their numerical model of the physical effects of vessel passage, which primarily deals with sediment transport and shoreline erosion potential. However, it was not directly incorporated into the numerical calculation scheme.

They found that a common source of turbidity was the clay shorelines common along the river and that wind-driven waves of 6 in. or more in height could generate a high level of turbidity extending from the shore to the navigation channel. Under those conditions, no effect of vessel passage could be discerned. Several of the sites used to monitor other vessel effects examined in their study were sufficiently turbid throughout all field periods that it was impossible to see the riverbed. Their major findings were:

- The nearshore zones have more turbidity than the navigation channel, both with an ice cover and no vessel traffic and with open-water and vessel passages.
- Navigation channel turbidity was less in March than in May or June.
- In general, near-shore turbidity decreased with the removal of the ice cover.
- The turbidity in offshore areas of Lake Munuscong (but away from the channel) was least with an ice cover and most in June.
- Sites on Lake Nicolet showed a decrease in turbidity after ice-out.
- The Charlotte River is a major contributor of sediments causing turbidity.

Finally, vessel-induced turbidity was observed to be slight near the channel and highest near the shore, indicating that ship waves and drawdown and surge were generally more significant than propeller wash.

Poe et al. (1980) also measured light extinction on the St. Marys River during the winter of 1978-79 during a period with winter navigation. They chose two river areas for study, and they selected what they considered to be high- and low-impact data collection sites within each of these areas based on a perceived difference in the potential for vessel passage effects. The basis for determining the level of vessel impact potential is not clear, nor are differences in site conditions apart from vessel effects explained.

All measurements were collected during or immediately following vessel passage except for those made during March. Observations in March had no vessel passages and were considered as a "control" condition. All measurements were taken through the ice, but by the April field period the ice cover had become fragmented. They found that light penetration was generally lower in February than in March or April and that light penetration was greater at their low-impact sites than at the high ones.

Based on records of ship passage they felt vessel traffic may have been responsible for the higher turbidity in February, but only one site was monitored during February, and all March and April measurements (except one) were collected at three other sites. It is questionable whether a comparison of samples collected at different sites on different dates can be used to infer navigation-induced turbidity. Further, the single March "control" measurement taken at the same site as the February measurements was less than the maximum light penetration recorded during February.

They also suggested that the greater light penetration at their low-impact sites supported the claim of ship-induced turbidity. However, their data from their March control period show this same relation between sites, suggesting natural variations may have contributed. Further, since Hodek et al. (1986) found turbidity levels to vary significantly with location (even for essentially simultaneous samples at a single site), drawing conclusions on ship effects by direct comparison of turbidity levels at sites more than 3000 ft apart is tenuous. Interestingly penetration was greater in April than in March despite heavier vessel traffic. They felt that this may be due to the fragmentation of the solid ice cover in April.

Benthic macroinvertebrates

Liston and McNabb (1986) sampled benthic macroinvertebrates on the St. Marys River during two years without winter navigation (1982 and 1983). A total of 670 samples were analyzed to estimate the populations occurring at selected sites along the river. Total benthic invertebrate abundance was generally high throughout the river, ranging from 21 to 64,278 organisms per square meter, with a median between 7,000 and 8,000. Abundance was almost always less in the navigation channel (the median was less than 1,000 per square meter) than at other locations. Further, abundance was about three times greater on the western shore than on the eastern shore. This was considered to be a reflection of a lower energy environment there due to prevailing winds from the west.

A total of 162 taxa were identified, with 118 taxa within the vegetated littoral zone and 41 taxa unique to that zone. Organisms characterizing the littoral zone include odonates, lepidopterans, coleopterans and nonchironomid dipterans. Both herbivores and predators were well represented. At offshore sites, 120 taxa were identified, of which 42 were unique. Organisms characterizing that zone include mollusks, trichopterans and chironomids. Omnivores were the most common functional group at offshore sites. Within the navigation channel, only 37 taxa were collected. None were unique or dominant. It was stated that extended season navigation could impact benthic invertebrates through loss of food and cover if aquatic macrophytes are damaged, through increased turbidity or sedimentation, or by causing direct contact with ice. This in turn would affect the abundance of food available to fish. However, no evidence of damage to aquatic macrophytes was cited, and no basis for hypothesis was provided.

During the winter of 1974-75, the Great Lakes Fisheries Laboratory conducted a field study of the macrobenthos in the Lake Nicolet portion of the St. Marys River to assess what, if any, effects could be attributed to navigation in ice (Hiltunen 1979). Results from the sampling sites were also compared against control sites in the West Neebish channel, which was closed to winter navigation. Although the winter of 1974-75 had the largest number of vessel transits and greatest tonnage shipped beyond the traditional navigation season, Hiltunen found no significant decline in the population densities of any macrozoobenthos or macrophytes in either test or control site areas.

Poe et al. (1980) sampled fish, benthic macroinvertebrate populations and drift at four sites on the St. Marys River as part of the 1978-79 Environmental Evaluation Work Group effort. Too few fish and eggs were sampled to examine the effects of vessel passage on fish distribution or abundance. Their results indicated no decrease in the density of benthic macroinvertebrates due to vessel-related disturbances, but they mentioned that their data were subject to some statistical uncertainty. Examination of their drift net records led them to conclude that only in February could an "unequivocal demonstration" be made of the effects of vessel passage. At other times vessel passage was too frequent to gather background-level data for comparison. Although they noted that the available data were not sufficient to assess the significance of vessel-induced drift, they nonetheless postulated that if an increase in transport were to occur it could indicate a net loss of energy (biomass) in the system.

Poe and Edsall (1982) conducted a follow-up study of vessel-induced drift on the St. Marys River during the period from January through May 1980. Their objective was to determine how the composition and amount of drift varied between the following conditions: ice covered with vessel traffic; ice covered without traffic; and ice free with traffic. However, they were unable to obtain additional data for ice-covered conditions with vessel traffic. Their major conclusions include:

- Macroinvertebrate drift was less for ice-covered conditions without vessel traffic than for open-water conditions with traffic.
- The average density and biomass of macroinvertebrate drift was higher in the navigation channel than in nearby littoral waters.
- The amount of macrophyte drift for ice-covered conditions without vessel traffic was less than that found during the 1979 study (Poe et al. 1980) for ice-covered conditions with vessel traffic.
- Zooplankton biomass was higher in the navigation channel than in littoral waters.
- Detrital biomass was higher in the channel than adjacent littoral waters for three out of four locations sampled.

They concluded that drift rates for all components were considerably higher when there was navigation in ice than when there was ice and no navigation or when there was navigation in open water. They also concluded that navigation in ice can cause considerable amounts of detritus, macrophytes, zooplankton and macroinvertebrates to be transported out of the system. While they noted that the significance of these losses could not be addressed with available data, they felt that it was important that the losses would occur at a time when production reaches an annual minimum.

Jude et al. (1986) examined benthic drift at three sites on the lower St. Marys River during 1985, including Frechette Point, lower Lake Nicolet and Point Aux Frenes. In addition to collecting consecutive samples over approximate 12-hour time increments during one winter and one summer field period, they also collected a series of five-minute samples during the passage of vessels during the summer. During the study a total of 71 taxa were identified. Drift densities during both winter and summer were found to be significantly greater (900–2200%) at night than during the day for all comparisons except at Frechette Point in summer. At all sites the number of taxa collected was greatest at night regardless of the season.

While the study of benthic density and diversity by Liston and McNabb (1986) found lesser benthic densities along the eastern shore, which they attributed to greater scouring of the bed by waves driven by prevailing winds from the west, Jude et al. found a general lack of benthic drift density differences across the river. They did note such a trend at one site, Frechette Point, but this was only during the winter field period when wind waves would not be active due to the ice cover. Consistently greater drift densities at Frechette Point than at the other two sites were attributed to higher ambient water velocities there.

When comparing their data to the earlier studies of Poe and Edsall (1982) at Frechette Point, they found that their winter, under-ice drift density was 2000% greater (989 vs. 47/1000 m^3) than in that earlier study. Similarly the 1985 summer measurements showed a drift density 2600% greater (1659 vs. 64/1000 m^3). While they cited annual biological variations and slight variations in seasonal sampling times as a partial cause, they felt that the disagreement was primarily due to differences in sampler mesh sizes. There was also disagreement between the two studies as to the variation of drift density with depth. While Poe and Edsall found that drift density decreased from the surface to the bottom, Jude et al. found drift densities to increase with depth. The cause of this disparity was considered unexplainable, but seasonal biological variations and slight differences in sampling dates were again cited as possible contributors.

Jude et al. (1986) considered it highly probable that vessel passage could result in increased benthic drift, and based on visual observations they speculated that upbound vessels would have the greatest impact on drift density. In reviewing their data, however, they were unable to demonstrate detectable increases in the density of drifting benthos due to vessel traffic. Noting the windy conditions prevalent during data collection, they concluded that ship passage had not significantly altered the already disturbed system.

While considering the distance that disrupted benthos might be expected to travel in the St. Marys River before resettlement, Jude et al. speculated that a great proportion resettle within a short distance, with only a small fraction consumed or destroyed by drifting activity. Since the period of ship disturbance is very short-lived in comparison with wind events, which could last for hours or days, they concluded that ship-induced drift would resettle more quickly than wind-induced drift. On that basis they felt that drift induced by windy weather has a greater overall, river-wide effect on drift than individual, though frequent, ice-free ship passages. They did not collect data for ship passages in ice.

Based on their review of the field data of Poe et al. (1980) for ship passage in ice, Jude et al. (1986) disagreed with the conclusion that there would be a considerable increase in drift density for ship passages in ice. While they agreed that the data collected during February 1979 for periods with and without vessel passages showed significant ship-induced drift, they noted that it is the only documented occurrence known to exist. Due to increased levels of ship traffic during field periods subsequent to the one in January, no data could be collected to represent the without-shipping case for those later data sets.

In arriving at their conclusion that ship passage in ice would increase drift rates in general, Poe et al. (1980) and Poe and Edson (1982) pointed out that drift catch per unit time was roughly equal for field periods in March and April 1979, even though there were only four vessel passages while drift nets were deployed in March and 22 while nets were deployed in April. Since water flow rates and temperatures were comparable for the two periods and limnological conditions that affect catch were considered little changed, they concluded in the 1980 report that greater drift rates occur with ship passage in solid ice than for ship passage under floe ice (broken ice) conditions. In their 1982 report, Poe et al. expanded this conclusion to state that drift rates were considerably higher for vessel passages with an ice cover than for ice-covered conditions without navigation or ice-free conditions with navigation.

Jude et al. (1986), however, were not convinced that the apparent ship-induced drift pulse continue to be evident with additional ship passages. They instead interpreted the data to indicate that ship passage through ice may cause a pulsed increase in drift density during some events (January data), while at other times (March data) it may cause little apparent effect. Further, they felt that short, ship-induced pulses of benthic drift in winter may not be subject to predation as severe as at other times due to generally lower metabolic rates. However, they were concerned about any additional loss of benthic populations at a time when numbers and productivity are minimal, and about disruption or loss of preferred habitat. They postulated that ship-generated drawdown and surge during spring breakup may result in ice floes disrupting the bed through direct contact. However, no documentation or observations were cited to support this proposed mechanism for increased drift rates.

In view of several years of year-round navigation under the demonstration program and the presence of reasonable benthic densities and production rates, Jude et al. concluded that the effects of winter shipping have been minimal. However, they felt that the available ship passage data and the observation that previous shipping did not appear to detrimentally affect the benthos is not a sufficient basis on which to forecast the future.

Gleason et al. (1979) studied the loss of benthos through nearshore, shore-parallel cracks along the St. Marys River. A system of one or more of these cracks can form due to water level fluctuations large enough to fail the ice cover in flexure. The first crack generally forms at the offshore limit of shore-fast grounded ice, and other offshore cracks have sometimes occurred at sharp changes in river bathymetry. With frequent water level fluctuations these cracks may not have time to refreeze, leading to open or active cracks persisting throughout the winter. For large, fast-moving ships it has been observed that the associated drawdown and surge can be large enough to cause water, sediment, vegetation and even small fish to be sprayed through these nearshore cracks (Wuebben 1978).

At three sites Gleason et al. (1979) monitored fluctuations in the elevation of the ice surface during ship passage, sampled the quantity and composition of materials washed through a crack, and collected dredged samples of bed material to define site characteristics. During the study period, 24 recorded ship-induced ice level fluctuations ranged from 2.8 to 72.5 cm. Twenty samples were retrieved from events causing material to pass through the active cracks. Of these, there were only five that contained benthic organisms, and they were collected during the three vessel passages causing the largest recorded vertical ice displacements.

The most abundant organisms found in the bed samples were snails at 45%, followed by dipterans at 17%, annelids at 17% and pelecypods at 12.4%. The most abundant in the crack samples were dipterans (75%), followed by annelids (15%) and ostracods (10%). From the bottom sample data the average benthic density was 9593 organisms per square meter, while the 20 crack samples yielded a total of 21 organisms. This yield of about one organism per vessel passage was extrapolated to 10 organisms per meter of crack per vessel passage, or about 0.1% of the existing benthos population along the vessel track.

They concluded that there was a correlation between the magnitude of vessel-induced fluctuation in ice elevation and benthic loss to the ice surface but that it was not a continuous relation. Rather, large events caused dislocation onto the ice, while events below some threshold did not. They felt that vessels transiting within existing speed limits should cause little damage to benthic populations. Loss of benthos to the ice surface was considered insignificant in comparison with total annual mortality due to all causes.

Hudson et al. (1986) examined the distribution and abundance of macrozoobenthos, aquatic macrophytes and juvenile fishes during the 1983 and 1984 open-water seasons in the SCDRS. A total of 756 benthic samples were collected along 21 transects. The diversity of macrozoobenthos was highest in the upper Detroit River, with 101 taxa, and lowest in Lake St. Clair, where 65 were recorded. Elsewhere, 98 taxa were identified in the upper St. Clair River, 95 in the lower St. Clair River, and 80 in the lower Detroit River.

Hudson et al. (1986) concluded that the benthic communities observed in their study did not exhibit obvious ill effects from existing levels of winter navigation. However, winter vessel traffic had already occurred for many years, and there was no truly unaffected baseline from which to judge prior effects. A major ice jam on the St. Clair River in 1984 did, however, afford an opportunity to examine conditions representing perhaps a worst-case scenario of winter ecosystem disruption by ice. While the St. Clair and Detroit Rivers normally remain nearly ice free, this jam persisted for three weeks, from late April into early May, and included significant ship traffic and icebreaking operations.

Macrozoobenthos populations appeared to be the most adversely affected of the three groups examined in their study. Densities of ten taxa and total biomass were lower in 1984 than in 1983, and most declines occurred in the lower St. Clair River. It is not known whether these declines were due to ice scour, lower temperatures or some other factor or combination of factors. If the low densities had not recovered by the fall of 1984, it might have seemed reasonable to postulate that the ice jam had caused long-term damage. However, most of the affected taxa had recovered by the fall of 1984 to levels equaling or exceeding those in the fall of 1983, and the remaining taxa were within 30% of the fall 1983 values.

Aquatic plants

Liston and McNabb (1986) examined aquatic plants and primary productivity on the St. Marys River. Composition, distribution, biomass and productivity were found to be typical of oligotrophic systems of the upper Great Lakes. The major species of phytoplankton were diatoms, but their biomass was low (on the order of 1 mg/m^3 based on chlorophyll *a*). Submersed macrophyte communities were simple in species composition, with three species dominating: *Chara globularis* (charophyte), *Isoetes riparia* (quillwort) and *Nitella flexilis* (charophyte). The maximum annual biomass of submersed stands ranged from 10 to 70 g/m^2 (ash-free dry weight). Extensive emergent wetlands were well developed in shore zones that were protected from waves, currents and shifting sand. Emergent wetlands were dominated by *Scirpus acutus* (hardstem bullrush) at 64% of the areas mapped, followed by secondary dominants *Sparganium eurycarpum* (bur reed) at 16% and *Eleocharis smallii* (spikerush) at 13%.

Submersed and emergent plant communities varied little in species composition, location, size and annual maximum biomass from year to year during the period of study. Submersed plant communities were 5–10 times more productive and emergent wetlands 300 times more productive than phytoplankton, indicating their importance in the food chains of the St. Marys River.

Aerial photographs revealed evidence of emergent wetland erosion at some locations in Lake Nicolet, but its cause was not readily apparent. Apparently dead rootstocks of emergent plants were evident in shallow water offshore of existing emergent stands. Ground surveys found these to be relics of previous bulrush stands in some locations. Liston and McNabb (1986) felt that patterns of vegetation and channels in the adjacent emergent stands supported the conclusion that erosion was occurring. The rate of erosion was not determined, however, since it was too slow to be measured from the photographs. At other sites along the Lake Nicolet shoreline, the outer fringe of the wetland had apparently undergone little change for over 30 years. Further, scuba observations and collections and Ponar dredge sampling have shown that the location and species of submerged macrophytes in the St. Marys River tended to be stable from year to year.

Further studies of the wetlands by personnel of the Detroit District, COE, using photointerpretation of historical aerial photographs has indicated a correlation between the outer boundary of wetlands and water levels.* It is question-

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* Personal communication, Don Williams, Detroit District, COE.

able whether the sediments were actually eroding, and the outer boundaries of the wetlands were probably responding to increases in water levels.

Both submersed plant communities and emergent wetlands occurred on clay sediments, leading Liston and McNabb to suggest that their destruction could lead to increased turbidity in the river. It might also be argued that the clays are more stable than sands, allowing colonization by plants. Periods of winter ice were identified as a time of potential damage to the rootstocks of emergent vegetation. Possible mechanisms include vertical movement of an ice cover frozen to the bed during water level fluctuations and scouring by moving ice floes during ice cover breakup.

Jude et al. (1986) found no strong seasonal differences in the occurrence of macrophytes in their St. Marys River drift samples (48% of all samples in winter, 57% in summer). However, only six macrophytic taxa were collected in winter compared with 10 in the summer. At one site, Frechette Point, macrophytes were both more frequent and more diverse in summer (89%, nine taxa) than in winter (77%, five taxa). In addition, the dominant plants were found to change seasonally at Frechette Point and Point Aux Frenes.

Hudson et al. (1986) sampled aquatic macrophytes in the Detroit and St. Clair Rivers during the open-water seasons of 1983 and 1984. Using a Ponar grab sampler they collected a total of 18 taxa of submersed macrophytes on the St. Clair River and 19 on the Detroit River. The average depths at which submersed plants were retrieved varied only between 6 and 8 ft for all sites, despite wide ranges in light transmission and water velocity. Mean light transmission varied from a low of 2% measured on the Detroit River to 86% at a site on the St. Clair River. Near-bottom water velocities ranged from essentially still water to 2.5 ft/s. Light transmission was typically two to three times greater and water velocities two times greater in the St. Clair River than in the Detroit River.

Hudson et al. (1986) concluded that the aquatic plant communities observed in their study did not exhibit obvious ill effects from existing levels of winter navigation. However, winter vessel traffic had occurred for many years, and there was no truly unaffected baseline from which to judge prior effects.

As discussed in the section on benthos, however, a major ice jam on the St. Clair River in 1984 afforded an opportunity to examine conditions representing perhaps a worst-case scenario from disruption of the community by ice. The distribution and occurrence of aquatic macrophyte taxa changed little over this period. Plant bed development was delayed in the St. Clair River and at Belle Isle in 1984, but by September the beds were little different than in 1983. There were significant differences in biomass between the two years, but there were no consistent differences between locations or months. No impacts on submersed macrophytes could be attributed to the jam, except perhaps for delayed development due to lower water temperatures.

Fish

Gleason et al. (n.d.) documented conditions at potential coregonine (lake whitefish and lake herring) spawning grounds as part of the Environmental Evaluation Working Group studies during the winter of 1978-79. There was concern that winter navigation could adversely affect incubating eggs due to excessive sedimentation, localized current alterations and dislocation. Their objectives were to identify spawning areas, determine species composition by sampling eggs, quantify the rate of sedimentation, and determine the composition of sediments in those areas. Their literature review generally indicated that sedimentation can adversely affect spawning grounds, but opinions in the literature often conflicted, perhaps due to a lack of quantification of mortality vs. sedimentation rates. It was also unclear whether coregonines have a "home" spawning ground, which could make individual sites important.

Nine potential spawning areas were identified, but attempts to sample eggs were unsuccessful. Sampling included visual searches by divers and dredging of areas thought to have a high potential as spawning beds. A single egg was recovered at one site, and "several" at a second site. None of the areas were conclusively shown to be spawning areas. However, the authors felt that the lack of success may have been due to low initial egg populations, high predation rates, dislocation of eggs by water currents, or inability to locate discrete spawning areas. It was recommended that future attempts take place during or immediately following spawning, along with sampling of fish at the sites.

Liston and McNabb (1986) sampled fish populations in the St. Marys River during years without winter navigation past December (1982-83) with the objective of providing baseline information for analyzing the effects of winter navigation. Larval, juvenile and adult life stages were examined at seven sites, with sampling locations at each site ranging from the navigation channel to nearshore zones. There were 896 samples of ichthyoplankton collected during the summers of 1982 and 1983, which yielded nearly 30,000 larvae of 34 taxa. The density of fish larvae and the number of taxa were generally greatest in the upper littoral zone and lowest in the channel. Rainbow smelt, cyprinid, yellow perch and emerald shiner larvae dominated the samples, reflecting their dominance as adults. Thirty-four taxa were identified, though not all were found each year, with temperature cited as a possible cause for differences. They also provided detailed descriptions of spatial and temporal distributions for the dominant taxa sampled.

Some 140,000 fish of 64 taxa were collected using trap nets, trawls and gill nets (Liston and McNabb 1986). They also tagged 14,946 fish, of which 42 were recovered, to document their movements. The shallow littoral zone was dominated annually by emerald shiners, spottail shiners, mimic shiners, bluntnose minnows, yellow perch and white suckers, though brown bullheads, rainbow smelt, gizzard shad and black crappies were also prominent during the warmer year of 1983. The demersal, offshore community was dominated by several small forage fish: trout-perch, spottail shiners, johnny darters, ninespine sticklebacks, yellow perch, mottled sculpins and mimic shiners. Top piscivores dominant in the river were northern pike and walleyes, followed by smallmouth and rock bass. Lake herring were a dominant species in the deeper, offshore areas. Shannon–Weaver diversity indices ranged from 1.4 to 2.8, with mid-river diversity the greatest at 2.4–2.8. Cold-water species such as salmonids were more prevalent in upstream areas, while downstream areas had both warm-water species such as centrarchids and cyprinids and cold-water species such as lake whitefish.

Liston and McNabb (1986) also made a significant effort, based on gill net sampling, to define the winter fish community. Almost half of the total samples were taken during winter, most from late January to mid-March. While open-water gill net sampling collected 6354 fish of 37 species, the winter catch consisted of 1904 fish of 19 species. The summer catch was dominated by lake herring (27%), followed by white suckers (18%), northern pike (11.4%), rainbow smelt (10%), yellow perch (9.7%), walleyes (9.5%) and rock bass (4.6%). In contrast, the winter catch consisted primarily of lake herring (49%), white suckers (17%), northern pike (12%), yellow perch (6%) and both walleye and rainbow smelt (5%).

The yellow perch catch was considered meager in winter, perhaps due to their generally lower mobility. Significantly, more fish were collected nearshore than near the channel, which is contrary to claims that they move into deeper water areas of the St. Marys during winter. Most yellow perch were found to be in good condition, but there was a moderate level of parasitization, which Liston and McNabb speculated could be increased if the fish were to be further stressed. The number of white suckers sampled was considerably lower in winter than during open water, and it was felt that their movements are very restricted during that time. More suckers and northern pike were found near the shore than near the channel.

There was no significant difference in catch per unit effort between nearchannel and nearshore areas for walleyes, lake herring or rainbow smelt sampled in winter. The catch per unit effort (CPE) was greater during summer for walleyes and rainbow smelt but less during summer for herring.

The peak CPE for herring occurred during fall spawning activities. While other fish were captured during the winter period, their numbers were insufficient for comparison. For example, only one brown bullhead and three rock bass were collected in winter gill nets, all at the same station. Other smaller fish were collected only incidentally (or not at all) in the gill net samplings.

The authors noted that the effects of winter navigation on fish populations are limited to conjecture. They cited potential changes due to direct mortality, alterations in suspended solids and alterations of macrophyte beds. For substantial direct mortalities to occur, fish would have to be concentrated in or near the shipping channels and exacerbated by low winter metabolic rates. This does not appear to be the case on the St. Marys River. From their studies on the SCDRS, Haas et al. (1985) concluded that fish concentrations are substantially reduced in the vicinity of the navigation channel during winter and that fish that remain near the channel seek out adjacent marshes and channels as overwintering sites. There has been no documentation of extended season navigation effects on macrophyte beds, but Liston and McNabb have speculated that they might be adversely affected by scour or excessive sedimentation. Such scour or sedimentation processes have not been documented, however. Hudson et al.

(1986) were able to compare the extent of macrophyte beds in the SCDRS before and after a massive ice jam in April 1984. Little change was noted in macrophyte beds due to this severe ice event, as noted earlier.

The potential effects of suspended solids included siltation of spawning beds, decreased productivity, reduced food availability, clogging of gills, reduced respiration and changes in behavior. Liston and McNabb (1986) mentioned that high turbidity is generally recognized as an acute stress that fish can tolerate for short periods of time and that they may migrate away from it. As discussed earlier in this report, there has not been substantive documentation of large or persistent increases in turbidity during ship passage on the Great Lakes connecting channels. Liston and McNabb (1986) also cited documentation where several species of fish were exposed to very high levels of suspended solids (as high as 20,000 ppm) and turbidity (up to 500 NTU) without abnormal behavior or apparent harm.

These levels are far in excess of those observed by Poe et al. (1980), Sletten (1986) or Hodek et al. (1986) for ship passages on the St. Marys, St. Clair and Detroit Rivers. Liston and McNabb (1986) found ambient turbidity levels at their sites on the St. Marys River to range from 1.3 to 45.5 NTU during the summer and 0.5 to 2.3 NTU in the winter. For ship passages monitored during the open-water season, no reading exceeded 11.8 NTU. The measurements of Hodek et al. (1986) on the St. Marys River showed typical ambient turbidity levels of 5–30 JTU, with a maximum reading of 380. During vessel passages their measurements typically ranged from 6 to 30 JTU, with a maximum of 53. On the Detroit and St. Clair Rivers, Sletten (1986) reviewed the Environmental Protection Agency STORET database and estimated that mean turbidities varied from 7.3 JTU in the summer to 8.7 in the winter. Sletten also monitored turbidity during 42 ship passages and found maximum levels ranging from 2.3 to 73 JTU. The maximum turbidity measured during his "winter" field periods (April and December 1984) was 7 JTU. Liston and McNabb (1986) concluded that suspended solids levels in the St. Marys River would cause no direct harm to the fishery unless catastrophic increases in sediment load occur.

Haas et al. (1985) studied the movement and harvest of adult fish in the SCDRS during 1983 and 1984. The objective of the study was to describe the existing adult fish community and to consider any potential impacts from operation of the locks on the St. Marys River to 31 January ±2 weeks. Since navigation throughout the winter was already occurring on the SCDRS, they presumed that the existing fish population was persisting without any severe stress from prior levels of shipping and limited their speculations to the potential effects of increased winter vessel traffic.

A total of 57,579 fish of 57 species and three hybrids were identified during the study. The predominant species included rock bass, yellow perch, walleye and white perch. They also made spawning condition determinations on 23 species. Yellow perch comprised 66% of the fish observed in spawning condition, followed by rock bass (14%) and white bass (8%). There was no apparent correlation with the species composition of fish eggs and larvae determined by Muth et al. (1986), in which alewife, smelt and logperch comprised the bulk of the eggs collected, while larvae were dominated by alewife, gizzard shad, white perch and emerald shiner.

A fish tagging and creel survey effort showed that the combined shore and boat angling effort in the U.S. waters of the SCDRS averaged 810,000 hours on the St. Clair River, 1,409,000 hours on the Detroit River and 1,953,000 hours on Lake St. Clair. The average annual harvest was 164,000 fish from the St. Clair River, 1,421,000 from the Detroit River and 1,198,000 from Lake St. Clair. A total of 29,168 fish of 43 species were tagged during the study to gather information on movements, exploitation and abundance. Angler tag returns during the period from December through March constituted only 10% of the total 1,081 returns by sport and commercial fishermen. Ice angling was determined to account for only 12% of angling hours and 17% of the total catch.

Haas et al. (1985) considered potential impacts of winter navigation on both the fish community and the winter angling fishery. They felt that fish spawning and food availability might be influenced by physical disruption of critical habitats by ice gouging and that additional vessel passages could alter patterns of ice formation that might interfere with ice fishing activities. Although considered less likely, they also mentioned the possibility of interference with fish migration. The significance of each of these effects was considered to decrease with distance from the navigation channel.

While they provided no documentation or speculation as to the significance of their proposed impact mechanisms, their observations on fish behavior are relevant. They noted that their data on winter fish distribution in the SCDRS suggest that fish generally move to overwintering areas in the fall and that wintertime movement rates are low. From their fish tagging and net catch data they further concluded that fish concentrations are substantially reduced in the vicinity of the channels and that fish that remain near the navigation channel seek out the adjacent marshes and channels as overwintering sites. They also noted that the angler effort and harvest on the SCDRS were quite low in winter with the exception of the yellow perch fishery. That fishery was concentrated in Anchor Bay, an apparent wintering area, which is well away from the navigation channel. Further, much of the St. Clair and Detroit Rivers remain ice free, limiting ice fishing opportunities.

To evaluate the validity of their postulated impact mechanisms, they proposed that a two-year study take place if the season were extended to evaluate possible impacts on fish and furbearers. They suggested that such a study should be concentrated on the St. Clair River, where they felt that winter shipping would have the most influence on fish and the sport fishery. Data from that effort could be compared with the information from their present report, which would serve as a baseline. Since their combined catch of nine selected species varied approximately 28% from 1983 to 1984, however, they noted that extended season operations would have to cause even greater changes in the fish population to be detectable. Further, since winter trap net catches yielded only about 8% of those during summer high-catch periods, it would be difficult to make judgments about winter fish behavior.

Hudson et al. (1986) captured 1771 fish of 36 species in 1983 and 1038 fish of 26 species in 1984 in the Detroit and St. Clair Rivers during the open-water season. The catches were dominated by yellow perch, rock bass, hornyhead chub, spottail shiners, striped shiners, rainbow smelt and white suckers. These species made up 86% of the total catch. They conjectured that the fish communities observed in their study did not exhibit obvious ill effects from existing levels of winter navigation. However, winter vessel traffic and other physical changes have occurred for many years, and there was no true baseline from which to judge prior effects.

As discussed in the section on benthos, however, a major ice jam on the St. Clair River in 1984 afforded an opportunity to compare conditions before (1983) with those after the ice jam. This jam represents perhaps a worst-case scenario for ice effects. Fish catches were usually lower in 1984 in both rivers, but Hudson et al. did not consider the difference to be statistically significant. They felt that the lower catches may have been due to the effect of lower water temperatures on the development of plant beds, general activity level and seasonal migrations.

Muth et al. (1986) conducted a study on the SCDRS to provide baseline information on the abundance and distribution of fish eggs and larvae and to assess potential impacts on fish reproduction that might occur from extending the lock operation season on the St. Marys River. Analyses of the distribution and abundance of the eggs of 19 species and the larvae of 29 species suggested that abundance varied significantly between the St. Clair and Detroit Rivers and between the 1983 and 1984 data collection seasons. The number of eggs collected from the Detroit River (22,000) was more than 2.5 times greater than from the St. Clair (8,974). Rainbow smelt eggs dominated the St. Clair River samples, while those of gizzard shad and white bass dominated samples from the Detroit River.

Egg abundance was less in 1983 than in 1984 for both rivers. Fish larvae were also less abundant in 1983, but the difference was greater for the St. Clair River. Alewives were the most abundant larvae in both rivers during both years. The larvae of rainbow smelt, various darters and logperch were also abundant in the St. Clair River, while gizzard shad and emerald shiners were abundant in the Detroit River. The distribution of larvae varied significantly between rivers, sites, months and study years.

Muth et al. (1986) noted that both water temperature and ice conditions can affect the abundance of eggs and larvae. They attributed low egg and larvae abundance in 1983 to low water temperatures and a slow rate of warming. Although the 1984 ice jam on the St. Clair River probably delayed fish spawning throughout the system, they felt that rapid warming in May and June may have resulted in greater egg and larvae production than in 1983. While the water temperatures at their sites on the St. Clair River were comparable in May of each year, June temperatures were typically 3–5°F lower in 1983 than in 1984 and July and August temperatures were typically 1–2°F lower. Water temperature differences between the two years were not as consistent on the Detroit River, but June and August temperatures were typically 3–6°F cooler in 1983. The Detroit River is typically about 5°F warmer than the St. Clair River during May through July, when many species spawn.

Interestingly the mean monthly water temperatures collected at the water intakes for the cities of Port Huron and Detroit cited by Hudson et al. (1986) as a possible cause of the lower abundance of macrophytes, benthos and fish in 1984 directly conflicts with the trends used by Muth et al. (1986) to explain lower egg and larvae abundance in 1983. Mean monthly water temperatures near Port Huron on the St. Clair River were higher for 1983 than for 1984 during April, May, July and September and were equal during June and August. On the Detroit River near Belle Isle, 1983 temperatures were higher from May through October, with the exception of June, when the 1984 temperature was 2°F higher.

Because only three species of fish identified during their study spawn during fall or winter (and none were abundant in their samples), Muth et al. (1986) felt that it was highly unlikely that extended season navigation would destroy significant numbers of fish eggs or recently hatched larvae. They did, however, speculate on the potential for adverse impact due to habitat alteration. They suggested that increased shipping could result in increased ice accumulations and movement that could scour spawning sites and reduce available habitat. Such scouring, however, has not been documented. They also felt that extended season navigation could alter water temperatures by facilitating or delaying ice breakup or jamming. If water temperatures were altered, the impact could be either positive or negative. Although a major jam occurred during their period of study, and significant shipping and icebreaking activities took place during its three-week duration, they did not attempt to directly address its impact on egg and larvae populations.

Birds

The potential effects of winter navigation on waterfowl and raptorial birds were studied by Robinson and Jensen (1980) in the vicinity of the St. Marys River as part of the FY79 Environmental Effects Working Group program. The objectives were to describe the species and numbers of waterfowl and raptors in the area, to define areas used by resident and migrating populations along with the frequency of visits and their activities while observed, and to analyze the effects of winter-navigation-related activities on bird behavior. Waterfowl and raptors were observed on 60 days between January and April 1979. About 1000 ducks were present in January, declining slightly in February due to emigration, and increasing again in late March. The most frequently observed raptors were a pair of adult bald eagles. Bird mortality appeared to be very low during the winter of 1978-79 (no dead birds were found) despite unusually harsh weather.

Critical areas occupied by wintering duck populations were identified as the St. Marys Rapids, the Edison Soo hydroplant outfall and open-water stretches along the Canadian shore near Sault Ste. Marie. Open water in the shipping lanes was scarcely used by ducks, perhaps due to a lack of food there. For eagles, two perch areas along the northeast shore of Sugar Island were found to be important. The direct impact of the 425 vessel passages that occurred during the study period was considered minor, with flushing of birds being the only observed effect. In virtually all incidents where ducks were flushed by ships, the number of ducks did not return to their pre-passage levels. During the colder months, however, both ducks and eagles tended to avoid the shipping lanes and incidents of flushing were rare. By April, with more open water and more ships, the number of incidents increased dramatically. The metabolic significance of flushing, because of energy expenditures, remains unknown. However, most flushing takes place in April (during the regular shipping season) when food resources are being uncovered and are becoming available.

The influence of ship-induced turbidity and ice scouring of vegetation on duck foods, and the possibility of spills of oil or toxic materials, were cited as potential effects but were not assessed, and no data were presented. The potential for scouring of vegetation by ice has been considered by Liston and McNabb (1986) and discussed in the section of this report on aquatic plants. Hudson et al. (1986) also described the 1984 ice jam on the St. Clair River and its impact on aquatic plants. The potential for oil or toxic material spills is addressed in a separate part of this report.

Although the critical open-water areas cited in the report have not been sampled, studies by Hodek et al. (1986), Sletten (1986), Gleason et al. (n.d.) do not support large or persistent increases in turbidity during vessel passages. This would appear to be particularly true for sites isolated from the navigation channel, such as the St. Marys Rapids and pools along the Canadian shoreline. Further, the lack of an ice cover in these areas is most often due to the presence of swift, turbulent ambient water velocities. There are some areas along the Sault Ste. Marie, Ontario, shoreline, however, where thermal discharges may contribute. Ship-induced water velocities would have to significantly exceed these ambient velocities before turbidity could be noticeably increased. The open water at the Edison Soo site is not only highly turbulent, but the large inflow of water from the power canal would serve to dilute or flush any ship-induced turbidity.

Summary

Although numerous potential mechanisms for environmental damage due to extended season navigation have been proposed, the results of studies on the Great Lakes connecting channels thus far provide no substantive documentation of actual damage. If these damage mechanisms are indeed valid, the lack of documentation may be because the effects are not sufficient to cause lasting changes or because of the complexity of biological response and its interpretation given a short period of record. Most of the documentation relevant to winter navigation on the Great Lakes occurred on the St. Marys River in 1979 or later. This allowed only one season, 1979, with nearly year-round navigation, and the "baseline" data collection efforts in subsequent years followed several seasons of year-round navigation under the demonstration program.

Increases in turbidity or suspended solids were cited as potential causes of damage for benthos, aquatic plants, fish and birds, but no significant damage was documented. Further, the data do not suggest large or persistent changes in these parameters, and ambient variations were found to equal or exceed vessel passage values. There was some evidence that benthic drift rates might be higher for navigation in ice, but the magnitude and significance of this increase could not be determined. Two studies showed that macrobenthos densities were not significantly affected by navigation in ice. Similarly the possibility of damage to emergent vegetation by the movement of ice frozen about rootstocks was discussed but not observed. The ice movements could be due to either vessel-induced water level fluctuations or ice breakup in the spring.

For fish the major effects were considered to be increases in suspended solids and damage to aquatic vegetation. Direct damage to fish by ships was largely discounted since the vast majority of fish were found to be outside the navigation channel. Those fish found in the channel were generally winter-active and could presumably avoid impacts during vessel passage. The major effect of winter navigation on waterfowl appeared to be flushing during vessel passage, but this occurred mainly in April in the St. Marys River, after the traditional shipping season had resumed. Its physiological significance is unclear. Other concerns were centered on changes in open-water areas, but it does not appear that the critical areas described would be significantly affected by vessel passage.

VIBRATIONS CAUSED BY SHIP TRAFFIC

One of the problems identified during the eight-year demonstration program was vibrations on shore caused by ship traffic in ice. Wuebben (1977)

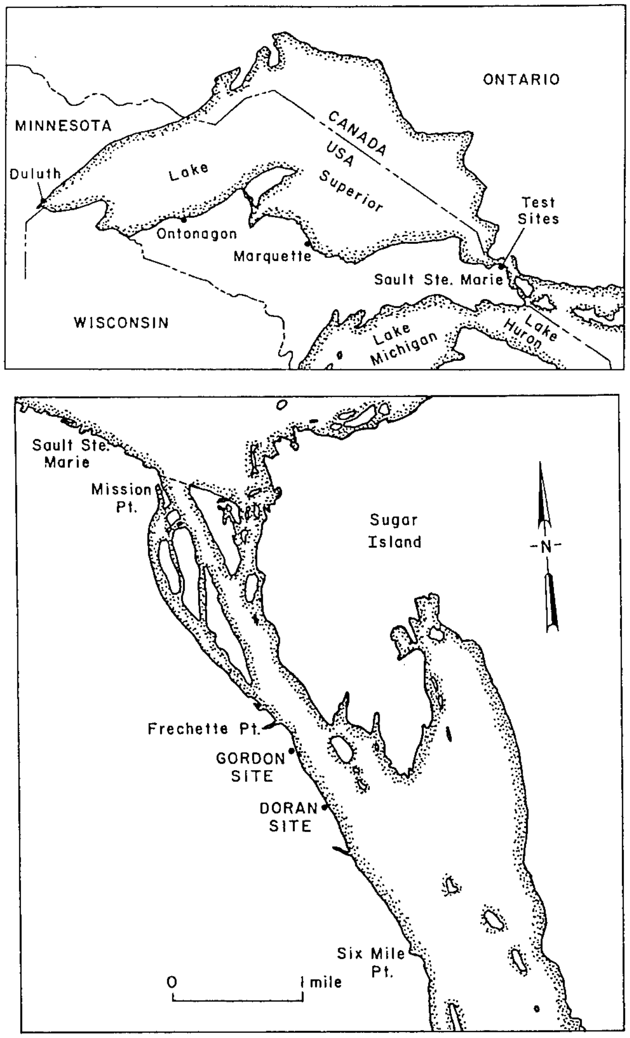

Figure 15. Location of test sites on the St. Marys River.

reported complaints by residents with homes on the St. Marys River south of Sault Ste. Marie, Michigan. The problem area is shown in Figure 15. These vibrations were reportedly most severe when an icebreaker was ramming an ice accumulation, with a thick ice cover on the river and frozen soil between the shore and the affected structure. An ice boom was installed at Little Rapids Cut in 1975 to control brash ice accumulation, reduce the resultant flow retardation and facilitate ferry operations to Sugar Island (Perham 1978b). The boom-induced changes in ice accumulation have also apparently mitigated the vibration problem to some degree. Although it was originally part of the Winter Navigation Demonstration Program, the boom has since become a regular feature of Corps operations on the river and is redeployed each year.

An extensive study of the onshore vibrations was made in the winter of 1978-79 by Haynes and Määttänen (1981). They instrumented two sites, the Gordon and Doran sites, shown in Figure 15. The instrumentation at each site consisted of accelerometers on a house, geophones in the soil between the house and shore, accelerometers on the ice between the shore and the ship channel, and a hydrophone below the ice near the accelerometers. A layout of the instrumentation is shown in Figure 16. Data from all of the instruments were recorded for 70 ship passages at the Gordon site and 30 at the Doran site.

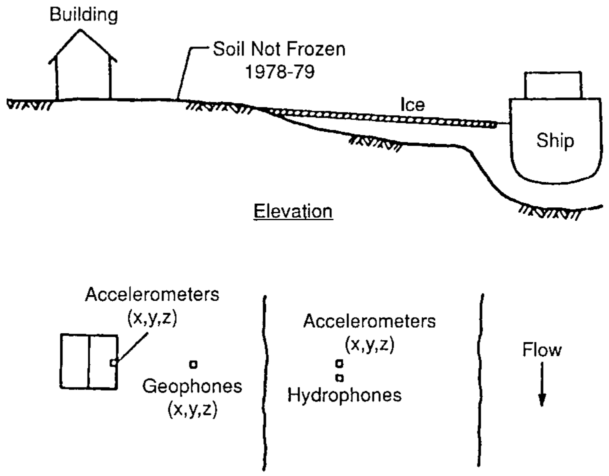

Figure 16. Vibration instrumentation layout.

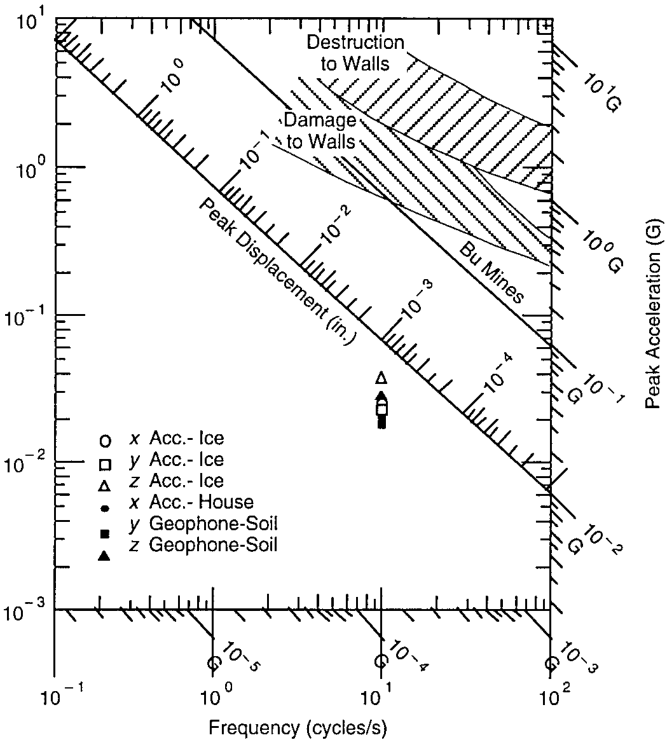

Figure 17. Magnitude of vibrations for the Roger Blough passing the Gordon site.

Analysis of the data enabled the magnitude of the vibrations to be identified. With a frequency analysis of the data, a dominant frequency associated with propeller noise was obtained for each ship. The vibration magnitudes were plotted on a standard vibration damage chart; a typical plot is shown in Figure 17. This figure indicates the vibration levels caused by the *Roger Blough* as it passed the Gordon site on 22 January 1979. Each ship had its own distinctive dominant frequency produced by the number of propeller blades and shaft rpm. For the *Roger Blough* this frequency was 8 Hz. In Figure 17 x is perpendicular to and y parallel to the ship channel; z is vertical.

During the one-year study the maximum vibration levels were about an order of magnitude lower than those required to cause damage to buildings. Vibration levels during 1979 may have been lower than those experienced during other winter seasons since there were no ice jams in the river and a deep snow cover prevented the ground from freezing. This unfrozen ground acted to alleviate the vibration levels. In fact, a deep snow cover (natural or artificial) or other means of keeping the ground unfrozen could be a strategy for reducing vibration levels. Two other results from the data analysis to note are:

- The vibration levels caused by a ship passage with an ice cover were about four times those without an ice cover; and
- The vibration levels with a solid ice cover and with a broken ice cover are about the same.

ENGINEERING AND ENVIRONMENTAL EFFECTS OF HEAT-TRANSFER BUBBLER SYSTEMS

Air bubblers are systems used to induce melting or retard the freezing of ice covers. Their use in locally reducing the ice cover thickness in navigation channels was investigated under the Winter Navigation Demonstration Program. The principle of operation is to release air at some depth below the ice cover; the rising bubbles create an upward current of water that impinges against and flows along the underside of the ice cover. If the water is above freezing, this flow of water results in heat transfer to the ice cover and causes melting. Both point-source bubblers (one orifice releasing air) or line-source bubblers (orifices spaced along a line) are used.

Figure 18 is a schematic of a bubbler system. A compressor at point A delivers air into a supply line B. The air flows through the diffuser line C and is discharged through very small orifices distributed along the length of the diffuser. The rising bubbler streams (region D) entrain water, creating a rising plume of water that impinges against the ice cover (region E), and this plume spreads and flows beneath the ice cover (region F), where it transfers heat to the underside, then gradually dissipates (region G).

The cause of the melting is the "wiping" of the warm water against the ice, and the only purpose of the air bubbling is to induce this current. If the water is at the freezing point of 0°C, no heat transfer or melting will occur, so it is the thermal reserve in the water represented by above-freezing temperatures that allows the bubblers to work. Other methods of inducing a current, such as a submerged motor-driven propeller or the natural flow currents, will have the same effect. Bubblers are generally chosen because they are convenient to install and operate, particularly if a long narrow zone of ice suppression is desired, since all that is required is to space orifices along a diffuser line. Limitations to the use of bubblers include limited thermal reserves in the water, limitations on the zone of influence due to the rather narrow zone of melting (rarely more than tens of feet), and their slow but persistent rate of action. They are particularly effective in local suppression of ice as at slips or docks or in providing a relief zone in an otherwise intact ice cover to allow easier vessel maneuvering in the adjacent ice cover.

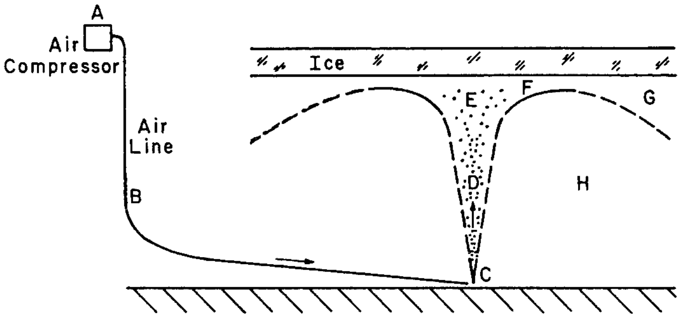

Figure 18. Schematic of a bubbler system.

Environmental effects

There have been two sites at which environmental effects of heat-transfer bubbler systems have been intensely studied under the Great Lakes Winter Navigation Program: at the Duluth–Superior Harbor area and in the St. Marys River. There were many environmental concerns addressed in these studies, but they may be summarized under three main subjects: effects on fish movement and population, effects on sediment resuspension, and changes in water quality.

A number of studies assessed the possible effects on fish movement and populations. Behmer and Gleason (1975) recorded fish movements at the edge of the shipping channel of the St. Marys River and Whitefish Bay. Dahlberg et al. (1980) also prepared two annotated bibliographies, attached to their report, on ecological effects of air bubblers and on winter fish and macrobenthos communities. Both reports should be consulted for details but the general findings were that the proposed bubbler systems would not have an adverse effect on the aquatic biota in winter. Bubbler systems similar to those proposed for navigation aids have been considered as a means of preventing fish from entering intakes and generally found to be ineffective. The less intense bubbler systems used for ice suppression are similarly ineffective; fish movement appears to be unimpeded by the bubble streams and associated currents, which are widely spaced relative to their diameters.

Two extensive studies were made to evaluate the effects of bubbler systems in the Duluth–Superior Harbor (Sydor et al. 1974, Swain et al. 1975). Neither study directly addressed fish movement and populations in detail, but since no apparent adverse changes were observed in the many water quality variables studied, it is reasonable to conclude that there would be no adverse effects on fish due to changes in the surrounding environment.

In January–April 1976 heated water from a power plant was released from a diffuser pipe in the vicinity of the Saginaw Bay shipping channel for the purpose of locally reducing the ice cover thickness. The water was released over short durations, and the excess water temperature was 1°C or less. The warmer water collected near the bottom and had little effect on the ice cover. (However, if a bubbler had been used to deliver the water to the ice cover, the suppression could have been significant.) Over the period 1972–1976 baseline and operational data were collected to evaluate the effects of the heated water release on the local benthic communities and fish (Argyle 1974, Hatcher 1977). No differences in populations of a wide variety of fauna were found that could be attributed to the heated water except one. Statistical tests and comparisons suggested the possibility that the under-ice release of warm water resulted in increased densities of immature oligochaetes (tubificids). The study did provide a good picture of the distribution and diversity of species present in the Saginaw Bay channel area.

The question of possible sediment resuspension in the vicinity of bubbler systems was considered by Swain et al. (1975), who found that any possible resuspension would be extremely small when compared to other factors that cause resuspension in the harbor, such as storm effects, natural runoff effects, vessel traffic effects, and industrial and municipal inflows. Sydor et al. (1974) measured currents in the vicinity of an operating bubbler system and described them as gentle near the bottom. A study by National Biocentric, Inc. (1973) similarly found that operation of a bubbler did not appear to be effective in resuspending organic material, sediments or nonsoluble nutrients.

Water quality during the operation of bubbler systems in the Duluth Superior Harbor was considered in detail by National Biocentric, Inc. (1973), Sydor et al. (1974) and Swain et al. (1975), including monitoring of temperature, dissolved oxygen and an extensive list of chemicals. In the very near vicinity of the bubbler, the temperatures become very uniform over the depth due to the mixing by the bubbler-induced flows and are contracted with the slight stratification that exists in undisturbed portions of the harbor. Swain et al. (1975) observed an increase in dissolved oxygen after the bubbler was turned on but a nearly similar increase 150 ft away. Whether the increase is due to bubbler operation or other effects is unclear, but there were no deleterious effects due to the bubbler operation. The National Biocentric, Inc. (1973) study found slightly higher oxygen contents at lower depths in the region of the bubbler but noted that the small increase could not be expected to much enhance fish populations. The Swain et al. (1975) study concluded that there was no increase in levels of major water quality variables due to bubbler operation but did find a tendency to damp large, naturally occurring oscillations of the variables measured. In summary, no adverse effects on water quality were found, while some slight evidence of beneficial effects were found. In most studies other effects greatly dominated the small influence of the bubbler operation. These include effects of vessel traffic and natural events such as runoff, which cause more marked changes.

ICE CONTROL STRUCTURES

This summary of ice control structures and related studies under the Great Lakes Winter Navigation Program is presented to the extent possible in chronological order. The use of ice booms as an ice control tool for winter navigation did not appear to be recognized at first. What was recognized was that navigable openings were needed in certain ice booms that the hydroelectric power companies set across the St. Lawrence River in early winter to ensure dependable electric power generation in winter. One scheme was to leave part of the boom open but connected, and then pull it closed after the last ship passed through using an electric winch mounted on a cell structure (USACE 1969). Before long it was seen that criteria required for the design of ice booms to retain ice on the St. Lawrence Seaway, St. Marys River and others were not available. In particular, information on the magnitude of ice forces was lacking. The task of making these determinations fell to the Ice Engineering Work Group.

St. Lawrence River

The first effort in the study of ice booms for the winter navigation program began 30 September 1971 with a meeting in Massena, New York, attended by representatives of the St. Lawrence Seaway Development Corporation, the Power Authority of the State of New York, Ontario Hydro of Canada and the Cold Regions Research and Engineering Laboratory. The meeting resulted in approval to use a crane boom weighing cell (100 kips capacity) at the shore anchor of the South Galop (Island) ice boom. A new design called a tension link was conceived and developed in 1972 and used in the Main Galop ice boom (Perham 1974). The tension link could be used in-line in ice boom structures without needing a supplemental safety loop. It was electrically operated, submersible, sensitive and fairly light. Eventually the tension link design, including signal cable, recorder, etc., was adapted for use in 1974 by Hydro Quebec in their forebay boom on the Beauharnois Power and Ship Canal 25 miles west of Montreal, Canada, by Arctec, Inc. for use in the Copeland Cut test boom (Uzuner 1975) and as an integral part of the St. Marys River ice boom since 1975 (Perham 1977). This study program has provided a wealth of information about ice, ship and boom interactions, about how booms are designed, built, installed and removed, about how they work, and about their contribution to ice cover formation.

Lake Erie

The Lake Erie ice boom was patterned after the Galop Island booms. The floating boom was a series of 22-in.-wide × 14-in.-thick × 30-ft-long Douglas fir timbers. Its primary functions are to hold back lake ice from the Niagara River and reinforce the easterly downstream ice edge to help it resist breakup from wind and wave action (Bryce and Berry 1967). The effects of this ice boom on the local climate have been a recurring theme of study (Acres, Ltd. 1972, Rumer et al. 1983), but its main purpose of improving the use of water for generating electric power in winter has been very beneficial to the area (Perham 1976).

St. Marys River

A perspective of the St. Marys River portion of the Great Lakes navigation route and a summary of the ice problems that developed there is illustrated by a quote taken from one of the annual reports:

> The St. Marys River has always been considered one of the key links in the Great Lakes–St. Lawrence Seaway transportation system. Both the United States and Canadian governments, as well as commercial concerns, have made considerable investments to ensure safe and economic transportation of goods and materials through the St. Marys River, especially in the Sault Ste. Marie area. Besides its involvement in building four of the five navigation locks, which bridge the 20-plus ft of fall at the St. Marys Rapids, and in erecting powerhouses and a compensating works in the same area, the United States government has constructed the Little Rapids Cut, which is a 600-ft-wide channel between Sugar Island and the mainland of Michigan. Prior to the winter of 1975-76, experience had shown that winter ship traffic produced some restriction of normal travel and commerce between Sugar Island and the mainland. These restrictions were caused by broken, floating ice entering Little Rapids Cut from the harbor at Sault Ste. Marie (Soo), Michigan and Ontario, causing ice build-up in the Cut. Periodically this would hinder normal ferry operations.

In addition to the influx of ice floes and brash ice, substantial quantities of frazil slush were often generated in Little Rapids Cut, and (on occasion) snow storms would aggravate the situation.

Acres American, Inc. of Buffalo, New York, conducted physical hydraulic model studies and analytical studies of the area. The purpose of the study was to select and evaluate possible remedial measures in alleviating the problems that arose from too much ice collecting in the Little Rapids Cut section of the St. Marys River. Cowley et al. (1977) provide an excellent summary of the work done in the study.

Acres built a scale model of the Soo Harbor and Little Rapids Cut Area and developed a capability of simulating the harbor ice breakup phenomena that were responsible for the movement of ice floes and the subsequent formation of ice jams in the Cut (Acres American, Inc. 1975). The 1:120-scale Froude model of the 4.5-mile reach from Soo Locks to below Frechette Point limited studies to macroscale effects and provided primarily qualitative rather than quantitative results.

Ice was simulated by using plastic pellets 0.1 in. on a side, with the same density as ice, to form a layer on the water. The layer was sprayed with a chemical compound to cause interpellet adhesion and provide a strength comparable to that in the prototype. The ice cover would be broken by radio-controlled scale models of a 20-ft-beam by 700-ft-long or 105-ft-beam by 1000-ft-long prototype, each having a 27-ft draft and a prototype speed of 3–5 mph. The ship speeds monitored during 125 vessel passages in ice averaged 9.7 ft/s (2.9 m/s) for upbound ships and 12 ft/s (3.7 m/s) for downbound ships (Perham 1978b). This is significantly above the 4.4- to 7.3-ft/s prototype speeds employed in the model study by Acres (1975) and may have influenced their results. In his final, general report on the performance of the St. Marys River ice boom, Perham (1984) included information on forces that can be exerted on the boom by vessel passage.

Open-water tests and ice-cover tests were run to calibrate the hydraulic performance of the model, followed by icebreaking tests to measure ice losses without structures. It was found that the fracturing, movements and accumulations of the model ice cover simulated the effects seen in the prototype very well.

The remedial measures evaluated in the model were lines of cells; lines of pile dolphins of various lengths, spacings and locations; booms of different lengths at different locations; and riprap jetties. Navigation gap lengths through these structures were also varied. An initial series of tests produced a most promising structural arrangement, which was then further evaluated to determine the proper location relative to the head of Little Rapids Cut, the navigation gap width and the gap position relative to the navigation course centerline. Certain remedial measures such as ice harvesting (removal of excess ice), ice suppression (air bubblers) and ferry crossing relocation were analyzed and found to be impractical (Acres American, Inc. 1975).

A baseline ice production test with a river flow of 75,000 cfs and no structural controls produced an average of 82,000 cubic yards of ice per ship passage through Soo Harbor at prototype scale, and ice pack thicknesses in the cut were estimated to be from 3–5 ft. Wide variations in ship-induced ice releases were observed.

Tests of possible ice control structures included the application of wind forces to move ice into and through lines of dolphins, and as a result dolphin spacing had to be reduced for better restraint. It was subsequently concluded that booms were a better solution than dolphins. Based on these tests it was concluded that configuration F (shown in Figure 19) had the best combination of location and structural element sizes, and it permitted ice losses averaging only 16,100 cubic yards per ship passage, or an 80% reduction. The need for the two rock islands shown upstream of the ice booms in Figure 19 to provide additional stability to the ice cover was recognized later, after the prototype structure had been installed for its second winter of use (Perham 1978a).

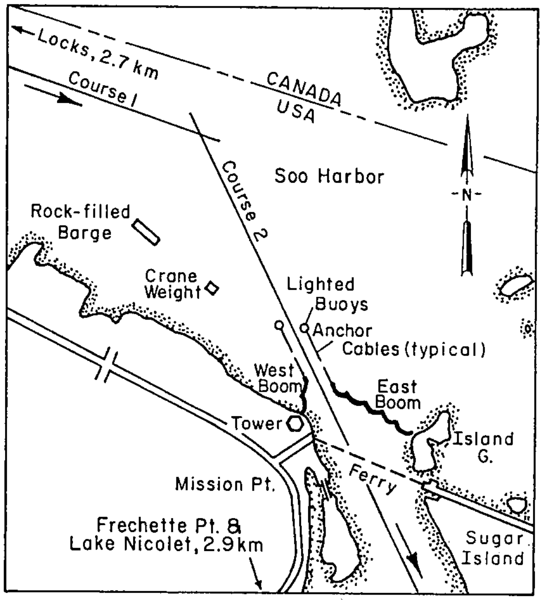

Figure 19. Location of the St. Marys River ice control structures. (From Perham 1984.)

The St. Marys River ice boom was designed in the summer of 1975 based on the best available information at that time. The forces on the ice boom would come mainly from the drag of water and wind on the Soo Harbor ice cover and from the action of ships passing through the ice cover. Since the latter effect was practically unknown, the boom was instrumented so that forces could be continuously monitored. A test program conducted the previous winter at Copeland Cut on the St. Lawrence River provided little guidance on ship forces except that the forces can be attenuated almost completely by a solid ice cover bonded to shore (Uzuner 1975).

The ice control structures, shown in Figure 20, are composed of 3 shore anchors, 13 river bottom anchors, 17 anchor cables and 7 boom cables. The boom cables are 250 ft long (76.2 m), and the length-to-chord ratio is approximately 1.3:1. Each timber is 1 ft × 2 ft × 20 ft long (0.30 × 0.61 × 6.10 m long). A novel feature used at the upstream

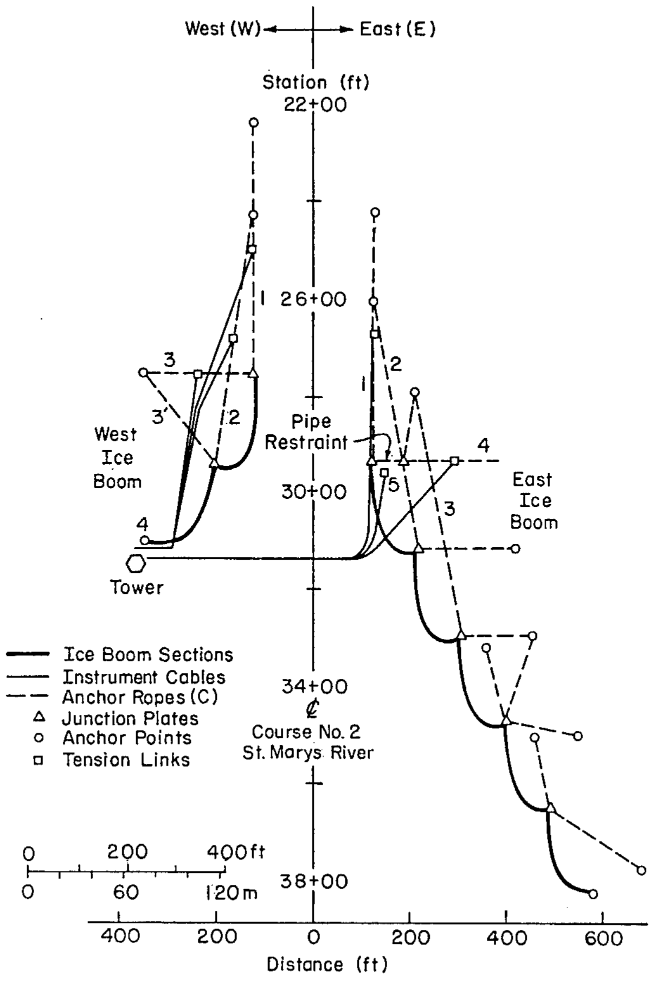

Figure 20. Details of the St. Marys River ice boom.

end of the east boom was a 60-ft-long floating horizontal column used to transfer forces so as to avoid putting an anchor line in the navigation openings.

The study of the performance of the St. Marys River ice boom lasted for four years, ending with the Winter Navigation Demonstration Program at the close of the winter 1978-79 season. During the early years a problem developed due to the stability of the ice sheet above the west boom. It was observed that this ice sheet could break free from the shoreline as a single sheet as much as 1.5 miles in length and would exert forces sufficient to damage some of the boom components. An additional anchor line (3′ in Fig. 20) was added following the first season to remedy the situation.

In January of 1977, however, two minor cables (3 and 3′ in Fig. 20) as well as the main shore anchor broke. Following the incident, cables 3 and 3′ were strengthened, and a 300-ton barge and six crane weights totaling 95 tons were positioned in shallow water upstream to help anchor the ice sheet. In addition, a small ship has been used to keep the ice sheet from freezing solidly to the ice boom timbers. The highest recorded boom forces occurred during the first two seasons, indicating that the performance was indeed improved by the anchor line modifications and the addition of the barge and crane weight ice anchors. While large ice sheets could still break free between the vessel track and anchors, the resultant forces were not sufficient to damage the boom. The temporary ice anchors were replaced with rock islands in 1981.

The peak loads that developed in some of the boom structures during the winter of 1976 are shown in Table 2. The anchor cables are identified as being in the west or east boom by the corresponding letter suffix on the cable number and are shown in Figure 20. The expected load is the design load and was calculated for each of the components (Perham 1977). The ice and ship effects on the booms during the winter of 1976-77 were also published by Perham (1978b). A noteworthy finding was that there was little difference in peak force levels on the boom between upbound and downbound ships, the force level being about 25,000 lbs.

Ice passage through the boom was also monitored. Ice release during periods that were busy

Table 2. Peak loads on the St. Marys River ice boom, 1976.

Anchor	*Expected load*		*Force recorder charts*		*Tension link design capacity*	
cable	*(lbf)*	*(kN)*	*(lbf)*	*(kN)*	*(lbf)*	*(kN)*
C1W	65,000	289	77,000	343	180,000	801
C2W	97,000	431	94,000	418	180,000	801
C3W	13,000	58	53,000	236	60,000	267
C1E	43,000	191	160,000	712	120,000	534
C4E	5,000	67	4,100	18	60,000	267
C5E	8,200	36	1,500	7	60,000	267

with ship transits varied from 5,200 to 10,000 cubic yards per ship passage and averaged 7,230 cubic yards. The maximum was approximately 40,000 cubic yards per passage. In the model study the average was 16,100 cubic yards. In terms of the dimensionless parameter Ar/b^2 (area of ice released per gap width squared), the average ice release values are 2.9, 4.3, 2.2 and 3.0 for the four winters studied (Perham 1985).

Reference measurements

The following information is a summary of data obtained by the Detroit District to monitor the ice boom performance and its effect on levels and flows. The primary survey of ice conditions and water levels for the Navigation Season Extension Demonstration program was conducted by the U.S. Army Engineer District, Detroit, and consisted of:

- Field observations using three time-lapse movie cameras;
- Aerial photography of the entire St. Marys River but with somewhat greater emphasis on Soo Harbor;
- Monitoring of water levels in Soo Harbor and Little Rapids Cut;
- Discharge measurements taken in the two channels around Sugar Island to determine the effect of the ice boom on flow distribution; and
- Ice thickness measurements throughout the winter above and below the boom.

From this information one can tell when the ice cover began, its area and extent during the winter, and some information about the ice edge location in Little Rapids Cut. Some conclusions reached during 1978 are:

- The ice boom helps maintain a fairly stable ice cover on Soo Harbor, similar to before winter navigation began, by retaining the ice that might otherwise move down into Little Rapids Cut.
- Ice in Little Rapids Cut is a major factor in retarding flow between Soo Harbor and Frechette Point, but the quantity of ice and degree of retardation do not directly correlate.
- The rock-filled scow and crane weights proved effective in anchoring the Soo Harbor ice field to shore.
- Ice jamming in and below Little Rapids Cut is believed to be due to large open-water areas in the Cut, frazil ice and heavy snowfall (USACE 1978).

In 1979 the same measurements were made as during 1978 except that a substantial effort was applied to measuring the flow distribution around Sugar Island. The winter measurements were taken from 27 February to 3 March 1979, and the data revealed that 67% of the flow went through Little Rapids Cut and 33% of the flow went through the North (Lake George) Channel. Summer flow measurements were taken from 13 June to 16 June 1979, and the data showed that 71% went down Little Rapids Cut and 29% went down the North Channel. The flow distribution measurements during the winter periods indicate that the variance of 5% is within the obtainable accuracy range for this type of measurement, and therefore no significant change (effect of the ice boom on river flows) is evident (USACE 1980).

Although the Winter Navigation program ended after the 1978-79 winter season, it was decided to continue installing the ice boom as part of the Soo Area Office, Detroit District regular winter operation. The boom system has been of value in stabilizing the ice cover in Soo Harbor, reducing the extent of ice accumulation in Little Rapids Cut and reducing the amount of ice in the Sugar Island ferry crossing. These benefits occur whether there is winter navigation or not, as the harbor ice usually breaks up due to wind and weather several times a year.

By lessening the possibility of ice jams in the Cut, the boom has decreased the chances of flooding in Soo Harbor along with possible power losses at the hydropower plants. By reducing the adverse effects of natural ice conditions on the Sugar Island ferry, it has contributed to more reliable transportation between Sugar Island and the mainland.

Port Huron

During 1979 a study was initiated to provide the necessary criteria for the detailed design of an ice control structure at Port Huron (Fig. 21), with the major criteria being structural configuration and forces. The main problem was that ice leaves Lake Huron via the St. Clair River, which is typically ice free, and passes through to Lake St. Clair, which is usually ice covered. The moving ice accumulates in this stagnant reach just north of Lake St. Clair and often forms deep jams. Two physical models were employed: one to evaluate hydraulic conditions, the other to evaluate the effects of wind.

The hydraulic model study used Froude scaling with an undistorted geometric scale of 1:85

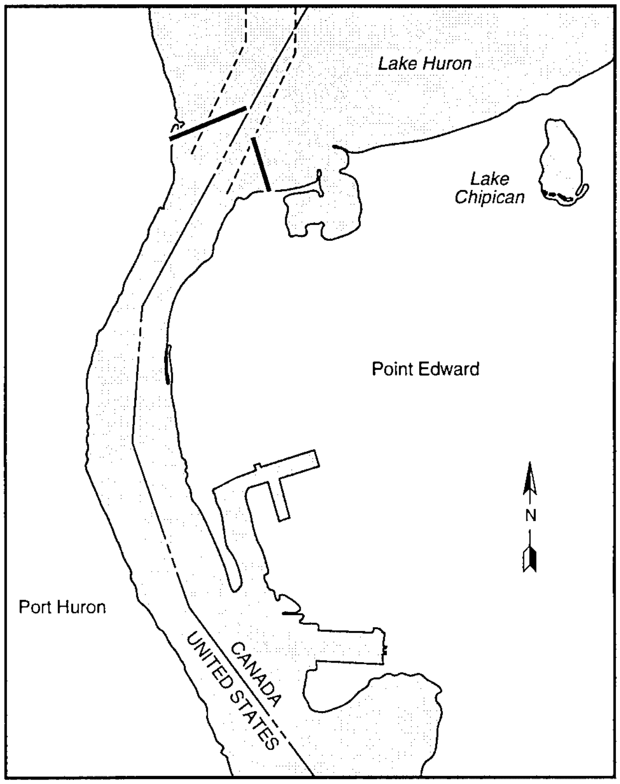

Figure 21. Location of the Port Huron ice control structure. (After USACE 1979a.)

covering approximately a 1-mile length of prototype (Calkins et al. 1982). A wire-line-towed model ship of prototype dimensions 105 ft beam, 1000 ft long and 27 ft draft was used to represent vessel passages. Plastic ice floes of both random and square shapes, as well as natural ice, were used in separate tests.

The results of the testing program showed that ice passage through the gap was greater for square floes than for random-shaped floes of comparable size and that for random-shaped floes the dominant variables affecting vessel-induced ice passage were the floe size/gap opening ratio, a/b, and the direction of vessel passage. The average ice discharge per vessel (in terms of ice area per the square of the gap width, Ar/b^2) varied from 0.1 to 1.0 depending on the floe size, with downbound transits causing greater ice releases than upbound ones. The minimum a/b ratio for reestablishing a stable arch across the gap was approximately 0.075 (or 30 ft for the proposed 400-ft gap).

The surface condition of the ice floes above the ice control structure was also very important, as a non-rafted ice field allowed a two- to five-fold greater ice release per vessel transit than a rafted ice field. Interestingly there appeared to be little difference in the forces exerted on the ice control structure during upbound and downbound passages. The conclusion that loads applied to the ice boom are independent of vessel direction was also made for the St. Marys River ice boom (Perham 1978b). The dynamic loading of the ice control structure during vessel passage was expected to average three to five times greater than the static load.

The effects of wind stress on the ice cover were examined in a follow-on study of a Port Huron ice control structure (Sodhi et al. 1982). Here water flowing beneath the model ice was used to simulate wind blowing over an ice cover. The ice was restrained by two configurations of barriers, which were instrumented for forces. One was a large funnel arrangement simulating the Lake Huron shoreline near Port Huron, and the other was a much smaller inverted funnel simulating an ice control structure.

Tests of ice releases resulting from ship transits were conducted for both upbound and downbound passages and for different ice control structure orientations. Sodhi et al. (1982) concluded that the ice cover could arch across the navigation gap at values of a/b ranging from 0.11 to 0.15, or 44 to 60 ft at the proposed gap width of 400 ft. Further, the mean value of ice area released per vessel passage, Ar/b^2, would be less than 3 (or 480,000 ft^2). Mean ice forces on the ice control structure due to wind loading by a 40-mph wind were estimated to be 380 lb/ft, with maximum forces of up to 1000 lb/ft of structure length.

The model tests for an ice control structure at Port Huron were conducted near the end of the Winter Navigation Demonstration Program. It was never constructed nor even designed in detail. If it were to be built at some future date, the design loads on the structure could be determined by superposition of the hydraulic and wind stress forces estimated in the studies by Calkins et al. (1982) and Sodhi et al. (1982).

ICE CONTROL AT LOCKS

A significant effort in the Winter Navigation Demonstration Program was to determine methods to minimize ice problems in and around navigation locks. There are two sources for the ice that causes the problems: ice that simply freezes in place and brash ice arriving at the lock from upstream. This section will review a number of concepts that were demonstrated at the Soo Locks during the Demonstration Program. Additional information on ice control at locks can be found in Hanamoto (1977) and USACE (1982).

Minimizing ice adhesion to lock walls

Ice can form on lock walls either by direct freezing of water or by the adhesion of broken ice that is crushed and smeared against a wall by ships. The most significant accumulations of ice occur in a several-foot-thick collar extending down from the water surface at the upper pool elevation. A number of techniques were investigated to try to either minimize the formation of such ice deposits or reduce the strength of ice adhesion to the lock walls.

Modification of operating procedures

Since the surface of a lock wall must be cooled below 32°F before significant ice can form on or adhere to a lock wall, it is unlikely that a submerged portion of a wall will undergo the necessary cooling. Thus, there is a strong incentive to hold the lock at the highest feasible water level during the long intervals between ship passages, preventing ice accumulation on the lower portions of the wall.

Built-in wall heaters

Ice adhesion can be prevented by maintaining the wall temperature above 32°F, or ice collars can be shed by raising the wall temperature above freezing periodically. Possible arrangements include embedded electrical heating cables, conductive surface materials and internal piping or ducts for warm fluids. No special merits have been found for a hot fluid system compared to an electrical system for heating lock walls.

Pavement heating systems designed to melt snow and ice usually use a power density of 30 W/ft^2. By using 11 lines of heating cable running horizontally at 5-in. centers, with a burial depth of 3 in., full heating coverage for a 5-ft depth of bonded ice collar is achieved. At a power density of 30 W/ft^2, the cable has to dissipate 15 W/ft. If the system is amortized over 20 years, the average annual cost for amortization plus direct operating cost is approximately $25,000 at 3 cents/kW-hr.

Conductive panels have also been considered, but they would find their best application where the conductive material can be recessed so as to maintain a flush face on the lock wall. Conductive panels attached directly to an existing lock wall would slightly decrease the effective width of the lock and be subject to damage by impact from ship hulls and shear forces transmitted through any attached ice. With ice tightly packed between a ship hull and the lock wall, lock operation could impose a vertical shearing force on the order of 100 lbf per foot of wall length in critical sections.

Surface coatings

There is a long history of study on adhesion reduction coatings for a variety of applications, but chemical coatings that shed ice reliably and repeatedly have not yet emerged for commercial use. The only chemical treatment that has been used successfully on a large scale is repeated application of chemicals that depress the freezing point of water. As far as horizontal concrete surfaces are concerned, the classic treatment for ice removal is application of sodium chloride or calcium chloride.

An ice collar control method using a chemical coating to reduce the adhesive force between the coated surface and the ice that forms on it was tested at the Soo Locks during the Demonstration Program (Frankenstein et al. 1976). The basic material is a long-chain copolymer compound of polycarbonates and polysiloxanes. The material is produced on order by the General Electric Co. in Pittsfield, Massachusetts, with a trade name of LR 5630 (new designation GR 5530). The compound comes in coarse powder form.

A solution of the compound, silicone oil and toluene leaves a thin coat of the copolymer and silicone on the surface of the lock wall. The surface to be coated must be clean and dry. For concrete and metal surfaces, steam cleaning is sufficient. A detergent was added to the steam cleaner water supply in one case where the walls were heavily coated with oil and algae. Once the surface is clean and dry, the solution can be sprayed on using an airless spray gun. A single pass will deposit a coat 1–2 mils thick. Three coats are recommended for a coating thickness of about 5 mils.

Tests were also conducted to examine the merits of an undercoating for the copolymer on concrete surfaces that are worn and rough. An epoxy-type coating was employed, acting as a filler over the rough concrete, and it resulted in a surface to which the copolymer adhered better. While sprayed-on coatings of copolymer can reduce the strength of adhesive bonds, it appears that a subsidiary mechanical system is need to actually dislodge the ice that accumulates. Periodic renewal of the coating is also required due to abrasion by ship hulls and ice.

Mechanical ice removal

At many lock installations, ice is removed mechanically. A frequently used expedient method involves scraping the ice off the wall with a backhoe. The wall is scraped vertically by drawing the bucket teeth up the face of the concrete. With a light machine, this may require multiple passes to scrape down to the concrete, and frequent repositioning of the machine is necessary. With a heavier, track-mounted machine, a single pass is usually sufficient. It is also easier to move the machine along the wall since there are no spuds to be set. However, with forceful operation, damage to the wall seems inevitable, and serious spalling of the concrete can occur on grooved or paneled walls.

Inflatable deicers, such as those used on the leading edge of aircraft wings, were tried at the Soo Locks to remove the collar from the lock wall (Itagaki et al. 1975). The device proved effective but is not used, primarily because of its vulnerability to ship-induced damage and its thickness, which reduces the available lock width.

A 150-hp high-pressure water jet capable of continuous duty at 10,000 lbf/in.^{2} was tested and found to be capable of cutting through a 3-ft-deep ice collar at a traverse speed of about 3.5 ft/min, which would require about five hours to clear a single 1000-ft wall. This approach was dropped due to its high operating costs (Calkins et al. 1976). Steam has frequently been used when it was available at the desired locations, but it too is time consuming.

Floating ice control

Ice problems at navigation locks are primarily caused by brash ice floating downstream or being pushed ahead of downbound traffic. The floating ice pieces can hinder gate opening and closing, adhere to lock walls reducing the effective lock width, and add significant additional loads to lock gates because of the weight of attached ice. Large quantities of ice pushed ahead of a downbound ship often require an additional lock cycle to clear ice before the vessel can enter.

Attempts have been made to control this ice by installing pipe manifolds that would allow hydraulic flushing while the lower lock gates were open (Oswalt 1976). However, this still required additional, time-consuming operations and extra cycling of the lock gates and water levels. If ice could be prevented from entering the lock in the first place, most of these problems would not occur. A high-flow, high-velocity air screen shown in Figure 22 was installed across the upper entry of the Poe Lock at Sault Ste. Marie, Michigan

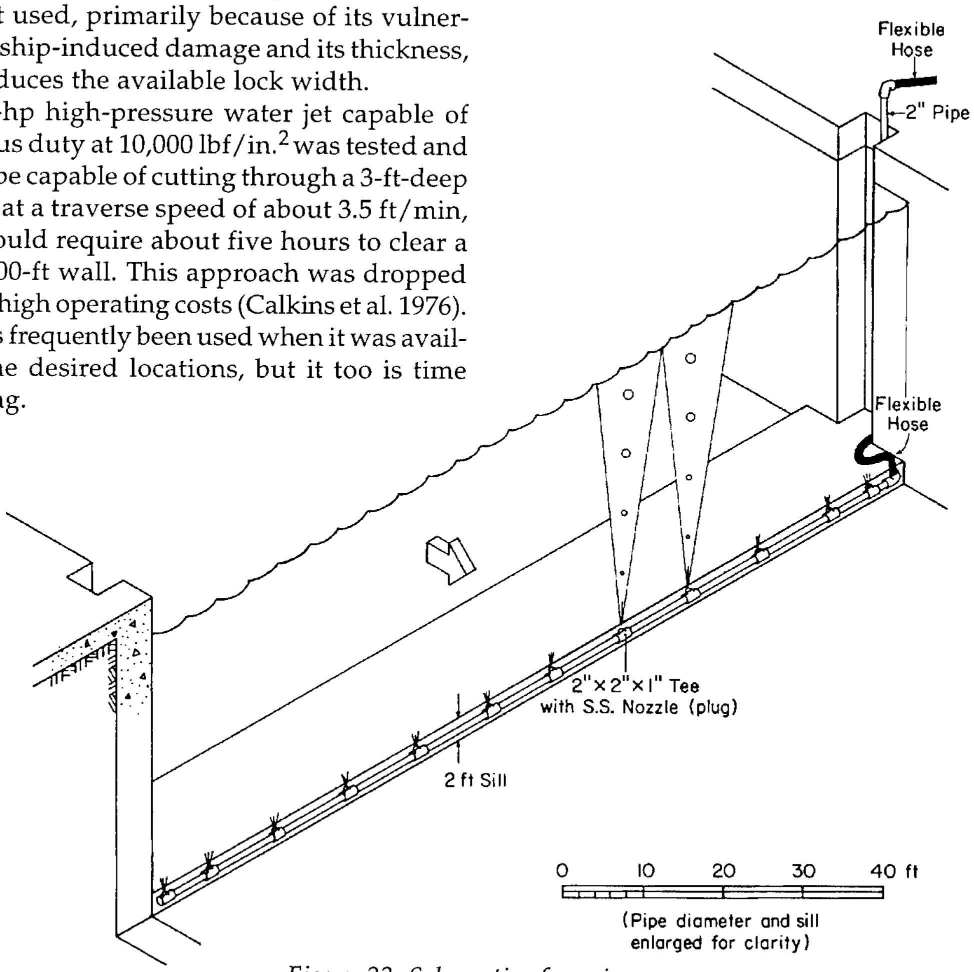

Figure 22. Schematic of an air screen.

(USACE 1982). The screen created sufficient horizontal water velocity in the upstream direction to keep the downbound ice from being pushed ahead by a ship. This system has also been used more recently to keep debris out of the lock approach during open water periods.

A compressor with an output of 1150 cfm at 110 psi was available at the Soo Locks for use in the air screen trials. The optimum air flow conditions were obtained using a 2-in.-diameter manifold and supply line system, with 0.40-in.-diameter nozzles spaced 10 ft apart. The manifold line was 2-in. galvanized pipe with 2- × 2- × 1-in. tee joints for each 10 ft of pipe. A 1-in. stainless steel plug was mounted at each tee, and each plug had a 0.4-in. hole drilled in it that acted as the nozzle.

The air screen was installed at the upper approach to the Poe Lock on the downstream, vertical face of an emergency stop-log gate sill. The sill is located about 200 ft above the lock gates. The riser line was installed in a stop-log recess in the wall. The width of the lock at this point is 110 ft, and the height from the top of the sill to the top of the lock wall is 39 ft.

The air screen has demonstrated that it can hold back ice pushed ahead of downbound traffic. With ships in the 70-ft-beam class, the ice was held back until the bow entered the air stream. The screen was not as effective with 105-ft-beam ships. Once the bows of these wider ships pass the nose pier about 130 ft upstream of the screen, the approach is just a little over 110 ft wide, so most of the ice remaining ahead of the ship is pushed into the lock. This problem might be remedied by relocating the air screen upstream of the nose pier area and providing an area for ice to be pushed out of the vessel track.

Summary

One of the major obstacles to be overcome in extending the navigation season on the St. Marys River was to develop methods to mitigate ice problems in and around the Soo Locks. The two major ice problems encountered were ice accumulations on lock walls, which reduced the usable width of the lock, and large quantities of brash ice entering the lock from upstream, which could hinder the operation of the miter gates and interfere with ships entering the locks.

During the program a variety of concepts were examined, including changing lock-operating procedures, minimizing ice adhesion, removing the mechanically and controlling floating ice. A chemical, ice-release coating was developed that significantly reduces the problem of ice accumulation on lock walls. The air screen system demonstrated during the program largely solves the floating ice problem by diverting ice from the lock and its approach. This not only limits the quantity of ice that can hinder gate operation and block the entry of ships into the lock, but it also reduces the supply of ice that can be crushed and smeared onto the lock wall.

LITERATURE CITED

Acres American, Inc. (1975) Ice model study of the Little Rapids Cut area of the St. Marys River, Michigan. Draft contract report to the Detroit District, U.S. Army Corps of Engineers, Contract No. DACW35-75-C-0014.

Acres, Ltd. (1972) Study of Lake Erie ice boom. Prepared by Water Supply Canada by H.G. Acres, Limited.

Alger, G.R. (1977a) A study of ice related sediment transport and shoreline erosion, St. Marys River–Sault Ste. Marie, Michigan, Vol. 1: Main Report. Contract Report to the USA Cold Regions Research and Engineering Laboratory, Contract No. DACA89-76-C-0013.

Alger, G.R. (1977b) A study of ice related sediment transport and shoreline erosion, St. Marys River–Sault Ste. Marie, Michigan, Vol. 2: Appendices. Contract Report to the USA Cold Regions Research and Engineering Laboratory, Contract No. DACA89-76-C-0013.

Alger, G.R. (1978) A study of ice related sediment transport and shoreline erosion, St. Marys River, St. Clair River, Detroit River, Michigan, Vol. 3. Contract Report to the USA Cold Regions Research and Engineering Laboratory, Contract No. DACA 89-76-C-0013.

Alger, G.R. (1979a) A study of ice related sediment transport and shoreline erosion; St. Marys River, St. Clair River, Detroit River, Michigan, Vol. 4, with Appendix. Contract Report to the USA Cold Regions Research and Engineering Laboratory, Contract No. DACA89-76-C-0013.

Alger, G.R. (1979b) Ship-induced waves: Ice and physical measurements on the St. Marys River. Report to the Great Lakes Basin Commission in support of the Winter Navigation Board-Environmental Evaluation Work Group.

Alger, G.R. (1980) A study of ice related sediment transport and shoreline erosion, St. Marys River–Sault Ste. Marie, Michigan, Vol. 5. Contract Report to the USA Cold Regions Research and Engineering Laboratory, Contract No. DACA89-80-M-795.

Alger, G.R. (1981) Field study of the effect of ice on sediment transport and shoreline erosion, St. Marys River, Michigan, Vol. 6. Contract Report to the USA Cold Regions Research and Engineering Laboratory, Contract No. DACA89-81-M-0649.

Alger, R.G. and R.J. Hodek (1986) Development of a predictive model to assess the effects of extended season navigation on Great Lakes connecting waters; Users' manual: Prediction of vessel impacts in a confined waterway. Supplemental volume to the main contract report (Hodek et al. 1986) submitted to the USA Cold Regions Research and Engineering Laboratory by Michigan Technological University, Contract No. DACA89-85-K-0001.

Argyle, R.L. (1974) Evaluation of environmental baseline data—Saginaw waste heat demonstration. Interim Report for the period November 1972 through October 1973, Fish and Wildlife Service, Great Lakes Fisheries Laboratory.

Ashton, G.D. (1974a) Evaluation of ice management problems associated with operation of a mechanical ice cutter on the Mississippi River. USA Cold Regions Research and Engineering Laboratory, Special Report 214.

Ashton, G.D. (1974b) Air bubbler systems to suppress ice. Report to the Detroit District, U.S. Army Corps of Engineers by the USA Cold Regions Research and Engineering Laboratory, Contract No. NCE-IA-73-108, USA Cold Regions Research and Engineering Laboratory, Special Report 210.

Ashton, G.D. (1975) Experimental evaluation of bubbler induced heat transfer coefficients. *Proceedings of the Third International Symposium on Ice Problems sponsored by the International Association for Hydraulic Research, Hanover, New Hampshire, August*, pp. 133–141.

Ashton, G.D. (1978) Numerical simulation of air bubbler systems. *Canadian Journal of Civil Engineering*, **5**(2): 231–238.

Ashton, G.D. (1979) Point source bubbler systems to suppress ice. *Cold Regions Science and Technology*, **1**(2): 93–100.

Ashton, G.D. (Ed.) (1986) *River and Lake Ice Engineering*. Littleton, Colorado: Water Resources Publications.

Baca, B.J., T.E. Lankford and E.R. Gundlach (1986) Environmental impacts of oil and hazardous material spills with emphasis on winter conditions in the Upper Great Lakes Region. Prepared for the Detroit District, U.S. Army Corps of Engineers by Coastal Science and Engineering, Inc.

Behmer, D.J. and G.R. Gleason (1975) Winter fish movement at a proposed bubbler site; St. Marys River system. Contract Report to the U.S. Fish and Wildlife Service by Lake Superior State College, Contract No. 14-16-0003-30.

Berlamont, J. and A. Van der Beken (1973) Solutions for lateral outflow in perforated conduits. *Journal of the Hydraulics Division, American Society of Civil Engineers*, **99**(HY9): 1531–1549.

Bryce, J.B. and G.T. Berry (1967) Lake Erie–Niagara River ice boom. *Proceedings of the 1967 Congress of Canadian Engineers, Montreal, EIC-68-CIV, May*, p. 28–35.

Calkins, D.J., D.S. Deck and D.S. Sodhi (1982) Hydraulic model study of Port Huron ice control structure. USA Cold Regions Research and Engineering Laboratory, CRREL Report 82-34.

Calkins, D.J., M. Mellor and H. Ueda (1976) Lockwall de-icing with high velocity water jets at Soo Locks, Michigan. USA Cold Regions Research and Engineering Laboratory, Technical Note (unpublished).

Camp, T.R. and S.D. Graber (1968) Dispersion conduits. *Journal of the Sanitary Division, American Society of Civil Engineers*, **94**(SAl): 31–39.

Carey, K.L. (1980) Estimating costs of ice damage to private shoreline structures on the Great Lakes connecting channels. Prepared for the Detroit District, U.S. Army Corps of Engineers by the USA Cold Regions Research and Engineering Laboratory, Contract No. NCE-IA-76-195, Special Report 80-22.

Carter, D., Y. Ouellet and P. Pay (1981) Fracture of a solid ice cover by wind-induced or ship-generated waves. In *Proceedings, 6th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC '81), 27–31 July, Quebec, Canada.* Université Laval, p. 843–856.

Cowley, J.E., J.W. Hayden and W.W. Willis (1977) A model study of St. Marys River ice navigation. *Canadian Journal of Civil Engineering*, **4**(3): 380–391.

Dahlberg, M.D., J.W. Duncan and J.M. Burke (1980) Winter fish population in probable locations of air bubblers in the St. Marys River–Lake Superior area. Contract Report by NUS Corporation to the U.S. Fish and Wildlife Service in cooperation with the Detroit District, U.S. Army Corps of Engineers, FWS Contract NO. 14-16-0009-79-087.

Dalton, Dalton, Little and Newport, Inc. (1975) Report on shoreline erosion and structural damage along the St. Marys River, Michigan. Contract

Report to the Detroit District, U.S. Army Corps of Engineers, Contract No. DACW35-74-C-0128.

Davis, T.E. and R.W. Irwin (1982) Potential impacts of winter navigation upon migratory birds on the Upper Great Lakes. Prepared for the Detroit District, U.S. Army Corps of Engineers by the Office of Biological Services, U.S. Fish and Wildlife Service, issued as OBS Report 82/51.

Frankenstein, G.E., J.L. Wuebben, H.H.G. Jellinek and R. Yokota (1976) Ice removal from the walls of navigation locks. *Proceedings of the American Society of Civil Engineers Conference Rivers 76, Fort Collins, Colorado, June,* p. 1487–1496.

Garfield, D.E., B. Hanamoto and M. Mellor (1976) Development of large ice saws. USA Cold Regions Research and Engineering Laboratory, CRREL Report 76-47.

Gates, E.T. and J.B. Herbich (1977) The squat phenomenon and related effects of channel geometry. *Hydraulics in the Coastal Zone, 25th Annual Hydraulics Division Specialty Conference, American Society of Civil Engineers, College Station, Texas.*

Gatto, L.W. (1978) Data base for environmental conditions along the U.S. shoreline of the St. Marys, St. Clair, Detroit, and St. Lawrence Rivers. USA Cold Regions Research and Engineering Laboratory, Internal Report No. 553.

Gatto, L.W. (1980a) Shoreline conditions and bank recession along the U.S. shoreline of the St. Marys, St. Clair, Detroit and St. Lawrence Rivers. USA Cold Regions Research and Engineering Laboratory, CRREL Report 82-11.

Gatto, L.W. (1980b) Shoreline conditions and shoreline recession along the U.S. shoreline of the St. Marys, St. Clair, Detroit, and St. Lawrence Rivers. Prepared for the Detroit District, U.S. Army Corps of Engineers by the USA Cold Regions Research and Engineering Laboratory, Internal Report No. 533.

Gatto, L.W. (1982) Bank conditions and recession along the U.S. shorelines of the St. Marys, St. Clair, Detroit and St. Lawrence Rivers: Ancillary data. Prepared for the Detroit District, U.S. Army Corps of Engineers by the USA Cold Regions Research and Engineering Laboratory, Internal Report No. 747.

Gleason, G.R., D.J. Behmer and R. Hook (n.d.) Evaluation of lake whitefish and herring spawning grounds as they may be affected by excessive sedimentation induced by vessel entrapment due to the ice environment within the St. Marys River system. Report to the Detroit District, U.S. Army Corps of Engineers by Lake Superior State College in support of the Winter Navigation Board—Environmental Evaluation Work Group, Contract No. DACW-35-79-M-0561.

Gleason, G.R., D.J. Behmer and K.L. Vincent (1979) Evaluation of benthic dislocation due to pressure waves initiated by vessel passage in the St. Marys River. Report to the Great Lakes Basin Commission by Lake Superior State College in support of the Winter Navigation Board—Environmental Evaluation Work Group.

Haas, R.C., W.C. Bryant, K.D. Smith and A.D. Nuhfer (1985) Movement and harvest of fish in Lake St. Clair, St. Clair River, and Detroit River. Michigan Department of Natural Resources, Fisheries Division, Contract Report to the Detroit District, U.S. Army Corps of Engineers.

Hanamoto, B. (1977) Lockwall deicing studies. USA Cold Regions Research and Engineering Laboratory, Special Report 77-22.

Hatcher, C.O. (1977) Evaluation of environmental impact data—Saginaw waste heat demonstration program, April 1973 through September 1976. Fish and Wildlife Service, Great Lakes Fisheries Laboratory.

Haynes, F.D. and M. Määttänen (1981) Vibrations caused by ship traffic on an ice-covered waterway. USA Cold Regions Research and Engineering Laboratory, CRREL Report 81-5.

Hiltunen, J.K. (1979) Investigation of macrobenthos in the St. Marys River during an experiment to extend navigation through winter, 1974-75. (Revised from version of 1978), U.S. Fish and Wildlife Service Report to the Detroit District, U.S. Army Corps of Engineers.

Hochstein, A.B. and C.E. Adams (1985a) An assessment of the effects of tow movements on the Kanawha River. Contract report to the Huntington District, U.S. Army Corps of Engineers.

Hochstein, A.B. and C.E. Adams (1985b) A numerical model of the effects of propeller wash from commercial navigation in an extended navigation season on erosion, sedimentation, and water quality in the Great Lakes connecting channels and harbors. Contract report to the Detroit District, U.S. Army Corps of Engineers.

Hochstein, A.B. and C.E. Adams (1986) A numerical model of the effects of propeller wash and ship-induced waves from commercial navigation in an extended navigation season on erosion, sedimentation, and water quality in the Great Lakes connecting channels and harbors. Contract report to the Detroit District, U.S. Army Corps of Engineers.

Hodek, R.J., M.D. Annable, G.R. Alger and H.S. Santeford (1986) Development of a predictive model to assess the effects of extended season navigation on Great Lakes connecting waters. Contract Report to the USA Cold Regions Research and Engineering Laboratory by Michigan Technological University, Contract No. DACA89-85-K-0001.

Hudson, P.L., B.M. Davis, S.J. Nichols and C.M. Tomcko (1986) Environmental studies of macrozoobenthos, aquatic macrophytes, and juvenile fishes in the St. Clair–Detroit River system, 1983–1984. U.S. Fish and Wildlife Service, Great Lakes Fisheries Laboratory, Contract Report to the Detroit District, U.S. Army Corps of Engineers.

Itagaki, K., M. Frank and S.F. Ackley (1975) Laboratory experiments on lock wall deicing using pneumatic devices. USA Cold Regions Research and Engineering Laboratory, Technical Note (unpublished).

Jude, D.J., M. Winnel, M.S. Evans, F.J. Tesar and R. Futyma (1986) Drift of zooplankton, benthos, and larval fish and distribution of macrophytes and larval fish during winter and summer, 1985. Contract report to the Detroit District, U.S. Army Corps of Engineers by the University of Michigan, Contract No. DACW35-85-C-0005.

Liston, C.R. and C.D. McNabb (1986) Limnological and fisheries studies of the St. Marys River, Michigan, in relation to proposed extension of the navigation season, 1982 and 1983. Contract Report to the U.S. Fish and Wildlife Service by Michigan State University, Contract No. 14-16-0009-790-13

Muth, K.M., D.R. Wolfert and M.T. Bur (1986) Environmental study of fish spawning and nursery areas in the St. Clair-Detroit River system. U.S. Fish and Wildlife Service, Sandusky Biological Station, Contract Report to the Detroit District, U.S. Army Corps of Engineers.

National Biocentric, Inc. (1973) Environmental review report for demonstration bubbler system in the Superior entry, Duluth–Superior Harbor. Prepared for the St. Paul District, U.S. Army Corps of Engineers, Contract No. DACW37-73-C-0058.

Nicholson, S.A. and K.W. Dixon (1979) Review and evaluation of existing contingency plans and response capabilities for spills of oil and hazardous substances in the Great Lakes system. Contract report to the Detroit District, U.S. Army Corps of Engineers by the St. Lawrence–Eastern Ontario Commission, Contract No. DACW35-79-R-0042.

Normandeau Associates (1979) Ship generated drawdown and surge study, St. Lawrence River near Ogdensburg, New York. Prepared for the St. Lawrence Seaway Development Corporation, Washington, D.C.

Ofuya, A.O. (1970) Shore erosion-ship and wind waves, St. Clair, Detroit, and St. Lawrence Rivers. Department of Public Works of Canada, Marine Directorate, Design and Construction Branch, Report No. 21.

Oswalt, N.R. (1976) Ice flushing from St. Lawrence Seaway locks. Prepared for the St. Lawrence Seaway Development Corporation by the USA Engineer Waterways Experiment Station, Technical Report H-76-9.

Palm, D.J. (1977a) Evaluation of shore structures and shore erodibility, St. Lawrence River, New York State. Prepared by the St. Lawrence–Eastern Ontario Commission for the St. Lawrence Seaway Development Corporation, U.S. Department of Transportation.

Palm, D.J. (1977b) Evaluation of shore structures and shore erodibility, St. Lawrence River, New York State, Appendix B. Prepared by the St. Lawrence–Eastern Ontario Commission for the St. Lawrence Seaway Development Corporation, U.S. Department of Transportation.

Palm, D.J. and T.M. Cutter (1978) Evaluation of shore structures and shore erodibility, St. Lawrence River, New York State, Phase II. Prepared by the St. Lawrence–Eastern Ontario Commission for the St. Lawrence Seaway Development Corporation, U.S. Department of Transportation.

Perham, R.E. (1974) Forces generated in ice boom structures. USA Cold Regions Research and Engineering Laboratory, Special Report 200.

Perham, R.E. (1976) Some economic benefits of ice booms. *Proceedings, 2nd International Symposium on Cold Regions Engineering, Fairbanks, Alaska, 12–14 August, University of Alaska–Fairbanks.* Cold Regions Engineers Professional Association, p. 570–591.

Perham, R.E. (1977) St. Marys River ice booms: Design force estimate and field measurements. USA Cold Regions Research and Engineering Laboratory, CRREL Report 77-4.

Perham, R.E. (1978a) Performance of the St. Marys River ice booms 1976–77. USA Cold Regions Research and Engineering Laboratory, CRREL Report 78-24.

Perham, R.E. (1978b) Ice and ship effects on the St. Marys River ice boom. *Canadian Journal of Civil Engineering*, **5**: 222–230.

Perham, R.E. (1984) The effectiveness and influences of the navigation ice boom on the St. Marys River. USA Cold Regions Research and Engineering Laboratory, CRREL Report 84-4.

Perham, R.E. (1985) Determining the effectiveness of a navigable ice boom. USA Cold Regions Research and Engineering Laboratory, Special Report 85-17.

Poe, T.P. and T.A. Edsall (1982) Effects of vessel-induced waves on the composition and amount of drift in an ice environment in the St. Marys River. Fish and Wildlife Service, Great Lakes Fisheries Laboratory Administrative Report No. 82-6.

Poe, T.P., T.A. Edsall and J.K. Hiltunen (1980) Effects of ship-induced waves in an ice environment on the St. Marys River ecosystem. U.S. Fish and Wildlife Service, Great Lakes Fisheries Laboratory, Administrative Report 80-6.

Robinson, W.L. and R.W. Jensen (1980) Effects of winter navigation on waterfowl and raptorial birds in the St. Marys River area. Report to the Great Lakes Basin Commission by Northern Michigan University in support of the Winter Navigation Board-Environmental Evaluation Work Group.

Rumer, R.R., W.F. Bialis, F.H. Quinn, R.A. Assel and D.W. Gaskill (1983) Niagara River ice boom, effect on environment. *Journal of Technical Topics in Civil Engineering, American Society of Civil Engineers,* 109(2): 104–116.

Schulze, R.H. and M. Horne (1982) Probability of hazardous substance spills on the St. Clair/ Detroit River system. Contract Report to the Detroit District, U.S. Army Corps of Engineers by Arctec, Inc., Contract No. DACW35-82-C-0049.

Schulze, R.H., G. Wohl and L. Wallendorf (1982) Probability of hazardous substance spills on the St. Marys River. Contract report to the Detroit District, U.S. Army Corps of Engineers by Arctec, Inc., Contract No. DACW35-81-C-0076.

Shen, H.T., P.D. Yapa and M.E. Petroski (1986) Simulation of oil slick transport in Great Lakes connecting channels, Four volumes: 1) Theory and model formulation, 2) User's manual for the river oil spill simulation model, 3) User's manual for the lake-river oil spill simulation model, and 4) User's manual for the microcomputer-based interactive program). Contract Report to the USA Cold Region Research and Engineering Laboratory by Clarkson University, Clarkson Report No. 86-1, Contract No. DACA33-85-C-0001.

Sletten, R.S. (1986) Investigation of potential water quality effects on the Detroit-St. Clair River system from operation of the Sault Locks to 31 January + 2 weeks. Contract Report to Detroit District, U.S. Army Corps of Engineers by the USA Cold Regions Research and Engineering Laboratory (Draft).

Sodhi, D.S., D.J. Calkins, and D.S. Deck (1982) Model study of Port Huron ice control structure: wind stress simulation. USA Cold Regions Research and Engineering Laboratory, CRREL Report 82-9.

Sorenson, R.M. (1973) Water waves produced by ships. *Journal of the Waterways, Harbors and Coastal Engineering Division, American Society of Civil Engineers,* **99**(WW2): 245–256.

Stortz, K.R. and M. Sydor (1980) Transports in the Duluth–Superior Harbor. *Journal of Great Lakes Research, International Association for Great Lakes Research,* **6**(3): 223–231.

Swain, W.R., R.M. Wilson, R.P. Neri and G.S. Porter (1975) Evaluation of the effects of a harbor bubbler system for winter navigation on the water quality of Howards Bay in the Duluth–Superior Harbor—Winter 1974-75. Prepared for the St. Paul District, U.S. Army Corps of Engineers by the University of Minnesota-Duluth, Contract No. DACW37-75-C-0124.

Sydor, M., B.O. Krogstad and T.O. Odlaug (1974) Evaluation of bubbler system for winter navigation, Howards Bay, Superior, Wisconsin, winter 1973–74. Prepared for the St. Paul District, U.S. Army Corps of Engineers by the University of Minnesota-Duluth, Contract No. DACW37-74-C-0060.

USACE (1969) Survey report on Great Lakes and St. Lawrence Seaway navigation season extension: Main report and final environmental impact statement. Prepared by the U.S. Army Corps of Engineers, Detroit District.

USACE (1974) Report on effects of winter navigation on erosion of shoreline and structure damage along the St. Marys River, Michigan. Prepared by the Detroit District, U.S. Army Corps of Engineers, Draft Report.

USACE (1978) Model study of the Little Rapids cut area of the St. Marys River, Michigan. Prepared by the U.S. Army Corps of Engineers, Detroit District.

USACE (1979a) Final survey study for Great Lakes and St. Lawrence Seaway navigation season extension: Main report and final environmental impact statement. Prepared by the U.S. Army Corps of Engineers, Detroit District.

USACE (1980) St. Marys River–Little Rapids cut ice boom and its effects on levels and flows in the Soo Harbor, winter of 1979-80. Prepared by the U.S. Army Corps of Engineers, Detroit District.

USACE (1982) *Ice Engineering*. U.S. Army Corps of Engineers, Office of the Chief of Engineers, Engineer Manual EM 1110-2-1612.

USACE (1988) Draft environmental impact statement: Supplement II to the final environmental impact statement—operations, maintenance, and minor improvements of the federal facilities at Sault Ste. Marie, Michigan (July 1977), operation of the lock facilities to 31 January + 2 weeks. Detroit District, U.S. Army Corps of Engineers.

USACE-SLSA (1972) Report on vessel speed and wave study, Detroit and St. Clair Rivers. U.S. Army Corps of Engineers, Detroit District and Operations Branch, St. Lawrence Seaway Authority.

USACERC (1984) *Shore Protection Manual*. U.S. Army Corps of Engineers, Coastal Engineering Research Center.

USCG (1973) Oil pollution problems associated with the extended navigation season.U.S. Coast Guard, p. 133–156.

Uzuner, M.S. (1975) Copeland cut ice boom design criteria and data analysis, winter 1974-75. Report to the St. Lawrence Seaway Development Corporation, Vol. 1 of 2.

WNB (1979) Demonstration program final report. Prepared by the Great Lakes and St. Lawrence Seaway Winter Navigation Board.

Wuebben, J.L. (1977) Ship induced vibration program, St. Marys River. USA Cold Regions Research and Engineering Laboratory, Technical Note (unpublished).

Wuebben, J.L. (1978) Vessel passage during winter ice conditions: Observations of 25 January 1978. Letter report to the Detroit District, U.S. Army Corps of Engineers, from the USA Cold Regions Research and Engineering Laboratory (unpublished).

Wuebben, J.L. (1981a) St. Marys River: Shoreline erosion and shore structure damage, 1980 closed navigation season. Contract report to the Detroit District, U.S. Army Corps of Engineers by the USA Cold Regions Research and Engineering Laboratory, Contract No. NCE-IA-80-035.

Wuebben, J.L. (1981b) Evaluation of the effect of vessel size on shoreline and shore structure damage. Prepared for the Detroit District, U.S. Army Corps of Engineers by the USA Cold Regions Research and Engineering Laboratory.

Wuebben, J.L. (1981c) St. Marys River: Shoreline erosion and shore structure damage, 1980–81 closed navigation season. Contract report to the Detroit District, U.S. Army Corps of Engineers by the USA Cold Regions Research and Engineering Laboratory, Contract No. NCE-IS-81-0027-ER.

Wuebben, J.L. (1983a) Effect of vessel size on shoreline and shore structure damage along the Great Lakes connecting channels. USA Cold Regions Research and Engineering Laboratory, Special Report 83-11.

Wuebben, J.L. (1983b) Shoreline erosion and shore structure damage on the St. Marys River, 1980 closed navigation season. USA Cold Regions Research and Engineering Laboratory, Special Report 83-15.

Wuebben, J.L., G.R. Alger and R.J. Hodek (1978a) Ice and navigation related sedimentation. *Proceedings of the Fourth International Symposium on Ice Problems sponsored by the International Association for Hydraulic Research, Luleå, Sweden, August*, p. 393–403.

Wuebben, J.L., L.W. Gatto and S.L. DenHartog (1978b) Assessment of shoreline areas potentially impacted during winter navigation. Contract report to Detroit District, U.S. Army Corps of Engineers, USA Cold Regions Research and Engineering Laboratory, Internal Report No. 590.

Wuebben, J.L., W.M. Brown and L.J. Zabilansky (1984) Analysis of the physical effects of commercial vessel passage through the Great Lakes connecting channels. Contract to the Detroit District, U.S. Army Corps of Engineers by the USA Cold Regions Research and Engineering Laboratory, Internal Report 884.

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In 1970, Congress authorized a three-part Great Lakes–St. Lawrence Seaway Navigation Season Extension Program. It authorized a winter navigation demonstration program, a detailed survey study of season extension feasibility and a study of insurance rates for shippers. This report provides a review of numerous environmental and engineering studies conducted as part of the demonstration and feasibility portions of the program, as well as many environmental studies conducted after the completion of the original program. Topics include sediment transport, shoreline erosion, shore structure damage, oil and hazardous substance spills, biological effects, ship-induced vibrations and ice control systems.

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