Chapter 7
Sediment Transport

7-1. Introduction

Ice and low temperatures play many roles in sediment transport and shoreline change. Ice formed on a shore or riverbank may isolate and thereby protect the soil. Ice formation can, however, cause significant local shoreline damage by gouging ordinarily stable beach or bank formations, removing protective vegetation, adfreezing sediment at the ice/soil interface, and entraining sediment within the ice structure. During spring breakup this nearshore ice may migrate considerable distances before melting and releasing the entrapped sediment. Even if the rate at which material is removed from a river or steep coastal bluff is small, it can be significant since this material is not easily replaced in nature. Ice jams, frazil dams, or other ice irregularities that cause a constriction of flow can increase velocities and cause scour. These same features can also deflect the flow of a river against an erodible bank or bed area.

a. Ice also affects the general hydraulics of a system. In a coastal zone, for example, ice tends to damp the effects of winds, waves, and currents during severe winter storms. The influence of the development and presence of an ice foot on nearshore bathymetry is, as yet, undefined. This nearshore bathymetry is important in the dissipation of wave energy during ice-free periods.

b. A complex interaction exists among the ice cover, fluid flow, and sediment and bed forms. The presence of an ice cover roughly doubles the wetted perimeter of a wide channel, which in turn affects the magnitude and distribution of water velocities and the boundary and internal shear stresses. In addition, the lower water temperatures associated with the presence of ice affect fluid properties, such as viscosity, which in turn alter the fall velocities of sediments. As an added element of complexity, the boundary roughness is not constant, since the roughness of both the sediment bed and ice cover may vary with composition, form, and time.

7-2. Sediment Transport Under Ice

Sediment discharge in ice-covered streams has not been widely studied to date. The techniques of measuring sediment discharge for periods of ice cover are quite different from those used during open-water conditions. People and equipment have problems functioning during severe winter conditions. The relatively unknown nature of the interaction of ice with sediment transport and the variability of ice conditions that affect this interaction also present a problem. While there have been some studies to evaluate the resistance to flow for ice-covered streams, there has been little documentation of sediment transport or bed forms for ice-covered streams. Because of the uncertain accuracy of winter measurements, even the limited amount of field data available is subject to question.

a. The effects of temperature on sediment transport have received fairly extensive study but are not yet fully understood. The primary effect of temperature is to change the viscosity of the water (the kinematic viscosity of water more than doubles when the temperature drops from 80°F [27°C] to near freezing). The decrease in sediment particle fall velocity attributable to this increase in water viscosity should increase suspended sediment discharge.

b. In general it might be expected that the added resistance to flow caused by an ice cover would reduce flow velocities and thereby increase water depth. Because of the reduction in flow velocity, bed shear stress and sediment discharge would also be reduced. However, when an ice jam or a hanging dam is present, flow may be impinged and the bed may be scoured.

c. Changes in water velocity may also affect bed shear and alluvial bed form. If the bed form is altered, the bed roughness and flow velocity may change substantially. Depending on a number of initial conditions, such as bed form, sediment characteristics, and flow regime, a decrease in water temperature could increase, decrease, or have very little effect on sediment transport. Although the effects of water temperature on sediment transport have been under study for some time, the resulting information is contradictory and confusing.

d. The effect of an ice cover on sediment transport and alluvial bed form has received almost no study. From related work on sediment transport in closed conduits, it appears that the presence of a surface boundary has a strong effect on the water velocity profile and on the distribution of pressure and shear stress.

e. The hydraulic roughness of ice covers has been studied by numerous researchers in the past, but because of the variability of ice conditions, a wide range of roughness values has resulted. Values of Manning's *n* have ranged from 0.008 to 0.10, corresponding to smooth sheet ice ranging up to thick ice jams. As with alluvial bed roughness, the ice roughness may vary with location on a river and with time. In addition to the shear resistance of a smooth ice cover, ripples (somewhat similar to those on an alluvial bed) may form, and there may be additional roughness from frazil deposits or other ice irregularities.

f. In summary, while it is clear that, for otherwise constant conditions, the addition of an ice cover should reduce flow velocity and sediment transport, the magnitude of this change is unknown. In addition there are the unknown influences of the ice cover on a shift in alluvial bed form and of the interaction of ice cover effects with water temperature effects. The limited amount of work on this is inconclusive and often contradictory. Further research is needed to allow accurate measurement or analysis of sediment transport, erosion, and deposition with ice present, as well as analysis of the combined influence of an ice cover, water temperature, and an alluvial riverbed on river flow depths and velocities.

7-3. Effects of Winter Navigation

Winter navigation may aggravate any natural effects of ice by disrupting the natural ice cover. Similarly, an ice cover may alter and even amplify the effects of navigation on system hydraulics and sediment transport. Specific sites have been studied to gain an understanding of the mechanics of the interaction between large-scale navigation and the hydraulics of a river system. This mechanistic approach is required, since vessel-related effects consist of short periods of intense and rapid activity between long periods of relatively mild conditions. In addition, until recently, few ships have operated through the entire winter in the areas studied.

a. In navigable waterways, there are several ways in which vessel passage can affect sediment transport and shoreline erosion, including direct movement of ice in contact with vessels, propeller wash, wave action, and other hydraulic effects. The significance of these effects depends on a number of local conditions, and the presence of other transport agents, such as natural currents or waves.

(1) Shore damage by lateral ice movement caused by vessel passage is ordinarily small, being limited to early or unstable ice conditions and shore areas close to the navigation track. The resulting damage, while possibly significant, is unpredictable, infrequent, and difficult to quantify. A long section of shoreline may or may not be affected in any one year. As a result, structural shore protection would be difficult to apply and most likely be uneconomical. The regulation of vessel speeds in affected areas during periods with certain ice conditions may provide the best method of preventing damage.

(2) Propeller wash, while sometimes significant, is generally unaffected by the presence of ice. It is also localized and distant from the shore, and so will not be considered here.

(3) Wave action is normally associated with ship-induced shoreline erosion. When a ship is in motion, a system of diverging and transverse waves develops. Diverging waves form the familiar V-shaped wave pattern associated with ship passage, while transverse waves form a less noticeable wave train that follows a vessel and is oriented normal to the sailing line. The waves produced by large-scale navigation are generally much smaller and less damaging than those produced by recreational craft, particularly when vessel speed and distance to shore are considered.

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

b. 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 (vessel squat). For the same ship, this effect increases as vessel speed increases or as water depth decreases. When a ship enters restricted water areas, 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 that increases vessel squat. In a channel that is restricted laterally, this effect is further exaggerated. A vessel in a laterally restricted channel may encounter a condition that tends to push the bow away from one side of the channel and draw the stern toward it. These effects can occur independently when a channel is restricted either laterally or vertically and unrestricted in the other direction.

c. There is, however, another problem associated with the water level drop caused by the presence and movement of a ship in restricted waters. This water level drop in the vicinity of the ship is in effect a trough that extends from the ship to the shore and that moves along the river or channel at the same velocity as the ship. As the ship's speed increases, the moving trough deepens. One can understand the phenomenon of nearshore drawdown and surge during vessel passage in terms of the moving trough. In sufficiently deep water, the moving trough appears as a fluctuation in the elevation of the water surface (the transverse wave). To an observer in a shallow or nearshore area where the depressed water level approaches or reaches the riverbed, it appears that the water recedes from the shoreline as the ship passes, then rushes in to an above-normal level, and finally returns to the normal level after the vessel-induced surface waves are damped.

d. For sediment transport to take place, near-bottom water velocities must exist that are sufficient to overcome a sediment particle's resistance to motion. These water velocities may be caused by ambient river conditions, wind-driven waves, general turbulence, or ship-induced effects and might be enhanced by channel configuration or ice irregularities. During vessel passage, large and rapid changes in river velocity and direction can occur.

e. To analyze the mechanics of sediment transport during vessel passage, two-dimensional near-bottom velocity measurements were made. An example of these measurements is presented in Figure 7-1 for a passage of the *Cason J. Callaway* at Six Mile Point on the St. Marys River. As shown in Figure 7-1, the point of observation was approximately 152 meters (500 feet) offshore in 3 meters

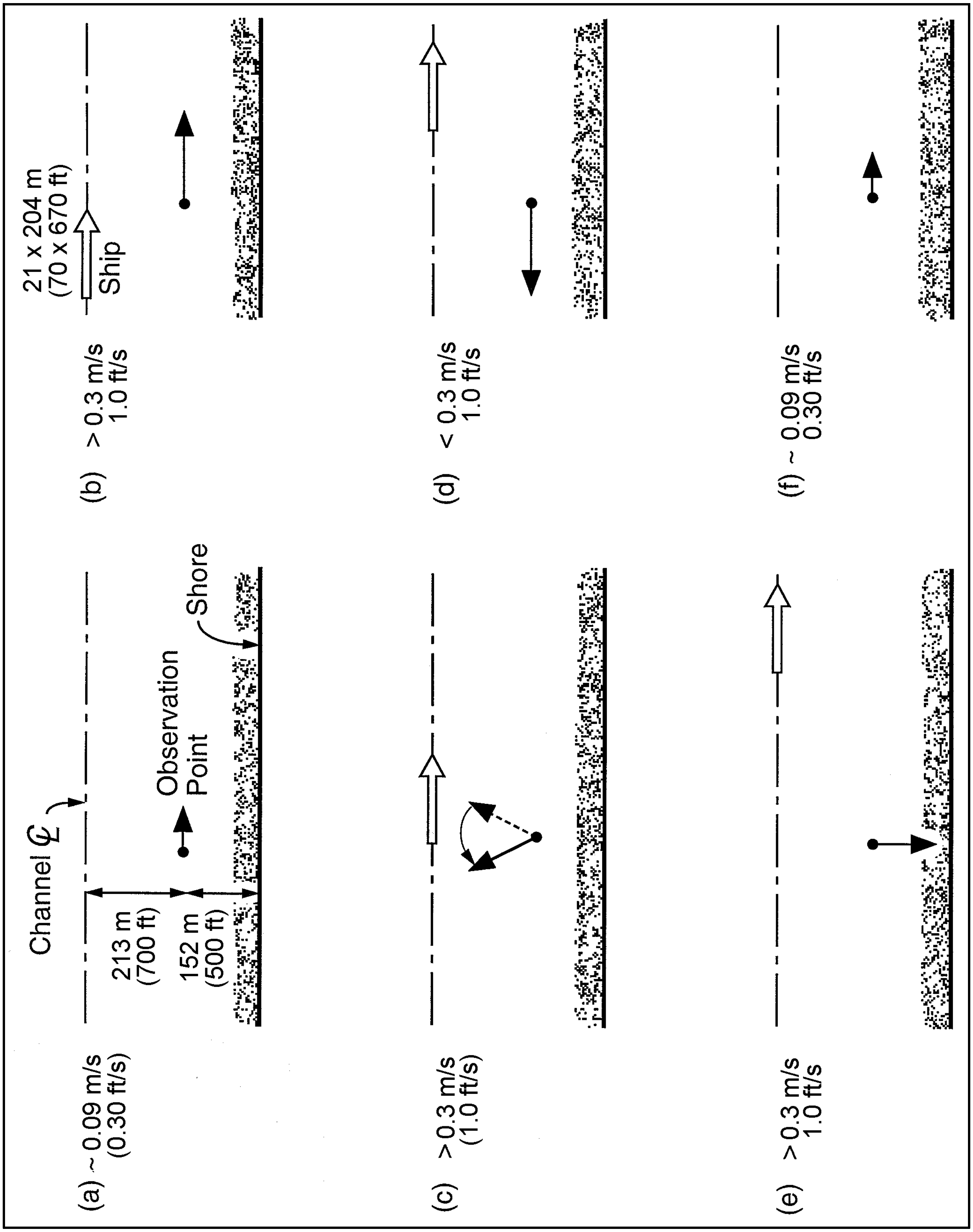

Figure 7-1. Ship-induced water movements

(10 feet) of water, while the navigation track was another 213 meters (700 feet) offshore. The ambient downstream water velocity was approximately 0.1 m/s (0.3 ft/s). The direction of the near-bottom water movement rotated 360 degrees during the passage of the *Callaway,* with velocities in all directions significantly greater than the ambient downstream current.

f. Water level measurements and directional water velocity measurements have been made at a number of locations under various conditions during the passage of ships. A set of water level and velocity measurements is shown in Figure 7-2 that illustrates the trough effect near the shoreline (in this instance, the river level temporarily fell below the base of the staff gage) and the complex velocity pattern that developed at an offshore point because of vessel passage. Velocity direction is indicated as an arrow at any particular point, with the magnitude of the velocity and time as the axes. The velocity meter was located approximately 40 meters (130 feet) from the shore in 0.9 meters (3 feet) of water. The velocities shown were measured within 20 centimeters (8 inches) of the bottom. The water level gage was located near the shore in about 20 centimeters (8 inches) of water. The ship that caused the situation illustrated in Figure 7-2 was the *J. Burton Ayers*, moving upriver near Nine Mile Point on the St. Marys River under ice-free conditions. The *Ayers* is 189 meters (620 feet) long, and has an 18-meter (60-foot) beam, with a midship draft of 7 meters (23 feet). The vessel was traveling at 17 km/hr (10.6 mph) and passed approximately 244 meters (800 feet) from the shore.

g. Figure 7-3 shows ice level changes at three offshore locations near Six Mile Point on the St. Marys River. The ice was approximately 38 centimeters (15 inches) thick. The ship passing the section was the *Seaway Queen,* moving upriver at 13.8 km/hr (8.6 mph). The ship is 219 meters (720 feet) long, with a beam of 22 meters (72 feet) and a midship draft of 5.2 meters (17 feet), and passed (305 meters) 1000 feet offshore. The typical river cross section at this location is shown in Figure 7-4. The two lower curves shown in Figure 7-3 illustrate ice level changes at two different locations on a line approximately normal to the direction of ship movement in different depths of water (labeled E_1 and E_2). The top curve (labeled H_1) shows the ice level change at a point 46 meters (150 feet) upstream on a line parallel to the line containing points E_1 and E_2. The time at which the bow and stern crossed the perpendicular range line (E or H) is indicated on each curve by dashed lines. The figure illustrates the trough effect in different depths of water at differing distances from shore, as well as the movement of the trough with the ship's passage. Note that the time displacement between E_1 and H_1 corresponds to the distance between the two range lines divided by the ship's speed.

h. Figure 7-5 shows ice elevation changes and the associated velocity pattern near the bottom as the *Edward L. Ryerson* passed down river. The ice was 28 centimeters (11 inches) thick. The range line used (E) is the same as that described in Figure 7-3. The ice level and velocity pattern are measured at a location about 91 meters (300 feet) from the shore, where the river depth is about 1.8 meters (6 feet). The ship is 222 meters (730 feet) long, has a beam of 22.8 meters (75 feet) and a draft of approximately 7.9 meters (26 feet), and was traveling at 11 km/hr (7 mph) about 305 meters (1000 feet) offshore. Figure 7-5 illustrates the ice level response to the moving trough and associated velocity pattern for a downbound vessel. Ice level fluctuations as large as 0.8 meters (2.6 feet) have been observed.

i. Three modes of transport of granular bottom sediments have been observed during both ice-covered and ice-free conditions. They are bed load, which is typified by a pattern of slowly migrating sand ripples on the riverbed; saltation load, where individual sand grains move in a series of small arcs beginning and ending at the riverbed; and a process called explosive liquefaction.

(1) Saltation transport has often been observed during the passage of large vessels. This can be explained by the ship-induced velocity increases, examples of which are shown in Figures 7-2 and 7-5.

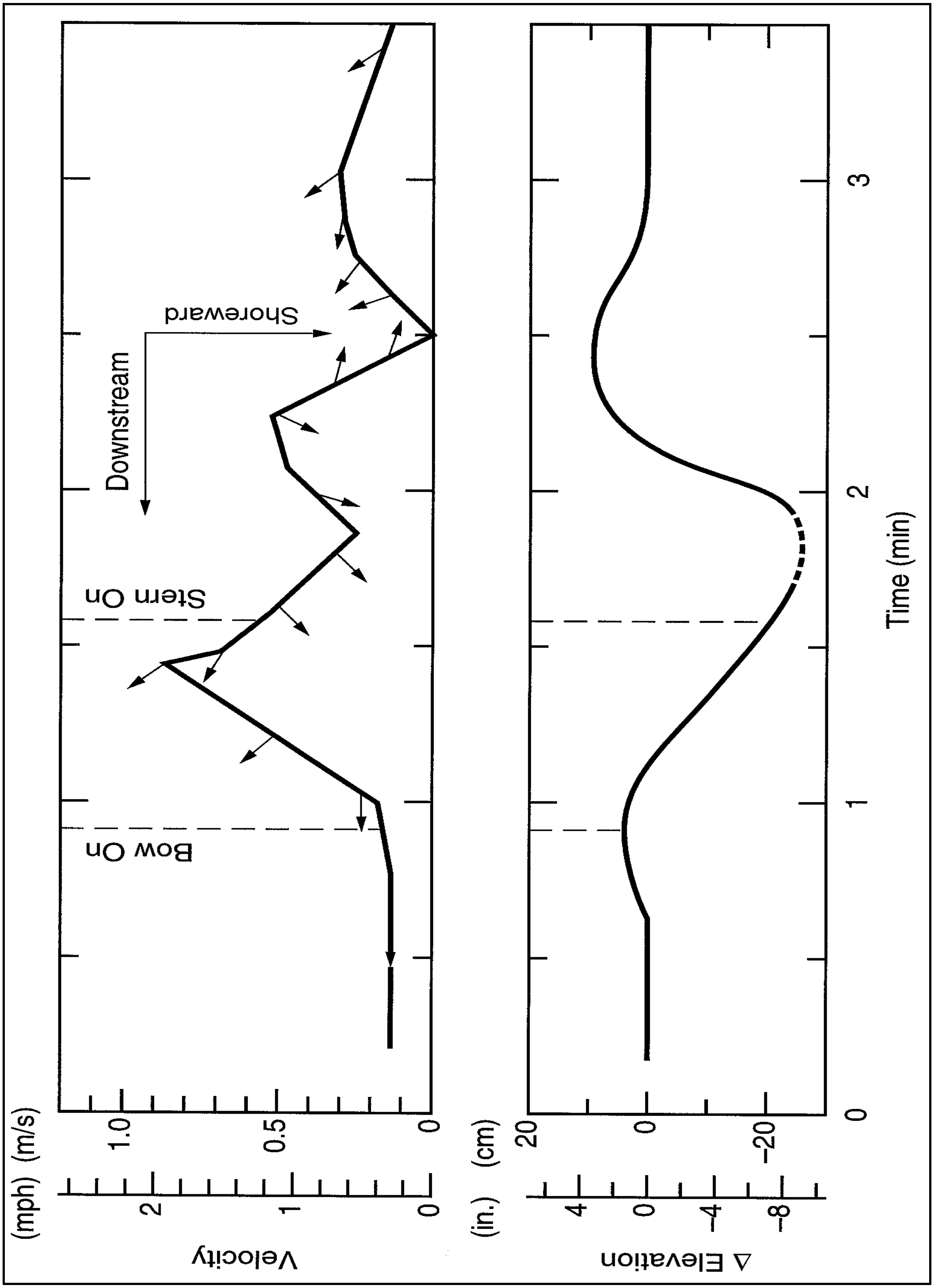

Figure 7-2. River level and near-bottom velocity pattern with upbound ship

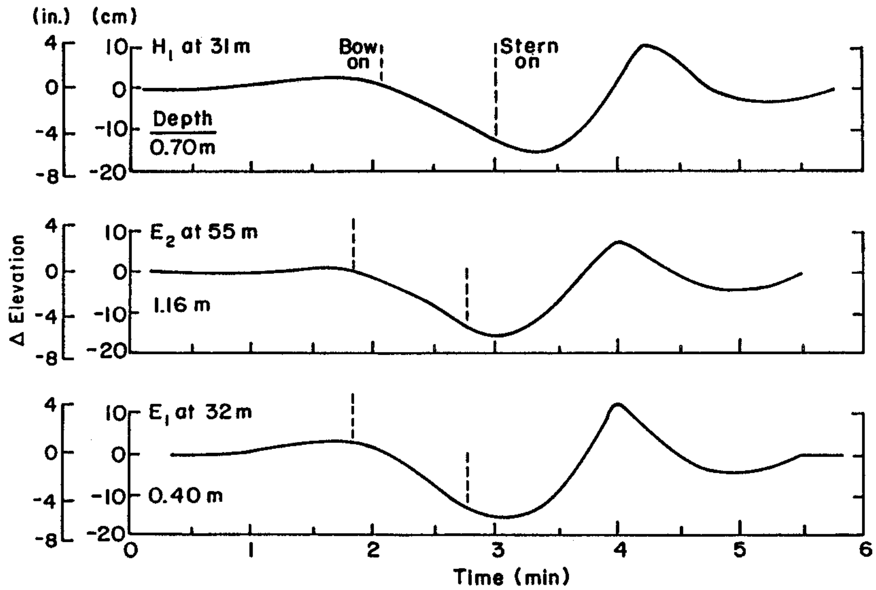

Figure 7-3. Ice level changes with upbound ship

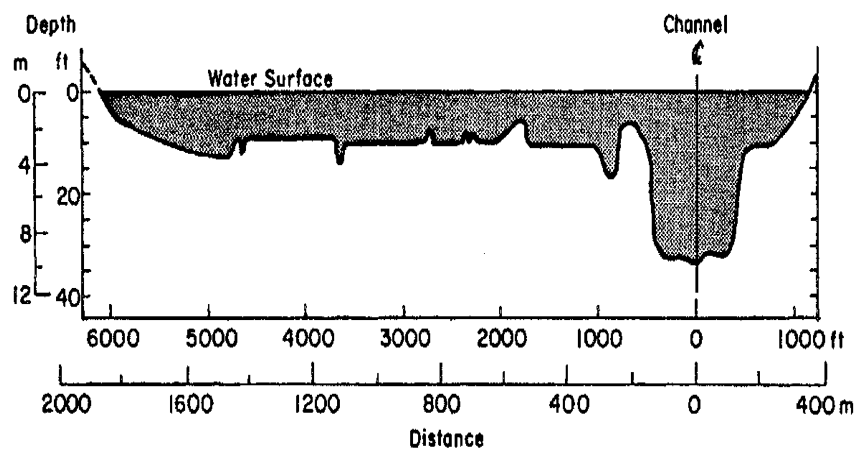

Figure 7-4. Cross section of the St. Marys River near Six Mile Point

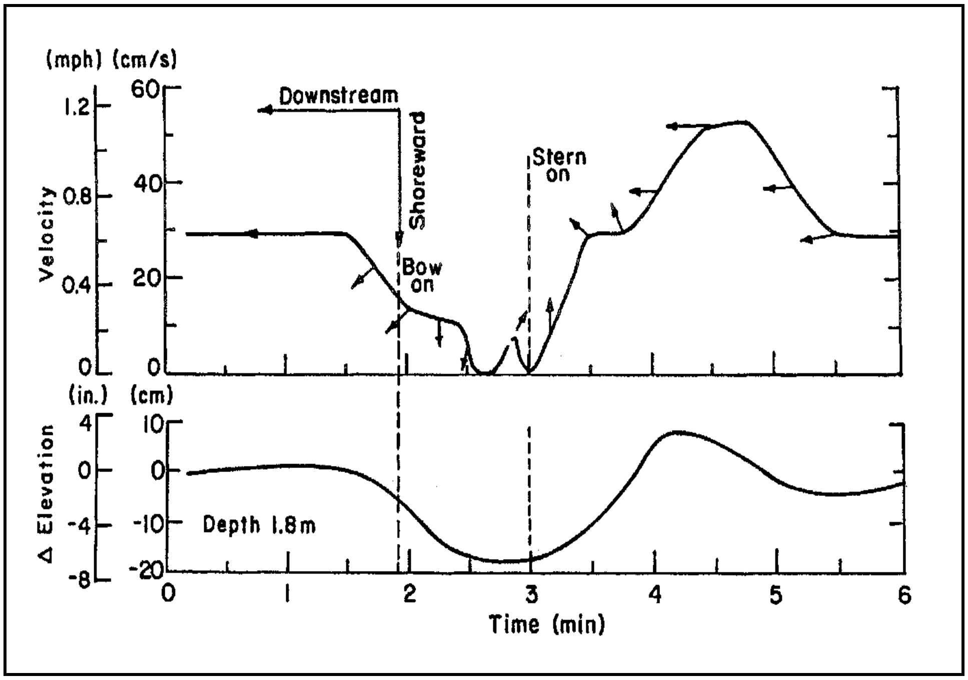

Figure 7-5. River level and near-bottom velocity pattern with downbound ship

(2) On several occasions, explosive liquefaction has occurred during the passage of large, deeply loaded vessels at speeds higher than normal. Divers have observed explosive liquefaction while working in the surf zones of lakes and oceans. It may also be observed from shore as waves break. In the presence of a reasonably horizontal velocity field, the action occurs in two steps. The bed expands upward, immediately followed by a dispersion into suspension mass in the water current. In the absence of a current, the bed simply quakes or expands and individual particles move upward. Bed equilibrium is rapidly reestablished by gravity forces.

j. Since the drawdown and surge mechanism usually sets up water velocities in opposite directions, their effects have a tendency to cancel. However, natural currents or a sloped bottom can act in conjunction with vessel effects to cause a net sediment transport downstream or offshore toward the navigation channel.

k. During winter ice conditions, the passage of the moving trough can cause the grounding of an ice cover in shallow water and nearshore areas, and nearshore cracks in the ice may develop running roughly parallel to the water depth contours. With recurring moderate water level fluctuations, these hinge cracks do not completely refreeze and can provide an ice-movement relief mechanism. Continuing vertical and horizontal movement of the ice cover may cause the accumulation of ice debris (which resembles pressure ridges) at these active cracks. Depending upon the characteristics of crack formation, ice dams extending to the riverbed may develop at the cracks (Figure 7-6).

l. The mechanism described above may have effects beyond shoreline erosion. Large areas of grounded ice that result from the packing of brash ice under the ice cover or increased frazil production because of increased open-water areas may have an impact on benthic environments and may transmit ship-induced vibrations to the shore and shore structures. The reported effects of these vibrations range from aesthetically disturbing to structurally damaging. In wetlands or shoaling areas, damage may occur

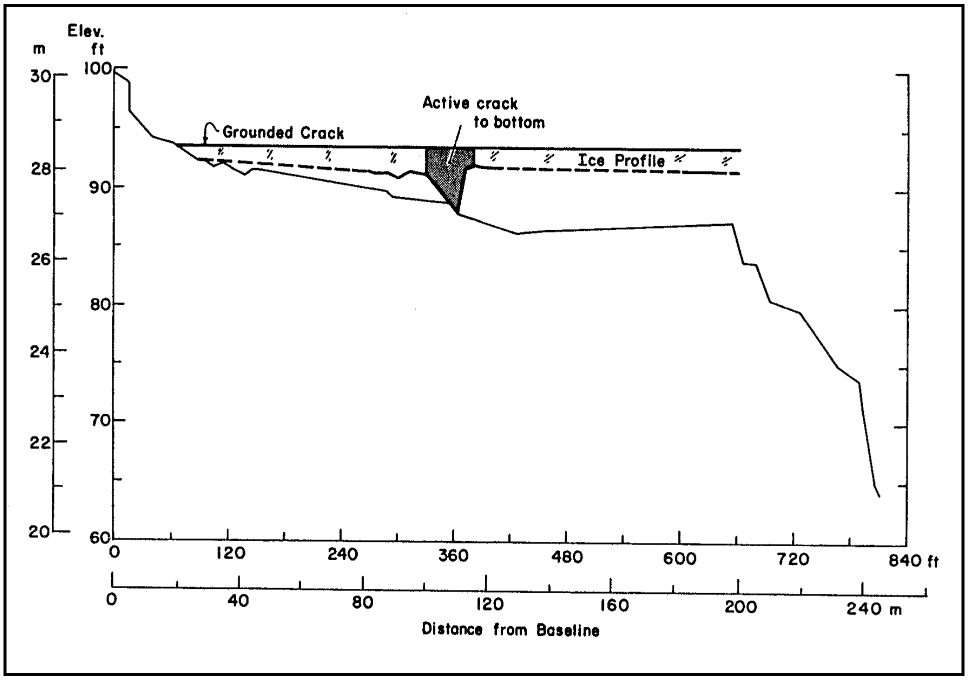

Figure 7-6. Active crack profile

even though erosion is negligible. In shallow water, ship-induced velocity and water level changes could be large, possibly disrupting vegetation by water and ice movement. An ice cover might even ground and directly strike the bed during vessel passage. Rapid water pressure changes might also be significant.

m. When a large enough ship-induced moving trough passes through a shallow water area, the movement of bottom sediment may disrupt benthic environments, and the translatory movement of the water has been observed to cause water, sediment, vegetation, and even small fish to be sprayed up through the cracks and onto the ice. During a specific vessel passage, about a dozen fish of various species, ranging in length up to about 15 centimeters (6 inches), were washed through a nearshore crack and onto the ice. It is possible that other smaller organisms went unnoticed.

n. Disruption of an ice cover may also have some as yet undefined effect on ice movement and damage caused by natural ice forces. In the case of relatively ice-free rivers, such as the Detroit or the St. Clair, the disruption of an ice cover on the lakes upstream may allow large quantities of ice to enter the rivers. This can cause bottom scour and ice pile-up at bends and the upstream ends of islands. The large forces that may result from such ice runs can also pose a special threat to shore protection structures.

o. In most coastal areas, natural shoreline modification forces, such as waves and currents, are far more significant than any vessel-related effects, and generally the shipping lanes do not come near enough to the shore for vessels to have a noticeable effect. In some protected areas this may not be true. After disruption of a natural ice cover, ice movement problems could be particularly important in coastal areas where significant wind exists to push the ice.

7-4. References

a. Required publications.
None.

b. Related publications.

Wuebben 1995
Wuebben, J.L., ed. 1995. *Winter Navigation on the Great Lakes: A Review of Environmental Studies*, CRREL Report 95-10, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.