Technical Report HL-96-10
August 1996

US Army Corps of Engineers
Waterways Experiment Station

Upper Mississippi River System Navigation/Sedimentation Study

Report 1
Bank Erosion Literature Study

by Stephen T. Maynord, Sandra K. Martin

Approved For Public Release; Distribution Is Unlimited

Prepared for U.S. Army Engineer Districts, Rock Island, St. Louis, and St. Paul

Contents

1 Introduction

Historical Perspective

Many of the geomorphic and ecological changes in the Upper Mississippi River System (UMRS) parallel the history of navigation developments. The UMRS includes the main stem Mississippi River above Cairo, IL, and the Illinois River (Figure 1). The navigability of the river has attracted settlers and development since the 1700's. By the late 1800's the U.S. Army Corps of Engineers had conducted sufficient channel improvement measures to encourage the regular navigation of the system by steamboats. Coupled with these activities, agricultural practices and lumbering activities (which peaked in the late 1800's) greatly affected the watershed erosion. According to Fremling and Claflin (1993) these activities can be "shown to have serious detrimental effects on the river system 100-yr later." Man's influences on the ecology of the river were observed as early as 1870 when fisheries resources rapidly declined (Fremling and Claflin 1993).

The Rivers and Harbors Acts of 1878 funded and authorized the Corps to maintain a 1.4-m (4.5-ft) channel, and in 1907 this authorization increased to 1.8 m (6 ft). This was accomplished by channel improvements including wing dams, dredging, channel alignment, closure of side channels and backwaters, and channel revetments. Many of these features are still evident today. During the depression of the 1930's the 2.7-m (9-ft) channel was authorized, and thus the lock and dam system was born. By 1940 the Upper Mississippi had 26 locks in place while the Illinois River had 7 locks.

While the actual ecological benefits or disadvantages from this navigation system, particularly the impoundments, are widely debated (and not the subject of this report), it is important to discuss at least some features of the system considered by some resource agencies to have detrimental effects on the ecology of the river. The first regards the operation of the system to maintain water levels as constant as possible to facilitate navigation, particularly during low-flow periods. This change in the regime could reduce the potential for bank erosion in areas where the energy potential has been lowered (for instance in the pools). On the other hand, the removal of the stage change during low to moderate discharge periods not only changes the river's hydraulic regime,

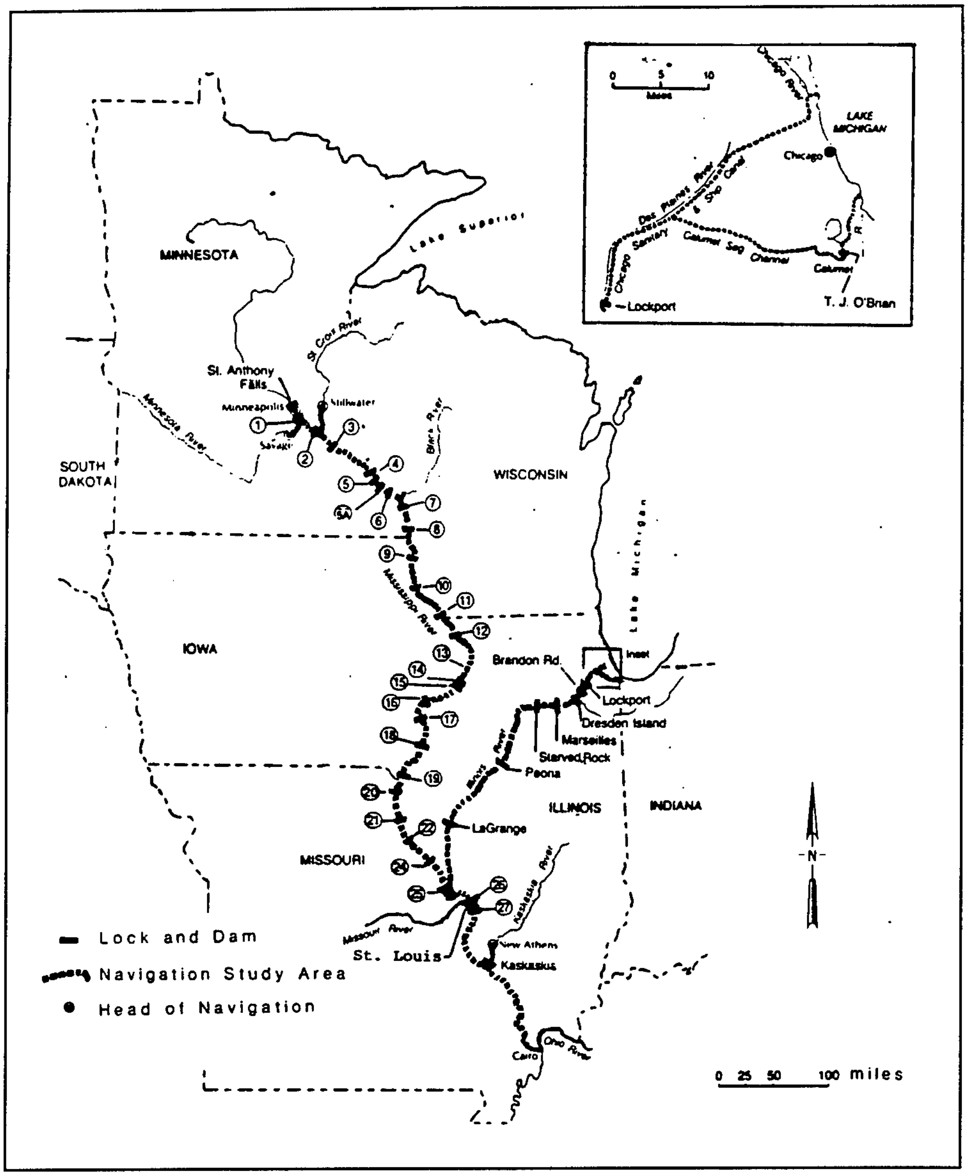

Figure 1. Location map of the UMRS

but also changes the ecological health of the system by reducing organic and nutrient cycling, reducing rate of oxidation in sediments, increasing rates of eutrophication, and permanently inundating areas that ultimately evolve through sedimentation to terrestrial habitats (Lubinski 1993; Fremling and Claflin 1993).

Even though the hydraulic energy may be lower during some hydrologic events, the actual length of shoreline exposed to periodic wetting and drying has increased as a result of permanent inundation of areas in the floodplain. From a habitat standpoint, an increase in shoreline is generally positive. However, a potential impact of this inundation could be the exposure of cultural (archeological or historical) resource sites to frequent hydraulic forces such as wind waves that had previously had only infrequent exposure to flooding.

Another attribute of the impounded system is the accumulation of sediments in ecologically sensitive aquatic areas. The original impoundment by itself would account for the greatest portion of the accretions due to the lower velocities and higher trap efficiencies of the dams. **Continued** accumulation of sediments in certain areas of the system would imply that materials must be generated from one of two basic sources: either they are introduced in the system through tributaries and upland erosion (sources outside the floodplain), or they are generated from bed sediments and bank materials (sources within the floodplain). Therefore, identification of bank erosion processes and their probable contribution to the system as a source of sediments are important to quantify.

Increasing levels of traffic and predictions of further increases have caused evaluation of upgrades to the existing system through repair, rehabilitation, or replacement of certain features. Studies considering lock rehabilitation or replacement alternatives require accurate projection of the size and power of future tows and traffic, and give careful consideration to the environment from both a local and system level (Armstrong et al. 1985) The Melvin Price replacement lock and dam was the first project completed on this system. The new lock and dam structure upgraded the existing lock capacity at Lock and Dam 26 from 182.9- and 109.7-m (600- and 360-ft) chambers to 365.8- and 182.9-m (1,200- and 600-ft) chambers. Use of the UMRS by recreational vessels has also increased significantly. The impacts of existing and projected levels of commercial and recreational traffic on bank erosion in the UMRS are important to determine.

Impacts of Bank Erosion

Bank erosion leads to the loss of cropland, forest, pasture, residential and municipal areas, wetlands, and riparian zones. The land that is lost may be replaced by land that will have value as habitat for a variety of organisms but may not be suitable for the aforementioned human uses for some time. Suspended sediment from bank erosion and other sources can increase water treatment costs and adversely affect the operating life of machinery, shellfish quality, recreational use, and aesthetic qualities (U.S. Army Corps of Engineers (USACE) 1981a, 1981b). Dredging is often necessary to remove accumulated sediment to maintain adequate harbor and waterway depths. Deposited sediment reduces fish habitat and depletes reservoir storage. Chemical compounds residing in banks may adversely affect water quality once entrained by bank erosion. Bank erosion undermines trees and brush, which can clog channels and adversely affect navigation, hydropower, and other hydraulic structures in the river environment. Boszhardt and Overstreet (1981) report on a workshop whose participants concluded that of the various navigational factors impacting on the cultural resources on the UMRS, bank erosion was the most serious. Sing (1986) used a sediment budget on the Sacramento River and determined that "bank eroded material contributes 60 percent, or 7.5 million tons per year, of the total sediment inflow of 12.7 million tons per year into the river system. Much of this eroded material is carried down through the river system and deposits into the flood control bypasses and downstream navigation channels."

The positive side of bank erosion lies in a natural system being able to meander freely across its floodplain through the processes of bank erosion and deposition. Meandering produces new habitats, marshes, and backwaters. If bank erosion is halted, no new marshes, habitats, or backwaters are created. On the UMRS, the channelization and dam construction of the 1900's-1930's has significantly reduced the rate of production of new habitats and the old marshes, habitats, and backwaters are being lost to sedimentation.

UMRS Bank Erosion Scope of Work

As a part of the environmental effort of the Upper Mississippi-Illinois Waterway Navigation Feasibility Study, the scope of a bank erosion study was described in the Initial Project Management Plan. It was determined that changes in the shoreline as a result of bank erosion could impact the riparian habitat of fish and wildlife and cultural resources along the shoreline. It is also important to understand these processes as they relate to the potential loss of land and its effect on property ownership, structural integrity, etc. Therefore, the study proposes an investigation into the extent of existing bank erosion, the probable processes that cause bank erosion, and the potential for further bank erosion, particularly as related to navigation traffic.

Basically six tasks were identified for this effort with a decision point after Task 3. Task 1, to which this report is devoted, was to conduct a literature search with the goal of identifying applicable and available references for use in decision making in the other tasks. Task 2 would conduct a systemwide inspection of the UMRS with a multidisciplinary team not only to quantify the present amount of bank erosion, but also to attempt to discern the probable cause of the erosion. Based on the pertinent literature and the field inspections, Task 3 involves qualitatively assessing the relative significance of commercial navigation on existing bank erosion. At this point, if navigation effects on bank erosion cannot be discerned from other causes, or navigation effects are not considered significant, the bank erosion study would terminate. Otherwise, Tasks 4 and 5 would require some type of "modeling" effort to establish with- and without-project future conditions; and Task 6 would be a final report.

Objective of This Study

The U.S. Army Engineer Waterways Experiment Station (WES) was asked to participate in Task 1, the literature search. The scope of work is as follows: "Obtain available pertinent data, research, and opinions regarding the process of bank erosion along the Upper Mississippi River and Illinois Waterway. Since erosion is a function of flow velocity, flow quantity, secondary currents, bank materials and covers, as well as wave energy from wind and navigation, all of these factors will be included in the literature search. Differentiation will be made between recreational and commercial navigation impacts. Reference material will be obtained with the goal of establishing the relative significance of each factor in the process of bank erosion."

Chapter 2 describes of all pertinent erosion mechanisms and causes expected to occur on the UMRS other than those related to navigation. No attempt was made to obtain every reference on the non-navigation processes, but every reference pertaining to non-navigation processes on the UMRS was documented. In Chapter 3, references pertinent to the extent of existing erosion on the UMRS were summarized. Chapter 4 includes a summary of each reference relevant to navigation processes. Of particular emphasis were studies on similar large alluvial rivers having navigation. Chapter 5 presents available bank erosion models which are also needed by the Recreational Boating Study, which is part of the UMRS Feasibility Study environmental plan. Chapter 6 identifies the dominant mechanisms and causes on the UMRS.

This report addresses bank erosion on only the main stem Illinois and Upper Mississippi Rivers.

2 Bank Erosion Mechanisms and Causes

Bank erosion is defined as loss of bank material from both fluvial processes in the channel as well as internal failure processes that occur within the bank. Lawson (1985) makes a useful distinction between erosion and recession. Erosion is a mass concept involving removal of a certain volume of material. Recession (or retreat in other references) is a geometric concept that involves the landward displacement of the waterline.

In this investigation, bank erosion mechanisms are different from bank erosion causes. Mechanisms are the processes by which bank material is lost. Bank erosion causes are the immediate action or event that led to the occurrence of the bank erosion mechanism. For example, the mechanism of piping loss of bank material could be caused by poor overbank drainage, overbank ponds or lakes, or water level variation due to flood flows. The mechanism of tractive force loss of bank material can be caused by a variety of events such as floods, propeller jets, flow concentration caused by failed vegetation, or breakup of an ice jam.

In USACE (1981a, 1981b) and Allen and Tingle (1993), erosion is classified as either natural or accelerated. Natural erosion occurs as a result of time-dependent climatic or geologic factors. Stream meandering and piping erosion resulting from recharge of the bank by flood flows are examples of natural erosion. Accelerated erosion occurs as a result of human actions or possibly atypical natural occurrences. Erosion resulting from increased discharge after urbanization of a watershed and piping erosion resulting from recharge of the bank by septic tanks or man-made overbank ponds are examples of accelerated erosion. The distinction can be quite important because landowners have filed claims against other parties alleging causation of accelerated erosion (U.S. Army Engineer Division, Ohio River, 1977).

The UMRS has been significantly altered by man, and any evaluation of bank erosion causes and mechanisms must consider the impact of these changes. At low flow, the UMRS is a series of impoundments separated by river reaches. The UMRS impoundments differ from typical reservoirs because the UMRS impoundments are shallow, limiting wave heights and reducing their ability to trap sediments. As flows increase, most of the navigation dams have less and less effect on the flow profiles and the system begins to look like a river over most of its length. Therefore, this chapter addresses both bank erosion causes and mechanisms in river environments as well as in impoundments. Simons and Li (1982) categorized erosion forces as

a. Those which have their major impact at the water surface.

b. Those which act with greatest intensity near the base of the submerged bank.

Impoundments generally follow the first category whereas river environments generally have both categories.

Lawler (1992) discussed the possibility that bank erosion is a supply-limited rather than a transport-limited process. Walling and Webb (1981) discussed a suspended sediment exhaustion effect. They presented a suspended sediment and streamflow hydrograph showing a double peak storm runoff with a corresponding single peak in sediment concentration. One possibility to be drawn from this is that previous floods not only decrease bank strength by factors such as saturation, but also increase the sediment scouring potential of subsequent floods by depleting the available supply of sediment.

Bank Soil Type and Stratigraphy

As reported in Hagerty, Sharifounnasab, and Spoor (1983), "The severity of erosional loss appeared to depend principally on the bank materials; sandy banks retreated farthest in the study." Banks that are predominantly cohesive can often resist surface erosion from intense attack by waves or currents. However, they can easily be failed by internal mechanisms (discussed in the following section) related to the layering of the bank soils. Layered streambanks are common in alluvial channels like the UMRS.

Geologic and Geomorphic Considerations

Schumm and Thorne (1989) stated that "[the Mississippi River drains] from areas that were subjected to continental glaciation and the valley alluvium will contain glacial outwash sediments that can be very different from the modern alluvium. The fine sands, silts, and clays deposited by the modern Mississippi River overlies [sic] coarse sand and gravel. The less cohesive older alluvium is more readily eroded, where exposed in bed and banks. However the older alluvium contains cobbles and boulders that can armor the channel thereby preventing the bed scour which is associated with bank erosion....[The] geologic history can have a significant effect on modern bank erosion." Nielsen, Rada, and Smart (1984) provided a geomorphic description of the UMRS basin and observed that "it has become apparent that many of the sedimentation problems of the Mississippi River are linked to the inability of the River to effectively remove all the sediment supplied by its tributaries. The main channel has adapted to an oversupply of sediment by becoming wider and more shallow." Overloading of coarse-grained sediments from tributaries is the cause of the island braided pattern of the UMRS. Nielsen, Rada, and Smart (1984) referenced Lane (1957), who suggested that the Mississippi River has not yet reached grade and is still responding to postglacial conditions, thus causing the overloading. According to Lubinski (1993), while the UMRS was aggrading during presettlement times, "land use changes, stream channelization designed to transport water rapidly off the basin, and the construction of dams have greatly accelerated the aggradation rate. The Illinois River has been impacted more by sedimentation than the Mississippi River because of its shallower gradient." A detailed description of the geologic history of the UMRS is provided in Fremling, Gray, and Nielsen (1973) and Church (1984).

Lubinski (1993) described a classification of the UMRS that may be useful in explaining or understanding the relative occurrence of bank erosion. On the UMRS three reaches are described as follows:

a. From Minneapolis, MN, to Clinton, IA, encompassing Pools 1-13. This reach is characterized by large areas of off-channel water, large acreages of aquatic vegetation, and few agricultural levees.

b. From Clinton, IA, to Missouri River encompassing Pools 14-26. This reach is characterized by a high proportion of water in channels, limited aquatic vegetation, and a moderate amount of land in agricultural levees.

c. From the Missouri River to Ohio River, an open river reach. This reach is characterized by a high proportion of water in channels, almost no aquatic vegetation, and extensive levees.

Lubinski divides the Illinois River into the following two reaches:

a. The confluence of Kankakee and Des Plaines Rivers to Hennepin, IL. It passes through a young geologic valley and has a relatively high gradient, narrow floodplain, and three navigation dams.

b. From Hennepin, IL, to Mississippi River. It is geologically older and wider than the upper reach. It was used by the Mississippi River before recent glacial activity redirected the Mississippi westward. It has a very shallow gradient, extensive levees, and two navigation dams.

Bank Erosion Mechanisms

Bank erosion mechanisms were classified in USACE (1981a, 1981b) as follows:

a. Mechanisms that cause displacement of soil particles from the bank surface.

b. Mechanisms that destabilize the internal structure of the bank and fail blocks or entire segments of the bank.

c. Mechanisms that transport the displaced soil particles or failed soil blocks away from the bank. Unless the stream is capable of removing the displaced soil particles or the failed soil blocks, the bank will tend toward a stable or aggrading condition. This concept is called basal end point control and is presented in Thorne, Reed, and Doornkamp[1] and discussed subsequently.

Tables 1, 2, and 3 describe individual mechanisms under these three categories based on USACE (1981a, 1981b).

An alternate classification system presented by Thorne, Reed, and Doornkamp[1] is as follows:

a. Erosion processes, which detach, entrain, and transport individual particles or assemblages of particles away from the bank. This category includes fluvial entrainment, waves, surface erosion, piping, and freeze/thaw.

b. Failure mechanisms, which lead to collapse of all or part of a bank. This category includes soil fall, shallow slide, rotational slip, slab type failure, cantilever failure, dry granular flow, and liquefaction.

c. Weakening processes, which operate on and within the bank to increase its erodibility and to reduce its geotechnical stability. This category includes leaching, trampling, destruction of vegetation, mechanical damage, positive pore-water pressures, and desiccation.

Reid (1993) categorizes factors controlling bank recession as either activating or passive. Activating factors are those that trigger erosion such as waves, runoff, groundwater discharge, and freeze-thaw, etc. Passive factors are properties of the bank material or bank geometry that cause the bank to be relatively susceptible to activating factors. Passive factors exist all or most of the time

---

[1] Colin R. Thorne, Sue Reed, and John C. Doornkamp. (1993). "Bank erosion on navigable waterways," Draft R&D Report 336/1/T, National Rivers Authority, Almondsbury, Bristol.

Table 1
Soil Particle Displacement Mechanisms

Mechanism	Description
Abrasion by ice and debris	Ice and debris carried by flowing water dislodge surface soil particles.
Biological	Bank surface destruction by animal movement and overgrazing. Tree falls or vegetation patterns that concentrate streamflow attack.
Chemical	Water chemistry affects cohesive and other types of particle-to-particle bonding.
Flow velocity or tractive forces	Soil displacement by tractive forces is a major cause of soil particle displacement. Many factors affect rate of displacement including magnitude of tractive force, turbulence level, bank soil characteristics, etc.
Freeze-thaw	Cyclic temperature changes cause fracture due to excessive contraction and expansion and spalling due to successive freezing and thawing of moisture within the bank.
Gravity	The stable slope of a cohesionless bank corresponds to gravitational stability; for steeper slopes, surface particles roll downslope.
Human actions	Many human actions are classified herein as causes and include farming/ranching operations, structures built in the stream, mining operations, and vessel-induced motions. Most of these fit under the heading of causes.
Precipitation	Surficial destruction occurs due to impact by rain or hail.
Waves	Waves due to wind or vessel traffic can cause displacement of soil particles along the bank surface.
Wet-dry	Alternate wetting and drying cause stress and chemical effects that result in surface soil loosening.

and include bank composition and stratigraphy, moisture content, bank height and slope, and vegetation, etc.

While these three methods have similarities, it is obvious that bank erosion can be categorized in different ways.

Table 2 Internal Failure Mechanisms	
Mechanism	**Description**
Slope instability	On banks experiencing surface soil displacement, the displacement will often take place at different rates over the bank height depending on the erodibility of the bank material or the variation of bank attack intensity. This often results in upper portions of the bank being placed in a geotechnically unstable geometry by removal of material on lower portions of the bank. Groundwater levels have a significant effect on slope stability.
Piping	Piping results in the removal of soil layers having relatively high permeability. Water concentrates in these layers and flows out after periods of flooding, significant precipitation, or other change in groundwater flow. Water flowing out of these layers causes these materials to be removed and results in failure of overlying layers of more cohesive materials.
Liquefaction or flow failures	Relates to fine-grained and loosely structured materials subject to a rapid increase in pore pressure (such as occurs during a rapid drawdown or earthquake) and results in a large segment of bank material flowing downslope as a fluidlike mixture.
Tension cracks	Deep tension cracks due to excessive drying of a cohesive soil may cause the streambank to weaken and become unstable when operating in conjunction with other mechanisms.
Swelling and shrinking	Swelling and shrinking during wetting and drying affect the stability of clay soils.
Overburden	Structures or material placed along the top of bank may cause an otherwise stable bank to become unstable.
Pore pressure	The shear strength of clay soils is highly dependent on pore-water pressure. Cohesive layers can be rendered unstable by water pressures in thin sand layers resulting in landslides.

Table 3 Mechanisms of Transport of Displaced and Failed Soil Away From Bank	
Mechanism	**Description**
Gravity	Gravity is an intermediate means of transport because either materials are removed from the site by other mechanisms or transport ceases due to accumulation.
Human action	Examples are dredging or mining activities.
Water flow	Transport by flowing water is the most significant transport mechanism as far as streambank erosion is concerned. Streamflow is the most common transport mechanism; but vessel-induced water motions are capable of moving displaced and failed soil away from the bank, and overbank flows are capable of transport down the bank.

Bank Erosion Causes

As stated previously, bank erosion causes are the actions or events that result in the occurrence of a bank erosion mechanism. Bank erosion can occasionally be traced to a specific cause, but multiple causes are more frequently the case. The following paragraphs present specific bank erosion causes, the resulting mechanisms, and references documenting their occurrence. All navigation-related causes are discussed in Chapter 4.

Meandering

Meandering may be more the result of erosion than a cause, but it is treated herein as a cause. Rivers have a natural tendency to meander or move across and down their floodplains by eroding one bank and building their opposite bank through deposition. Fisk (1944) surveyed courses of the Mississippi River below Cairo, IL, and demonstrated that a great amount of channel migration has occurred over the last 200 years. Crickmay (1960) reported that the Mississippi River below Cairo, IL, showed an average annual migration on bends of 13.4 m (44 ft) based on surveys dating back to 1765. Hooke (1979) reported that maximum erosion rates are directly related to stream size but the composition and resistance of the banks and the channel slope are significant in determining variation in rates. Simons et al. (1979) stated that "in rivers of this [Connecticut River] type, geomorphologists and engineers have documented that the outside banks will annually erode landward a distance about equal to the depth of flow." Biedenharn et al. (1989) found channel migration depends on planform geometry as described by the ratio of radius R to width W. An R/W of 5 separated sites having low and high erosion rates on the Red River in Louisiana. Hickin (1974) found a critical value of channel curvature which "exerts considerable control over subsequent direction and rate of lateral migration." Meandering as a cause is often indistinguishable from high flows, described in the next section, and could also fit under a previous section, "Geologic and Geomorphic Considerations."

High flow

Hooke (1979) and Simons et al. (1979) have evaluated erosion causes on specific rivers and concluded that most erosion occurred as a result of high flows. Simons et al. (1979) stated that "in most instances when considering the instability of alluvial rivers, it can be shown that approximately 90 percent of all river changes occur during 5 to 10 percent of the time when large flows occur." Everitt (1968) used corings from cottonwood trees to demonstrate that erosion on the Little Missouri River is related to episodic events, namely high flows. While flood flows are generally greater than bank-full stage, erosion can be significant for lesser events. Thorne and Tovey (1981) observed significant undercutting and movement of failed soil blocks in the River Severn at a stage corresponding to one-third of bank-full stage. Hughes (1977) found minimal erosion for flows occurring 10 to 12 times per year and major erosion for flows that have a return interval of 1.5 years or greater. However, extreme events are not always effective in producing bank erosion; as Schumm (1973) reported, large events did not significantly affect the Connecticut River. According to Hooke (1980), "The lack of effectiveness of large floods is also reinforced by the lack of field or documentary evidence of large amounts of erosion associated with events such as the 1960 Exe River floods when a peak flow of 457 cumecs, recurrence interval 264 years, was reached."

High flows cause bank erosion through the following mechanisms:

a. High flows create tractive forces (Lane 1955) great enough to displace inplace soil and/or transport failed soil from the bank. Secondary flows, which depend on channel curvature, cause higher tractive forces to occur along the outer bank of channel bends where erosion is prevalent (Bathurst, Thorne, and Hey 1979). Krinitzsky (1965) reported that the processes of bank failure on the Lower Mississippi River were as follows: "(a) seasonal deepening of the scour pool in bendways occurs during high river stage, (b) oversteepening at the toe of the bank slope causes subaqueous bank failure, and (c) subaqueous failure may induce failure in the remainder of the bank." Thorne and Tovey (1981) and Okagbue and Abam (1986) observed that for rivers with a flow through alluvial deposits of cohesive soils over sand and gravel materials, bank erosion occurs by fluvial entrainment of material from the lower cohesionless bank at a much higher rate than occurs in the material in the upper, cohesive bank. Thorne and Tovey found "field investigations show that unless the surface of a cohesive bank is loosened or weakened by such processes as frost heave or thorough wetting, fluvial entrainment alone is not particularly effective in causing erosion." Fluvial entrainment of the lower cohesionless bank leads to undermining that produces cantilevers of cohesive bank materials. According to Hickin and Nanson (1984), bank migration is largely governed by the size of material at the toe of the bank. Based on Thorne, Reed, and Doornkamp,[1] the concept of basal end point control states that the rate of bank retreat depends primarily on the rate of tractive force scour at the toe. The three states of basal end point control are as follows:

(1) *Basal scour.* Sediment removal exceeds supply; therefore, toe scour and undercutting occur. Decreased bank stability due to toe scour increases rate of bank retreat, tending toward the second state.

(2) *Dynamic equilibrium.* Rates of sediment removal by the flow and supply from bank erosion are matched; therefore, the bank

[1] Thorne, Reed, and Doornkamp, op. cit.

maintains its profile and undergoes parallel retreat at a rate determined by the rate of fluvial scour.

(3) *Berm and beach building*. The sediment supply exceeds removal; therefore, sediment accumulates at the toe. The increased bank stability due to toe accumulation reduces the rate of supply, tending toward the second state.

b. High flows cause high-water levels, which infiltrate the bank to a degree that depends on the characteristics of the flood hydrograph and of the bank. Leopold (1994) stated, "It is generally assumed that erosion of a riverbank occurs during peak discharge from the shear caused by high-velocity flow against the banks, but in many types of rivers this factor is not important. Rather, bank material is softened, crumbled, granulated, or slumped by other processes which prepare a supply of debris for movement by the high flow." In fact, Browne (1980) concluded that velocity-induced shear failure is not a major cause of bank erosion on the Ohio River. Studies by the U.S. Army Engineer Division, Ohio River (1977), and Hagerty (1991a, 1991b) documented that during the recession of the hydrograph, the falling water levels result in seepage and piping of the groundwater back to the stream through noncohesive layers typically found in the fluvial system. The piping mechanism results from the seepage flow and is the transport of the noncohesive layer by the groundwater flow. Loss of this layer destabilizes upper cohesive layers, which fail in blocks or segments of the bank. Tension cracks contribute to the bank instability. The failed cohesive soils, resistant to erosion while in place, are often easily eroded by subsequent flood flows. Piping is the formation of tubular conduits whereas seepage erosion occurs over a broad areal extent (Keller, Kondolf, and Hagerty 1990). Ullrich, Hagerty, and Holmberg (1986) reported that "the most important factors governing piping were permeability and capillarity suction in sand seams, slope of sand seams, and water in tension cracks behind the bank face. Flood hydrograph parameters... were less important, though significant." According to Hamel (1983), high flows and high precipitation often occur jointly and both increase groundwater flow. Also bank instability is "fundamentally a geotechnical phenomenon working outward from bank soils rather than inward from the water in the channel." Clough (1966) presented data showing the time lag between the water level in the river and in the bank. Duration of discharge, affecting the amount of recharge of a bank, is an important factor in bank erosion. Simons et al. (1979) constructed a physical model of a bank with a layered soil configuration and demonstrated the piping mechanism leading to failure of the overlying cohesive layers. They also reported that wave activity can cause piping to occur. Erosion due to piping has also been reported by Twidale (1964), Bell (1968), Camfield, Ray, and Eckert (1980), and Odgaard, Jain, and Luzbetak (1989). Hagerty (1991a, 1991b) documented other examples. Budhu and Gobin (1994) reported seepage-induced erosion is extensive below Glen Canyon Dam on the Colorado River. The dam is operated to satisfy peak power demands resulting in a daily stage variation downstream of the dam of 1-4 m. Leopold, Wolman, and Miller (1964) discuss the importance of piping on the movement of headcuts in gully formation. Laboratory studies by Burgi and Karaki (1971) showed that seepage caused by a high water table in the bank reduces the stability of sand. Negative seepage (out of the channel) was reported by Harrison and Clayton (1970) to increase bank stability due to the formation of a silt seal caused by movement of suspended sediment into the bank or bed.

c. High water levels associated with high flows also cause bank erosion through saturation of the bank. Thomas and Watt (1913) observed that the bank breaks off piece by piece and that "this breaking is most severe after wet weather, or when a flood has saturated the earth and has receded quickly, leaving a weight of water in the bank, which was scarcely able to support its particles even under ordinary conditions." Thorne and Tovey (1981) analyzed the stability of cantilevered banks using static equilibrium and beam theory.

d. High water levels associated with high flows saturate bank material, which decreases the shear strength of cohesive soils (American Society of Civil Engineers Task Committee on Cohesive Materials 1966) and results in greater rates of particle entrainment. High water levels also create high uplift pressures along highly permeable noncohesive layers that can result in slumping of overlying cohesive layers.

e. Changing water levels associated with high flows have resulted in various types of bank failures including flow failures on the Mississippi River on areas of sand overlain by overburden (Turnbull, Krinitzsky, and Weaver 1966) termed retrogressive flow failures by Torrey, Dunbar, and Peterson (1988).

Antecedent moisture

Although not a cause by itself, antecedent moisture was found by Hooke (1979) on streams in England as a statistically important parameter in relation to mean erosion on the banks and the proportion of the bank exhibiting some erosion at a given study site. Hill (1973) observed that major rises in stream level during the summer when the banks were in a dry, hard state did not result in large amounts of erosion, in comparison to similar floods in the winter. Hughes (1977) attributed lack of bank erosion during a summer flood to a dry, hard bank as opposed to significant erosion during two winter floods having similar magnitude but preceded by a pattern of minor floods. Hagerty, Sharifounnasab, and Spoor (1983) found greater amounts of bank erosion on the Ohio River when banks were wetted by antecedent precipitation before flood events.

Back of bank water sources

Uncontrolled overbank drainage can lead to sheet and rill erosion of streambanks. Poor overbank drainage patterns and man-made or natural lakes behind bank lines provide groundwater sources that move toward the stream and cause piping-related failures. Twidale (1964) observed water emerging from the bank and subsequent failures when overbank depressions were filled with water on a river in Australia. Hagerty (1983) reported that much greater than average precipitation from the late 1960's through the 1970's resulted in increased groundwater elevations for several areas within the Ohio River basin. Higher groundwater resulted in increased flow out of riverbanks, increasing piping failures.

Wind waves

Lawson (1985) stated, "Net erosion by wind waves depends primarily upon the following factors: wind velocity, duration, and effective fetch; near shore and offshore bathymetry; shoreline configuration (plan view); water level; and beach and bluff composition." Lawson discussed shoreline and erosion processes relative to the two main parts of the shore zone—the beach and the bluff. The distinction between the beach and bluff areas is not nearly as apparent in river environments having significant stage fluctuation as it is in impoundments having relatively constant water level. Similar to the river environment where flood flows are often reported to be dominant, Lawson singles out storms because of "their potential importance as events that can cause rapid and extensive modification of the shore zone over short time intervals."

Walker and Morgan (1964) described bank erosion on the Colville River in Alaska where wind waves cause erosion in summer months when banks thaw from their frozen winter condition. Wave erosion undercuts the bank resulting in soil blocks falling into the river. The greatest activity occurs when persistent winds coincide with high rainfall. Ouellet and Baird (1978) concluded that wind waves are the primary cause of erosion on relatively wide sections of the St. Lawrence River while erosion on narrow sections is attributed to both wind- and vessel-induced waves. Markle (1983) conducted a demonstration model of sand bank erosion under wave and drawdown conditions. His model used wave heights comparable to wave heights in the UMRS, but no erosion rates were measured in this study.

Wind wave erosion at Lake Orwell is the dominant cause of erosion producing an average annual retreat of 0.36 m based on analysis of 13 erosion stations (Reid 1984). Reid, Sandberg, and Millsop (1988) found shoreline erosion on Lake Sakakawea a function of different variables in summer versus winter. In summer, the primary factors affecting recession rate were bank angle relative to dominant wind, offshore slope angle, beach width, bank height, effective fetch, and percent of coarse beach clasts. In the winter, bank height and bank orientation relative to the sun were the dominant factors. Reid (1993), in his description of the mechanics of shoreline erosion, stated that the most significant factor in bank erosion is waves, whether wind-induced or boat-induced. Reid, Sandberg, and Millsop (1988) reported that in Lake Sakakawea, most bank failures occur through mass movements rather than from surface erosion processes, but most movements are the result of undercutting by waves. He cites two references for determining the rate of bank erosion due to waves: Quigley and Gelinas (1976) and Sunamura (1984). Benn (1994) reported on bank erosion on the Hog Hollow archaeological site due to wind waves in pool 12 of the UMRS. Nairn (1992) discussed wind wave shoreline erosion of cohesive soils and how the erosion processes differ from that in noncohesive materials. Nairn stated that the controlling process of wind wave erosion of cohesive soils is downcutting of the cohesive foreshore slope.

Sunamura (1984) presents an excellent summary of wind wave erosion of cliffs and an extensive list of references. His fundamental relation of cliff erosion by waves is as follows:

$$X = \phi(f_w, f_r, t) \tag{1}$$

where

X = eroded distance

f_w = force exerted by waves

f_r = resisting force of the cliff

t = time

Sunamura noted that there is no suitable physical or quantitative index for f_w and resorted to wave height like most other investigators. Sunamura presents a diagram for waves which is comparable to the previously discussed basal end point control. Sunamura presents an equation for bluff recession

$$R = K\left(C + Ln\ \frac{\rho g H}{S_c}\right) \tag{2}$$

where

R = recession rate

K = constant having dimensions of length/time

C = a nondimensional constant

ρ = water density

g = gravitational constant

H = wave height

S_c = compressive strength of the bluff forming material

Kamphuis (1987) stated that in the wind wave environment, "the erosional debris from the cohesive till bluff normally disappears rapidly as suspended load. It forms virtually no protection and hence the height of the bluff does not exert much influence on the recession rate." He presented plots showing that cohesive foreshores under wind wave attack have profiles similar to noncohesive foreshore profiles. Kamphuis also emphasized that recession rate ultimately depends on the ability of the wave to downcut the foreshore slope. He developed the following expression that the recession rate of a till bluff R should be proportional to the incident wave height H:

$$R = AH^{3.5} \tag{3}$$

or the incident wave power P_b as

$$R = BP_b^{1.4} \tag{4}$$

The coefficients A and B are calibrated to reflect different geotechnical properties. This formulation assumes that the wave height or power is much greater than the difficult-to-determine critical wave height or power, which is the condition required to initiate erosion. The exponents in these equations vary for breaking versus nonbreaking wave zones. Wave power per unit length of shoreline is defined as

$$P_b = \frac{\rho g^{3/2} H^{5/2}}{8\lambda^{1/2}} \cos \alpha \tag{5}$$

where

λ = breaker index = H/d

d = depth of water at breaking

α = angle of wave breaking

Observed recession rates from wind waves at several sites on Lake Erie resulted in

$$R = 1.06P^{1.37} \tag{6}$$

where

R = long-term recession rate, meters/year

P = long-term average wave power, kilowatts/meter, arriving at the shoreline

Bishop, Skafel, and Nairn (1992) presented results of laboratory wave erosion tests on undisturbed cohesive soils under wave heights of 0.3 m. Downcutting of the cohesive profile is attributed to shear stress at the bed caused by orbital velocities (for unbroken waves) and wave energy dissipation in the surf zone (for broken waves).

Effect of structures, including UMRS navigation dams

Nielsen, Rada, and Smart (1984) report that the lower one-third of Pool 4 on the UMRS has aggraded 0.4 m, whereas the upper third has degraded 0.7 m since lock and dam construction. The degradation is attributed to clear water discharges from the dam that result from sediment trapping in the upstream pool areas. Streambed degradation can lead to bank erosion because the degradation causes banks to be placed in a geotechnically unstable condition and slope failures occur. In Great River Environmental Action Team (GREAT) (1980b), dredging quantities and sediment inflow and outflow are examined and their impact on downstream bed degradation is discussed.

Stage fluctuations due to reservoir operations such as lock surges and hydropower can result in rapid drawdown, leading to piping failures (Budhu and Gobin 1994), slope stability failures of saturated banks, and instability due to excess pore-water pressures. Linder and Wei (1986) reported that bank erosion from hydropower releases below Harry S. Truman Dam was not a significant problem after evaluation of prototype experience. Simons et al. (1979) concluded that pool fluctuation due to structure operation was the second leading cause of bank erosion on the Connecticut River; however, magnitude was small compared to the primary cause of tractive force erosion during high flows. Boszhardt and Overstreet (1981) concluded that boat wakes and natural erosion are increasing the rate of shoreline erosion in Pool 12 of the UMRS primarily through vegetation loss. According to Boszhardt and Overstreet, "Pool maintenance has apparently created a situation where the water levels change to such intense degrees and at such irregular intervals, that floral species are unable to adapt, and die off leaving exposed soil." Another potential source of erosion due to structures is the large pool created upstream of navigation dams on the UMRS which could increase the occurrence of wind wave erosion. Simons et al.[1] evaluated change in surface area, surface width, bed elevation, and discharge/ stage as a result of dike and navigation dam construction on the UMRS. Surface area, width, and bed elevation increased upstream of navigation dams and decreased downstream.

Browne (1980) concluded that "bank erosion is not caused by or related to the construction and operation of navigation dams" on the Ohio River. Browne further concludes that navigation structures have reduced the natural fluctuations of river stage, therefore, reduced the drawdown failures. Hagerty, Linker, and Beatty (1989) surveyed bank erosion before and up to 4 years after construction of the Smithland Dam Pool. The authors found no indication that the pool raise caused any increase in bank erosion. Hagerty, Spoor, and Parola (1995) report: "It has not been proven conclusively whether maintenance of a navigation pool accelerates, decelerates, or does not affect the rate of retreat above the regulated stage." They also state: "It is also possible that the bank near the navigation pool elevation is subject to persistent conditions which previously did not exist, and that retention of a navigation pool has accelerated bank retreat above the maintained stage level." Neill and Yaremko (1989) reported obstructions at bridge structures accelerate and concentrate flow forces. Bridge abutments often create back eddies that can erode large embayments into the bank. Richardson and Stevens (1986) reported on another structural form, levees. The Lower Citanduy River in Indonesia remained stable after 23 cutoffs reduced the channel length from 98.7 to 78.6 km. The subsequent addition of levees to this river resulted in increased bank erosion. Volker (1986) also reported that embanking (levees) may increase bank erosion.

Flow impingement

Flow impingement occurs when channel bed forms, structures, debris, or vessel propeller jets direct flow against a bank at a large acute angle. It can occur at a wide range of flows and causes large tractive forces. Flow impingement frequently results in bank erosion in braided streams having multiple channels that often experience rapid shifts in alignment. Woody debris and ice jams also cause flow impingement that can result in bank erosion. Wallerstein and Thorne (1994) observed that the presence of organic debris increases channel width in certain stream sizes.

[1] D.B. Simons et al. (1981). "Investigation of effects of navigation development and maintenance activities on hydrologic, hydraulic, and geomorphic characteristics," Working Paper 1 for Task D, submitted to Upper Mississippi River Basin Commission, Minneapolis, MN.

Winter effects

On a stream evaluated by Hill (1973), precipitation and frost action together resulted in bank soil being loosened first by frost action and then swept away easily by flood flows. Added precipitation after the flood increased the subsequent frost action effects. On the significance of frost action, Leopold (1994) reported: "Erosion in Watts Branch is concentrated in the winter months and rarely occurs in the summer. Maximum flows are most likely from summer thunderstorms, at which time the stream banks are dry and resistant to erosion. There was practically no erosion during the high flow in July, 1956." Twidale (1964) considered frost action to assist other mechanisms by loosening soil and soil blocks on the face of the bank. Lawler (1987) studied channel bank erosion in Wales and concluded that groundwater movement to locations of freezing and frost action prepared riverbank materials for erosion. Erosion was lacking without such preparation. Reid (1984) reported that thaw failure at Lake Orwell was the second most effective erosion process. According to Reid, "Thaw failure begins with slab slips along joints in the insitu till that have been enlarged by frost action, and mud and earthflows then occur when thaw has progressed." Gatto (1982b) stated: "When ice covers a river, lake, or reservoir from shore to shore, it dampens waves and protects the banks from normal wave erosion processes. Erosion restarts at breakup when the ice becomes mobile; the ice scrapes, shoves, and scours the shore or bank, and transports sediment away." Wuebben[1] reports that ship and wind waves on the St. Marys River were "undetectable for periods with ice cover." Gatto (1982b) discussed various ice erosion processes and provided references on ice erosion. As reported by the *Shore Protection Manual* (1984), the net effects of ice on shoreline stability are largely beneficial.

Land use/basin/channel changes

Since the size (width, cross-sectional area) of a stream is largely a function of the flows that have occurred historically in that basin, changes in flow (rate, timing, duration) from land use changes will almost certainly result in a change in the channel size. Hammer (1972) studied 78 watersheds in Pennsylvania and demonstrated increased stream size as a result of urbanization. The study showed that effects decreased after about 30 years and that the effect of urbanization decreases for larger watersheds. Land use changes such as the clearing of riparian vegetation can result in bank and channel instability (Oswalt and Strauser 1983). The contribution of riparian vegetation to bank stability tends to decrease with increase in size of the system (Keller, Kondolf, and Hagerty 1990). Smaller systems have lesser erosive forces and vegetation increases stability unless the bank is high in relation to the depth of rooting (Neill and

---

[1] James L. Wuebben. "Environmental effects of extended season navigation on the Great Lakes - St. Lawrence Seaway System," draft report, Cold Regions Research Engineering Laboratory, Hanover, HN.

Yaremko 1989). Keller, Kondolf, and Hagerty (1990) documented cases of increased bank erosion following loss of suitable riparian vegetation. Loss of riparian vegetation resulted from either rising or falling groundwater levels brought on by either pumping of aquifers or stream aggradation resulting from timber harvesting. Gravel mining is another basin change that is a possible source of channel instability (Lagasse, Winkley, and Simons 1980). Browne (1980), in a study of the Ohio River, concluded that "changes in land use tend to increase infiltration rates and piping losses."

Bank erosion can also be caused by aggradation of the channel brought on by increased sediment load in a river. Smith and Patrick (1979) reported that bank erosion in the Eel River in California is caused by high sediment production resulting from both natural environmental conditions and man's land use activities. According to Sparks et al. (1990), basin changes on the Illinois River that included intense agriculture and barge traffic resulted in increased turbidity that killed submerged plants. Loss of vegetation allowed larger waves to occur, which uprooted even more plants and further increased turbidity. This cycle continued allowing wave attack to erode banks adding to the turbidity. As Neill and Yaremko (1989) reported, channelization or straightening often initiates a long sequence of response that can include incision or degradation, slope undercutting, and a tendency to develop new meanders.

Relative Significance of Bank Erosion Mechanisms and Causes

Studies have been conducted to define the major mechanisms and causes of bank erosion that have occurred historically over a specific area. Simons et al. (1979) evaluated erosion causes on the Connecticut River and concluded that shear stress and velocity were by far the dominant causes of bank erosion. Pool fluctuations caused by structures was a distant second followed by boat waves, gravitational forces, and seepage forces. Reid (1984) found wind wave erosion in Orwell Lake, Minnesota, accounted for 76 percent of the total erosion in 1981-1982 and 88 percent in 1982-1983. The second most significant mechanism, thaw failure, accounted for 20 and 10 percent of the erosion following 1982 and 1983, respectively. USACE (1981a) studies on the Ohio River concluded that the major causes of erosion are rapid drawdown and stage fluctuation triggering slumpages, and removal of bank soil by water seepage through zones of low resistance with slabbing and caving of overlying soils. Ofuya (1970) presented a method for evaluating the relative significance of wind- versus boat-generated waves based on comparison of the total energy of waves striking the bank. Bhowmik and Schicht (1980) evaluated bank erosion sites along the Illinois River and concluded that wind and vessel waves were responsible for most bank erosion. Spoor and Hagerty (1989) concluded that most bank erosion on the Illinois River was the result of piping.

Erosion of Islands

Lagasse, Winkley, and Simons (1980) reported that the upstream ends of islands are areas where gravel armor layers form. These areas are subject to scour after gravel mining by dredging. Weigel and Hagerty (1983) reported on riverbank change at Sixmile Island in the Ohio River. Erosion resulted from exit of bank recharge after flood recession. Wind and vessel waves "were of little significance in causing bank failure." Tractive forces and wave action "were effective only in removing soft sediments or loose debris from upper bank failures. Sediments deposited by spring floods, if allowed to dry for two to three months, strongly resisted subsequent wave attack." Boszhardt and Overstreet (1981) reported that in Pool 12 of the UMRS "islands surrounded by the main channel and side channels exhibit both sedimentation and erosion. The upper ends of these insular units, in most cases, are being severely eroded, illustrated by high vertical banks......The lower ends of islands typically consist of recent sand bar formations." Boszhardt (1990) reported that after inundation by construction of Lock and Dam No. 8, the highest landforms in the lower end of Pool 8 remained above water as low islands. These islands were then subjected to accelerated erosion due to wind wave action. Boszhardt reported that little remains of these islands after 50 years.

Cohesive Soil Erosion

The state of the art of the investigation of cohesive soil erosion is one of the factors preventing reliable prediction of erosion rates. Investigators of the initiation and rate of cohesive soil erosion have found a large and complex number of factors to affect this process (Paaswell 1974) for both wave erosion and tractive force erosion. Kamphuis (1990) reported that understanding cohesive bed erosion is greatly simplified by the finding that the noncohesive material carried by the eroding stream plays a significant role in the cohesive soils erosion. Clear water erosion of cohesive soils is much less than erosion with flows containing a small amount of sand. In his bridge crossing example, the critical shear stress determined experimentally for the cohesive soil was the same critical shear stress from the Shields diagram for the sand carried by the flow. Kamphuis stated: "If any sand or gravel is presented in the eroding stream or overlying the cohesive formation in a discontinuous layer, the design should be based on the sediment transport characteristics of the granular material. The complex geotechnical properties of the cohesive formation are only of secondary importance in that they modify the erosion rate resulting from abrasion and protection by the granular material." Relegating geotechnical parameters to secondary importance has not been widely accepted as indicated by the listing of 32 important cohesive sediment parameters in Boyt (1992).

Bank Erosion Monitoring

Thorne (1981), Gatto and Doe (1987), Reid (1993), and Lawler (1993) review methods for monitoring bank erosion rates. Lawler (1993) explains that these methods are not automatic or quasi-continuous, which is needed to quantify the erosion or deposition impact of a given event. Lawler developed a Photo Electronic Erosion Pin System providing a continuous monitor of the bank position.

3 Extent of Existing Bank Erosion on the UMRS

Potential Sources of Data

There are several sources of data and field observations that cover many areas within the UMRS and could assist in establishing the baseline bank erosion conditions: aerial photographs, questionnaire results, field studies by the Corps and other agencies, and hydrographic surveys, etc. These data could be pertinent to determining geomorphic changes in the bankline, identifying reaches with moderate to severe erosion, and providing supplementary data to sites where detailed investigations are warranted.

A recent survey queried the Corps offices in the UMRS, the Illinois State Water Survey, and the Environmental Management Technical Center attempting to locate and compile sources of existing hydrodynamic and sediment data. Various levels of details for bathymetric and hydraulic data exist in either hard copy or digital format. In a Water Operation Technical Support Program questionnaire conducted in February 1990, all Corps Districts were surveyed for reservoir shoreline erosion problems. The St. Paul District reported they had less than 160 km (100 miles) of erosion, and St. Louis and Rock Island Districts had from 160 to 320 km (100 to 199 miles) of eroded shoreline (Allen and Tingle 1993). Both these surveys may have details pertinent to this study.

The Environmental Management Technical Center, Onalaska, WI, is responsible for storing data on the UMRS as part of the Long Term Resource Monitoring Program. They are building and maintaining a Geographic Information System for the UMRS that includes historical land coverages from as far back as 1890 to detailed coverages in more recent years (*River Almanac* 1994).

Several studies that were completed on UMRS bank erosion whose data may be accessible are described in detail in the following sections.

Extent of Illinois River Bank Erosion

According to Schumm (1971), the Illinois River has such a low gradient that meandering is inhibited. The Ouachita River in Louisiana is similar and was reported by Biedenharn, Raphelt, and Montague (1983) to be relatively stable with intermittent areas of bank erosion. Stability on the Ouachita was also attributed to cohesive bank material, heavily vegetated banks, and low sediment loads. Bhowmik and Schicht (1980) evaluated erosion at 20 sites on the Illinois River and reported erosion ranging from negligible to severe. Warren (1987) monitored five prehistoric archaeological sites on the lower Illinois River over a 4- to 6-month period and determined that the mean horizontal erosion rate was about 1 mm per day. Warren concluded that bank erosion is an important problem on the lower Illinois River and it poses a widespread and often severe threat to significant cultural and natural resources near the river's edge. He stated: "The pattern observed in this study is consistent with the hypothesis that a substantial amount of bank erosion along the lower Illinois River is caused by wave action, much of which is an artificial consequence of vessel traffic on the river." Based on a 1988 evaluation by Spoor and Hagerty (1989), severe erosion on the Illinois Waterway was very limited. They also observed that undercutting of banks by waves and currents was not encountered. Areas experiencing bank erosion were caused by piping-induced erosion. Good (1993) reported that shoreline erosion on Illinois lakes and reservoirs is caused by "fluctuating water levels, easily erodible shoreline soil types, steep shoreline slopes, heavy visitor usage, lack or disturbance of nearshore aquatic vegetation and/or rock barriers, deep nearshore water depths, boat and wind induced waves, and ice damage." Also the average percentage of eroded shoreline was 15 percent for lakes larger than 202.3 ha (500 acres).

Extent of Mississippi River Bank Erosion

Through the more recent history of navigation on the UMRS, numerous studies have been conducted by several agencies regarding some aspect of bank erosion. One study, begun in 1974, was conducted by a multidiscipline, multi-agency team established through a partnership between the Corps and the U.S. Fish and Wildlife Service. Their mission was a long-range management strategy for the Upper Mississippi River (UMR). The team, known as GREAT, was a consortium of interests authorized by Congress in Section 117 of the Water Resources Development Act of 1976. The first team, GREAT I, established in 1974 was responsible for studying the river from Minneapolis/St. Paul, MN, to Lock and Dam 10 (all within St. Paul District) (GREAT 1980a). The second team, GREAT II, began in 1976, and picked up the river from Guttenberg, IA, to Saverton, MO (Rock Island District). And finally, GREAT III, organized in 1977, continued from Saverton to the mouth of the Ohio River (St. Louis District).

Work groups addressed the following problem areas: commercial transportation, dredged material uses, dredging requirements, fish and wildlife management, floodplain management, material and equipment needs, public participation and information, sediment and erosion, side channel, water quality, and plan formulation. The sedimentation and erosion work group had multiple tasks including identification of sources of sediments and their fate. One task was to "monitor rates of sedimentation and erosion within the river corridor." Technical results of the sediment and erosion work groups are found in separate appendices (GREAT 1980b, 1980c).

GREAT (1980b) stated that "shoreline protection has benefitted the environment by preventing tow propwash and flood flows from eroding channel banks." GREAT I also developed an inventory of areas needing shoreline protection, but did not discuss the extent of erosion. From the GREAT II study (GREAT 1980c), 15 percent of the 5,934 bank miles of main stem rivers were experiencing erosion. No figures were given for the UMR alone. From the GREAT III study (Morris 1982), bank erosion was determined from mappings of the UMR from Saverton, MO, to Cairo, IL. "The results of the mapping of the high bankline indicate there have been only small changes over the 22 years studied." Above St. Louis no changes were found, which was attributed to the many locks and dams. The GREAT III study further concluded that bank erosion is not a significant factor in the total sediment budget of the river. This report also stated that the Corps of Engineers revetment program has resulted in the high bank being in virtual equilibrium.

1993 Flood

Specific attention is focused on bank erosion resulting from the 1993 flood on the UMRS and Missouri River. The U.S. Army Engineer District, Rock Island (1994), evaluated channel changes resulting from the 1993 flood based on 26 cross sections compared from 1992 and 1993. Thirteen of the twenty-six cross sections showed deposition, and only four showed degradation across the entire channel. The remaining nine had equal amounts of aggradation and deposition. According to this report, "Due to the torrential downpours which occurred during this period and the resultant swelling of rivers and streams, both sheet and bank erosion were tremendous." The report does not delineate which rivers within the District experienced tremendous erosion. In a short helicopter overflight of parts of the UMR in the Rock Island District in October of 1993, the authors of the present report observed relatively stable banks and little evidence of bank erosion. Benn (1994) documents several Mississippi River archaeological sites that experienced erosion during the 1993 flood. Benn reported that the erosion signature of fluctuating water levels is "treads and risers" or stepwise lines of erosion on the bank. He reported that of 33 selected sites, 42 percent had some degree of damage and 21 percent had "flood damage [that] either accelerated the rate of erosion or started new erosion to the extent that the cultural deposit is considered adversely affected...." Benn goes on to say that "the rate of flood effects among all sites in the valley is much lower, probably less than five percent." A potential long-term effect of the 1993 flood is the bank instability resulting from die-off of vegetation as a result of the long inundation by the flood. U.S. Army Engineer District, Omaha (1994), documents that streambank erosion was either the sole cause or a partial cause of levee failure at 9 out of 29 Omaha District levees damaged in the 1993 flood. U.S. Army Engineer District, Kansas City (1994), documents 56 locations of significant (several hundred feet) bankline blowouts and 14 locations of major (305 to 610 m (1,000 to 2,000 ft or more)) blowouts between river miles 486.8 and 25.0 on the Missouri River as a result of the 1993 flood.

4 Summary of Navigation-Related Processes and Bank Erosion Studies

A number of bank erosion studies have been conducted specifically related to navigation for either navigation channels or in reservoirs. These efforts range from multiple-effort large-scale projects such as those on the Great Lakes connecting channels in the late 1970's and early 1980's to smaller efforts by individual researchers. Some studies were site specific and involved detailed field investigations, while others were broad in scope involving perhaps only a literature review. In some cases the research was cumulative over years of field data, multiple scientists, and laboratory efforts (see section, "Dutch studies," later in this chapter). However, it became apparent that much of the research covered navigation effects and bank protection. Research containing actual relationships between navigation processes (or any processes for that matter) and bank erosion were rare and often unverified in the field. Only two articles presented a shoreline retreat model related to boat energy, Grigor'eva (1987) and Nanson et al. (1993). This lack of applicable models and need for further research are expressed in many articles, for example the article by Pilarczyk et al. (1989), which stated, "The mechanics of bank erosion and the stability of protective structures subject to hydraulic loading are complex problems. The understanding of erosion processes and failure mechanisms of structures is still in a rudimentary stage, and it is not yet possible to describe many important phenomena and their interactions by theory."

After the difference between commercial and recreational vessels is discussed, summaries and conclusions from references pertaining to navigation and bank erosion are presented.

Commercial Versus Recreational Vessels

Commercial and recreational vessels, each having the potential to cause bank erosion, differ in the forces they generate and where they are able to navigate. To understand the difference in forces, the vessels can be classified as either confined or unconfined. Commercial tows on the UMRS are classified as confined because their submerged cross-sectional area takes up a significant part (greater than 2 to 5 percent) of the cross-sectional area of the waterway. The ratio of channel cross-sectional area to submerged vessel cross sectional area is called the blockage ratio. Recreational vessels are unconfined because they do not take up a significant part of the waterway. The water motions created by confined vessels (commercial tows) that can attack banks are return currents, water level drawdown, transverse stern wave (significant only for small blockage ratios and high vessel speeds), propeller wash, and if vessel speeds are high enough, short-period waves. The water motions created by unconfined vessels (recreational vessels or workboats) are primarily short-period (1 to 3 sec) waves, which are larger than short-period waves from commercial vessels because of the higher speeds for recreational vessels. Johnson (1994) reported maximum wave heights of 30.5 and 61.0 cm (12 and 24 in.) from commercial and recreational vessels, respectively. Regarding the differences in where they navigate, commercial vessels are generally confined to a narrow portion of the channel that is removed from the shoreline except in bendways. With some dependence on size, recreational vessels have few restrictions on where they operate.

Commercial and recreational vessels also differ in frequency of occurrence. Bhowmik et al. (1992) reported that up to 704 recreational vessels passed a highly used area on the UMR in one day whereas commercial tows on the UMR are presently about 35 tows per day in the lower pooled reaches. Commercial and recreational vessels also differ in their location of maximum frequency of occurrence. Frequency of vessel passage for recreational vessels is often closely related to proximity to metropolitan areas whereas commercial vessel traffic on the UMRS decreases as one proceeds upstream from St. Louis.

St. Lawrence Seaway Studies (Connecting Waterways)

The connecting channels of the Great Lakes-St. Lawrence Seaway are the main topic of several studies:

Ofuya

Ofuya (1970) investigated wind, ship, and cruiser waves in the St. Clair, Detroit, and St. Lawrence Rivers to determine their relative contribution to shore erosion. Ofuya assumed the quantity of sediments dislodged from the riverbank is proportional to the work done by the waves and is calculated as the wave energy propagated to the shoreline by

$$W_t = \frac{20}{S_{max}} H_{max}^2 \, T_{max} \, Q_s \tag{7}$$

where

W_t = wave energy at shoreline in ft-lb/hr/ft of shoreline

S_{max} = slope of the average maximum power versus energy curve

H_{max} = maximum wave height

T_{max} = period of maximum wave

Q_s = number of ships per hour

For ships $S_{max} = 0.11 - (0.87)(10)^{-5}X$ and for cruisers $S_{max} = 0.19 - (2.56)(10)^{-5}X$ where X = distance from shoreline to sailing line in feet and is limited to 0 to 1,524 m (5,000 ft). Ofuya also provides equations for wind wave energy and examples comparing the relative contribution of wind, ships, and cruisers.

Ouellet and Baird

Ouellet and Baird (1978) investigated shoreline erosion along the St. Lawrence Seaway between Quebec and Montreal. Using a total energy approach to compare processes, they concluded that the relative contribution of each process can be calculated. Their equations for evaluating energy due to wind and boat waves that consider duration tie the number of vessel passages to total potential energy. The authors repeatedly characterize ship waves as ones that "pound" the shoreline. According to Ouellet and Baird, the majority of bank erosion along this section of the river was caused by wind waves, followed by ship passage. The least damaging process was the effects of ice. Also since the costs of monitoring were prohibitive due to long-term nature of active bank erosion sites, the processes were not specifically linked to rates of bank erosion.

Gatto

Gatto (1982a) conducted a study of shoreline damages to determine increases in bank erosion resulting from winter navigation. Regarding ship effects, he referenced Wuebben (1978) in the introduction stating "the rapid water level changes associated with ship passage can occur faster than the pore water pressure in river bottom sediments can adjust. This imbalance can create explosive liquefaction, in which a mass of bottom sediment is rapidly resuspended.... When the offshore slope is altered by this ship-induced resuspension, a readjustment at the shoreline can eventually result." A potential winter problem caused by ship motion regards not only the direct contact of ice when shoved against the bank, but also the disruption of ice formations allowing wave and prop action to cause damages. This study summarized other studies conducted in the Great Lakes area and gave conclusions from each regarding their contributions to bank erosion resulting from navigation. Surveys, field observations, historical maps and records were used in the analysis. The author concluded that 24.2 km (15.1 miles) of eroding banks on the four rivers (70.2 percent) could **not** be attributed to **winter** navigation, and hydraulic changes due to ships are important in narrow reaches or where the ships sail close to the shoreline. However, the author also concluded "that the contribution of winter or summer navigation to bank erosion is minor."

Wuebben (1983)

Wuebben (1983) investigated increased erosion due to **increased vessel sizes** whereas Gatto dealt with potential increased erosion due to **winter navigation**. Both studies were conducted for the Detroit District on the Great Lakes connecting rivers. The largest existing ship on the Great Lakes channels is 305 m (1,000 ft) long by 32 m (105 ft) wide with a draft of 7.8 m (25.5 ft). The proposed ship size is 366 m (1,200 ft) in length with a 40-m (130-ft) beam and a maximum 9.3-m (30.5-ft) draft. Wuebben's study identified areas where an increase in ship size might affect the hydraulics. The author stated in the introduction, "The analysis cannot predict the occurrence or magnitude of damage at those sites because of the interdependence of the effect of vessel size with uncontrolled factors such as water levels and vessel speeds. The result of the study is an estimate of shore areas that could be affected by an increase in vessel size."

It is important to reiterate that the analysis was conducted for incremental increases in damages due to changes in vessel size. Vessel-induced damages based on existing conditions were not considered.

Based on energy and continuity, the author compared idealized channels and increasing drafts. It is assumed the effects are negligible since the channel depth is also increased with ship draft. Based on a family of curves for various channel depth to ship draft ratios, the author states: "Even at a relatively high speed of 17 fps, where the drawdown would be an unacceptable 2 feet, the difference in drawdown between existing conditions and the maximum proposed draft would be less than that due to a change in vessel speed of only 1 fps."

To evaluate effects of different channel geometries and how increases in draft affect them, the author described a channel shape factor S_f between 0.2 and 1.0. A triangle has a shape of 0.5, a parabola, 0.67, and a rectangle, 1.0. It is important to note, based on the author's calculations, the tremendous effect channel shape has on the magnitude of the drawdown for a given vessel speed. This is not surprising since the author fixed the channel depth and top width but did not keep the cross-sectional area when calculating the shape factor. As the author investigated beam width of the ship, he concluded that it **does** have a significant impact on drawdown.

Regarding sediment resuspension and the potential for shoreline damage, Wuebben described the vessel passage mechanism that changes bed load or ripple migration direction, how saltation occurs due to increased velocities, and the explosive liquefaction of bottom sediments caused by a rapid change in the pore-water pressure gradient resulting from vessel-induced drawdown. He stated, "If the decrease in water pressure on the riverbed during the passage of the moving trough occurs faster than the change in soil pore pressure, a net uplift force on the soil near the surface will occur. After the trough passes and the water level rises, the process reverses and there is a net downward force on the riverbed sediment. As the ship passage cycle is repeated, this mechanism, in conjunction with gravity acting downslope, encourages a net offshore migration of sediment that is in addition to any transport due to water velocities alone."

To evaluate **potential** damage to shorelines from increased vessel size, Wuebben "defined" ship-induced effects that are unacceptable and then determined the effects of a larger vessel. The criterion adopted, based on the author's observations nearshore, was that drawdowns greater than 0.3 m (1 ft) and current changes of 0.6 m/sec (2 ft/sec) caused unacceptable sediment movement. Study areas were excluded if drawdown was calculated as less than about 0.3 m (1 ft) for a 366- by 39.6- by 9.3-m (1,200- by 130- by 30.5-ft) upbound ship traveling at the speed limit.

Wuebben then examined reach by reach the areas where increased vessel sizes exceeded the criteria. Although he admits that pilots often exceed existing speed limits, he recommended for areas of potential increases in erosion that the speed limit be lowered except in severe cases where bank protection may be warranted.

Hochstein and Adams

Hochstein and Adams (1989) applied analytical solutions on the St. Marys River (connecting river of the Great Lakes) to quantify environmental effects of ship passage in open and ice-covered waters. The authors describe and present equations for predicting return current, drawdown, propeller jet velocity, diverging waves, horsepower in ice, bed-load transport, and suspended load transport. Kinetic energy was calculated as a function of the combined total velocity (ambient, return current and prop velocity) squared. Field measurements (approximately 84) were used to verify and adjust models for vessel motion hydrodynamics. Sediment predictive techniques were not verified. Only erosion of the bed, not banks, was considered in this study.

Wuebben (1993)

Wuebben (1993)[1] is a compilation of writings on literature and studies on the extended season navigation for the St. Lawrence Seaway. It covers a multitude of topics including 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.

Chapter 2, "The effects of extended season navigation on sediment transport, shoreline erosion, and shore structure damage," written by Wuebben, basically reiterates conclusions from his 1983 report. He refers to models by Hodek and Algers and Hochstein and Adams. He concluded that the major vessel effects during periods of ice are propeller wash, drawdown, and surge and that ship-generated waves are dampened by the ice.

Nearshore turbidity was observed by Hodek et al. (1986) due to ship passage. Sediment studies by these researchers indicated that upbound vessels caused more net sediment transport than downbound and drawdowns of less than 152 mm (6 in.) resulted in minimal disturbances. A criterion was set assuming that nearshore wave heights (not drawdown) of 152 mm (0.5 ft) result in the onset of sediment motion in sand bed systems.

Studies by the Detroit District concluded that on the St. Marys River, erosion of the shorelines occurs during the traditional navigation season and is minor during the extended season. The District concluded that high-water levels were the cause of this erosion, while a follow-up study by a consultant concluded that erosion was due to all causes. Furthermore, waves due to wind and small boats were more significant than ship waves. Their recommendation was bank protection against these other causes rather than a reduction of ship speeds since in their conclusion, these forces were insignificant. Following these two studies in the mid 1970's, the U.S. Army Engineer Cold Regions Research Engineering Laboratory (CRREL) began a series of studies.

The author summarized: "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 show no appreciable difference."

---

[1] James L. Wuebben. (1993). "A review of the environmental effects of extended season navigation on the Great Lakes-St. Lawrence seaway system," Cold Regions Research Engineering Laboratory, Hanover, NH.

European Studies

Dutch studies

Jansen and Schijf (1953). They elaborated on Dutch studies evaluating vessel forces. The authors reintroduced, from a 1949 study, the concepts of limiting velocity criteria, evaluating the vessel drawdown and return current based on the energy principle. As ship size increased and Dutch navigable waterways did not, it became necessary to reevaluate revetment practices. Alternatives to revetment could include speed restrictions.

Bouwmeester et al. (1977). The physical forces produced by a pushtow and the processes contributing to bank erosion are described. This study correlates to information described in Bekendam et al. (1988). When pushtows were introduced in the Rhine waterways, these studies were conducted to determine the effects on the existing waterway. The authors stated: "The increasing dimensions and engine power of ships result in more violent movements of the water (currents and waves) and consequently in more serious erosion of the bottom and banks of rivers and canals. "

This paper studied these forces and the bank protection required for pushtows. A 1:25-scale model was used with a free-running pushtow unit with two, four, and six barges to measure waves and currents in a straight reach and bendway both with and without ambient currents. It describes the mechanics of sailing ships that cause bank erosion. In fact, the authors stated: "The banks and beds of navigable waterways are mainly attacked by the water motion set up by the passage of ships, though tidal movements, swell, wind-generated waves and other currents may also affect the structure." No method of predicting bank erosion was given. It was apparently assumed that these forces will cause erosion.

Blaauw and van de Kaa (1978). They gave equations for predicting the jet velocity and turbulence intensity of a propeller jet. They provided equations for designing graded stone for bottom protection and gave some rules of thumb regarding the scouring depth of unprotected bottoms.

Verhey (1983). This report presented propeller velocity predictive equations. The author used shear stress to evaluate stability. A formula is presented for predicting scour depth.

Blaauw et al. (1984). As in many Dutch reports, they described very well the physical forces of vessel motion. They presented a method for design of bank protection but did not deal with bank erosion.

van der Knaap (1986)[1]. He summarized Dutch methods for predicting vessel forces and designing bank protection.

Bekendam et al. (1988). They reported a major study effort on the Rhine River addressing increasing pushtow traffic from four barges to six on portions of the river system in The Netherlands. As a result, numerous studies were conducted including analytical studies, physical model studies, and prototype studies. Determining navigability was the main objective, particularly bendway widths and maneuvering situations in various flow conditions and the associated economics. This report also presented conclusions of studies related to navigation effects and their relationship to bank erosion, sedimentation, and ecological factors.

A summary of data obtained from the comparisons of aerial photographs shows that in reaches with pushtow traffic on the Dutch section of the Rhine system, about half the system has bank protection and the other half is unprotected. Of the unprotected banks, approximately 14 percent have erosion rates of greater than 1 m/year and 70 percent have erosion rates of 0 to 1 m/year. Due to the complexity of the phenomena, the Dutch authors stated that differentiation between cause and effect was difficult. Therefore, they took the approach of studying the physical forces from the pushtows instead of measuring the erosion itself.

Previous studies concluded "pushtows induce large currents and indicated that the impact on river banks without groynes is the same for six-barge pushtows as four-barge pushtows" assuming vessel speeds are the same. The tests described in this paper focused on sediment movement within groyne fields (unsubmerged dikes). Field tests were conducted in two river reaches (a bend and a straight reach) with groyne fields where velocities, waves, and suspended sediment were measured **without** the presence of tows. These data were used to calibrate a 1:25 physical model with groynes in which hydrodynamic data were collected and tracer tests with polystyrene were conducted in the presence of pushtows.

The following conclusions were reported regarding sedimentation and erosion:

a. Four- and six-barge tows increased sediment transport downstream of the groyne head.

b. Net transport of tracer materials in the small-scale model out of the groyne field was 1.5 to 2 times higher with the bigger barge train.

---

[1] F. C. M. van der Knaap. (1986). "Load and strength aspects of bank and bottom protection in ship canals," Lecture, Postdoctoral course on bank and bottom protection, Delft University of Technology, The Netherlands.

c. Pushtows cause erosion in groyne fields.

d. Erosion downstream of the groyne field can ultimately lead to bank collapse.

And finally, "the rate of bank erosion due to pushtows cannot yet be predicted and more information is required about the recovery capability and local sediment transport." The authors suggested bank protection, as they would for four-barge tows.

It is interesting to note some of the comments on the ecological aspects of the Rhine system as presented by the same authors. In fact this section spells out concerns that have been raised on the UMRS, except that the Dutch waited too late. Many of the viable habitat areas and ecological factors necessary to maintain biotic diversity are already gone. The river channel that formerly meandered through the floodplain is now fixed. Small islands and sand banks have disappeared. Riverbank maintenance has flattened natural levees and disconnected contiguous side channels and back waters. Annual hydrographs have moderate fluctuations.

According to the authors, "The loss of natural environment has been considerable, continuing still because of the severe water pollution originating from large industrial zones and densely populated areas. The direct influence of navigation on the natural environment of the river banks causes the loss of bank and channel edge vegetation. The banks are exposed to intense water movement as ships pass. Introduction of larger scale nautical units such as six-barge pushtows may increase the influences already exerted on the natural environment of the river banks."

And in the conclusions, "A substantial loss of plant and animal habitat has taken place, due to river bank erosion, enforced wave action on unprotected beaches and artificial bank protection constructions that suppress natural processes.... Apart from nautical restrictions, methods not contrary to the natural river regime must be developed."

Pilarczyk et al. (1989). This report presented the general philosophies and experiences of the Dutch in protecting their navigable rivers from erosion caused both by natural processes and navigation effects. It reiterated the study conducted to determine the effect of increasing pushtow units to six barges from four and provided summaries of both field and laboratory studies in groyne fields. See Bekendam et al. (1988) for further conclusions.

Verhey and Bogaerts (1989). The authors used available data, physical models, and field investigations to develop predictive equations for secondary waves produced by ships. A modification of the wave height prediction included coefficients for various ship types and wave characteristics developed from a relationship by Havelock that included the independent variables of ship speed, water depth, and sailing line. The authors then developed bank protection criteria of riprap and blocks against secondary waves using small-scale physical model testing. An equation was also given for the extent of bank protection required based on wave runup. Profile data were collected on the transport of the stone slope protection. No information was given on bank erosion of natural soils.

USSR studies

Balanin et al. (1977). They defined variables of ship motion in USSR canals. They discussed the impact of navigation increases on the system with respect to design of the canal, bank stabilization, and navigability. Other than stating that increases in navigation are expected to increase bed and bank erosion, the paper does not deal with bank erosion. There are other references providing better estimation techniques for determination of navigation-induced forces.

Grigor'eva (1987). He used a method developed by the State Hydrological Institute for predicting reservoir banks reforming due to wind waves. The author applied the method to small canals (less than 30 m wide and 2 m deep) where small ships navigate and produce wakes. The method was adapted by converting time to number of ship passages. This exercise was purely mathematical and did not involve verification in the field. A volumetric displacement of materials was calculated based on the wave energy produced and a coefficient of resistance for four different soil types. The conclusions were as follows: small ships rework the channel banks, bank reworking is highly dependent upon ship wave height, the banks change by increasing the top width of the canal while simultaneously narrowing the deeper sections, since bank deformation is directly attributed to the number of vessel passages, and in areas of concern the traffic should be limited.

German studies

Fuehrer and Romisch (1977). They presented study results on calculations of return current, squat, and critical speed of a vessel. The paper gave a description of the propeller jet and methods for calculating the jet velocity. The paper stated that erosion near hydraulic structures is often due to the propeller jet velocities and turbulence, and gave a formula based on a steady jet load for evaluating scour.

Fuehrer, Romisch, and Engelke (1981). They conducted physical model tests in a trapezoidal channel for two types of vessels. They used sand on the banks and determined the erosion potential due to vessel passage. In general, they determined that propeller jets had more influence on stability during maneuvers and waves dominated bank erosion for ships underway. Furthermore, ships maneuvering bends can scour both banks due to drift angle. They gave methods for calculating stable bank protective layers for straight and curved reaches.

Oebius (1984). He presented formulas for predicting the velocity distributions in a propeller jet. He also provided equations for estimating the shear stresses on the bed or embankment caused by loads induced by parallel jets, inclined jets, and impinging jets. Since scour depth is a function of reaction time, the author stated: "It can be seen that about 50% of final erosion depth is reached within half an hour, a relatively long time compared with the reaction time. This means that the risk of damages in regions of low density of traffic is low, but extremely high in areas which are very near to the propulsion system or where the sequence of individual events is very short thus provoking long term effects."

Swedish studies

Bergh (1981) and Bergh and Cederwall (1981). They described research conducted in Sweden on the scouring action of propellers in harbor areas. The researchers presented propeller jet predictive equations and suggested the use of critical bottom velocity to determine the initiation of motion or scour potential. A simple equation was presented for critical velocity that can be used to estimate the risk of erosion.

British studies

Prosser (1986). This report gave methods for predicting propeller jet velocities. Shields' criteria were applied to determine if materials are erodible and, if so, an equation was given for predicting maximum scour depth. An example shows how these methods can compare different operational constraints such as reduced jet velocities, increased underkeel clearance, vessel position, etc.

Garrad and Hey (1988). As stated in the summary, "Since 1945 the width of the Broadland rivers has increased dramatically. This is shown to be mainly due to wave attack by boat traffic aggravated by a decline in bankside vegetation. Management options to reduce bank erosion include curbs on boat speed and bank protection."

Studying historical surveys since 1883, the authors stated that bank retreat on lower reaches of the Bure River in eastern England has dramatically increased during the period 1946-1976. Further investigations using aerial photographs showed even steeper increases at some sites after approximately 1970.

Due to the naturally low intensity energy of the system as calculated by the authors and the relatively high intensity energy from passing boats, the authors concluded that boats are indeed causing the banks to retreat.

This study provided interesting conclusions to more detailed investigations not presented in the paper. It discussed such things as emerged macrophytes and their ability to dampen wave energy up to a threshold in which the mat fails, and the erosional resistance of the bank materials which in this case were silts, clays, and organic peat. Although the rivers studied were much smaller than the Upper Mississippi (on the order of 46 m (150 ft) wide), the research presented warrants further attention.

Hamill (1988). He used two different scale model propellers and four different uniform grain sizes. The author conducted laboratory experiments varying the distance to the bed and propeller speeds to determine the scour characteristics associated with the propeller jet. The author presented an equation for the development of the rate of scour due to a propeller jet for use on sands in the medium to coarse range.

Thorne, Reed, and Doornkamp[1]. They developed guidance on bank erosion studies and solutions for the National Rivers Authority in England. One of the many processes they described is boat wash. By their definition, boat wash includes vessel-generated waves, water level changes and currents, and propeller wash. The authors stated: "Boat wash can be a primary cause of bank erosion and retreat. Its severity increases non-linearly with boat speed, but is also affected by vessel design, waterway size and geometry, and the proximity of the sailing line to the bank." No equations or relationships were given to predict the rate of erosion due to boat wash.

Australian Study of Gordon River, Tasmania

Nanson et al. (1993) focused on correlating boat wave characteristics to erosion rates. They made the following statement (as the authors of this report have also found): "The American studies tend to fall into two groups: those that investigated the waves produced by river vessels and those that dealt with the extent and processes of bank erosion. Few studies examined both the magnitude of wave attack and the amount of bank erosion, and none have attempted to establish a relationship between these variables."

In their literature review the authors cited many references also used in this report (Camfield, Ray, and Eckert (1980); Garrad and Hey (1988); Bhowmik and Demissie (1983); Oswalt and Strauser (1983), etc.). One reference, by Limerinos and Smith (1975), compared wind waves, boat traffic, and flood

[1] Thorne, Reed, and Doornkamp, op. cit.

flows in two narrow navigation channels on the Sacramento-San Joaquin River Delta, California. In that study, the channel dominated by flood flows attributed 20 percent of the annual energy expended on the banks to boat waves (twice as much as wind waves), and on the other channel 80 percent of the energy was attributed to boat waves.

In this study, the authors measured bank retreat, basal swash load, upper swash load, and wave trains for three recreational craft passing approximately 31 m offshore. The boats were the "wave generators." Each wave train was analyzed for wave periods, wave lengths, wave heights, and wave steepness, etc. Mean wave power per unit crest length was calculated from Komar (1976) as

$$\bar{P} = \frac{1}{8}\rho g H^2 C n \tag{8}$$

where

$\overline{P}$ = mean wave power

ρ = water density

g = gravity

H = wave height

C = wave speed

n = fraction of wave power that travels forward with the wave group

For waves in deep water, $n = 0.5$. Wave power was calculated for both the maximum wave height and the significant wave height. The wave power for the significant wave height was multiplied by one-third the total number of wave crests in the wave train to give a comparative measure of the total wave power in each wave train. A correlation matrix was made between wave characteristics and erosion characteristics.

The highest correlations were found between significant wave power and erosion. Also there was a good correlation between significant wave height and erosion. ("Significant" is defined as the average height of the highest one-third of waves in each wave train.) The analysis also showed erosion increases with wave length, but does not correlate to wave steepness.

The authors pointed out some inherent problems with the measurements, but still found reasonable correlations to the variables. They concluded that even though the correlations to erosion are slightly less for maximum wave height than significant wave height and other parameters, maximum wave height should be used due to the ease in measuring that parameter. Therefore, the threshold for noncohesive alluvial sand is a maximum wave height of 30 cm. Based upon their analysis of the swash loads, they stated that erosion processes can be accelerated by destabilizing the base of the bank and moving unconsolidated materials from the bank to the channel at wave heights of 5 to 10 cm. The controlled tests resulted in relatively large rates of recession because the waves were breaking at the base of a 2-m-high sandy bluff.

In the study of pre- and post-speed limit restrictions in the 45- to 55-km/hr area and 17 km/hr, respectively, erosion rates decreased from about 1 m/year to 0.3 m/year.

Nile River Study

El-Moattassem and Hassan (1991) investigated the River Nile fleet effects on bank erosion and river evolution. The authors assumed that the major hydrodynamic effects on the bank are river current and ship waves. The authors concluded that drawdown and return velocity are negligible in regard to bank erosion effects. Other factors were not considered in this study.

The authors studied several existing equations for wave height predictions including Balanin and Bykov (1965), Hochstein (U.S. Army Engineer District, Huntington, 1980), Bhowmik and Demissie (1982), and Sorensen and Weggel (1984). Sorensen's deepwater ship wave equations were assumed applicable and were applied with new coefficients for hull types. The predictions were found to be valid in the deep section near the channel thalweg but not as accurate in the shallows where refraction can occur.

The authors concluded the following: (a) upbound ships produce higher waves than downbound ships (Note: it is not clear if boat speed is relative to earth or water); (b) when a ship travels in the thalweg close to a bank, the diverging ship waves result in significant erosion (no data or erosion rates are given to support this theory); and (c) sediment transport in the shallows was significant due to ship motion.

Ohio River Studies

Hagerty, Spoor, and others have conducted studies and authored numerous papers about bank erosion. In particular, Hagerty has studied in detail both the Ohio and Illinois Rivers (see also section, "UMRS Navigation Erosion Studies"). There were numerous other papers by Hagerty and colleagues describing the Ohio River studies and the mechanisms of piping and sapping. Some of these studies were Hagerty, Spoor, and Kennedy (1986), Hagerty, Spoor and Parola (1995), Ullrich, Hagerty, and Holmberg (1986), and Springer, Ullrich, and Hagerty (1985). Several studies are discussed in the following paragraphs.

WES field efforts on the Ohio River and the Gallipolis General Design Memorandum

In January 1978, a scope of work was prepared for field studies on the Ohio River to identify and evaluate the physical effects of tow traffic on the river environment in the Gallipolis and Greenup pools. The data were collected in May and August of 1978. Data from these studies were given to the Huntington District in support of litigation regarding claims against the Corps and for replacement studies for the Gallipolis lock.[1] Results of this field effort are also referenced in Hagerty, Spoor, and Ullrich (1981). The maximum wave height for trip 1 was 1.0 m (3.3 ft) and 0.43 m (1.4 ft) for trip 2. The field trip analysis in summary stated that wave heights decreased with distance from the sailing line, increased with vessel speed, were smaller over a sloping bottom, and smaller for upbound vessels.

U.S. Army Engineer District, Huntington (1980)

This appendix to the Gallipolis General Design Memorandum entitled, "Environmental and Social Impact Analysis," contains data and results of field tests conducted by WES in 1978. This part of the planning study developed the Environmental Impact Statement for the lock replacement at Gallipolis on the Ohio River. The scope of the study was similar, if not identical, in nature to the UMRS environmental studies in that both the physical and environmental effects of tow traffic were to be addressed. The introduction stated: "An attempt was made to identify impacts of navigation as they related to the physical and biological environment in and along all navigable inland waterways." The investigation included bank stability.

The environmental study objectives were accomplished through field investigations of primarily physical forces and biological indicators, such as chlorophyll and plankton samples, at five field sites in the Gallipolis and Greenup pools. Criteria for site selection were established by an interdisciplinary team and included areas of active bank caving, reaches where tows navigated near the bank, temporary mooring areas in shallow waters, and areas downstream of tributaries.

Based on the study of historical photographs, maps, and aerial photography, the report stated there are and have been many locations of moderate to severe

---

[1] Personal communication, 9 October 1979, Tim Fagerburg, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

bank erosion along the Ohio and its tributaries. Regarding bank failure and erosion the report said, "Erosion, sediment transport, and deposition processes are at dynamic near-equilibrium within the Ohio River Drainage basin. Significant bank erosion and bank and slope failures occur during and immediately after storms and floods...Lack of understanding of causative mechanisms has resulted in misassignments of these significant increments of bank failure and erosion to effects of navigation use and establishment of navigation pools; however, bank and slope failures and erosion have occurred through time."

A reconnaissance study was undertaken to map the location of existing bank erosion and "place causative mechanisms in perspective." The conclusions stated that the Ohio River is a relatively stable large river with bed and bank failures and erosion, primarily as a result of flood flows or natural mechanisms. Less than 5 percent of the total physical and biological impacts were navigation related.

Regarding the field studies for tow passage, three general categories described data collections: bank studies, shallow-water studies, and channel studies (both water column and river bottom). The bank and shallow-water studies assessed wave impacts, and the channel studies evaluated return currents and propeller jets. The data collection appeared very intensive using many instruments and collecting as much information as was physically and technically possible at the time. Over 200 tow events were recorded at the five field sites during two trips (high and low water).

Measurements of velocities and wave heights at an embayment near the main channel were taken during tow passages. Ambient velocities were essentially zero until tow passage. Flow reversals were noted at a maximum 0.85-m/sec (2.8-fps) velocity. Wave heights (maximum recorded, 10.2 cm (4 in.)) were smaller than corresponding wave heights in the main channel. This was attributed to waves dissipating in the shoaled area.

To determine impacts of increased navigation on the Ohio River, worst-case conditions were selected. An upbound, fully loaded fleet of tows 354 m (1,160 ft) long, 5,600 hp was used. An analysis of tows navigating along the sailing line and 46 m (150 ft) from shore for several riverflow conditions was made. The frequency of proposed traffic was assumed to be 24 tows per day. The most critical effects were assumed at minimum depths of 3.7 m (12 ft) in the upper reaches of the pools. Twelve representative cross sections were selected and analytical equations were applied to predict wave heights, return currents, propeller jets, etc., for the different scenarios.

For large blockage ratios such as those on the Ohio River, diverging waves, not drawdown, dominated the wave spectrum except when the tow was traveling within 30.5 m (100 ft) of the shore. The study concluded that since tows within 100 ft of the shore are a rare occurrence for this condition, effects of drawdown on the bank are insignificant. Since eroding potential increased when sailing lines were within 46 m (150 ft), the study suggested avoiding this condition. The report stated that "as far as wave energy generated by a tow is concerned, calculations indicate that it takes approximately 50 tows to deliver as much energy as would a four hour storm, with wind velocities of about 40 fps."

Hagerty, Spoor, and Ullrich (1981)

In response to complaints that increasing traffic and vessel draft were responsible for bank erosion on the Ohio River, the authors conducted a study for the Corps. They reference studies conducted for the Huntington District in which waves from more than 200 commercial tows were recorded. The maximum wave height recorded was 1 m. The authors stated: "The wave data and observations made during numerous reconnaissance trips indicate that wave-related erosion is not significant in comparison to storm- and flood-related bank failures and erosion. On the other hand, it was noted that prop wash and direct impact from motor vessels (e.g., temporary moorings) can significantly alter bank areas. Also, in the Ohio River system, islands were found on which banks near the designated channel areas (thus potentially most subject to vessel waves) were vegetated and apparently stable, while the opposite banks of these islands (remote from potential traffic effects) were bare and apparently failed and eroded."

Hagerty (1983)

The author stated in the conclusions (as found in his other papers as well) that neither wave attack (whether wind or tow-generated) nor propeller turbulence (whether commercial or recreational craft) contributed significantly to bank failure or erosion on the Ohio River.

Hagerty and Hagerty (1989)

After first conducting an extensive bank erosion study on the Ohio River from 1976 to 1983, the authors were asked to reevaluate the situation in 1986. Louisville District requested this reevaluation to settle the controversy surrounding alleged erosive effects of commercial navigation traffic. The authors went back to 150 sites on the Ohio and reevaluated them with the same criteria as before. They also evaluated the relative increases and decreases in commercial traffic over this time frame and concluded there was no correlation between commercial traffic effects and bank erosion. In fact, the authors reported major increases in bank stability in 1986 compared to the original survey in spite of increases in commercial traffic between the two surveys.

Hagerty, Linker, and Beatty (1989)

A short-term investigation of bank erosion was conducted before and after construction of Smithland Lock and Dam on the Ohio River. The study was designed to evaluate bank appearance before and after the pool was raised. Efforts were made to isolate the effects of stage and seasonal vegetation coverage. According to the authors, "The changes in the appearances of the river banks which had taken place from one inspection trip to the next were attributable to permanent inundation, to differences in river stage, and to differences in seasonal vegetative cover at the times of the inspections."

Hagerty and Hamel (1989)

Regarding cross sections analyzed on the Ohio River and the Illinois River in 1988, the authors stated, "These cross-sections indicated that undercutting by waves or by currents during floods is not an important cause of bank failure on these alluvial stream banks. The topography seen on the banks indicated conclusively that bank failure and erosion occurred almost exclusively above the minimum navigation pool level."

Hagerty and Spoor (1989)

This report reviewed the bank erosion studies on the Ohio, Kanawha and Illinois Rivers conducted by the authors. On the Ohio, two-thirds of severely eroding sites in 1977 through 1983 were found stable in 1986. Since all sites were exposed to similar navigation effects, since traffic had increased as much as 49 percent between 1977 and 1986, and as a result of site-specific investigations, the authors concluded: "Waves and turbulence from commercial traffic in the stream channel do not initiate significant bank erosion along the Ohio River. However, fleeting activities and maneuvering near the bank could cause localized impacts." They also eliminated in-channel forces (secondary currents and turbulence) as causal mechanisms on the Ohio River. Failures were attributed to piping.

UMRS Navigation Erosion Studies

There are several studies on the influence of vessel-generated forces on bank erosion in the UMRS. The following authors conducted studies by measuring either the wave heights from commercial and recreation craft, changes in velocity, sediment resuspension, and/or bank line retreat on reaches of the Upper Mississippi and Illinois River now under consideration in the navigation study.

Bhowmik (1976)

A field data collection program was conducted in Lake Carlyle on the Kaskaskia River, a tributary to the Mississippi between the Illinois and Ohio Rivers. Wind data, wind wave data, and boat-generated wave data were collected, and existing stone protection around the lake was evaluated. The author offered a design procedure for riprap protection on banks due to wave action. To validate this design equation, he compared the computed stone sizes to his field observations.

Regarding boat-generated waves, he stated: "It is reasonable to expect that the lake shore must dissipate a major amount of wave energy in a shorter period of time whenever the boat is running close to the shore. Therefore, it might be advisable to ban any high-speed motor boat, say within 100 ft of the shore line."

In his conclusions he stated: "Extensive lake shore erosion caused by wind-generated waves is present in Illinois." He also showed a picture of an eroded bank that presumably failed as a result of wind waves. No criteria relating wave height to bank erosion, measurements of bank recession, or method for analysis was given to substantiate these conclusions.

Bhowmik and Schicht (1980)

The Corps employed the Illinois State Water Survey to conduct a 5-year demonstration program on the effects of increased Lake Michigan diversion on the bank stability of the Illinois River. The main objectives of the study were to "1) document present bank erosion areas, 2) develop present plan views of severely eroded banks at about 20 selected reaches, 3) make bank stability analyses for each reach, 4) attempt to assess the effect of the increase in the Lake Michigan diversion on bank erosion, 5) propose a monitoring system to document any future changes in bank conditions, 6) suggest future research areas that should be undertaken to better identify the causes of the bank erosion of the Illinois River."

Twenty-four reaches of severely eroded riverbank were charted during a 5-day field inspection trip. Suspended sediment and soil samples were collected at these sites. Based on evaluation of the sites considering proximity to sailing line, wind fetch, riverine hydraulics, etc., the report hypothesized the causes of the erosion.

The stability analyses techniques were Lane's critical tractive force method, permissible velocity for bank material sizes, and Shields' criteria. For waves, the authors calculated the significant wind wave height and used a riprap stability equation to determine a stable rock size. The authors did not give a minimum wave in which no protection is required. In fact, they stated that banks subjected to waves without protection will erode.

The conclusions stated the following: "On the basis of present and anticipated flow conditions and of measured and estimated hydraulic parameters, bank stability analyses at each study reach were made following different accepted procedures. Stability analyses indicate that as far as the flow hydraulics are concerned, bank erosion along the Illinois River will not be affected by the proposed increase in diversion. In all probability, the main cause of the bank erosion of the Illinois River is the wave action caused by the wind and/or waterway traffic."

Environmental Science and Engineering (1981)

This report documented the results of two 1-week field collection studies. During this study two-directional velocities and water quality data were collected during tow passage. Although no data were gathered regarding sediments or bank erosion, the authors postulated conclusions regarding potential impacts to sedimentation.

Boszhardt and Overstreet (1981)

This study was conducted under contract for the Rock Island District to survey cultural resources in Pool 12 of the UMR. The authors stated that all 15 archaeological sites, of which 12 are located on main or side channels and 3 in backwaters in Pool 12, are being destroyed by erosion associated with maintenance of the 2.74-m (9-ft) channel and the lock and dam system. The authors stated: "All individuals consulted agree that navigation improvements and navigation practices contribute to erosion of landforms within the pool."

In the study the authors, citing Gramann (1981) and others, stated that waves, both boat-induced and natural, are causing increases in erosion rates exacerbated by losses of vegetation along the shorelines due to pool operations. Since the information collected at each of the sites included only geologic attributes, cultural artifacts, and condition of banks, the authors used the opinions of other researchers to form general conclusions regarding the causal effects of erosion at the sites.

The authors, estimating that the annual losses of shoreline are 1-2 m per year in Pool 12, expect total destruction of some sites within a few years if no action is taken.

Bhowmik, Demissie, and Osakada (1981)

The authors stated that along some reaches of the Illinois River, 75 percent of the banks are eroded by wind- and traffic-generated waves, citing a 1980 study. In this study, the authors conducted six field studies at two sites on the

Illinois River and two sites on the Mississippi River. They measured waves from passing tows and collected data for a total of 59 events. The maximum wave height measured was 0.33 m (1.08 ft) and the maximum drawdown 0.21 m (0.69 ft). The relative significance of tow-generated waves versus wind waves could not be ascertained from this study.

Bhowmik and Demissie (1982)

They present an empirical equation developed from field studies on the Illinois and Mississippi Rivers for maximum wave height as a function of vessel Froude number (based on tow draft).

Bhowmik and Demissie (1983)

This article summarized some of Bhowmik's work to date. The authors described the processes of erosion due to wind- and boat-generated waves. Specific information was not given, and the authors referred to studies described in more detail in this literature review. They concluded with the following specific information regarding the Illinois and Mississippi Rivers, "River traffic generated waves in most parts are less than 1 ft in height. For a 2-year, 6-hour duration wind, the significant wave heights can reach up to 0.9 ft on the Illinois River and 1.3 ft on the Mississippi River. For a 50-year, 6-hour duration wind, the significant wave heights can be as much as 1.6 ft on the Illinois River and 2.4 ft on the Mississippi River. A thorough analysis of wind-generated waves and river traffic generated waves over a certain period of time is needed before the relative importance of these two types of waves on the bank erosion potential of any river can be estimated."

Oswalt and Strauser (1983)

The authors stated that navigation effects differ according to whether the system is open river, a confined waterway, or a maneuvering area. Only small changes in the bankline were observed by the Erosion and Sediment Work Group of the GREAT III study on the UMR, St. Louis District. Furthermore, the authors stated: "The total bank erosion experienced in today's improved waterway is less than that experienced by the river in its natural state. Of the bank erosion that is experienced, the portion attributable to navigation is presently difficult to quantify. Some types of bank erosion are erroneously attributed to navigation when, in fact, other more subtle causes are responsible." The authors suggested when blockage ratios are less than 10, problems could occur.

Warren (1987)

Based on historical observations, the author found the Illinois River geologically stable until the early 20th century. He summarized the findings of previous studies, citing many of Bhowmik's papers on the Illinois River. The summary stated: "Although it is difficult to judge the amount of bank erosion that occurred along the Illinois River under natural conditions, there is little question that erosion rates are much higher today. The modern channel is still straight, but a variety of artificial changes in the regimen of the Illinois have both reinforced old causes and introduced new causes of erosion... some of the more important of these changes include the heightened water-surface elevation of the river; the increased frequency and magnitude of flooding along the river; the increase in wave action generated by vessel traffic and, perhaps, by wind; the introduction of drawdown as a new erosive force; and probably also the feedback between these various factors and the modern characteristics of cutbanks along the river. Together, these man-made causes and conditions have helped to create a severe erosion problem along many stretches of the Illinois River."

A field study was conducted at five archaeologically important sites on the Illinois River. Rates of erosion were measured both horizontally and vertically over a period of approximately 6 months. At all but one site, banks were generally eroding. A statistical analysis using multiregression of 14 variables related to site characteristics and erosion measurements was conducted. (None of the variables related to processes such as wind energy, or vessel waves, etc.) The average horizontal erosion rate at the five sites was 1 mm/day, with a high of 2.5 mm/day at one site and a low of -1 mm/day at another. Extrapolation of these rates indicates a 35-cm loss of bank deposits per year along the lower Illinois River. The author concluded that since erosion occurred on both sides of the river in both convex and concave channel areas, natural phenomena could not have caused the erosion; therefore, much of the erosion must be due to vessel traffic.

Spoor and Hagerty (1989)

The authors conducted a detailed bank erosion study on the Illinois River. They investigated 31 sites, 20 where previous erosion had been observed by Bhowmik and Schicht (1980) and 11 considered more typical of those found on the waterway. Their study objectives were to observe existing bank conditions, to determine the erosion or failure mechanisms involved, and to describe the relative significance of each.

The study area was first observed by a helicopter overflight, followed by a boat trip where detailed information was obtained. Navigation charts were color coded to indicate bank conditions.

According to the authors, wave action from winds or vessels was not a significant cause of bank erosion; this conclusion differed from that of studies by Bhowmik. Their conclusions were based on the lack of eroding banks near areas where the banks were protected by sunken barges. The failures were attributed primarily to seepage mechanisms.

In conclusion the authors stated: "Investigations conducted in 1988 along the Illinois Waterway indicated that bank failure and erosion are initiated by the flow of water out of the banks and removal of soil particles by piping/sapping.... Wave swash did not appear to be a significant mechanism for removal of inplace soils, although levee notching indicated erosion by a combination of waves and tractive forces during floods. Propeller turbulence was a cause of only very localized bed/bench scour.... Waterway bank erosion was not severe or widespread; even within the pools where erosion was most extensive, only 6 percent of the total bank length was severely eroded."

Karaki and van Hoften (1975) studied the resuspension of bed sediments by tows and wave effects from tows and recreational vessels on the UMRS. The authors report that "the effects of increase in waves on river banks will depend on bank stability, and river bank form. Most sections of the river system have had wave wash from winds and boats for many years and are quite stable. Additional waves of the same heights generated by increased traffic are not likely to cause any significant increased rates of bank erosion where none is presently evident. Also, any river bank area that is being eroded by waves will continue to be affected, at an accelerated rate....The effects of fast moving boats are more destructive to river banks than waves from slower moving towboats."

Bhowmik, Soong, Reichelt, and Bogner (1990)

Recreational boat wave data were collected at an Illinois River site near Havanna, IL, and a Mississippi River site near Red Wing, MN. The data consisted of controlled boat runs and waves generated by recreational vessels during a busy Labor day weekend.

Statistical analysis of data from the controlled runs showed that the maximum duration of waves by individual crafts is about 42 sec with an average of 22 sec and within each wave train there could be a maximum of 30 waves and an average of 12 sec. Frequency analysis indicated the waves were predominantly 0.14 m with a maximum of 0.58 m.

In the uncontrolled data from the Red Wing site, a significant hourly wave height was determined. The significant wave height was defined as the wave height where one-third of the waves are larger. Maximum significant wave heights at this site were 0.4 to 0.5 m.

Bhowmik, Reichelt, Seddik, and Soong (1992)

Wave height data were collected and analyzed from recreational craft at a site on the Illinois River near Havana, IL, and a site on the Mississippi River near Red Wing, MN. Wave data were collected for over 240 controlled runs with 12 different boats. A regression equation was developed from these data and presented in this paper. Data were also collected on uncontrolled boating events on the Mississippi River. Over 700 boats passed one site in one day with a peak of 120 boats in 1 hour. Bed material samples were collected at both sites and suspended samples were collected at Red Wing. Other data collected were ambient velocity information, field site characterization data, and wind data.

Johnson (1994)

A study was conducted by the Minnesota Department of Natural Resources in cooperation with the U.S. Fish and Wildlife Service Environmental Management Technical Center to evaluate the recreational boating impacts on bank erosion in Pool 4 of the UMR. The study reach is upstream of Lake Pepin adjacent to Red Wing, MN. Three sites on the main channel and two control sites on the Wisconsin side channel were selected for monitoring. The main channel and side channel have similar geologic and hydrologic characteristics. Therefore, it was assumed that influences in the main channel could be attributed to vessel influences, particularly since all commercial traffic and most recreational traffic is in the main channel, and only limited recreational use of shallow-draft boats occurs in the side channel. An analysis of wind data and fetch suggested that wind waves were not responsible for the observed erosion.

Transects of the five sites have been surveyed approximately 15 times since 1989 including two surveys in the fall of 1993 and 1994, not included in the publication. The transects in the side channel remained stable over the study period, while the main channel transects showed shoreline recession of 3.0 to 4.3 m (10 to 14 ft) over this time frame.

Erosion rates were calculated in terms of area lost per day and normalized to a baseline selected during the winter months. A figure in the report shows the relative erosion rates over the survey period and indicates the recreational boating season. During the study, commercial traffic remained steady or slightly declined, whereas recreational boating increased. The relative erosion rates indicated increases in erosion during the recreational boating season in the main channel.

Turbidity data were collected in the main and side channels along with data on recreational boating activities. There was a strong diurnal flux in the turbidity levels in the main channel with peaks occurring on weekend afternoons during peak boating activities. Turbidities during boating activities when compared to no-wake zones were much higher. The author concluded, "From the results of the field investigations, it can be concluded that recreational boating on the Mississippi River Main Channel is the contributing influence most responsible for the documented high rate of shoreline erosion. Recreational boating is also directly responsible for elevated turbidity levels in the littoral zone during peak boating times."

It may be significant to note that Johnson observed that the main channel contains significant sand on top of the cohesive banks from dredged material placement whereas the cohesive banks in the side channel are exposed. Observations by Kamphuis (1990) suggest that the presence of sand in the main channel could have a significant effect on erosion rate. Studies are being conducted at WES to determine if beach nourishment sand is actually having a negative effect on shoreline stability.

Other Navigation-Related Studies in the United States

This section discusses several studies on bank erosion in other areas of the United States.

Das and Johnson

This study was conducted for the U.S. Army Coastal Engineering Research Center by the University of California (Das and Johnson 1970). Wave characteristics and total energy were obtained in towing tank tests of two vessel types, a mariner class cargo ship and a pleasure cruiser. The energy density was the mean square height of the waves, which varies with distance from the sailing line and ship speed. There was no information about the relationship between this energy and bank erosion, but the authors concluded that small boats can induce more serious wave conditions than can a large ship.

Anderson

Anderson (1974) conducted a field study measuring the suspended load in a tidal flat as several boats passed at specified testing conditions. His main study purpose was to determine the quantity of sediment resuspended by boat waves and track its fate or transport potential. If the resuspended matter is removed, one concern was that it could result in a potential erosion problem. If it is deposited elsewhere, it can have detrimental effects on either dredging requirements or sensitive environmental habitats.

A matrix of 16 foot valves connected to onshore pumps collected suspended sediment samples. Half were placed at 15 cm and half at 30 cm above the sediment/water interface. The sampling frequency was not given. Other data collected were temperatures and wave heights.

Six different boat types, from a 4.0-m (13-ft) aluminum skiff to a 10.4-m (34-ft) fiberglass tri-hull with 300 hp, were used. It is not clear from the testing descriptions the distance and speed at which each boat operated as it passed the nearshore sampling matrix. On page 2, last paragraph, the author stated that **one** of the six boats ran 46 m (150 ft) from the sampling matrix twice in rapid succession. He later discusses results based on the "first wave," "second wave," etc. It appeared the tests were designed to collect suspended sediments before, during, and following a "test."

The author concluded that the smaller boats actually caused decreases in suspended sediment probably due to mixing. The largest waves observed (20 cm) were from a 10.4-m (34-ft) lobster boat. The author states that its "first boat wave caused considerable in situ resuspension." The author describes the processes affecting the measured suspended sediments as mixing of concentrations already there, resupension occurring within the testing matrix, and materials being transported by tidal currents into the matrix from wave-resuspended materials outside the matrix.

Although supporting data were not given, the author stated the following in his conclusions, "The largest boat examined (34 foot lobster boat) with a displacement type hull caused considerable sediment resuspension at even slow speeds (5 knots). In contrast, tri-hulled type vessels which planed on top of the water caused relatively minor resupension and only resuspended sediment when operated at speeds less than planing."

The author also concluded from his study that more sediments were resuspended as a result of boat waves during the flood cycle than the ebb. In general, resuspended sediments could have a net landward transport. This report may be more useful in the sediment or recreational boat wave studies.

Liou and Herbich

Liou and Herbich (1976) presented a math model for predicting propeller jet distributions and a Shields approach for predicting incipient motion of bed materials. This was not related to bank erosion, but may be considered in evaluating propeller jets in areas where tows maneuver close to the bank.

Simons, Andrew, Li, and Alawady

Simons et al. (1979) determined that one process causing erosion is boat waves. While they characterized the boat waves as quite different from wind waves, they described their erosional processes as similar. The authors subjectively rated the relative significance of various processes on bank erosion. This qualitative assessment gave the most significant rating to shear stresses acting on a noncohesive bank and the least significant to freeze-thaw processes. Boat waves ranked third behind pool fluctuations.

Camfield, Ray, and Eckert

This report is very closely related to the purpose of this literature review. Camfield, Ray, and Eckert (1980) conducted a literature survey for the U.S. Coast Guard to identify causes of bank erosion, and summarized available information on vessel-generated forces with possible connections to bank erosion. This report is significant to the bank erosion study since it describes erosional processes and existing techniques for predicting forces very well. The following abstract summarizes the report:

"The purpose of this report is to provide a summary of the knowledge available on vessel generated wake, and the possible impact of this vessel wake on bank erosion. A literature survey was conducted to identify the various causes of bank erosion along waterways. A summary of the various natural effects and possible vessel effects is provided.

"Recession of waterway banks involves a large number of effects. The physical and chemical nature of the channel's water, the materials forming the bank, and the groundwater may increase the soil's erodibility by formerly noneroding water currents, wind waves, or vessel wakes.

"No computational methods exist for linking a vessel with a chosen hull shape, traveling at a chosen speed in a channel of chosen depth and chosen cross-sectional area and shape with banks of chosen height and materials, to a predicted occurrence of erosion."

Zabawa and Ostrom

Zabawa and Ostrom (1980) included a summary brochure highlighting important findings. Their purpose was "to evaluate whether recreational motorboat traffic is detrimental to the ecology of small creeks and coves in Anne Arundel County, Maryland." The Maryland Department of Natural Resources conducted field studies on two tributaries of the Chesapeake Bay at five site-specific locations where recreational boating is popular. To address critical questions, the study was designed to compare energies from wind waves and boat wakes, to measure shoreline changes on a monthly basis, and to relate wave energies to boating conditions.

Of the five sites monitored, erosion at one was determined to be directly attributable to boat wake energies. Even though this site did not have the highest level of traffic, it had the highest wake energies. In the study, it was concluded this was due to a higher number of boats getting closer to the shore, caused partly by the fact that the site was located in a narrow cove. In fact, the critical distance to avoid high-wave intensities was determined as 61 m (200 ft). They also determined that wave energies decreased at higher speeds. That is, maximum wake occurred before the boats planed. According to the study, maximum energies occurred at 3.1 to 4.1 m/sec (6 to 8 knots) especially in shallow water.

The article stated: "The (boat) wakes which were measured far exceeded the heights of normal wind-generated waves." And later it stated: "Wind waves ranked behind the storm effects in causing shoreline changes over the year of observations, and in all cases boat wakes represented lower levels of wave energy." These two statements can be interpreted as follows: even though individual boat waves can be higher than wind waves, the total annual energy produced by wind waves was found to be higher than the annual energy produced by boat waves, which only occur for shorter periods.

According to the conclusions, "The type of shoreline most susceptible to erosion would have a combination of :

- exposed point of land in a narrow creek or cove;
- fastland consisting of easily-erodible material such as sand or gravel;
- steep nearshore gradient on the shoreline profile;
- location adjacent to a high rate of boating, with boat passes relatively close to the shoreline."

At Site C where erosional activity was influenced by boating, suspended sediment data were also collected. It was concluded that the near-shore short-term suspended materials increased by more than two orders of magnitude after repeated passes of a recreational craft passing at 10.8 m/sec (21 knots) at a distance of 61 m (200 ft) from the shore.

This study provides regression equations between wave energy and boating frequency. It parallels the objectives given for the UMRS recreational boat wave study. Simple "rules," analytical methods, and guidance for field studies could be obtained from this reference.

Oswalt, Mellema, and Perry

Oswalt, Mellema, and Perry (1981) summarized mechanisms and studies on several Corps projects. Other than verbal descriptions of tow motion, no real connections were made to bank erosion. The authors recommended offshore mooring and lower speed limits in areas that may be susceptible to navigation effects.

U.S. Army Corps of Engineers

As a part of the streambank program, 20 sites were evaluated nationwide (U.S. Army Corps of Engineers 1981b). At the Delaware Estuary, the noted cause of bank erosion was vessel-induced waves. Erosion was more severe at high tides due to the wave attack at the base of the bank. Observed wave heights were from 0.6-0.9 m (2-3 ft). The observed bank erosion rate was approximately 0.6 m (2 ft) per year.

Kuo

Kuo (1983) is a literature review much like this one. Kuo summarized the work of Camfield, Ray, and Eckert (1980), Gatto (1982a), Anderson (1974), and Liou and Herbich (1976). In summary he stated, "Boat generated waves are not seen as a major problem affecting the rate of shore erosion, except in inlets, restricted navigational channels and relatively calm sheltered coves."

Linder and Wei

Linder and Wei (1986) attempted to determine whether hydropower operations at the Harry S. Truman Dam and Reservoir were contributing to erosion in the Lake of the Ozarks. The authors found power operations had no impact on bank failures. They suggested, without any supporting data, boat wake waves "appears to be a major cause of bank erosion."

Sorensen

Sorensen (1986)[1] characterized vessel-generated waves and reviewed available literature on bank protection for vessel-generated waves. Regarding sloped embankment failure, the author stated: "It may fail by sliding under its own weight and irrespective of external waterway forces. An embankment

---

[1] Robert M. Sorensen. (1986). "Bank protection for vessel generated waves," prepared by Lehigh University, Bethlehem, PA, for U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

along a water course may also fail because of hydraulic forces including those due to currents and waves, both of which have some similar effects....

"...When waves attack the embankment they will break on the slope, loosen and suspend soil, and carry some of the soil away from the embankment. A "notch" will form above the mean water level with an upper slope at about the soil's angle of repose, or possibly steeper to nearly vertical if the soil has cohesive properties. The submerged slope, which is similar to the beach face slope at an ocean beach, will typically be much flatter than the original embankment slope. The resulting submerged slope geometry will depend on the soil particle size and to some extent on the level of wave agitation.

"As the wave attack continues the notch will progress into the bank, increasing in size, until the steepened and possibly undercut slope collapses. The collapsed slope will leave a talus pile at the toe of the slope. The talus will then be removed by wave and current action so the bank recession process can continue again.

"Water level drawdown and return flow caused by a passing vessel will impact on this process primarily in two ways. Water flow down and back up, as well as horizontally, past the embankment will cause scour at the embankment toe. This will supplement the wave induced scour at the toe and talus removal from the toe. Also, the temporarily lowered water level during drawdown causes brief, but significant, outward hydraulic pressure gradients near the embankment face. These gradients and resulting seepage decrease bank structural stability which can lead to sliding, they can cause soil particle migration from the bank, and they can decrease the ability of surface particles to resist wave and current scour."

Davis

This study[1] investigated erosion along approximately 22 km (14 miles) of the Gulf Intracoastal Waterway (GIWW) near the Aransas National Wildlife Refuge.

Shoreline retreat rates determined from aerial photo comparisons were 0.6-0.9 m (2-3 ft) per year along certain reaches of the GIWW. (Note: Johnson (1994) reported a similar rate in high traffic areas on UMRS.) The eroded area along this segment of the waterway has been about 36.4 hectares (90 acres) since 1944. Erosion rates (shoreline retreat) were evaluated over segments of the study area for three different historic periods between 1950 and 1986.

Although no erosion data were collected relating to vessel passages, the

---

[1] Jack Davis. (1988). "Study of erosion along the GIWW in the Aransas National Wildlife Refuge" (unpublished), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

author concluded that traffic contributes to erosion since traffic occurs on both sides of the waterway and in areas protected from the wind. Since erosion on one bank is higher than on the other, the author stated that other mechanisms are also influencing erosion.

In the study, two types of erosional problems were identified, a gradual widening of the waterway and breaching into inland bays. The report indicated a loss of materials from the shallow bays. This observation was noted in some other studies as well. Some concepts were presented for stabilizing bank erosion.

Abbe and Eriksen

Abbe and Eriksen (1989) used energy as computed by Ofuya (1970) to examine onshore, offshore, and alongshore sediment movement along the banks of the Columbia River.

Knutson, Allen, and Webb

This study (Knutson, Allen, and Webb 1990) was funded by the Corps under the Dredging Operations Technical Support program. It classified dredged material shorelines, provided guidance for stabilization through vegetative techniques, and compared the energies from ship- and wind-generated waves.

The report stated that frequently sediment deposition occurs rather than erosion due to the energy dissipation of waves in vegetated marsh zones near the shoreline. In fact, one study referenced reported accretion of 15 to 30 cm of sediment in a 2-year period along a vegetated shoreline. Due to this aggradation, some shoreline marshes have advanced at rates of more than 10 m per year. Beaches of certain soil types and unprotected by marsh plants were more susceptible to erosion.

In describing the changes to beach geometry due to waves, the authors stated that generally steep waves move material offshore and long-period waves move material onshore. Also "when disposal areas are close to navigation channels, movement of sediment may be primarily offshore."

To determine the relative importance of wind versus boat waves, a sheltered dredged material island in North Carolina was studied. The study found the following: "The island is exposed to a fetch of only 0.5 km, but is located on the Atlantic Intracoastal Waterway where it is exposed to waves produced by the passing of approximately 25,000 boats per year at a distance of 100 to 200 m. The magnitude and frequency of wind and boat waves were studied at this site over a 2-year period. The study found that boats could produce waves equal to those produced by extreme wind conditions. However, in every category of waves, wind-generated waves were 10 times more frequent than were boat-generated waves. Boat waves are probably responsible for less than 5 percent of the wave energy impacting this site. Considering the limited fetch and the heavy vessel traffic of this example, it would appear that vessel traffic alone will seldom be the limiting factor in establishing coastal marshes for erosion control."

It does not say that boats do not contribute to erosion of the shoreline, but establishment of vegetation is a function of the wave energy environment. The report offers three methods of establishing vegetation based on the wave energy classifications of low, moderate, and high.

At the North Carolina site (with limited fetch and high vessel traffic), boat characteristic and wave data were collected. The majority of the motor-powered boats passing this site were in the 6- to 10-m length range. Each boat was assumed to produce 10 waves with a period of approximately 2 seconds. The majority of these waves were on the order of 15 cm (< 0.5 ft) and a rare maximum of 30 cm (<1.0 ft). These boats classify as recreational craft and would not likely produce drawdown and return currents.

Way, Miller, Paine, and Wakely

Way et al. (1990) described a software report that summarizes technical information available on the physical effects of navigation. Many of the references discussed navigation-related processes and are included in more detail in this report on bank erosion.

Bottin, McCormick, and Chasten

This report was also prepared for the Maryland Department of Natural Resources by WES (Bottin, McCormick, and Chasten 1993) as a guide to aid in the design of marinas in the Chesapeake Bay against boat waves. It provides a series of graphs for estimating wave heights for eight typical vessels found in the bay.

Thorne

This study (Thorne 1993) was conducted for WES under the Flood Control Channels research program. Thorne presented evaluation forms for field stud- ies of bank erosion. Along with listing other mechanisms for bank erosion, he described the impact of vessel forces. According to Thorne, damages can occur as a result of vessel-produced surface waves that are similar to wind waves, drawdown and surges that can loosen and erode materials, propeller wash if the vessel is close to shore, and the mooring of vessels along the bank.

As Thorne stated, "Evidence includes: use of river for navigation; large vessels moving close to the bank; high speeds and observation of significant vessel-induced waves and surges; a wave-cut notch just above the normal low-water plane; a wave-cut platform or 'spending' beach around normal low-water plane." He also noted the potential for mistaking the notch and platform, produced by the mechanisms of piping and sapping as described by Hagerty, for those produced by vessels.

Zhang, Hershberger, Spell, Ting, and Yu

Zhang et al. (1993) did a field investigation along the same stretch of GIWW near the Aransas National Wildlife Refuge as did Davis.[1] Two sites were selected to measure navigation effects, wind, and erosion rates. The sites selected had already experienced high erosion rates and had some form of shoreline protection in place. No sites were selected as a control.

Wind waves, tidal currents, boat waves, and velocities were measured at these two sites. Wind wave data were compared to an analytical model, ACES, based on the Great Lakes fetch and wave data. The model tended to overpredict wave heights when wind was blowing along the channel and underpredict when the wind was blowing across the channel. Annual and seasonal energy flux were calculated.

Attempts to verify existing models for ship waves (secondary waves) with data gathered from different vessel types were unsuccessful. The authors stated that "ship waves are the main source of energy to cause bank erosion."

Using a modification to the Bouwmeester momentum approach that considers boundary layer development, the authors found a good correlation between barge-tug drawdown and return current calculations and field measurements. They calculated the energy associated with drawdown and return flow based on a form resistance formula. "The energy impact on a unit length of bank is assumed to be equal to the work done by a ship to overcome ship resistance." This energy is the sum of the energy from drawdown return velocity, and secondary waves.

The authors did not directly link energy to measured bank erosion. They stated, however, that ship-induced waves and surges dominate the erosion mechanisms in the confined areas of the GIWW.

[1] Jack Davis. (1988). "Study of erosion along the GIWW in the Aransas National Wildlife Refuge" (unpublished), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

5 Bank Erosion Models

Literature on bank erosion modeling was reviewed to determine if a model exists or could be modified to assist the UMRS bank erosion study. The types of models related to navigation-induced mechanisms that may have bearing on the techniques selected for the UMRS bank erosion study fall into several categories. They are as follows:

a. Much research has been done in hydrodynamic models of ship motion (Jansen and Schijf 1953; Sorensen[1]; Pilarzcyk et al. 1989; Bouwmeester et al. 1977; Hochstein and Adams 1989, etc.). Many predictive formulas exist for quantification of vessel-induced forces including propeller jets, drawdown, secondary wave heights, and return currents. These formulas have in large part been verified in field and laboratory studies. Currently at WES, physical forces modeling is addressing the adaptation of these formulas to the specific characteristics of commercial navigation traffic and waterways on the UMRS. New techniques are being developed and verified using physical model testing, particularly with numerical solutions.

b. Another class of models or analysis techniques might be called relative importance models. The authors go beyond simply predicting vessel forces by calculating the energy produced by vessel forces and comparing it with energy from other mechanisms. The most common technique compares wind waves and boat waves (Ouellet and Baird 1978; Zabawa and Ostrom 1980; Knutson, Allen, and Webb 1990; Zhang et al. 1993). A few attempt to include other natural mechanisms such as river currents.

c. The most important, but least available, is erosion prediction models. The literature had several levels of sophistication regarding this modeling type. In many cases the "models" are based on threshold criteria such as Shields tractive force or critical velocities (for example, Bergh 1981). Darby and Thorne (1993, 1995) discussed various numerical models of

[1] Sorenson (1986), op. cit.

width adjustment in curved alluvial channels. The approaches described are limited to erosion initiated by flow-induced tractive force scour of the channel. Copeland and Thomas (1989) used a numerical model to evaluate bank erosion potential by determining the magnitude of bed degradation on the San Francisco River. River meander models have been developed by Ikeda, Parker, and Swai (1981), Kitanidis and Kennedy (1984), and Blondeaux and Seminara (1985). In a wave model, Hodek et al. (1986) set a wave height criterion of 0.15 m (0.5 ft) as a threshold for the onset of sediment motion. Hanson and Kraus (1989) presented a generalized model for simulating long-term shoreline changes as produced by longshore sand movement. Reservoirs with significant wind wave duration experience significant longshore transport, but vessel-generated waves are not of sufficient duration to allow application of this model. Larson and Kraus (1989) developed a two-dimensional numerical model, SBEACH, for simulating dune and beach erosion from wind waves. Nairn (1992) presented a summary of the complex wave-induced erosion processes of cohesive shorelines and presented results comparing his wind wave model to observed shoreline changes. Hagerty, Spoor, and Kennedy (1986) developed an analytical model for piping failure of streambanks.

d. Blaauw and van de Kaa (1978) presented a slightly more useful approach on rules of thumb for scour depths due to propeller jets, beyond initiation of motion criteria. Prosser (1986) also presented an equation for predicting maximum scour depth due to propellers.

e. Only two references, however, made an attempt to actually develop a model relating navigation causes to effect. One (Grigor'eva 1987) was unverified and showed a conceptual method for bank reworking due to wind waves only. The other reference is a study conducted on the Gordon River in Australia (Nanson et al. 1993). The authors actually measured erosion rates while boats passed a site. They found good correlations between wave power or wave height and erosion. In spite of these relationships, they ultimately reduced their relationships to "thresholds." In particular, the threshold for noncohesive alluvial sand is a maximum wave height of 30 cm. For removal of unconsolidated materials as swash loads, the threshold is 5 to 10 cm. Erosion rates were presented for pre- and post-boating speed limits.

In developing a boat wave erosion model, concepts from the wind wave erosion models similar to Kamphuis (1987) are a possible beginning point but need modification. Wave power appears a commonly used parameter, but existing wind wave models generally deal with large enough waves that the threshold wave power to initiate erosion can be ignored. This is not the case in boat waves, and a formulation similar to Kamphuis but including threshold wave power P_t, such as

$$R = A(P - P_t)^B \tag{9}$$

where P is the long-term average wave power may be required. Coefficient A and exponent B will vary with the parameters (soil type and shoreline bathymetry). More sophisticated models like SBEACH for sandy banklines and Nairn's (1992) model for cohesive shorelines need modification for the lower wave heights and different wave characteristics of boat waves. Modification of these models may be beyond the resources of the UMRS bank erosion study.

Wind wave erosion literature focused on the importance of foreshore slope erosion. Consider the bank profile in Figure 2 where the minimum pool elevation intersects the low sloping portion of the bank, referred to as the beach. If bank recession is defined as the movement of the waterline at a constant elevation such as the minimum pool elevation, then bank recession will not occur unless the waves are capable of downcutting the foreshore slope. Even if temporary high-water levels cause wave activity to break against the bluff, the resulting erosion will eventually be limited if the waves are not capable of downcutting the foreshore slope. This is the reason Kamphuis related long-term wind wave erosion to the rate of foreshore movement. Use of measured bluff recession rates over short periods of time when water levels are temporarily high and causing waves to impact against the bluff can lead to overestimates of long-term recession rates.

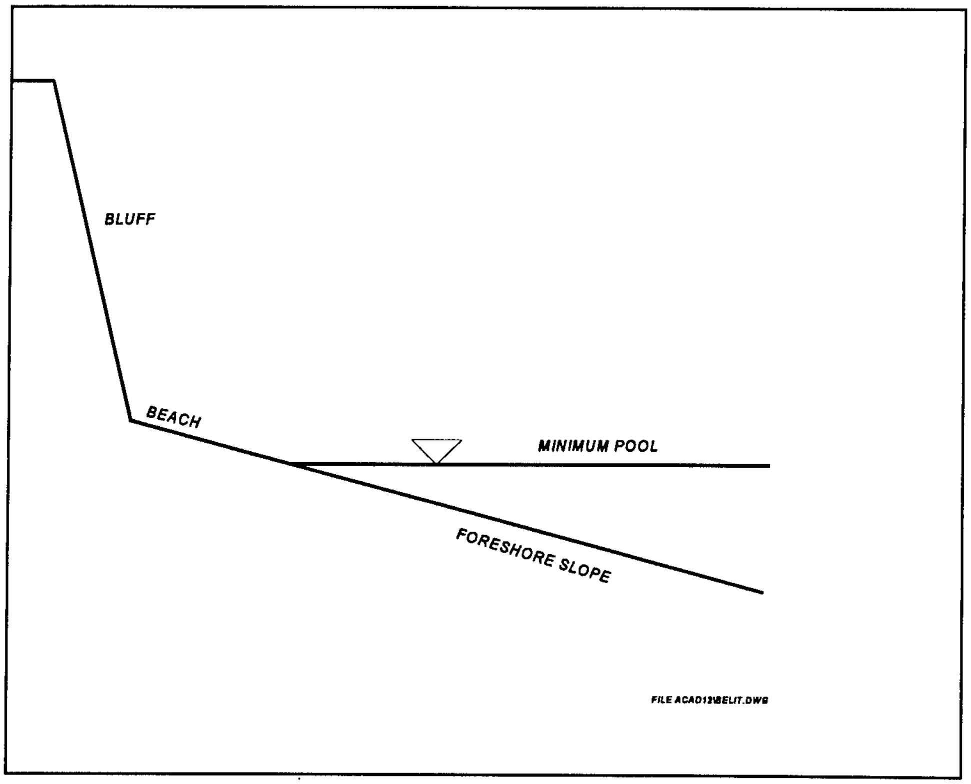

Figure 2. Schematic of shoreline

6 Dominant UMRS Bank Erosion Mechanisms and Their Identification

Dominant Mechanisms

Based on the cited UMRS reports, the experience of the authors of those reports, and the dominant mechanisms reported on similar streams, the dominant bank erosion mechanisms on the UMRS are listed in alphabetical order as follows:

a. Piping caused by flood recharge of banks and back of bank water sources. It is unknown if short-term drawdown from commercial vessels contributes significantly to piping-related failures. If true, piping caused by vessel drawdown would be limited to UMRS reaches having blockage ratios where drawdown magnitude is significant. Piping was classified as dominant because of the studies by Spoor and Hagerty (1989) on the Illinois River and the numerous studies by Hagerty and others on similar large, navigable, alluvial rivers.

b. Slope stability failures caused by undercutting due to waves, tractive force scour at high flows, piping, stage changes from flow variations and hydraulic structures, and moisture conditions in the bank. Bed degradation below UMRS dams can also contribute to slope instability. Again it is unknown if vessel-induced drawdown contributes significantly to slope failures. Slope stability failures are classified as dominant because their occurrence frequently follows the other four dominant mechanisms on the list.

c. Tractive force scour caused by high flows is generally accepted as a dominant mechanism on any alluvial stream like the UMRS. However, the literature did not reveal widespread occurrence of tractive force scour on the UMRS. Tractive force erosion is probably not extensive on the lower reach of the Illinois River (Lubinski 1993) (reach 2) because of the mild gradient. The 1993 Flood reports on the UMRS documented no significant bank erosion from an extremely large event both in magnitude and duration (USAED, Rock Island, 1994; USAED, Kansas City, 1994). It is likely that the numerous dikes and revetments on the UMRS partially explain the lack of tractive force scour. Tractive force scour at high flows was classified as dominant by the many authors who reported it as the major cause of erosion on alluvial rivers.

d. Wave erosion caused by vessels can be dominant in areas where traffic levels are high. Because of the lower amplitude and much less frequent occurrence from commercial tows, waves caused by vessels (short period) are predominantly caused by recreational vessels. Erosion from this mechanism would likely be greatest near metropolitan areas. Soil type plays a critical role in determining whether short-period waves are a dominant mechanism at a given site. Vessel waves (short period) were classified as dominant based on the studies by Bhowmik et al. (1992) and Johnson (1994) on the UMR.

e. Wave erosion caused by wind, primarily in the lower portion of UMRS pools, can be dominant where fetch distances are large. Wind waves were classified as dominant based on the many reservoirs experiencing wind wave erosion throughout the Corps in the presence of large impoundments on the lower portion of UMRS pools and the reports by Benn (1994) and Boszhardt (1990).

While these five mechanisms probably account for the majority of bank erosion on the UMRS, other less dominant or locally occurring mechanisms are present. The less dominant mechanisms are as follows (alphabetical order):

a. Freeze/thaw has been documented as an erosion mechanism on northern reservoirs.

b. Ice and debris have been documented as mechanisms of bank erosion.

c. Overbank drainage, when uncontrolled, can create local bank erosion.

d. Tractive force scour from propeller jets, primarily in bendways and bridge approaches, is a local cause of bank erosion and may be more prevalent in the upper reaches of the UMRS due to decreased channel widths.

Of unknown significance is the impact of sediment overloading from tributary streams that is widely reported on the UMRS. Geomorphic texts reported that sediment overloading will often result in channel widening by bank erosion. The impact of sediment overloading is somewhat offset by dredging as discussed in GREAT I (1980a). Also of unknown significance is the occurrence of transverse stern waves. These waves could occur in straight reaches of the upper UMRS, which has low blockage ratios.

Identification

How are various bank erosion mechanisms and causes recognized in the field? Keller, Kondolf, and Hagerty (1990) reported that piping type failures continue long after the flood event whereas failures of a saturated bank following a rapid drawdown tend to occur soon after the flood event. Hagerty (1991b) discussed the following factors in identification of piping-induced bank erosion:

a. Piping can be identified by active flow of soil and water from exfiltration zones, but such evidence is rarely found.

b. Strong indications of piping activity are furnished by features produced solely or principally by that mechanism such as piping cavities, blind gullies, and accumulations of piped-out soil particles.

c. Locations having soils stained a different color in exposed banks and shores are indirect evidence of piping activity, as are collapsed soil pipes at locations far from a bank or slope.

d. Other indirect evidence of piping activity includes features typical of certain localized failure modes associated with undercutting by piping (cracks, fallen blocks or slabs, and multiple scarps).

e. Piping ceases if soils displaced by piping are not removed by other transport mechanisms, but interaction with other mechanisms of erosion and sedimentation often obscures the evidence of piping and/or stops or retards piping activity.

Hagerty (1992) provided extensive photographs illustrating the piping mechanism. Hagerty, Spoor, and Parola (1995) observed that streams having a controlled stage and a gently sloping subaqueous bench at or just below minimum pool stage have been observed at hundreds of sites. "Bench formation is the result of bank failure and erosion processes including seepage induced erosion, localized failure of undermined layers, reworking of failed soils by waves, and erosion by current forces. Benches are prevalent along alluvial banks composed of layered soils." Location of benches was not related to planform; benches were found on the inside and outside of bendways.

Thorne (1993) developed bank erosion assessment sheets to aid in the field identification of channel stability, bank retreat, bank characteristics, erosive forces and processes, failure mechanisms, and extent of erosion. Pictures and descriptions of various erosion processes were provided.

Table 4 summarizes identification of the dominant bank erosion mechanisms using identification guidance by Hagerty (1991b) and Thorne (1993) and provides potential causes for their occurrence.

Table 4
Identification of Erosion Mechanisms on the UMRS

Mechanism	Primary Evidence	Potential Causes
Freeze/thaw	Periods of below-freezing temperatures; a loose crumbling surface layer of soil on the bank; loosened crumbs accumulated at the foot of the bank after a frost event; jumbled blocks of loose bank material	Climate
Ice and debris	Severe winters with rivers prone to ice over; rivers prone to heavy debris load; gouging and disruption of the bank line; toppling and cantilever failures of bank and attached ice masses during spring breakup	Climate, watershed characteristics
Overbank drainage (rilling and gullying)	Corrugated appearance of the bank surface due to closely spaced rills; larger gullied channels incised into the bank face; headward erosion of small tributary gullies into the floodplain surface; eroded material on lower bank	Uncontrolled surface runoff
Piping	Active flow of soil/water from exfiltration zones; piping cavities; blind gullies; accumulations of piped-out soil particles; stained zones; collapsed soil pipes away from bank	River stage variation, vessel drawdown, septic tanks, adjacent water bodies, poor overbank drainage, excess precipitation, land use change
Slope instability (various types of slope instability detailed in Thorne (1993))	Failure debris at base of slope; debris can be blocks, slabs, cantilevers, or loose depending on failure type and bank material	Stage fluctuation; rapid drawdown; undercutting and undermining by other mechanisms such as tractive force scour, waves, piping, bed degradation
Tractive force	High flow velocity near bank; near bank scouring of bed; undercutting of toe/lower bank relative to bank top;fresh ragged appearance to bank face	Meandering, high flow, flow impingement, structures, vessel currents, land use change such as removal of riparian vegetation
Waves	Large wind fetch; acute angle between eroding bank and direction of significant waves; high vessel traffic frequency and small distance from sailing line; wave cut notch just above normal low-water plane; wave cut platform or run up beach around normal low-water plane	Wind or vessels

7 Summary and Conclusions

Extent of Bank Erosion

Illinois River

Warren (1987) described the Illinois River as a river with a severe erosion problem; however, Spoor and Hagerty (1989) reported waterway bank erosion was not severe or widespread. The 1993 flood reports by USACE and others did not report the occurrence of significant bank erosion on the Illinois River.

Upper Mississippi River

GREAT II (1980c) (Lock and Dam 10 to Saverton, MO) reported that 15 percent of total bank miles for all main stem rivers were experiencing bank erosion. GREAT III (Morris 1982) (Saverton to mouth of Ohio River) reported small high bank line changes over the 22 years studied. The USACE 1993 flood reports did not mention relative occurrence of the UMR bank erosion. Benn (1994) reported that flood damage in the Rock Island District from the 1993 Flood occurred at less than 5 percent of all sites in the valley.

Dominant Bank Erosion Mechanisms and Causes

The following dominant erosion mechanisms on the UMRS and their potential causes are listed in alphabetical order:

a. Piping caused by flood recharge or back of bank water sources with the possible addition of drawdown from commercial vessels.

b. Slope stability failures caused by undercutting by waves, tractive force scour at high flow, or piping in conjunction with stage changes from flow variation or structure operation and vessel drawdown.

c. Tractive force scour caused by high flow.

d. Waves caused by vessels (short period).

e. Waves caused by wind.

Less dominant or locally occurring erosion mechanisms are freeze/thaw, ice and debris, uncontrolled overbank drainage, and tractive force scour from propeller jets.

Channel widening by tractive force scour is a geomorphic response to overloading of sediments reported on the UMR due to tributary inputs. It is not known whether this is a significant cause of erosion on the UMRS.

Bank Erosion Models

Little modeling effort relating boating activity to bank recession was found. It is likely that a wind wave bank recession model could be modified to address boat wave induced bank erosion. The ability of waves to downcut the foreshore slope must be considered in predicting long-term recession rates.

Significance of Commercial Navigation in Bank Erosion

Summary of navigation-related studies

The references cited on navigation-related bank erosion are broad in scope and content. The St. Lawrence studies and the studies on the Rhine River are important because their objective is similar to that of the UMRS navigation study. Those studies evaluated incremental effects of navigation (specifically increases in vessel size and a longer navigation season) on bank erosion. Studies on the UMRS and Illinois combined the previous and the current efforts to identify bank erosion and its potential causes. These studies provided diverse approaches and opinions regarding the nature of existing conditions and what has the most application for these conditions. Several studies may be important for follow-up. Although no bank erosion data were collected by Bhowmik et al. (1992) on the site near Red Wing, MN, this study could provide data for correlations to the Minnesota Department of Natural Resources (Johnson 1994) bank erosion study. Actual erosion rates on the UMRS could be determined by follow-up investigations at sites like those described in Boszhardt and Overstreet (1981) and Warren (1987).

Recurring throughout the references was the recommendation of bank protection in locations where there were active erosion sites, forces exceeded threshold criteria, and potential erosion might occur. In some cases, where the dominant cause was traffic, restrictions on vessel size, speed, or proximity to the shoreline might also be recommended.

Wuebben described a phenomenon he calls "explosive liquefaction." It states that during ship-induced drawdown, an imbalance is created in the pore pressures of bottom sediments, resulting in sediment resuspension followed by a net offshore migration of sediments.

Gatto stated that during ice, ships can disrupt the bank by directly shoving ice on the bank and by breaking up the ice near the shore that protects the bank from wave erosion. Gatto concluded from his studies that contributions to erosion from navigation are minor.

Wuebben, Pilarzyck, and others recognized that predicting the actual magnitude of damages at a site is not possible at this time. Wuebben attempted to estimate areas that **could** be affected by navigation.

The Detroit District concluded that wind waves and small boats had more significant impacts than ships on the St. Marys River. Reported erosion was attributed to high flows.

Summary of commercial navigation effects

Based on the cited reports, the following conclusions are drawn relative to bank erosion resulting from commercial navigation:

a. Short-period waves from commercial navigation may not be a significant cause of erosion on the UMRS because of the low wave height and infrequent occurrence when compared to recreational vessels.

b. The importance of tow drawdown causing slope failures or piping is unknown. Wuebben reported that vessel-induced drawdown can cause liquefaction of streambeds. Since drawdown magnitude is highly correlated with blockage ratio (channel area/vessel area), it is almost certain that if drawdown causes failures, these failures will be most frequent in the upper reaches of the UMRS where channel sizes are smallest.

c. It is possible that in straight reaches (where vessels can travel at high speed) of the UMRS upper reaches where blockage ratios are small, transverse stern waves form and cause significant attack of bank lines.

d. Propeller wash was assigned a less dominant role in causing erosion because the UMRS literature was relatively quiet on this issue. Propeller jet scour is generally limited to unprotected low-radius bendways or bridge crossings with difficult approaches. It is likely that in the upper reaches of the UMRS, the smaller channel sizes result in greater occurrence of propeller jet effects.

e. The pattern that emerges from these statements is that bank erosion from commercial navigation, if any, will be most prevalent in areas where channel sizes are smallest or in larger channels where navigation is close to erodible bank lines.

References

Abbe, Timothy, and Eriksen, Karl. (1989). "Shallow water sand transport by ship waves." *Coastal Zone '89*, Proceedings of the Sixth Symposium on Coastal and Ocean Management, Charleston, SC, July 11-14, 1989. ASCE, New York. 3795-3808.

Allen, Hollis H., and Tingle, John L. (1993). "Proceedings, U.S. Army Corps of Engineers workshop on reservoir shoreline erosion: a national problem," Miscellaneous Paper W-93-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

American Society of Civil Engineers Task Committee on Cohesive Materials (1966). "Committee on Sedimentation, "Abstracted Bibliography on Erosion of Cohesive Materials," *Journal, Hydraulics Division, American Society of Civil Engineers*, 92(HY2), 242-244.

Anderson, Franz E. (1974). "The effect of boat waves on the sedimentary processes of a New England tidal flat," Technical Report 1, Jackson Estuarine Laboratory and University of New Hampshire, Durham, NH.

Armstrong, Richard C., Cingle, George, Jr., Kiper, Jack E., Niemi, Jack R., and Waddell, Kennard M. (1985). "Replacement and rehabilitation of aging navigation structures on the Mississippi and Ohio river navigation systems." *26th International Navigation Congress,* Brussels, Belgium, June 16-22, 1985. Permanent International Association of Navigation Congresses, Brussels, Belgium. Section I, 205-214.

Balanin, V. V., and Bykov, L. S. (1965). "Selection of leading dimensions of navigation channel selections and modern method of bank protection." *21st International Navigation Congress*, Stockholm. Permanent International Association of Navigation Congresses, Brussels, Belgium, Section I - Subject 3, 151-170.

Balanin, V., Zernov, D., Kirjakov, S., Metelitsina, G., Polunin, A., and Schegolev, V. (1977). "Peculiarities of navigation on canals and restricted channels, originating hydraulic pheneomena associated with them and their effect on the canal bed; measures preventing slope deterioration." *24th International Navigation Congress*, Leningrad, 1977. Permanent International Association of Navigation Congresses, Brussels, Belgium. Section I - Subject 3, 183-202.

Bathurst, J. C., Thorne, C. R. and Hey, R. D. (1979). "Secondary flow and shear stress at river bends," *Journal, Hydraulics Division, American Society of Civil Engineers*, 105(10), 1277-1295.

Bekendam, A. J., et al. (1988). "Six-barge pushtow trials," Bulletin No. 62, Permanent International Association of Navigation Congresses, Brussels, Belgium, 21-84.

Bell, G. L. (1968). "Piping in the Badlands of North Dakota." *Proceedings, Sixth annual engineering geology and soils engineering symposium.* University of Idaho, 242-257.

Benn, D. W. (1994). "Reconnoitering archaeological sites after the flood in the Rock Island District, Upper Mississippi Valley." *Archeology and the great midwestern floods of 1993*, William Green and Robin M. Lillie, ed., Office of State Archaeologist,University of Iowa, Iowa City, IA. Vol 19(4).

Bergh, Hans. (1981). "The influence on harbors of the action of the jet behind a propeller," Bulletin No. TRITA-VBI-123, Hydraulics Laboratory, Royal Institute of Technology, Stockholm, Sweden.

Bergh, Hans, and Cederwall, Klas. (1981). "Propeller erosion in harbors," Bulletin TRITA-VBI-107, Royal Institute of Technology, Stockholm, Sweden.

Bhowmik, Nani G. (1976). "Development of criteria for shore protection against wind-generated waves for lakes and ponds in Illinois," UILU-WRC-76--0107 Research Report No. 107, Water Resources Center, University of Illinois at Urbana-Champaign.

Bhowmik, Nani G., and Demissie, Misganaw. (1982). "Waves generated by river traffic." *Applying research to hydraulic practice,* proceedings of the Conference, Jackson, MS, August 17-20, 1982. Peter E. Smith, ed., American Society of Civil Engineers, New York, 179-188.

Bhowmik, Nani G. and Demissie, Misganaw. (1983). "Bank erosion by waves." *Proceedings of the conference on frontiers in hydraulic engineering*. American Society of Civil Engineers, New York, NY.

Bhowmik, Nani G., and Schicht, Richard J. (1980). "Bank erosion of the Illinois river," Report No. ISWS/RI-92/80, Illinois State Water Survey, Urbana, IL.

Bhowmik, Nani G., Demissie, Misganaw, and Osakada, S. (1981). "Waves and drawdown generated by river traffic on the Illinois and Mississippi Rivers," SWS Contract Report 271, Illinois Institute of Natural Resources, University of Illinois, Champaign.

Bhowmik, Nani G., Reichelt, Walter F., Seddick, Hoha M. L., and Soong, Ta-Wei. (1992). "Waves generated by recreational traffic on the upper Mississippi river system," Long Term Resource Monitoring Program Special Report 92-S003, Illinois State Water Survey, Champaign, IL.

Bhowmik, Nani G., Soong, Ta Wei, Reichelt, Walter, and Bogner, William C. (1990). "Waves generated by recreational traffic on the upper Mississippi River System." *Proceedings of the 1990 conference on hydraulic engineering*, San Diego, CA, July 30-August 3, 1990. American Society of Civil Engineers, New York, 855-860.

Biedenharn, D. S., Raphelt, N. K., and Montague, C. A. (1983). "Long term stability of the Ouachita River," *River meandering*, Proceedings of the Conference on Rivers '83, New Orleans, 1983. C. M. Elliot, ed., American Society of Civil Engineers, New York.

Biedenharn, David S., Combs, Phil G., Hill, Glenda J., Pinkard, C. Fred, Jr., and Pinkston, Clara B. (1989). "Relationship between channel migration and radius of curvature on the Red River." *Sediment transport modeling*, Proceedings of the international symposium, New Orleans, LA, Aug. 14-18, 1989. Sam S.Y. Wang, ed., American Society of Civil Engineers, New York.

Bishop, C. T., Skafel, M. G., and Nairn, R. B. (1992). "Cohesive profile erosion by waves." *23rd international conference on coastal engineering*, Venice, Italy, 4-9 October 1992. American Society of Civil Engineers, New York, 173-174.

Blaauw, H. G., and van de Kaa, E. J. (1978). "Erosion of bottom and sloping banks caused by the screw race of maneuvering ships." *7th International Harbour Congress*, Antwerp, Belgium, May 22-26, 1978. Published as Delft Hydraulics Laboratory Publication No. 202, Delft, The Netherlands.

Blaauw, H. G., de Groot, M. T., Pilarczyk, K. W., and van der Knapp, F. C. M. (1984). "Design of bank protection of inland navigation fairways." Delft Hydraulics Laboratory Publication No. 320, Delft, The Netherlands.

Blondeaux, P., and Seminara, G. (1985). "A unified bar-bend theory of river meanders," *Journal of Fluid Mechanics* 157, 449-470.

Boszhardt, R. F. (1990). "A phase I archaeological survey of proposed barrier islands, Navigation Pool 8, Upper Mississippi River," Report of

Investigations No. 101, Prepared under Contract No. DACW37-89-M-1104 by the Mississippi Valley Archaeology Center, University of Wisconsin, La Cross, WI, for the U.S. Army Engineer District, St. Paul, St. Paul, MN.

Boszhardt, Robert F., and Overstreet, David F. (1981). "Preliminary investigations: archaeology and sediment geomorphology, Navigation Pool 12, Upper Mississippi River, volume 1," performed under Contract No. DACW25-81-C-0045 by Great Lakes Archaeological Research Center, Inc., Waukesha, WI, for U.S. Army Engineer District, Rock Island, Rock Island, IL.

Bottin, Robert R., Jr., McCormick, John W., and Chasten, Monica A. (1993). "Maryland guidebook for marina owners and operators on alternatives available for the protection of small craft against vessel-generated waves," prepared by U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, for Maryland Department of Natural Resources, Annapolis, MD.

Bouwmeester, J., van de Kaa, E. J., Nuhoff, H. A., and van Orden, R. G. J. (1977). "Recent studies on push-towing as a base for dimensioning waterways," Publication No. 194, Delft Hydraulics Laboratory, The Netherlands. Paper presented at *24th International Navigation Congress,* Leningrad, September 1977, Permanent International Association of Navigation Congresses, Brussels, Belgium.

Boyt, W.L. (1992). *Cohesive Sediments Research Newsletter*. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, June.

Browne, W. H. (1980). "Effect of navigation dams on banks of the Ohio River." *Proceedings of the National Waterways Roundtable*, Norfolk, VA, April 22-24, 1980. U.S. Army Engineer Water Resources Support Center, Fort Belvoir, VA.

Budhu, Muniram, and Gobin, Roger. (1994). "Instability of sandbars in Grand Canyon," *Journal of Hydraulic Engineering* 120(8), August 1994, Paper No. 5537.

Burgi, P. H. and Karaki, S. (1971). "Seepate effect of channel bank stability," *Journal of the Irrigation and Drainage Division, American Society of Civil Engineers,* 97 (IR1), 59-72.

Camfield, Frederick E., Ray, Robert E. L., and Eckert, James W. (1980). "The possible impact of vessel wakes on bank erosion," Technical Report No. CG-W-1-80, National Technical Information Service, Springfield, VA.

Church, Peter E. (1984). "Archaeological potential of pool number 10, upper Mississippi river: a geomorphological perspective," prepared for the

U.S. Army Engineer District, St. Paul, by the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Clough, G. W. (1966). "Ground water level in silty and sandy Mississippi Upper Banks," published by Mississippi River Commission, Vicksburg, MS.

Copeland, R. R., and Thomas, W. A. (1989). "Evaluation of bank erosion potential, Clifton, Arizona; Numerical model investigation," Miscellaneous Paper HL-89-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Crickmay, C. H. (1960). "Lateral activity in a river of northwestern Canada," *Journal of Geology* 68, 377-391.

Darby, Stephen E., and Thorne, Colin R. (1993). "Approaches to modeling width adjustment in curved alluvial channels," Performed under Research Contract DAJA45-92-M-0248 by Department of Geography, University of Nottingham, Nottingham, UK, for U.S. Army European Research Office, London, NW1 5th, England.

Darby, Stephen E., and Thorne, Colin R. (1995). "Bank stability algorithm for numerical modeling of width adjustment," Performed under Contract No. N68171940C9062 by Department of Geography, University of Nottingham, Nottingham, UK, for U.S. Army European Research and Development and Standarization Group, London, England.

Das, M. M and Johnson, J. (1970). "Waves generated by large ships and small boats." *Proceedings of the 12th conference on coastal engineering*, Washington, DC. American Society of Civil Engineers, New York, 2281-2285.

El-Moattessem, M., and Hassan, R. M. (1991). "Hydraulic phenomena accompanied by the movement of the river Nile fleet," *Physical responses of the river Nile to interventions,* Cairo, Egypt, Canadian International Development Agency, Hull, Quebec, Canada.

Environmental Science and Engineering. (1981). "Navigation impact study," Phase III, Task 9, Prepared for Illinois Natural History Survey.

Everitt, B. L. (1968). "Use of cottonwood in the investigation of the recent history of a flood plain," *American Journal of Science* 206, 417-439.

Fisk, H. N. (1944). "Geological investigation of the alluvial valley of the Lower Mississippi River," Mississippi River Commission, Vicksburg, MS.

Fremling, Calvin R., and Claflin, Thomas O. (1993). "Ecological history of the Upper Mississippi River." *Proceedings of the 15th Annual Meeting of* *the Mississippi River Research Consortium.* James G. Wiener, Richard V. Anderson, and David R. McConville, ed., Butterworth, Boston, Chapter 2, 5-24.

Fremling, C. R., Gray, D. V., and Nielsen, D. N. (1973). "Environmental impact study of Pool 5 of the northern section of the Upper Mississippi River Valley," Phase III Report, Winona State College, Winona, MN.

Fuehrer, Met. M., and Romisch, Ing. K. (1977). "Effects of modern ship traffic on inland- and ocean-waterways and their structures." *24th international navigation congress,* Leningrad, 1977, Section I, Subject 3, Permanent International Association of Navigation Congresses, Brussels, Belgium.

Fuehrer, M., Romisch, K., and Engelke, G. (1981). "Criteria for dimensioning the bottom and slope protections and for applying the new methods of protecting navigation canals." *Proceedings of the 25th international navigation congress,* Edinburgh. Permanent International Association of Navigation Congresses, Subject 1, 29-50.

Garrad, P. N. and Hey, R. D. (1988). "Effect of boat traffic on river regime." *International conference on river regime,* Wallingford, Oxfordshire, England, 18-20 May 1988. John Wiley, Chichester, 395-409.

Gatto, Lawrence W. (1982a). "Shoreline conditions and bank recession along the U.S. shorelines of the Saint Marys, Saint Clair, Detroit and Saint Lawrence rivers," Report No. CRREL-82-11, Cold Regions Research and Engineering Laboratory, Hanover, NH.

Gatto, Lawrence W. (1982b). "Reservoir bank erosion caused and influenced by ice cover," Report CRREL-SR-82-31, U.S. Army Engineer Cold Regions Research and Engineering Laboratory, Hanover, NH.

Gatto, Lawrence W., and Doe, William W., III. (1987). "Bank conditions and erosion along selected reservoirs," *Environmental Geological Water Science* 9(3), 143-154.

Good, G. (1993). "The costs associated with shoreline erosion on Illinois lakes and reservoirs," Miscellaneous Paper W-93-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Gramann, J. H. (1981). "Navigation-related impacts on cultural resources of the U.S. EMBRACE," *Contract Abstracts and CAM Archaeology* 2(3), 11-16.

Great River Environmental Action Team. (1980a). "GREAT I: Main report; Volume 1, a study of the Upper Mississippi River," St. Paul, MN.

Great River Environmental Action Team. (1980b). "GREAT I: Water quality, sediment and erosion," Technical Appendixes, Volume 4, St. Paul, MN.

Great River Environmental Action Team. (1980c). "GREAT II: Sediment and Erosion Work Group Appendix," report prepared by GREAT II on Upper Mississippi River from Guttenberg, Iowa, to Saverton, Missouri.

Grigor'eva, O. G. (1987). "Assessment of the reformation of canal banks by waves from small ships," *Soviet Meteorology and Hydrology* 3, 65-69.

Hagerty, D. J. (1983). "Mechanisms of erosion and meandering-Ohio River," *River meandering-proceedings of the conference Rivers '83*, Hydraulics Division Specialty Conference, New Orleans, LA. American Society of Civil Engineers, New York, 259-270.

Hagerty, D. J. (1991a). "Piping/sapping erosion. I: basic considerations," *Journal of Hydraulic Engineering*, American Society of Civil Engineers, 117(8), 991-1008.

Hagerty, D. J. (1991b). "Piping/sapping erosion. II: identification-diagnosis," *Journal of Hydraulic Engineering,* American Society of Civil Engineers, 117(8), 1009-1025.

Hagerty, D. J. (1992). "Identification of piping and sapping erosion of streambanks," Technical Report HL-92-1, prepared by University of Louisville, Louisville, KY, for U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Hagerty, D. J., and Hagerty, M. J. (1989). "Ohio River bank erosion—traffic effects," *Journal of Waterway, Port, Coastal, and Ocean Engineering* 115(3), 404-408.

Hagerty, D. J., and Hamel, James V. (1989). "Geotechnical aspects of river-bank erosion." *Proceedings of the 1989 national conference on hydraulic engineering*, New Orleans, August 14-18, 1989. Michael Ports, ed., American Society of Civil Engineers, New York, 118-123.

Hagerty, D. J., and Spoor, M. F. (1989). "Alluvial stream bank erosion--a ten year study," *Proceedings of the international symposium, sediment transport modeling*, New Orleans, August 14-18, 1989. Sam Wang, ed. American Society of Civil Engineers, New York, 594-599.

Hagerty, D. J., Linker, R. A., and Beatty, D. A. (1989). "Evaluation of navigation dam effects on riverbanks," *Journal of Waterway, Port, Coastal, and Ocean Engineering* 115(3).

Hagerty, D. J., Sharifounnasab, M., and Spoor, Michael F. (1983). "River-bank erosion — a case study," *Bulletin of the Association of Engineering Geologists* XX(4), 411-437.

Hagerty, D. J., Spoor, Michael F., and Kennedy, John F. (1986). "Interactive mechanisms of alluvial-stream bank erosion," *3rd international symposium on river sedimentation*, Jackson, Mississippi, March 31-April 4. S. Y. Wang, H. W. Shen, L. Z. Ding, ed., University of Mississippi, University, MS. 1160-1168.

Hagerty, D. J., Spoor, M. F., and Parola, A. C. (1995). "Near-bank impacts of river stage control," *Journal of Hydraulic Engineering, American Society of Civil Engineers,* 121 (2), 196-207.

Hagerty, D. J., Spoor, M. F., and Ullrich, C. R. (1981). "Bank failure and erosion on the Ohio River," *Engineering Geology* 17, 141-158.

Hamel, James V. (1983). "Geotechnical perspective on river bank instability." *Proceedings of the conference on frontiers in hydraulic engineering*, Cambridge, MA, August 9-13, 1983. 212-217.

Hamill, G. A. (1988). "The scouring action of the propeller jet produced by a slowly manoeuvring ship," Bulletin No. 62, Permanent International Association for Navigation Congress (A.I.P.C.N.), Brussels, Belgium.

Hammer, T. R. (1972). "Stream channel enlargement due to urbanization," *Water Resources Research* 8, 1530-1540.

Hanson, H., and Kraus, N. C. (1989). "Genesis: Generalized Model for Simulating Shoreline Changes," Technical Report CERC-89-19, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Harrison, S. S., and Clayton, L. (1970). "Effects of ground-water seepage on fluvial processes," *Geological Society of America Bulletin* 81, 1217-1226.

Headquarters, U.S. Army Corps of Engineers. (1994). "Channel stability assessment for flood control projects," Engineer Manual 1110-2-1418, U.S. Government Printing Office, Washington, DC.

Hickin, E. J. (1974). "The development of meanders in natural river-channels," *American Journal of Science* 274, 414-442.

Hickin, E. J., and Nanson, G. C. (1984). "Lateral migration rates of river bends," *Journal of Hydraulic Engineering, American Society of Civil Engineers,* 110(11), 1557-1567.

Hill, A. R. (1973). "Erosion of river banks composed of glacial till near Belfast, Northern Ireland," *Zeitschrift fur Geomorphologie* 17, 428-442.

Hochstein, Anatoly B., and Adams, Charles E., Jr. (1989). "Influence of vessel movements on stability of restricted channels," *Journal of Waterway, Port, Coastal, and Ocean Engineering*, American Society of Civil Engineers, 115(4), 44-465.

Hodek, R. J., Annable, M. D., Alger, G. R., and Santeford, H. S. (1986). "Development of a predictive model to assess the effects of extended season navigation on Great Lakes Connecting Waters," Performed under Contract No. DACA 89-85-K-0001 by Michigan Technological University for U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

Hooke, J. M. (1979). "An analysis of the processes of river bank erosion," *Journal of Hydrology* 42, 143-157.

Hooke, J. M. (1980). "Magnitude and distribution of rates of river bank erosion," *Earth Surface Processes and Landforms* 5(2),143-157.

Hughes, D. J. (1977). "Rates of erosion on meander arcs." *River Channel Changes*. K. L. Gregory, ed., John Wiley, London, 193-205.

Ikeda, S., Parker, G., and Swai, K. (1981). "Bend theory of river meanders; Part I, Linear development," *Journal of Fluid Mechanics* 112, 363-377.

Jansen, P., and Schijf, J. B. (1953). *Eighteenth international navigation congress*, Rome. Permanent International Association of Navigation Congresses, Brussels, Belgium, Section 1, Communication 1, 175-197.

Johnson, Scot. (1994). "Recreational boating impact investigations, upper Mississippi River system, pool 4, Red Wing, Minnesota," Minnesota Department of Natural Resources, and U.S. Fish and Wildlife Service, Environmental Management Technical Center, Lake City, MN.

Kamphuis, J. W. (1987). "Recession rate of glacial till bluff," *Journal of Waterway Port, Coastal, and Ocean Engineering*, American Society of Civil Engineers, 113(1).

Kamphuis, J. W. (1990). "Influence of sand or gravel on the erosion of cohesive sediment," *Journal of Hydrology Research* 28(1), 43-53.

Karaki, S., and Van Hoften, J. (1975). "Resuspension of bed material and wave effects on the Illinois and Upper Mississippi rivers by boat traffic," performed under Contract No. LMSSD 75-881 by Colorado State University, Fort Collins, CO, for U.S. Army Engineer District, St. Louis, St. Louis, MO.

Keller, E. A., Kondolf, G. M., and Hagerty, D. J. (1990). "Groundwater and fluvial processes; selected observations." *Groundwater geomorphology: the role of subsurface water in earth-surface processes and landforms.* Special Paper 252, Geological Society of America, Boulder, CO, Chapter 15, 319-340.

Kitanidis, P., and Kennedy, J. F. (1984). "Secondary current and river-meander formation," *Journal of Fluid Mechanics* 144, 217-229.

Knutson, Paul L., Allen, Hollis H., and Webb, James W. (1990). "Guidelines for vegetative erosion control on wave-impacted coastal dredged material sites," Technical Report D-90-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Komar, P. D. (1976). *Beach processes and sedimentation.* Prentice Hall, NJ.

Krinitzsky, E. L. (1965). "Geological influences on bank erosion along meanders of the lower Mississippi River," Potomology Investigations Report 12-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Kuo, Chin Y. (1983). "Navigation and shore erosion in coastal waterways," Frontiers in Hydraulic Engineering. Virginia Polytechnic Institute and State University, Blacksburg, VA.

Lagasse, P. F., Winkley, B. R., and Simons, D. B. (1980). "Impact of gravel mining on river system stability," *Journal of the Waterway, Port, Coastal and Ocean Division*, American Society of Civil Engineers, 106(WW3) Proceedings Paper 15643.

Lane, E. W. (1955). "Design of stable channels," *Transactions, American Society of Civil Engineers* 120, 1234-1260.

Lane, E. W. (1957). "The importance of fluvial morphology in hydraulic engineering," *Proceedings, American Society of Civil Engineers,* 81(745).

Larson, M., and Kraus, N. C. (1989). "SBEACH: Numerical model for simulating storm induced beach change," Technical Report CERC-89-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Lawler, D. M. (1987). "Bank erosion and frost action; An example from South Wales." *International geomorphology 1968,* Part I. V. Gardiner, ed., John Wiley, London.

Lawler, D. M. (1992). "Process dominance in bank erosion systems." *Low land floodplain river geomorphological perspectives*, P. A. Carling and G. E. Petts, ed., John Wiley, Chichester, 117-143.

Lawler, D. M. (1993). "The measurement of river bank erosion and lateral channel change: a review." *Earth surface processes and landforms* 18, 777-821.

Lawson, Daniel E. (1985). "Erosion of northern reservoir shores—analysis and application of pertinent literature," Monograph 85-1, U.S. Army Engineer Cold Regions Research Engineering Laboratory, Hanover, New Hampshire.

Leopold, L. B. (1994). *A view of the river*, Harvard University Press, Cambridge, MA.

Leopold, L. B., Wolman, M. G., and Miller, J. P. (1964). *Fluvial processes in geomorphology*. W. H. Freeman, San Francisco, CA.

Limerinos, J. T., and Smith, W. (1975). "Evaluation of the causes of levee erosion in the Sacramento-San Joaquin Delta, California," Water Resources Investigation 28-74, U.S. Geological Survey, Menlo Park, CA.

Linder, W. M., and Wei, T. C. (1986). "Hydropower impacts on erosion and sedimentation." *Proceedings of the 4th Federal Interagency Sedimentation Conference,* Las Vegas, NV, March 24-27, 1986, U.S. Government Printing Office, Washington, DC, I, 261-270.

Liou, Yi-Chung, and Herbich, John B. (1976). "Sediment movement induced by ships in restricted waterways," Report 188, TAMU-SG-76-209, Texas A&M University, College Station, TX.

Lubinski, Ken. (1993). "A conceptual model of the upper Mississippi River system ecosystem," Technical Report 93-TOO1, U.S. Fish and Wildlife Service, Environmental Management Technical Center, Onalaska, WI.

Markle, Dennis G. (1983). "Wave and seepage-flow effects on sand stream-banks and their protective cover layers; demonstration hydraulic models," Miscellaneous Paper No. HL-83-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Morris, Charles D. (1982). "Quantifying minor sediment sources, bank erosion and flood plain scour, GREAT III," prepared by University of Missouri-Rolla, Institute of River Studies, for U.S. Army Engineer District, St. Louis, St. Louis, MO.

Nairn, R. B. (1992). "Designing for Cohesive Shores," Coastal Engineering in Canada, Queens University Kingston.

Nanson, Gerald C., von Krusenstierna, Axel, Bryant, Edward A., and Renilson, Martin R. (1993). "Experimental measurements of river-bank erosion caused by boat-generated waves on the Gordon River, Tasmania," *Regulated Rivers: Research and Management* 9, 1-14.

Neill, Charles R., and Yaremko, Eugene K. (1989). "Identifying causes and predicting effects of bank erosion," *Hydraulic Engineering, Proceedings of the 1989 National Conference on Hydraulic Engineering*. American Society of Civil Engineers, New Orleans, LA, August 14-18, 1989. Michael A. Ports, ed., American Society of Civil Engineers, New York, 101-105.

Nielsen, Dennis N., Rada, Ronald G., and Smart, Miles M. (1984). "Sediments of the upper Mississippi River: their sources, distribution, and charactersitics." *Proceedings of the 15th Annual Meeting of the Mississippi River Research Consortium,* James G. Wiener, Richard V. Anderson, and David R. McConville, ed., Butterworth, Boston, 67-98.

Odgaard, A. Jacob, Jain, Subhash C., and Luzbetak, Douglas J. (1989). "Hydraulic mechanisms of riverbank erosion." *Hydraulic Engineering, Proceedings of the 1989 National Conference on Hydraulic Engineering*. American Society of Civil Engineers, New Orleans, LA, August 14-18, 1989. Michael A. Ports, ed., American Society of Civil Engineers, New York.

Oebius, H. U. (1984). "Loads on beds and banks caused by ship propulsion systems." *Flexible armoured revetments incorporating geotextiles*, Proceedings of the international conference, Institution of Civil Engineers, London, March 1994. Thomas Telford Ltd, London, 13-23.

Ofuya, A. O. (1970). "Shore erosion - ship and wind waves, St. Clair, Detroit, and St. Lawrence Rivers," Report # 21, Marine Engineering, Design Branch, Department of Public Works, Canada.

Okagbue, C. O., and Abam, T. K. S. (1986). "Analysis of stratigraphic control on river bank failure," *Engineering Geology* 22(3), 231-245.

Oswalt, N. R., and Strauser, Claude N. (1983). "Prototype experience and model studies of navigation effects on inland waterways." *Frontiers in hydraulic engineering,* Cambridge, MA, August 9-13, 1983. American Society of Civil Engineers, New York, 201-206.

Oswalt, N. R., Mellema, W. J., and Perry, E. B. (1981). "Riverbank erosion: evaluation, prevention and control," *Proceedings of the 25th International Navigation Congress,* Edinburgh. Permanent International Association of Navigation Congresses, Section 1, Vol 1 - N, 155-165.

Ouellet, Yvon, and Baird, William. (1978). "Shore erosion in the St. Lawrence River," *Canadian Journal of Civil Engineering*, 5, 311-323.

Paaswell, R. E. (1974). "Causes and mechanisms of cohesive soil erosion: the state of the art," *Soil erosion: Causes and mechanisms, prevention and control,* Highway Research Board, Special Report 135, 52-72.

Pilarczyk, K. W., Havinga, H., Klassen, G. J., Leemans, J. A. A. M., Mosselman, E., and Verhey, H. J. (1989). "Control of bank erosions in the Netherlands," *Hydraulic engineering: Proceedings of the 1989 National Conference on Hydraulic Engineering*, New Orleans, LA, August 14-18, 1989. Michael A. Ports, ed., American Society of Civil Engineers, New York, 302-307.

Prosser, M. J. (1986). "Propeller induced scour," RR 2570, The British Ports Association, London, England.

Quigley, R. M. and Gelinas, P. J. (1976). "Soil mechanics aspects of shoreline erosion," *Geoscience Canada* 3(3), 160-173.

Reid, J. R. (1993). "Mechanisms of shoreline erosion along lakes and reservoirs," Miscellaneous Paper W-93-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. Also published in *Proceedings, USACE Workshop on Reservoir Shoreline Erosion,* McAlester, OK, 26-30 October 1992. H. H. Allen and J. L. Tingle, ed.

Reid, John R. (1984). "Shoreline erosion processes: Orwell Lake, Minnesota," U.S. Army Engineer Cold Regions Research and Engineering Laboratory, Hanover, NH.

Reid, J. R., Sandberg, B. S., and Millsop, M. D. (1988). "Bank recession processes, rates, prediction, Lake Sakakawea, North Dakota," *Geomorphology* 1(2), 161-189.

Richardson, Jerry R., and Stevens, Michael A. (1986). "Response of the Citanduy River to developments," *Water forum '86: World water issues in evolution, proceedings of the conference*, Long Beach, CA. 1678-1685.

River Almanac. (November 1994). "An information sharing bulletin of the Long Term Resource Monitoring Program," *River Almanac*, National Biological Survey, Environmental Management Technical Center, Onalaska, WI.

Schumm, S. A. (1971). "Fluvial geomorphology: The historical perspective." *River mechanics*, H.W. Shen, ed, Fort Collins, CO, 5-1 - 5-22.

Schumm, S. A. (1973). "Geomorphic thresholds and complex response of drainage systems." *Proceedings of symposia, fluvial geomorphology*. M. Morisawa, ed., Binghamton, New York, 299-310.

Schumm, S. A., and Thorne, Colin R. (1989). "Geologic and geomorphic controls on bank erosion." *Hydraulic engineering, Proceedings of the 1989 National Conference on Hydraulic Engineering*. American Society of Civil Engineers, New Orleans, LA, August 14-18, 1989. Michael A. Ports, ed., American Society of Civil Engineers, New York.

Shore protection manual. (1984). 4th ed., 2 Vol, U. S. Army Engineer Waterways Experiment Station, U.S. Government Printing Office, Washington, DC.

Simons, D. B., Andrew, J. W., Li, R. M., and Alawady, M. A. (1979). "Connecticut River streambank erosion study, Massachusetts, New Hampshire and Vermont," Performed under Contract DACW 33-78-C-0297 by Colorado State University Research Institute, Fort Collins, for U.S. Army Engineer Division, New England, Waltham, MA.

Simons, D. B., and Li, Ruh-Ming. (1982). "Bank erosion on regulated rivers." *Gravel-bed rivers: fluvial processes, engineering and management conference,* proceedings of International Workshop on Engineering Problems in the Management of Gravel-bed Rivers, Gregynog, Newtown, UK, 23-27 June 1980. R. D. Hey, J. C. Bathurst, C. R. Thorne, ed., John Wiley, Chichester, 717-754

Sing, E. F. (1986). "River sediment budget." *Proceedings of the 4th Federal Interagency Sediment Conference*, Las Vegas, NV, 24-27 March 1986. U.S. Government Printing Office, Washington, DC.

Smith, Lawson M., and Patrick, David M. (1979). "Engineering geology and geomorphology of streambank erosion," Technical Report GL-79-9, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Sorensen, R. M., and Weggel, J. R. (1984). "Development of ship wave design information," *Proceedings of the 19th Coastal Engineering Conference,* Houston, TX. American Society of Civil Engineers, New York, 3227-3243.

Sparks, R. E., Bayley, P. B., Kohler, S. L., and Osborne, L. L. (1990). "Disturbance and recovery of large floodplain rivers," *Environmental Management* 14(5), 699-709.

Spoor, M. F., and Hagerty, D. J. (1989). "Bank failure and erosion on the Illinois Waterway," *Proceedings of international symposium on sediment transport and modeling*. New Orleans, LA, August 14-18, 1989. Sam S. Y. Wang, ed., American Society of Civil Engineers, New York, 600-605.

Springer, Floyd M., Jr., Ullrich, C. Robert, and Hagerty, D. J. (1985). "Steambank stability," *Journal of Geotechnical Engineering* III(5), 624-640.

Sunamura, T. (1984). "Processes of sea cliff and platform erosion." *CRC handbook of coastal processes and erosion*. Chapter 12. CRC Press, Boca Raton, FL, 233-265.

Thomas, B. F. and Watt, D. A. (1913). *The improvement of rivers*. John Wiley, New York.

Thorne, C. R. (1981). "Field measurement of rates of bank erosion and bank material strength." *Erosion and sediment transport measurement,* Proceedings of the International Association of Hydrological Sciences, Florence Symposium, June 1981. Washington, DC, 133, 503-572.

Thorne, C. R. (1993). "Guidelines for the use of stream reconnaissance record sheets in the field," Contract Report HL-93-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Thorne, Colin R., and Tovey, N. Keith. (1981). "Stability of composite river banks," *Earth Surface Processes and Landforms* 6(5), 469-484.

Torrey, Victor H. III, Dunbar, Joseph B., and Peterson, Richard W. (1988). "Retrogressive failures in sand deposits of the Mississippi River: report 1. field investigations, laboratory studies, and analysis of the hypothesized failure mechanism," Technical Report GL-88-9, U.S. Army Engineer Waterways Experiment Station Vicksburg, MS.

Turnbull, W. J., Krinitzsky, E. L, and Weaver, F. J. (1966). "Bank erosion in soils of the lower Mississippi Valley," *Journal, Soil Mechanics and Foundations Division*, American Society of Civil Engineers, 92(SM 1), 121-136.

Twidale, C. R. (1964). "Erosion of an alluvial bank at Birdwood, South Australia," *Zeitschrift Fuer Geomorphologie* 8 NS, 189-211.

Ullrich, C. Robert, Hagerty, D. Joseph, and Holmberg, Ronald W. (1986). "Surficial failures of alluvial stream banks," *Canadian Geotechnical Journal* 23(Feb), 304-316.

U.S. Army Corps of Engineers. (1981a). "Main Report: final report to Congress, the Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, Public Law 93-251," Washington, DC.

U.S. Army Corps of Engineers. (1981b). "Final report to Congress: the Streambank Erosion Control Evaluation and Demonstration Act of 1974, Section 32, Public law 93-251, Appendix G," Washington, DC.

U.S. Army Engineer District, Huntington. (1980). "Gallipolis locks and dam replacement, Ohio River, phase 1, advanced engineering and design, General Design Memorandum; Appendix J, volume 1, environmental and social impact analysis," Huntington, WV.

U.S. Army Engineer District, Kansas City. (1994). "The great flood of 1993 post-flood report: upper Mississippi River basin," Kansas City, MO.

U.S. Army Engineer Division, Ohio River. (1977). "Ohio River bank erosion study," The Division Engineer's Steering Committee, Cincinnati, OH.

U.S. Army Engineer District, Omaha. (1994). "The great flood of 1993 post-flood report: upper Mississippi River basin," Omaha, NE.

U.S. Army Engineer District, Rock Island. (1994). "The great flood of 1993 post-flood report: upper Mississippi River basin," Rock Island, IL.

Verhey, H. J. (1983). "The stability of bottom and banks subjected to the velocities in the propeller jet behind ships," Publication 303, Delft Hydraulics Laboratory, Delft, The Netherlands.

Verhey, H. J., and Bogaerts, M. P. (1989). "Ship waves and the stability of armour layers protecting slopes." *9th international harbour congress*, Antwerp, Belgium, 20-24 June 1989. Publication 428, Delft Hydraulics Laboratory, Delft, The Netherlands.

Volker, A. (1986). "Effect of embanking on river and sea floods." *Flood hydrology: Proceedings of the International Symposium on Flood Frequency and Risk Analyses*, Louisiana State University, Baton Rouge, LA, 14-17 May 1986. V. P. Singh, ed., D. Reidel, Norwell, MA, 289-297.

Walker, H. H., and Morgan, H. N. (1964). "Unusual weather and river bank erosion in the delta of the Colville River, Alaska," *Arctic* 17(1), 41-47.

Wallerstein, N., and Thorne, C. R. (1994). "Impact of in-channel organic debris on fluvial process and channel morphology, Yazoo Basin, Mississippi," Working Paper 29, University of Nottingham, Department of Geography, Nottingham, England.

Walling, D. E., and Webb, B. W. (1981). "Water quality." *British Rivers*. John Lewin, ed., University College of Wales, Abergstwyth, George Allen and Unwin, London.

Warren, Robert E. (1987). "The impact of bank erosion on prehistoric cultural resources in the lower Illinois River valley," Technical Report 87-211-10, Illinois State Museum Society, Springfield, IL.

Way, C. B., Miller, A. A., Paine, B. S., and Wakeley, J. (1990). "Traffic: An information retrieval system to evaluate the environmental impacts of commercial navigation traffic," Technical Report EL-90-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Weigel, T. A., and Hagerty, D. J. (1983). "Riverbank change-Sixmile Island, Ohio River U.S.A.," *Engineering Geology* 19, 119-132.

Wuebben, James L. (1978). "Non-structural alternatives for shore erosion and shore structure protection-winter navigation program," Contract Report for U.S. Army Engineer District, Detroit, Detroit, MI.

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

Zabawa, Chris, and Ostrom, Chris. (1980). "Final report on the role of boat wakes in shore erosion in Anne Arundel County, Maryland," Maryland Coast Report 5, Maryland Zone Management Program, Annapolis, MD.

Zhang, J., Hershberger, D., Spell, C. A., Ting, F., and Yu, H. (1993). "Bank erosion of the Gulf Intracoastal Waterway at the Aransas National Wildlife Refuge," COE Report 332, Texas A&M Research Foundation, College Station, TX.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
August 1996

3. REPORT TYPE AND DATES COVERED
Report 1 of a series

4. TITLE AND SUBTITLE
Upper Mississippi River System Navigation/Sedimentation Study; Report 1, Bank Erosion Literature Study

5. FUNDING NUMBERS

6. AUTHOR(S)
Stephen T. Maynord, Sandra K. Martin

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report HL-96-10

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
See reverse

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This literature search was conducted to obtain pertinent data and research regarding the process of bank erosion along the Upper Mississippi River System (UMRS). References were identified pertaining to bank erosion resulting from flow velocity, flow quantity, secondary currents, bank materials and covers, wave energy from wind and navigation, and other forces resulting from navigation. References were from both studies on the Upper Mississippi River System and other similar alluvial rivers.

14. SUBJECT TERMS

Bank erosion	Literature search
Illinois Waterway	Mississippi river
Literature review	Navigation

15. NUMBER OF PAGES
96

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

9. (Concluded).

U.S. Army Engineer District, Rock Island, Clock Tower Building, P.O. Box 2004, Rock Island, IL 61204-2004
U.S. Army Engineer District, St. Louis, 1222 Spruce Street, St. Louis, MO 63103-2833
U.S. Army Engineer District, St. Paul, Army Corps of Engineers Centre, 190 5th Street East, St. Paul, MN 55101-1638