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BIBLIOGRAPHY OF EFFECTS OF COMMERCIAL NAVIGATION TRAFFIC IN LARGE WATERWAYS

by

Andrew C. Miller, K. Jack Killgore, Barry S. Payne

Environmental Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

and

Daniel Buckley

Syracuse University, Syracuse, New York

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Literature dealing with the physical, biological, and chemical effects of commercial navigation traffic in large waterways is reviewed and analyzed. The majority of the information on this topic does not pertain directly to traffic, but deals with sedimentation, water quality changes, or other features of large waterways that are not always caused by passage of a commercial navigation vessel. The major physical effects of traffic are brief periods of often severe turbulence and wave wash. Water drawdown and elevated turbidity can also occur as a result of vessel passage, although environmental effects of these perturbations are usually not severe. A period of turbulence can disturb feeding and respiration of aquatic insects, mussels, and fish larvae. Brief periods of elevated suspended solids and turbidity can affect respiratory structures and sensory apparatus of aquatic organisms; however, these effects are usually temporary. Field studies on navigation traffic are difficult to design and to perform. However, the

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effects of traffic can be evaluated with carefully designed laboratory and field experiments. Laboratory experiments do not duplicate natural habitat conditions; however, they provide a mechanism for understanding basic effects of traffic. In the laboratory, test apparatus can be built for subjecting fish eggs and larvae, as well as freshwater mussels, to frequent and infrequent periods of turbulence and elevated suspended solids. Field manipulative experiments in which organisms are caged and transferred to sites impacted by various levels of commercial traffic provide the best technique for evaluating navigation traffic effects. These studies can be designed to evaluate traffic effects on growth rates, mortality, and physical condition of aquatic organisms.

PREFACE

In October 1982, the US Army Engineer Waterways Experiment Station (WES) initiated a 3-year study of the effects of navigation activities in large waterways. This project was part of the Environmental and Water Quality Operational Studies (EWQOS) Program, Work Unit VB, at the WES. The purpose was to review and evaluate existing literature and to design and execute pilot laboratory and field studies on navigation effects. Information obtained from the literature review and the results from the pilot studies were used to prepare this report.

This report was prepared by Dr. Andrew C. Miller, Mr. K. Jack Killgore, Dr. Barry S. Payne, from WES, and Dr. Daniel Buckley from Syracuse University. Additional information was provided by Mr. Terry Siemsen, Navigation Planning Support Center, US Army Engineer District, Louisville; Dr. Dan Wilcox, US Army Engineer District, St. Paul; Dr. Richard Sparks, Illinois Natural History Survey; and Mr. David Kennedy and Mr. Steve Read, Wisconsin Department of Natural Resources. This report was edited by Ms. Lee T. Byrne, Information Technology Laboratory, WES.

The navigation studies at WES were under the general supervision of Dr. Thomas D. Wright, Chief, Aquatic Habitat Group; Dr. Conrad J. Kirby, Chief, Environmental Resources Division; and Dr. John Harrison, Chief, Environmental Laboratory. Dr. Jerome L. Mahloch was Program Manager of EWQOS.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

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CONTENTS

CONVERSION FACTORS, NON-SI to SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square metres
cubic feet	0.02831685	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
gallons (US liquid)	3.785412	cubic decimetres
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres
ounces (US fluid)	0.02957353	cubic decimetres
pounds (mass)	0.4535924	kilograms
pounds per acre	0.000112	kilograms per square metre
square miles	2.589998	square kilometres
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	metres

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

BIBLIOGRAPHY OF EFFECTS OF COMMERCIAL NAVIGATION TRAFFIC IN LARGE WATERWAYS

PART I: INTRODUCTION

Background

1. Since the passage of the National Environmental Policy Act (NEPA) in 1969, biologists, planners, engineers, and other personnel in government agencies and academic institutions have had to deal with a variety of environmental issues related to water resource development and management. Often a unique habitat or identification of an unusual or uncommon species draws public attention to a specific problem. For example, identification of the snail darter in the Teleco River, Tennessee, and its subsequent listing as "endangered" focused the attention of biologists and nonbiologists on questions of critical habitat and the perceived importance of uncommon or rare organisms.

2. Public concern relating to navigation issues has been the result of at least three major projects designed to further develop this nation's waterway system. These three navigation projects include the Tennessee-Tombigbee Waterway in Alabama and Mississippi, the replacement lock and dam near Alton, Illinois, and the construction of a lock at Gallopolis, West Virginia. In addition to these Corps of Engineers (CE) projects, many small construction activities frequently raise local concern over commercial use of waterways. These activities include construction of ports, granting of permits for barge fleeting and loading facilities, and dredging, as well as construction, operation, and maintenance of navigation structures. Ultimately these development projects encourage the increased use of waterways by commercial navigation traffic. Possible adverse impacts from this increased traffic include formation of surge waves, turbulence from hull friction or propeller action, resuspension of sediments, and water drawdown associated with vessel passage. Impacts not directly related to the movement of

commercial traffic are the increased possibility of spilling toxic materials, discharge of wastes, and construction of ports and fleeting areas.

Purpose and Scope

3. This report is a synthesis and review of pertinent published and unpublished literature on the environmental effects of commercial navigation activities in large waterways. It provides information on the physical effects of traffic on aquatic biota. Included are impacts such as propeller wash, water drawdown associated with vessel passage, turbulence, and turbidity. This report does not deal with the environmental effects of existing structures, such as locks and dams, the placement of bank control or river training devices, or the impacts of dredging, clearing, or snagging.

4. Instead of following the traditional alphabetical format of an annotated bibliography, the literature on navigation effects in this report has been organized into specific groups. There are sections on the effects of navigation on fish, bivalve molluscs, macroinvertebrates, and invertebrate drift. Each section begins with a general literature review of the topical area and a discussion of how it relates to navigation activities. This is followed by an analysis of major findings from laboratory or field studies on navigation effects. In the majority of cases, the number of well-designed biological studies of navigation effects are few.

5. This report is intended to be used by biologists and planners in Federal, State, and local governments as well as in academic institutions. It will guide the user to the most useful publications on the environmental effects of commercial navigation activities. In addition, this report will provide information for determining navigation-related impacts in the preparation of Environmental Impact Statements and Environmental Assessments and granting permits for regulated activities on waterways.

PART II: COMMERCIAL NAVIGATION TRAFFIC

Development of Waterways

6. In 1824 Congress passed the General Survey Act of 1824, which involved the CE in improving the navigation system on the Mississippi River. Captain Henry Miller Shreve designed and used a boat to remove snags that frequently impeded movement of steamboats. In 1878 Congress initiated the first comprehensive project on the Mississippi River, development of a 4-1/2-ft* navigation channel. The major features of that project were to remove obstructive rapids and bypass treacherous reaches with short, lateral canals. In 1907 Congress authorized a 6-ft channel that was achieved by creation of rock and brush wing dams. When the steamboat era began to fade, other forms of transportation offered faster, more dependable service. However, by the early 20th century, engineering advancements and new construction methods enabled a return to the use of inland waterway systems. Extensive studies were made to create a single integrated system that would use channels of the Mississippi, Ohio, and Illinois water systems. In the early part of the 19th century, Congress authorized development of a 9-ft channel with a minimum width of 300 ft. In the Mississippi River this channel was created by a series of 29 locks and dams that made commercial navigation possible between Minneapolis, St. Paul, and St. Louis. Since the initiation of that project in 1939, the growth of commercial navigation traffic has been rapid and strong.

7. The commercial navigation system in this country is particularly appropriate for bulk commodities and petroleum products. Bulk items include grains, such as corn, wheat, oats, barley, and rye, and petroleum products, such as fuel oils, lubricating oils, kerosenes, and gasolines, as well as coke and coal. Most of these materials are moved

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

downriver to ports and are destined to be sent to other countries. Scrap iron, steel, fertilizers, sulfur, cement, aluminum, sugar, and molasses are other materials moved in bulk along the waterways of the nation.

Existing Literature on Navigation Traffic

8. Lubinski et al. (1981) reviewed over 900 documents pertaining to navigation effects; of these only 56 were considered relevant (Wright 1982). Of the 56 references, only six were judged to contain information pertinent to the movement of commercial traffic and did not concern dredging, channel maintenance, or lock and dam operation. An examination of these six studies indicated that they were largely subjective and did not clearly identify the actual biological effects of navigation traffic. While much has been written on this topic, there have been few well-designed laboratory or field studies that clearly document the biological effects of navigation traffic.

9. In the existing literature on the impacts of commercial traffic, one encounters many studies such as those of Rosen and Hales (1980). In their work they demonstrated that paddlefish in the Missouri River were scarred or otherwise physically damaged either as a result of collisions with power boats or commercial vessels or because of snag fishing (thereby resulting in low condition factors). The authors were unable to identify commercial traffic as a specific causative factor. Studies by Kiorbee, Mohlenbwerg, and Nohr (1981), Morgan et al. (1976), as well as others, illustrate that fish eggs and larvae are sensitive to suspended sediments and turbulence. However, in these studies the link between the effects of a physical action caused by commercial traffic and biological impact was not clearly documented.

10. Some reasons for a paucity of information on navigation traffic are the following:

- a. Difficulty in conducting a controlled experiment in rivers where navigation traffic has been taking place for years.

b. The possible confounding effects of levees, dikes, and other structures in addition to channel maintenance activities and operation of locks and dams.

c. Problems with collecting samples and making observations in large rivers as compared with streams and lakes.

d. A general lack of established techniques to assess impacts caused by water-resource or other activities. Since the passage of NEPA, there has been considerable interest in attempts to document environmental effects of man's actions. However, an examination of the literature reveals that most estimates of the impacts of navigation traffic are judgmental and anecdotal, based upon natural history studies, or directly keyed to physical losses of habitat. The chronic or sublethal effects of low levels of stress, a major concern of impact analysis, appear to have been poorly accounted for or completely ignored.

11. The best information on navigation-related effects pertains to the physical consequences of commercial vessel passage (Herricks et al. 1982, Simons 1981). Physical effects such as turbulence, drawdown, waves, and sediment suspension can be measured using conventional equipment. In addition, these phenomena can be predicted with good confidence levels with formulae or models developed empirically or from an understanding of hull design, channel morphometry, and similar factors.

PART III: EFFECTS OF NAVIGATION TRAFFIC

Physical Effects of Tow Passage

Physical force

12. Saunders (1975) predicted ship-generated bow-wave height (H) in deep water with the following equation:

$$H = kw[(B/LE) * (V^2/2g)] \quad (1)$$

where

kw = coefficient

B = ship beam, ft

LE = distance from bow to midbody, ft

V = ship velocity, ft/sec

g = acceleration due to gravity, ft/sec

Investigation of the physical effects of ship-generated waves has been reported by Sorenson et al. (1977) and Fuehrer and Romish (1977). In the former study, maximum ship-generated wave heights were measured at various distances from the sailing line. In the study by Fuehrer and Romish (1977), model investigations and mathematical equations addressed problems of:

a. Distribution of the displacement current of a ship during navigation in canals and channels of limited width and depth.

b. The squat (the settling at the stern when under way at a specific speed) of ships in canals and channels.

c. The damages to waterways and hydraulic structures caused by the action of propeller jets.

13. In a study by Bhowmik et al. (1981), wave height, velocity, and suspended sediments were measured during the passage of barges. All three parameters showed significant changes following vessel passage. In addition, they determined that the total net input of sediments and nutrients into side channels was very small and often nonexistent following passage of a barge.

14. Gates and Herbich (1977) determined that the height of a ship-generated wave is mainly the function of vessel speed. Helwig (1966) stated that the bow and stern of a ship are responsible for most of a ship's wave-making ability. An empirical relationship for predicting ship wave heights in a restricted channel (irrespective of geometry) was presented by Balanin and Bykov (1965). McNown (1976) determined that vessel length is usually insignificant in determining the extent of water drawdown, and Stelczer (1981) discussed scour velocities necessary to move different-size sediment particles.

Suspended sediments

15. Commercial navigation traffic causes turbulence, which can be accompanied by increased levels of suspended solids in addition to turbidity. The elevated suspended solids in the water originate from shoreline erosion or resuspension of bottom sediments. Two separable mechanical forces are involved in the resuspension of bottom sediments: hull compression waves and propeller vortices (or propeller wash). Suspension of bottom sediments by these forces declines with increased distance between the ship and bottom and is a function of particle size. Bhowmik et al. (1981) determined that tows can increase suspended-sediment concentrations for 60 to 90 min following tow passage, and increases are greater in channel borders than in the navigation channel. North Star Research Institute (1973) reported changes of from 30 to 70 Jackson Turbidity Units (JTU) (surface water) and from 20 to 80 JTU following commercial tow passage. Herricks et al. (1982) reported values that changed from 91 to 362 mg/ℓ and 125 to 253 mg/ℓ in the Kaskaskia River (1 m deep) after commercial tows had passed.

Shore erosion

16. Ofuya (1970) used graphical techniques to estimate decay of wave heights with respect to distance from the sailing line. It was reported that a direct relationship between ship-wave characteristics and sediment transport from erosion does not exist. Hagerty, Spoor, and Ullrich (1981) assessed the problem of bank stability along the Ohio River. They indicated that erosional mechanisms were complex and episodic; however, the principal causative agent was floods. It was

concluded that waves generated by tow and recreational vessels have little effect on bank stability, although land-use changes can affect slope stability and erosion. However, Hurst and Brebner (1969) evaluated shore erosion and protection mechanisms on the St. Lawrence River in Canada. In that river they determined that bank erosion was mainly the result of vessel speed and size of the waterway. With respect to navigation traffic in the upper Mississippi River System, it should be recognized that sensitive areas, such as eroding banks and adjacent wetlands, are likely to be impacted by commercial traffic.

17. Shore erosion as a result of traffic in a navigable waterway is most likely to be a problem in sensitive areas. These areas include narrow channels, sharp bends, or sites where steep, poorly vegetated banks are likely to be damaged by wave wash. In addition, these areas are subject to erosion during normal fluctuations in water level, i.e., during spring floods.

Mixing effects

18. Yousef et al. (1978) investigated the mixing effects of recreational boats with small motors (from 28 to 165 hp) in small bodies of water. Stefan and Riley (1985) noted that thermal stratification in waterways could be disrupted by the passage of barges.

Drawdown

19. The passage of commercial traffic along restricted navigation channels results in a temporary decrease in water level, a phenomenon referred to as drawdown. Typically, drawdown lasts no more than 3 min, although it can be accompanied by turbulence and wave wash. Factors affecting drawdown include vessel displacement, velocity, direction, and channel morphometry. Drawdown can cause temporary atmospheric exposure of benthic organisms along the shore. However, communities in these zones are usually adapted to wave-wash and water-level fluctuations. More important are the temporary turbulence and water loss in shallow wetlands that are adjacent to the navigation channel and can be affected by drawdown. These effects are of most concern in the spring when juvenile fish or fish larvae are present. It has been determined that vessel speed is the most important determinant of the magnitude of

drawdown; the reduction of vessel speed by only 1 to 2 knots will reduce drawdown by an amount equal to the difference between a class 5 and class 10 vessel (Wuebben, Brown, and Zabilansky 1984). In a study of drawdown and sediment transport, Demissie and Osakada (1981) collected depth-integrated, suspended-sediment samples at three locations on a river transect following vessel passage. Increases in suspended-sediment levels following tow passage were noted. It was concluded that tow passage and the resulting drawdown brought sediment out of the channel borders and into the navigation channel.

Water quality

20. Changes in dissolved oxygen in the water column have been associated with tow-induced increases in suspended-sediment concentrations (Lubinski et al. 1981). Simons (1981) reported that barge passage could induce a 50 percent decrease in dissolved oxygen at the surface of the water, but virtually no effect was found at a depth of 3 m. Further, it was found that the decrease in oxygen returned to near ambient levels within 60 min. Similar phenomena were reported as a result of studies on the Illinois River (Sparks 1975) and Kaskaskia River (Herricks and Gantzer 1980, Herricks et al. 1982). Conversely, other authors have reported slight increases in dissolved oxygen concentrations following tow passage (Johnson 1976, Berger Associates 1980).

Turbulence

21. Turbulence, or nonlaminar flow, is a major impact of the movement of a commercial vessel in a waterway. Turbulence can cause sediment suspension; however, the rapid movement of water is a physical force which may disrupt feeding and can physically damage aquatic organisms.

Macroinvertebrates

Background

22. Benthic invertebrates can be affected by a variety of environmental perturbations associated with navigation traffic. In shallow

water, commercial traffic increases suspended sediments and the amount of turbulence to which benthic communities are typically exposed. Increased particulate matter in the water column can affect invertebrates directly by burial or by interference with feeding and respiratory action or indirectly through decreased oxygen concentrations. Another tow-related factor that can affect benthic organisms is temporary exposure to air resulting from vessel drawdown. However, this temporary exposure to the atmosphere is probably insignificant to most benthic organisms.

23. Tow-induced turbulence results in a short-term increase in suspended sediment and turbidity. While the increases in turbidity associated with navigation traffic can be substantial, it is doubtful that they are sufficiently high to be acutely lethal to most benthic species. Furthermore, the incremental increase in turbidity pulses because of additional traffic rates are probably not as significant as the ambient turbidity conditions during high-water conditions. Recent reviews by Stern and Stickle (1978) have included information on the effects of turbidity upon benthic organisms. In most cases, turbidity-generated responses were considered only when the length of exposure exceeded weeks or months. For example, Gray and Ward (1982) reported that 2-week exposures to suspended sediment of 300 mg/ℓ were sufficient to decimate (reduce by 90 percent) two chironomid populations. Additionally, lethal suspended-sediment concentrations are generally greater than or must occur over a greater time period than those usually associated with barge traffic.

24. Abrupt shifts in current direction or velocity can adversely affect benthic organisms adapted to life within restricted current ranges. Temporary fluctuations in current direction induced by tow passage can affect benthic species such as trichopterans. These invertebrates have food-capture nets that work well only within a restricted current range (Rabeni and Gibbs 1980). These nets can collapse under conditions of low flow, or they can rupture if subjected to high-velocity currents. However, trichopterans are a common invertebrate in

moderate-velocity water of large waterways. There are no reports of these organisms being disrupted by navigation traffic.

Drawdown effects

25. Various authors (Sparks 1975, Berger Associates 1980, and Lubinski et al. 1981) have indicated that the biological effects of traffic-induced drawdown, while probably not severe, should be studied in greater detail. Eckblad (1981) reported that areas exposed to the air by drawdown supported fewer taxa than did adjacent, unexposed areas (3.2 species versus 4.3 species). In addition, he found that the average total number of benthic individuals per Ponar sample from exposed areas was less than one third that found in unexposed areas (23.3 individuals versus 73.2 individuals per sample). However, benthic communities can vary from year to year and site to site based upon discharge, substrate, temperatures, and season.

26. Drawdown probably has a more significant effect upon side channels or shallow wetland areas adjacent to navigation channels than to shoreline habitats. The sudden influx and outflow of water created by tow passage could result in disruption of benthic invertebrates or other aquatic organisms utilizing these areas (Sparks 1975; Lubinski et al. 1981; Eckblad, Volden, and Weilgart 1984). However, detailed studies of the effects of drawdown on natural populations of aquatic organisms have not been undertaken.

27. The number of drawdowns in a navigation channel per unit time will be related to the frequency of traffic. However, the biological consequences of drawdown are related to the life requisites of the organism of interest. For example, freshwater bivalves are not affected by brief periods of exposure to the atmosphere (Payne and Miller 1986); larvae of centrarchids and soft-bodied, immature insects such as mayflies and caddisflies are more likely to be affected negatively by frequent drawdown.

Invertebrate Drift

Background

28. The downstream movement of benthic invertebrates (organisms usually found on or in sediments) in flowing water is referred to as benthic or invertebrate drift. Drift has been categorized as constant, behavioral, or catastrophic (Waters 1972; Muller 1974; Eckblad, Volden, and Weilgart 1984).

29. Constant drift is the species composition and relative abundances of benthos that are usually found in the water column. Constant drift results from random interactions among individuals, and it is also a function of community composition, individual species abundances, and habitat characteristics.

30. Behavioral drift is a means of moving from one habitat to another. It is affected by population density and community composition and generally exhibits diurnal fluctuations. Typically the greatest pulse of drifting insects occurs at night. It has been hypothesized that drift at night lessens the risk of predation by visually oriented predators. Other conditions resulting in lowered incident light levels during the day are positively correlated with increased drift (Gammon 1970; Ciborowski, Pointing, and Corkum 1977).

31. Catastrophic drift is the downstream transport of unusually large numbers of benthic individuals. In such instances there are shifts not only in abundances, but also in the species composition of the drift community. Catastrophic drift can be brought about by temperature changes, by turbidity, or from habitat disruption.

Natural drift in large waterways

32. Beckett et al. (1986) and Bingham, Cobb, and Magoun (1980) conducted drift studies on the lower Mississippi River. While the lower Mississippi River is different from the upper Mississippi, there is more similarity within these systems than with small streams where the majority of drift studies have been undertaken. In the study by Beckett et al. (1986), invertebrate drift was higher in May than in June. Evidently many of the drifting organisms had emerged after the first

sampling date. A similar annual peak probably occurs in the northern United States, although because of cooler temperatures it is shifted more toward the summer season. Seagle and Zumwalt (1981) and Waters (1972) also found seasonal variations in drift, with greater invertebrate activity taking place from June to August.

33. According to the study by Beckett et al. (1986), the total number of macroinvertebrates ranged from 22 to 70 per 100 m^3. It was estimated that approximately 0.5 billion macroinvertebrates passed a given point during a 24-hr period in May. In a study of drift in the upper Mississippi River, Eckblad, Volden, and Weilgart (1984) estimated that approximately 10 times the number of invertebrates originated from side channels that drained backwater areas as from the main navigation channel. These researchers indicated that drift from areas outside the main channel could be an important component of large-river ecosystems. The above workers did not relate their studies to impacts associated with navigation traffic or other man-made perturbations.

34. There are no data on the extent to which predators depend on drift as compared with organisms on the substrate or associated with plants. However, as the above data indicate, a large invertebrate biomass is available for predators in the water column. In addition, drifting invertebrates are a resource for recolonizing new habitats. In studies on the lower Mississippi River, workers have found that newly deposited sediments are colonized very quickly by invertebrates known to be present in drift.

Navigation traffic effects

35. The effect of navigation traffic upon drift either directly from disruption of substrate or indirectly through turbulence or turbidity has been the focus of several investigations. Various workers have related the increased resuspension of sediment by navigation traffic to changes in numbers of drifting organisms. For example, changes in suspended sediment following vessel passage have approached 2,000 g/m^3 (Academy of Natural Sciences of Philadelphia 1980). Such increases could elevate invertebrate drift in two ways. First there is the behavioral response in which subsequent lowered light levels could

invoke increased rates of drift. The second and most probable is the mechanical suspension of aquatic invertebrates along with the bottom sediments. The lifting of benthic individuals off the bottom is a function not only of the ship and channel characteristics, but also of habits of the various species and sediment characteristics. For example, chironomid larvae or oligochaete worms that bury into the substrate would be less affected by physical disturbance than invertebrates that move about on the bottom, such as isopods, crayfish, or immature mayflies. However, it is important to note that chironomids generally are the dominant invertebrate in drift samples. This is probably a reflection of their overall density in aquatic systems.

36. Two major efforts to determine the effects of navigation traffic upon invertebrate drift were made by Eckblad (1981) and by Seagle and Zumwalt (1981). In the latter study, no information about tow-induced turbidity was collected, and as a consequence nothing can be said about bottom disruption. In regards to the effect of tow passage upon benthic drift, Seagle and Zumwalt (1981) found that in 7 out of 28 monitored tow passages, there were significant changes in the species composition or density of the posttow-drift samples as compared with the pretow samples. Significantly greater drift densities were found in posttow samples only on two occasions. There was no evidence that tow passage resulted in an increased suspension of invertebrates in the water column.

37. When interpreting results of large-river drift studies, it is important to realize that navigation traffic and other man-made activities influence the design, conduct, and outcome of the research. It would take a well-designed study and fortuitous set of circumstances (i.e., temporary suspension of all navigation traffic) to define precisely the effects of commercial traffic on invertebrate drift.

Plankton

38. The passage of commercial tows and the resulting increases in turbulence and turbidity could affect plankton in two possible ways. By

resuspending bottom sediments, this greater turbulence could provide additional nutrient availability, with a resulting increase in primary productivity. This phenomenon is probably unlikely in a flowing water system where the water column is nearly always well mixed. However, tow-induced turbidity might decrease productivity by limiting light penetration (Odum and Wilson 1962). Dorris, Copeland, and Lauer (1963) found that in the middle Mississippi River primary productivity was greatest during times of low flow and low turbidity. However, it is not known what effect pulses of increased turbidity (such as those caused by barge passage) have on primary productivity in large waterways.

39. Increased suspended solids can decrease the amount of food available for zooplankton and bring about a concurrent decrease in oxygen production because of decreased photosynthesis (Angino and O'Brien 1968). Suspended solids can affect ingestion rates and the percentage of usable food-per-unit material ingested for zooplankton. Arruda, Marzolf, and Faulk (1983) found that an inorganic suspended-sediment concentration of 50 to 100 mg/ℓ caused a 99 percent decrease in algal-carbon ingestion for *Daphnia parvula* and *D. similis*. McCabe and O'Brien (1983) found that increasing turbidity decreased the fecundity of *Daphnia* sp. These workers found that for *D. pulex* increased concentrations of suspended sediment decreased filtering rates from approximately 4 ml/animal/hr to less than 0.3 ml/animal/hr. As these laboratory experiments illustrate, zooplankton are affected by increased levels of suspended solids.

40. Turbulence and wave wash along nonvegetated banks can cause erosion and elevated suspended solids in the water column. However, concern over the effects of traffic-induced turbidity brought about by additional traffic can be lessened by three considerations. First, the food base of most riverine communities is not plankton, but fine-grained detritus of terrestrial origin. Second, other sources of sediment, such as high spring floods and wind-driven waves, can cause periods of increased sediment resuspension that are in excess of those generated from tow traffic. Finally, sediment resuspension resulting from factors other than commercial traffic already exists in a river system. Since

large-river systems are not dependent upon primary productivity as a major food source, it is not likely that increased traffic will have a detrimental effect on riverine biota because of food supply.

Molluscs

41. Many authors have suggested that man's activities, including the use of navigable waterways, have had a deleterious effect upon various molluscan species, especially the freshwater bivalves. Several studies, including Sparks (1975), Sparks et al. (1979), and Lubinski et al. (1981), noted that the decline of unionid molluscs within navigation channels could be the result of navigation traffic. These assertions are based upon the categories of information discussed below.

42. The first type of information alluding to navigation-traffic impacts upon molluscs deals with habitat preferences of various freshwater taxa. Many descriptive ecological studies have indicated the importance of stable substrate for the development of a diverse community. Shifting sand, heavy sedimentation, or any destabilization of substrate has negative impacts upon molluscan populations. For examples using bivalves, see Ellis (1931, 1936), Starrett (1972), Yokely (1976), Horne and McIntosh (1979), Sickel (1980), Suloway (1981), Salmon and Green (1983), and Strayer (1983). For gastropod examples, see Harmon (1972) and Clampett (1973).

43. The second category of information results from experiments such as those conducted by Ellis (1936), who reported that silt accumulations of from one-fourth to 1 in. could result in 90 percent mortality (or greater) among four species of unionids. In the same study it was noted that increased turbidity resulted in the cessation of water pumping and closing of valves for up to 90 percent of the time as opposed to only 50 percent of the time in less turbid waters. Recently Payne and Miller (1986) have shown in the laboratory that periodic short-term exposures to suspended-solids concentrations of 600 to 700 mg/ℓ will decrease food clearance, respiration, and excretion rates

in three bivalve species by 26, 59, and 39 percent, respectively. In more stressed situations, individuals stopped feeding and turned to use of stored carbohydrate or lipid reserves. This was the first laboratory study on the physiological effects of periodic, short-term, and sublethal exposure to suspended sediments on freshwater mussels. However, these data should not be extrapolated to make careless judgements on large-river ecosystems.

44. Field data from Kat (1982) showed that *Elliptio complanata* from sandy substrates had higher growth rates than did individuals from muddy substrates. These differences in growth rates could be the result of phenomena similar to those observed by Ellis (1936) and Payne, Aldridge, and Miller (1986). However, a host of other factors, notably current, available nutrients, etc., could explain these differences.

45. Similar data have been reported for marine organisms; for example, turbidity-induced reductions in organic assimilation have been reported for the bivalve species *Sipsula* (Robinson, Wehling, and Morse 1984). Alternately, Kiorboe, Mohlenbwerg, and Nohr (1981) have reported enhanced growth rates among *Mytilus edulis* when exposed to algal cultures containing low concentrations of suspended solids (5.0 mg/ℓ) as compared with cultures lacking suspended solids.

46. Gastropod populations could also be affected by suspended sediment associated with navigation traffic. It is important to note that gastropods feed by grazing on attached algae on a solid surface, such as rocks, logs, or plant stems, whereas bivalves filter particulate material out of the water. Harrison and Farina (1965) found that the eggs of some gastropod species were intolerant of sediment accumulation, and with concentrations of 360 mg/ℓ, the schistomsome vector, *Biomphalaria pfeifferia* (a snail), did not lay eggs.

47. Along with sedimentation and turbidity, Eckblad (1981) has suggested that tow passage may affect molluscan distribution and productivity. In his study of the upper Mississippi, both *Physa* and *Campeloma* spp. (Gastropoda) were found in areas exposed by drawdown but were not found in adjacent unexposed areas. Conversely, in unexposed areas bivalves *Sphaerium* sp. and *Lampsilis* sp. and the prosobranch

Viviparus sp. were found. The latter bivalves were not found on substrates exposed to the atmosphere during drawdown.

Fish

48. Direct physical impact by a propeller or boat hull has caused injury and death to fish in navigable waters. Rosen and Hales (1980) reported that of 458 paddlefish (*Polydon spatula*) examined, 36 percent were scarred; they concluded that the main cause of scarring was collision with boats, although it was impossible to determine if these were commercial navigation vessels. They hypothesized that this high incidence of injury could be related to the escape behavior of this species. Increased swimming speed and body morphology could combine to force paddlefish to rise when startled, thereby increasing the chance of collision. Hubert (undated) described an instance when paddlefish were cut in half by a propeller of a tow. The central question in this issue, and one not addressed easily by experimental work, is whether or not these instances of mortality are detrimental to long-term survival of the species. The gradual decline of paddlefish during this century is the result of a variety of physical and chemical habitat changes. Movement of vessels in a waterway can be considered a perturbation; however, it is not possible to determine quantitatively the magnitude of the impacts associated with commercial navigation traffic or to quantify impacts associated only with navigation traffic. These effects can be determined only through long-term (10 to 20 years) population studies.

49. Turbulence associated with tow passage has varying effects, depending upon the species. Morgan et al. (1976) found that the shear forces needed to cause 50 percent egg mortality for white perch and striped bass were five times greater than what most eggs would be exposed to during ship or tow passage (425 versus 78 dynes/cm^2). Seasonality, spatial orientation, and periodicity of vessel passage influence the potential effects of navigation traffic on fish larvae and eggs (Holland and Sylvester 1983).

50. Movement of commercial and recreational vessels can affect fishes with nests. Mueller (1980) found that boat passage at slow speeds (1 m/sec) caused male longear sunfish to leave their nests, thus increasing the risks of predation on eggs and larvae. As an environmental effect, the turbulence will increase as the positive linear function of traffic rate increases. However, the overall effects of this percentage increase on the total numbers of fishes, or on those organisms that feed on various life stages of fishes, have not been identified.

51. Vinyard and O'Brien (1976) reported that the bluegill (*Lepomis machrochirus*) exhibited decreasing reactive distances to prey as turbidity increased (1.0 to 30.0 JTU). Buck (1956) and Smith, Kramer, and Oseid (1966) reported that fish inhabiting turbid waters were stunted, and they suggested that this could be partially the result of reduced foraging efficiency. Physiological responses to increased turbidity have been reported for several species of fish. Horkel and Pearson (1976) found that at 25° C, turbidities of 898 Formazine Turbidity Units (FTU) caused a 50 to 70 percent increase in ventilation rates (without a concurrent increase in oxygen consumption) in the green sunfish (*Lepomis cyanellus*). It has been suggested that this increase in opercular activity could be an effort to keep the gills free of sediment. Heimstra, Damkot, and Benson (1969) described coughing in largemouth bass and green sunfish and proposed that this was a mechanism by which gill chambers were kept clean. Carlson (1984) has observed coughing in bluegill sunfish when first exposed to turbidity increases greater than 100 Nephelometric Turbidity Units (NTU).

52. Among most fishes it is doubtful that the magnitude and duration of tow-induced turbidity are sufficient to cause significant mortality to healthy adult fish. Both indirect and direct effects of suspended sediment upon various life stages of fishes have been reported in the literature. In most cases, the effects are more pronounced on eggs, larvae, and juveniles than on adults. The limited mobility of immature life stages could expose them to higher concentrations of suspended solids for longer periods of time.

53. Turbulence from commercial navigation vessels will result in short-term increases in suspended solids. However, an examination of the literature reveals that it is difficult to extrapolate from many laboratory observations to conditions in the field since most laboratory studies involved levels of suspended solids far greater and for much longer times than those associated with passage of commercial tows. For example, Morgan et al. (1976) reported a lengthened incubation time for striped bass and white perch when exposed to more than 1,500 mg/ℓ suspended solids. Wang and Tatham (1971) reported delays in the hatching of eggs from yellow perch, white perch, striped bass, and American shad when exposed to 100 to 500 mg/ℓ of suspended solids.

54. The impact of tow-related drawdown on fishes remains largely unknown. Larval fishes that congregate in shallow water could be stranded for several minutes by drawdown. However, the effects that this could have on the population structure of selected species have not been investigated.

55. Drawdown will have its greatest effect on eggs deposited on the substrate in shallow water. Hubert (undated) has indicated that 26 of the 36 fish species collected in Pool 9 spawn in the shallows, where the eggs may be affected by drawdown. Holland and Sylvester (1983) in a laboratory experiment found that short-term, atmospheric exposure (2 min) at frequent intervals (once every hour or every 3 hr) caused significant reductions in survival of walleye and northern pike eggs. These researchers indicated that, in the Mississippi River, drawdown-related egg mortality would be the greatest in walleye, sauger, sunfish, and other organisms that spawn in shallow water (since shallow water would be most affected by drawdown). However, no research indicates that tow-induced drawdown has been detrimental to standing stocks of fishes.

PART IV: EFFECTS OF WINTER NAVIGATION

56. The proposed extension of commercial navigation (possibly to include year-round use) in northern waterways has generated interest in environmental impacts of navigation. Few environmental studies have been completed on this topic, and existing information is difficult to interpret because of the lack of good baseline data. Such deficiencies are being corrected by studies such as those of Hubert, Darnell, and Dalk (1983).

Physical Effects

57. Navigation along ice-covered waterways has physical impacts similar to those caused by navigation along ice-free waterways. However, the environmental impact of commercial traffic could be greater during the winter because of increased shoreline erosion caused by abrading ice. This ice can scour the river bottom in shallow water. Alger (1979) found that winter navigation had similar effects on current as did summer navigation; the magnitude of these effects depended upon vessel speed, size, and direction of travel. The turbulence generated by boat passage increases turbidity; Alger (1979) reported that the magnitude of the turbidity caused by passage could be greater in the winter than in summer because of greater impact of ice flows and erosive forces on shorelines and benthic sediments in shallow water. Poe, Edsall, and Hiltunen (1979) also found that commercial traffic increased turbidity in the St. Mary's River during February and March. This increased turbidity is more notable during a season when ambient turbidity levels are low, as discussed by Alger (1979). However, when aquatic organisms are dormant and respire and feed less than they do in the warmer months, these winter navigation effects could be minimal.

Effects on Fish

58. It has been reported that winter navigation has a possible additional impact upon catfish because of their seasonal shift in activity patterns. Catfish are lethargic during the winter (Hawkinson and Grunwald 1979, Peterson 1983) and are often found lying on the bottom, usually behind obstructions to the current, where position can be maintained with a minimum of activity. Hawkinson and Grunwald (1979) suggest that this behavior places them in risk of collision with passing vessels. Most fish species become relatively inactive during the winter and have a reduced ability to avoid navigation-induced perturbations. While it is likely that inactivity of fishes in the winter places them at risk, there is no evidence that significant numbers of certain species have been reduced by navigation traffic. Hawkinson and Grunwald (1979) and Peterson (1983) have also noted that silt accumulates on the backs of flathead catfish during these periods. Such sedimentation could clog gill chambers and be partly responsible for increased parasite loads often observed on these fish at this time. However, detailed studies on these observations have not been initiated.

Invertebrate Drift

59. As discussed by Beckett et al. (1986) and Seagle and Zumwalt (1981), drift has annual periodicity with maximum values occurring in spring. However, the disruptive forces of a vessel moving through ice can bring about an increase in drifting organisms. During winter, drifting organisms are susceptible to predation, although predators are also sluggish and not as active as they are during warmer months. Dislodged invertebrates are unable to regain cover easily, especially if they are swept into the channel. Since they are a potential food source for aquatic and terrestrial animals (and will provide offspring when winter is over), a large reduction in benthos could be detrimental to the system. However, no well-designed studies that document the impacts of winter navigation on invertebrate drift are in the literature.

PART V: NAVIGATION EFFECTS STUDIES

Techniques to Study Navigation Effects

60. The effects of navigation traffic can be assessed through the following methods:

- a. Studies in which sessil organisms are caged and transferred to impact and control sites where growth and other functions can be monitored.
- b. Laboratory studies in which the physical effects of traffic can be simulated and the response of target organisms to these effects measured.
- c. Controlled field experiments in which significant community or population parameters (relative abundances of organisms with specific habitat requirements, shifts in standing crop, evidence of recent mortality or recruitment, growth rates, feeding strategies, etc.) for key organisms are measured. These approaches are useful for site-specific as well as more general studies. For the latter, the results of studies of dissimilar sites can be compared to help decisionmakers gain a clearer understanding of the range of effects of navigation activity.

61. Sensitive areas in a waterway can be identified by using previously developed formulae or models that relate degree of perturbation (turbulence, turbidity, etc.) to channel depth, hull morphometry, and type and speed of the vessel. While this approach will not provide information on biological effects, it will be possible to identify those areas where physical conditions could be altered enough to stress aquatic life. For example, in their analysis of commercial vessel passage in the Great Lakes, Wuebben, Brown, and Zabilansky (1984) illustrated the usefulness of this technique. Based upon their analysis, it was determined that many environmental effects could be reduced simply by lowering vessel speed by 1 to 2 mph.

Field Studies

Prairie du Chien, Wisconsin

62. A barge-loading facility is located in the northeastern portion of the east channel of the Mississippi River at Prairie du Chien, Wisconsin. To reach this facility, barges must make a sharp turn through fairly shallow water while moving over a diverse and dense community of mussels that includes commercially valuable species (*Amblema plicata*, the threeridge mussel) as well as the endangered Higgins' eye mussel, *Lampsilis higginsi*. US Army Engineer Waterways Experiment Station (WES) scientists initiated a program of quantitatively sampling mussels from sites impacted to various degrees by the movement of barges at Prairie du Chien. The purpose of this program was to provide annual information on mollusc community and population dynamics that would enable planners and scientists to evaluate the long-term health of the mussel bed and to interpret possible effects of the barge activity. In October 1984, a total of 60 quantitative samples were taken from six sites variously impacted by navigation traffic. In July of 1985, 116 samples were taken from four of the previously studied sites. The study consisted of having divers collect a series of quantitative substrate samples using a 0.25 m^2 quadrat. All of the substrate, which included sand, shells, and live molluscs, was removed and sent to the surface, where it was sieved and picked for live organisms. This technique differs from previous methods in which a single diver was sent to the bottom with a 1.0 m^2 (or larger) quadrat and instructed to bring back all live mussels that he felt while moving his hands over the substrate. Techniques used by WES (i.e., total substrate removal) provide a more accurate estimate of density and ensure obtaining very small organisms if they are present.

63. Length-frequency histograms from three sites receiving various degrees of stress from the movement of barges for *Amblema plicata* are shown in Figure 1. Site I was directly over the barge-turning zone, whereas Sites II and III were at increasing distances downriver of the impact area. These data illustrate three major points:

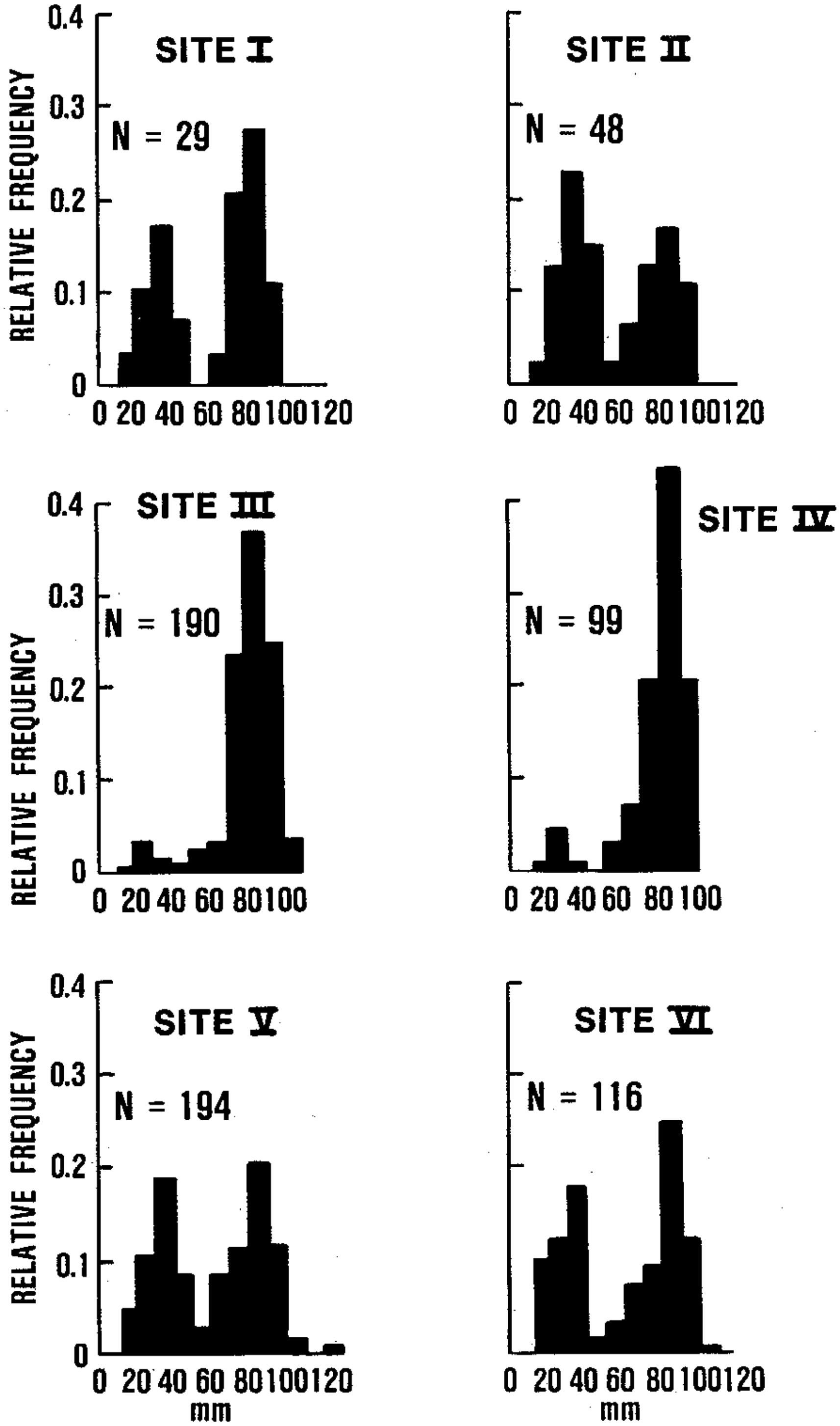

Figure 1. Bimodal length-frequency distribution of *Amblema plicata* in the Upper Mississippi River, near Prairie du Chien, Wisconsin

(a) recruitment (as a percentage of the population) of *A. plicata* (presence of juveniles) does not occur uniformly at the mussel bed in Prairie du Chien and seems to be unrelated to the movement of barges; (b) mussel density increased moving downstream of the barge-turning zone; and (c) a missing age class occurred between the 40- to 60-mm size for this species. Apparently this gap was unrelated to barge activity and was fairly widespread in the area; a site investigated about 3 miles upriver exhibited similar characteristics. This missing age class illustrates that recruitment at a mussel bed could be a cyclic phenomenon; a diverse community still exists if there are years when no successful reproduction occurs.

Transfer studies

64. Smith (1984) describes the caging of organisms (in this case marine clams) from two distinctly different habitats and reciprocally transferring them between the two sites. After the clams were held for about 45 weeks at the new sites, their physical condition (the ratio of soft tissue mass to internal shell volume as well as other measures) was assessed. This type of study enables one to test the effects of physical perturbations on naturally occurring organisms without the problems associated with laboratory experiments.

65. In the fall of 1985 the Louisville District funded WES to conduct a transfer study of juvenile *Fusconaia ebena* in the Ohio River near Olmsted, Illinois. Specimens were collected by divers, placed in mesh baskets, and returned to the substrate. One set was placed at the original capture site (near Olmsted, Illinois) to compare the growth of caged versus uncaged mussels. Other mussels were transferred to lightly and heavily trafficked sites upriver of the Olmsted site. Organisms will be recollected at specific time periods and assessed for growth, mortality, and physiological condition. The purpose of this work will be to assess navigation traffic effects using experimental techniques in the field.

Studies on mussel growth

66. The Illinois Natural History Survey conducted studies of mussel growth at two sites on the Illinois River at Naples, Illinois.

Mussels were collected and marked, their total length was measured, and they were placed in a substrate protected by metal exclosures. At the end of the summer, the mussels were retrieved, and their rate of growth was computed for experimental and control groups. It was determined that from two species, *Quadrula pustulosa* and *Amblema plicata*, rate of growth in the barge-fleeted (experimental) area was reduced when compared with the unfleeted (control) site. However, the reverse was true for the thin-shelled species *Leptodea fragilis*; the group exposed to barge fleeting grew faster than the control group. A longer period of time is probably required to demonstrate changes, if any, from commercial traffic. It should be noted the Illinois River is severely affected by point-source effluents and elevated suspended solids and is not the most suitable river in which to conduct these studies. Additional data are now being collected by scientists at the Illinois Natural History Survey.

Laboratory Studies

67. Water drawdown created by navigation traffic can expose shoreline areas to the atmosphere for several minutes (Bhowmik et al. 1981). To evaluate the effects of water drawdown on commercially valuable fish, WES scientists designed and completed laboratory studies on the effects of atmospheric exposure to channel catfish eggs (*Ictalurus punctatus*). Channel catfish are typical of species that build nests and spawn in shallow water and would be susceptible to the effects of water drawdown. Results of this work indicated that eggs exposed from 0 to 2 hr exhibited a 90 percent hatching rate. Eggs exposed to the atmosphere for 4 hr or more exhibited a substantial reduction in hatching rates; i.e., less than 40 percent hatched. Based upon these laboratory studies, it appears that water drawdown of several minutes, as typically takes place following vessel passage, has little or no effect on eggs produced by channel catfish.

68. Scientists at WES also tested the effect of cyclic suspended solids on three species of freshwater clams (*Fusconaia flava*, *Pleurobema*

beadleanum, and *Quadrula pustulosa*). This was done by exposing the clams to approximately 500 mg/ℓ of artificial sediment (diatomaceous earth) at two intervals indicative of possible traffic patterns in a large waterway: frequent (two events per hour) and infrequent exposure (one event per 3 hr) while feeding them a proteinaceous yeast suspension. The ratio of oxygen consumed to nitrogen excreted by clams could then be used to detect shifts from a food-based to a body-storage-based metabolism. Low molar-oxygen-to-nitrogen ratios indicated that proteinaceous yeast was being eaten and used to meet energy demands. High oxygen-to-nitrogen ratios indicated that shifts had been made to burning of tissue-stored carbohydrate. When exposed to 7-min pulse of turbulence plus suspended sediments, *Q. pustulosa*, *F. flava*, and *P. beadleanum* maintained a food-based metabolism no different from control clams exposed to a 7-min pulse of turbulence alone. However, clams exposed to this 7-min pulse of turbulence twice per hour shifted partially toward burning of tissue-stored carbohydrate. When frequent turbulence also involved suspended-sediment exposure, clams shifted from feeding to total reliance on body stores to meet maintenance requirements. Thus, frequent exposure to turbulence or turbulence plus suspended sediments adversely affected these clams' growth potential, with the additive effects of suspended sediments being especially severe.

69. Based upon this experiment, it appeared that frequent resuspension of bottom sediments can impair the food-gathering capability of freshwater mussels (and probably other suspension feeders as well). However, the infrequent exposure may or may not be deleterious. Long-term field studies on density and recruitment ratios, such as are being conducted near Prairie du Chien, will help answer these questions. The extent of reduction observed in the laboratory study was sufficient to suggest that sustained changes in the physiological conditions of adversely affected individuals could result (Payne, Aldridge, and Miller 1986). Related studies of juvenile *F. ebena* have shown that periodic or continuous exposure to turbulence alone can adversely affect the growth potential of this species under laboratory conditions.

70. In another experiment with clams, food-clearance rates were measured as a result of exposure to two levels of suspended solids. It was found that two species of mussels exposed to a single 7-min pulse every 3 hr for 3 days reduced their food-clearance rates relative to controls (Table 1). Stress was determined to be related to the periodicity of cyclic disruption of feeding by exposure to suspended solids. If protection of filter-feeders is a major consideration in habitats where navigation traffic causes bottom-sediment resuspension, then the passage rate of commercial vessels is an important factor.

Table 1

Descriptive Statistics (mean +/- standard deviation) and Student's t-test Analysis of *Quadrula pustulosa* and *Fusconaia flava* Food-clearance Rates* after 3 Days of Exposure to Suspended Solids Once Every 3 hr

Species	Treatment		Student's t-test		
	Control	Exposed	df	t	p**
Quadrula pustulosa	7.86 +/- 5.63	3.35 +/- 1.74	24	2.76	<0.02
Fusconaia flava	9.29 +/- 8.69	4.19 +/- 2.83	66	3.25	<0.001

* Clearance rates were determined as milligrams of yeast cleared per hour per gram of dried mussel tissue.

** Probability is the difference observed between control and exposed mussels due to chance alone.

71. Juvenile Asiatic clams (*Corbicula*) were tested for their response to cyclic suspended solids. A total of 112 clams were divided into equal-sized groups for a 37-day study. Group I was an infrequent-exposure group; clams were cyclically exposed to a 7-min pulse of 750 to 1,000 mg/ℓ suspended inorganic solids and associate turbulence once every 3 hr. In group II the organisms were exposed to a 7-min pulse of turbulence with no suspended solids once every 3 hr. In group III the clams were cyclically exposed to a 7-min pulse of 750 to 1,000 mg/ℓ

suspended inorganic solids and associated turbulence once every 0.5 hr. Finally, the last group was cyclically exposed to a 7-min pulse of turbulence without suspended solids once every 0.5 hr. No mortality was observed for the control groups. However, mortality in both the exposed groups showed a sigmoid pattern. The onset of mortality was delayed, and total deaths were less extensive in the infrequent versus frequent group.

72. Paddlefish (*Polydon spatula*) occur in large rivers where navigation traffic frequently occurs. In the early 1900s paddlefish were a large component of the commercial fishery in the Mississippi River basin, but recently their numbers have drastically decreased. Reasons for the decline of these species include: (a) loss of gravel substrates, (b) alteration of flow from construction of dams, (c) pollution, and (d) navigation traffic effects. A study was conducted at WES to determine the effects of turbulence on the survival of paddlefish larvae. This was accomplished by measuring survival rates for paddlefish exposed to cyclic turbulence.

73. The survival rate of the paddlefish larvae exposed to two intensities of turbulence at frequent and infrequent time intervals appear in Figure 2. For the larvae exposed every hour, the survival

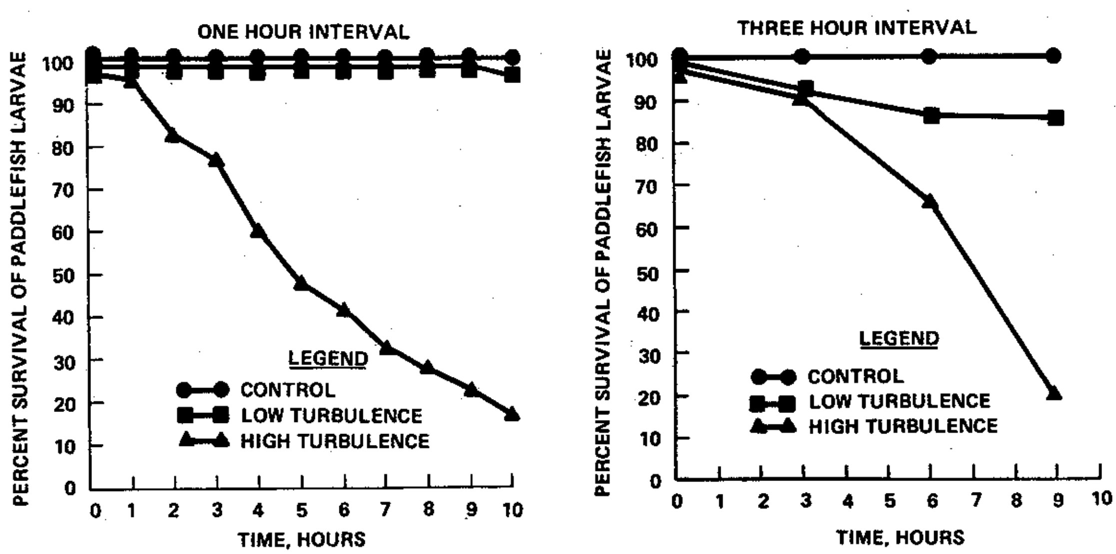

Figure 2. Effects of laboratory-induced turbulence on paddlefish larvae

rate of the high-turbulence group was significantly ($p < 0.05$) different from the survival rates of the low-turbulence and control groups. The high-turbulence group had a 17 percent survival rate after 10 hr (10 exposures) while the low-turbulence and control groups exhibited a 98 and 100 percent survival rate. A similar response occurred for the larvae exposed every 3 hr, although the survival rates of both the high- and low-turbulence groups were significantly different ($p < 0.05$) from the control group. The high-turbulence group had a 20 percent survival rate at 9 hr (three exposures) while the low-turbulence and control groups had 85 and 100 percent survival rates, respectively. The survival rates of the two treatments and control groups exposed every hour were not significantly different from their counterparts exposed once every 3 hr.

74. Turbulence created by navigation traffic can exert a highly variable but stressful force on aquatic organisms. Turbulence created by barge traffic has not been measured in the field, although Morgan (1976) calculated that certain oceangoing ships generate a shear of 78.9 dynes/cm^2, which is considerably less than experimental conditions (6,000 dynes/cm^2) for this study. Assuming that high intensities of turbulence could be associated with propeller wash (6,000 dynes/cm^2) while low levels of turbulence (less than 2,000 dynes/cm^2) would result from barge-generated waves, this study would indicate the paddlefish are tolerant of low turbulence, but will experience high mortality rates if entrained in the propeller wash. In addition, the frequency of the event appeared to be less serious than the intensity of the event. Further, physical abrasion on solid objects during turbulent episodes could also account for high mortality rates during barge passage. Further studies will be conducted to determine the extent of force generated by commercial vessels at various distances from the vessel. Results of studies such as these can then be used to interpret the effects of navigation traffic in large waterways.

PART VI: CONCLUSIONS

75. While there is considerable concern over the biological effects of commercial navigation traffic, studies that demonstrate conclusively that such impacts exist are few. For example, many workers have evaluated the effects of high levels of suspended solids (often not natural sediment) or other perturbations on aquatic organisms. Unfortunately, the results of these studies have been extrapolated to evaluate the effects of commercial navigation traffic. However, there are two problems with this approach. First, navigation traffic does not usually cause excessively high levels of turbulence or turbidity. Immediately beneath a moving tow, velocities could exceed several meters per second; however, navigation-induced velocities in adjacent shallow-water habitats are considerably less. Therefore, results of many of these laboratory studies cannot realistically be used to assess general effects of navigation traffic throughout a large-river ecosystem. They could be appropriate to assess navigation effects at a specific site, such as a barge terminal or fleeting area. There is a need to evaluate the results and experimental design of some of these earlier studies and to initiate laboratory work that more closely reflects the physical effects of navigation activities identified in the field. In addition, field verification of the laboratory results is necessary.

76. The second problem with much of the recent work on navigation impacts is that there is no easy way to measure quantitatively (or to predict) the effects of tow-induced turbulence and turbidity in the vicinity of the organisms of interest. To determine impacts to aquatic biota, levels of turbulence and turbidity must be known at a site. These physical data can then be coupled to the results of carefully conducted laboratory studies on the physiological responses of animals to sublethal episodic events to predict environmental effects of navigation traffic.

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