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Effects of Increased Commercial Navigation Traffic on Freshwater Mussels in the Upper Mississippi River: Final Synthesis Report

by Andrew C. Miller, Barry S. Payne

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Prepared for U.S. Army Engineer District, St. Louis

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Final report

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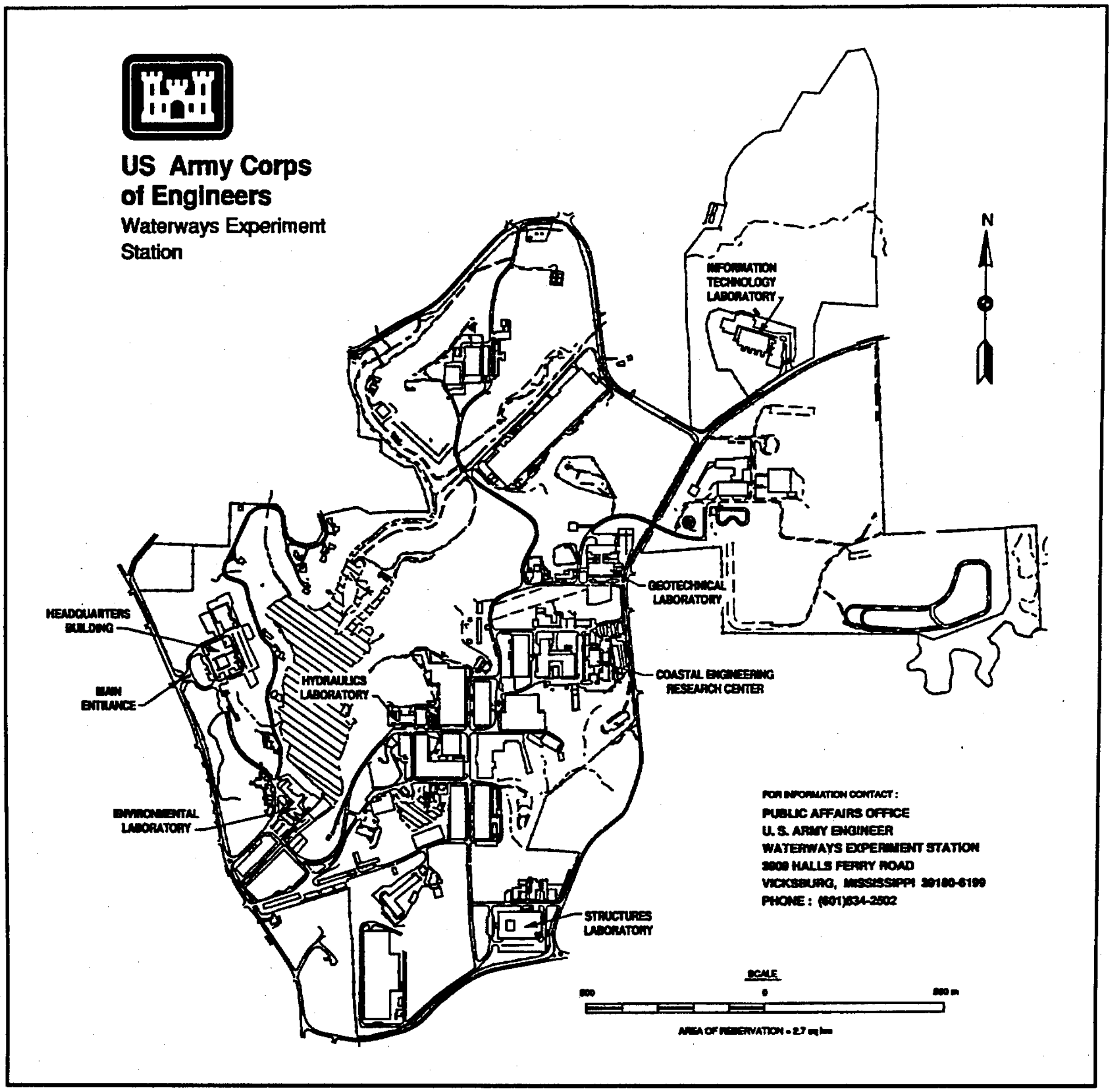

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Preface

In accordance with the Endangered Species Act, Section 7, Consultation Procedures, personnel from the U.S. Army Engineer District, St. Louis, and the U.S. Fish and Wildlife Service (FWS) determined that a monitoring program should be initiated in the upper Mississippi River (UMR) to assess the effects of existing and projected future increased commercial navigation traffic levels on freshwater mussels including the endangered Higgins eye mussel, *Lampsilis higginsi*. Concern had been expressed by the FWS and other agencies that projected increases in traffic resulting from completion of the Melvin Price Locks and Dam, Second Lock Project (formerly known as the Locks and Dam 26 (Replacement)), at Alton, IL, could negatively affect freshwater mussels. In 1988, the St. Louis District contracted with the U.S. Army Engineer Waterways Experiment Station (WES) to initiate studies on traffic effects in the UMR. Sample sites were identified in 1988 and 1989, and studies continued until 1994. This report contains a synthesis of the results of the entire study. Funds for this project were provided by the St. Louis District. During 1992, 1993, and 1994, funds from the U.S. Environmental Protection Agency were also used to collect and analyze information on the introduction and spread of zebra mussels in the UMR.

This report was prepared by Drs. Andrew C. Miller and Barry S. Payne, Aquatic Ecology Branch (AEB), Ecological Research Division (ERD), Environmental Laboratory (EL), WES.

The authors acknowledge all individuals who participated in this 7-year study. Divers were Messrs. Ron Fetting, Ed Strand, Kenneth Schroeder, Bob Sikkila, and Bill Wolf, U.S. Army Engineer District, St. Paul, and Messrs. Larry Neill, William H. Host, Jr., Johnny Miller, Mitchell Marks, Dennis Baxter, Robert Warden, Larry Armstrong, Pat Hjelm, Kevin Chalk, Rob James, Jeff Montgomery, and Johnny Buchannan, Tennessee Valley Authority (TVA). Assistance in the field was provided by Messrs. Robert Whiting, Dan Hornbach, Tony Deneka, B. Will Green, Steve Thomas, Gabrielle Meyer, Travis Whiting, Todd Pedderson, Chris Weggs, David Beckett, Dan Ragland, Leo Nico, and Ms. Sherrie Zenk-Reed. Diving inspectors were Mr. Ken Hollingsworth, Ms. Katherine Meadows, Mr. Stanley Zurweller, Mr. David Rogillio, and Ms. Debora Shafer. Laboratory assistance was provided by Ms. Geralline Wilkerson, Ms. Sarah Wilkerson, Ms. Erica Hubertz, Mr. David Armistead, Mr. Ken Gordon, Ms. Cheryl Tansky, Mr. David Felder, and Ms. Monica Sanders. Messrs. Dan Ragland and Gene Buglewicz were extremely supportive and assisted greatly with study design, location of study sites, and background information on the project area. Assistance with study design and choice of parameters to measure was also provided by Messrs. Alan Buchanan and Leroy Koch, Missouri Department of Conservation; Dr. Edward Cawley, Loras College; Mr. Kevin Cummings, Illinois Natural History Survey; Mr. Mike Knott, Stanley Consultants; and Ms. Marian Havlik, Malacological Consultants. Foul weather and safety gear was provided by TVA. Special thanks to Mr. Robert Read, deceased, of the Wisconsin Department of Natural Resources. Mr. Read first introduced the authors to the molluscan resources of the east channel at Prairie du Chien and donated his time to assist at this location each year from 1988 to 1993.

Dr. John W. Keeley was Director, EL; Dr. Conrad J. Kirby was Chief, ERD; and Dr. Alfred F. Cofrancesco was Chief, AEB, during the preparation of this report.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

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

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms

Summary

Background

In 1988, the U.S. Army Engineer District, St. Louis, requested that personnel at the U.S. Army Engineer Waterways Experiment Station (WES) initiate a monitoring program to analyze the biological and physical effects of movement of commercial navigation traffic in the upper Mississippi River (UMR). A moving commercial vessel produces a brief period of turbulence, increased water velocity, and elevated suspended solids caused by propeller wash, water displacement, and hull friction. These intermittent disturbances could interfere with their feeding and water circulation or physically dislodge freshwater mussels (Mollusca: Unionidae). Specific concern exists because of the presence of the endangered *Lampsilis higginsi* (Lea) in much of the UMR. Freshwater mussels dominate the benthic biomass in many places in most large rivers in the United States. Their sedentary lifestyle and reliance on suspended particulate organic matter as food makes them particularly susceptible to turbulence, sedimentation, and fluctuating water levels.

The purpose was to collect baseline data between 1988 and 1994 that could be used to evaluate the effects of increased commercial traffic in the UMR that could result from completion of the Melvin Price Locks and Dam, Second Lock Project (previously the Locks and Dam 26 Replacement Project), at Alton, IL. This study took place during a period when traffic levels were not expected to increase. After 1994, biological and physical data will be collected at each bed once every 5 years. This will be done until traffic levels have increased as a result of completion of the Melvin Price Locks and Dam, Second Lock Project, by an average of one tow per day above 1990 levels in the pool where monitoring took place. Studies will then resume at the original rate (annually) and continue until 2040, the economic life of the project. In 1990, the mean number of tows passing up and downriver per day was as follows: Lock 10 (7.5), Lock 12 (8.8), Lock 14 (12.3), Lock 17 (11.0), and Lock 24 (12.3).

Data in this report will be used to (a) evaluate biotic conditions during the 1988-94 study and (b) provide a database to compare results from future studies conducted after traffic increases above current levels. Monitoring was initiated as a result of concerns expressed by personnel from the U.S. Fish and Wildlife Service (FWS), State conservation agencies, and conservation groups.

Many other studies of mussels and physical effects of traffic have been conducted in the UMR (see References section). This study was unique in that physical effects studies were conducted immediately over beds that supported dense and diverse assemblages of mussels. Studies were designed to allow comparisons among years, among beds, and between nearshore and farshore sampling sites. Design of field studies was partially based upon results of laboratory experiments on the effects of intermittent turbulence and elevated suspended solids on mussels.

Studies were conducted at historically prominent mussel beds at the following river miles: 299.6 (Pool 24), 450.4 (Pool 17), 504.8 (Pool 14), 571.5 (Pool 12), and the main channel of the UMR at RM 635.2 (Pool 10). Qualitative and quantitative samples (0.25-m^2 total substratum) were obtained to assess density, species richness, species diversity, evidence of recent recruitment, presence of *L. higginsi*, relative species abundance, and occurrence of mussel species. The effects of commercial vessel passage on ambient water velocity and turbidity (Jackson Turbidity Units, JTU) or suspended solids (gravimetric measurements) were also studied.

Physical Effects of Vessel Movement

Water velocity

Water velocity was measured approximately 9 in. (23 cm) above the substratum-water interface using Marsh McBirney Model 527 current meters. This Model 527 meter measures velocity in two directions (X and Y components that are at right angles to each other) and is equipped with a compass. Two meters were equipped with 1,000 ft (305 m) of cable, and two were equipped with 200 ft (61 m) of cable. Water velocity in two directions and a compass reading were obtained at 1-sec intervals and stored on a Model CR10 data logger (Campbell Scientific, Inc., Logan, UT). Depending upon conditions, up to four sensors were deployed at distances ranging from approximately 50 to 500 ft (15 to 152 m) from the riverbank. In all cases, velocity sensors were placed directly over mussel beds. When a commercial vessel was sighted, the meters and data logger were turned on (usually approximately 250 sec before the vessel reached the sensors), and continuous data on water velocity and compass readings were obtained.

Of the 60 events in which data were collected, 12 (20 percent) were considered to have a major effect on ambient conditions. Thirty-seven percent produced a minor effect, and 43 percent produced no measurable change. For example, major effect caused ambient velocity 105 ft (32 m) from the bank to change from 0.348 ft/sec (10.6 cm/sec) to 0.720 ft/sec (21.9 cm/sec) for approximately 100 sec. In a minor but measurable event, combined velocity changed from 0.80 ft/sec (24.4 cm/sec) to 0.56 ft/sec (17.1 cm/sec) immediately following passage. Many velocity changes were considered minor, especially when compared with ambient conditions during normal high water, between 2 and 3 ft/sec (61 and 91 cm/sec) in January through April for most years.

Suspended solids and turbidity

Water was collected 4 in. (10 cm) above the substratum-water interface at the same locations where velocity was measured. Water was brought to the surface through a 25-ft (7.6-m) length of rubber hose secured to a concrete block. Suction was provided by a 12-V Water Puppy pump. The pump ran continuously, and a 500-ml bottle was filled every 2 min as the vessel passed. Turbidity was measured in the field with a Hach portable turbidimeter, and total suspended solids were measured in the laboratory using gravimetric procedures.

Vessel-induced changes in turbidity and suspended solids at mussel beds in the UMR were minor, of short duration, and usually lasted no more than several minutes. Vessel motion increased these values more at the substratum-water interface than the surface. Typically, a vessel caused an increase in total suspended solids of no more than 2 times ambient conditions and had a measurable effect for several minutes. In one event, mean suspended solids changed from 20.4 $\pm$ 5.3 (standard deviation) to 21.1 $\pm$ 5.7 mg/ℓ and 37.4 $\pm$ 12.4 mg/ℓ at a nearshore and farshore site, respectively. In the UMR, mussels are found in firmly packed substratum that is relatively free of recently settled sediments; therefore, movement of large vessels had minimal effects on ambient suspended solids and turbidity.

Results of Laboratory Studies Designed to Mimic the Effects of Commercial Traffic

Turbulence and turbidity

In a study conducted at WES in the early 1980s, metabolic rate and catabolic substrate shifts were measured for three species of mussels (*Quadrula p. pustulosa, Pleurobema beadleanum*, *Fusconaia cerina*) and that were cyclically exposed to unnaturally high levels of turbulence and turbidity at two distinct frequencies. This experiment was designed to evaluate the importance of frequency of cyclic exposure to physiologically disruptive changes in hydrologic conditions and to assess the utility of food clearance, respiration, and nitrogen excretion rate measures as quantitative indices of stress.

Intermittent exposure of freshwater mussels to high levels of suspended solids disrupted feeding and caused shifts to catabolism of endogenous nonproteinaceous energy reserves. Exposure of all three species of unionid mussels to infrequent (once every 3 hr) and frequent turbidity (once every 0.5 hr) at levels of 750 and 600 mg/ℓ, respectively, caused reduced food clearance rates. Frequent exposure to turbidity resulted in reduced nitrogenous excretion rates in all three species and higher 0:N ratios. The response to infrequent exposure to turbidity was more variable; only *Q. p. pustulosa* and *P. beadleanum* showed major responses. Both species reduced oxygen uptake and nitrogenous excretion rates in tandem. The fact that the animals exposed to turbidity infrequently showed no shift in catabolic substrates (O:N ratio) suggests that they were less seriously affected than mussels exposed frequently to turbidity.

Field studies of navigation effects on turbidity show that levels of suspended solids (600 to 750 mg/ℓ) used in laboratory experiments designed to elicit physiological stress responses will rarely be encountered by natural populations of mussels during periods of normal flow as a result of navigation traffic. Laboratory studies indicate the potential for disruption of normal feeding and metabolism due to exposure to high levels and frequencies of turbulence and suspended solids. The ecological significance of any shifts from food-to-body storage-based metabolism associated with stressful conditions of turbulence and suspended-solids exposure ultimately depends on these shifts being translated into reduced growth, reproduction, or survival of individuals in naturally occurring populations.

Water velocity

The effects of continuous versus intermittent exposure to turbulence on the freshwater bivalve *Fusconaia ebena* was studied in a second experiment at WES. Mussels were exposed to one of three conditions: continuous-low, continuous-high, and cyclic-high water velocity. The Tissue Condition Index (TCI) of juvenile *F. ebena* in the continuous-low- and cyclic-high-velocity treatments was 20 and 22 percent less than the TCI of field-fixed juveniles (control organisms). Continuous exposure to high-velocity water caused a 34-percent reduction in TCI. Comparison of the mean TCI by Duncan's multiple range test indicated that weight loss was not significantly different ($p > 0.05$) between continuous-low- and cyclic-high-velocity treatments, but weight loss was significantly less in these two treatments than in the continuous-high-velocity group. Respiration rates, measured in still water, did not differ significantly among mussels from the three treatments.

Juvenile *F. ebena* were not affected by 5 min exposure to high-velocity water once per hour, a result directly relevant to evaluating the environmental effects of commercial navigation traffic. Commercial traffic rates do not often exceed one tow per hour. Thus, turbulence caused by routine traffic is not likely to deleteriously affect mussels. Conversely, at sites where barges are fleeted, towboats sometimes work essentially continuously. Potential impacts to mussels by abrupt water-velocity changes in fleeting areas need to be evaluated on a site-specific basis.

Overall Health of the Five Mussel Beds, Results of 1988-94 Field Studies

Background

Six criteria, designed to reflect the overall health of a mussel bed, were used to determine if mussels were being negatively affected by commercial traffic. These six criteria were as follows:

a. *Decrease in density of five common-to-abundant species*. Negative effects will be assumed if there is a significant ($p < 0.1$) decline in density, sustained over each of at least two consecutive sampling periods (i.e., a study year), for at least five common-to-abundant species.

b. *Absence of L. higginsi*. If L. *higginsi* is not collected on two consecutive sampling periods, it will be assumed that this species is declining in abundance. This criterion applies only to beds in Pools 10, 12, and 14, where it is typically collected.

c. *Decrease in live-to-recently dead ratios for dominant species*. Negative effects will be assumed if there is a continual decrease in the live-to-recently dead ratio for three consecutive sampling periods.

d. *Loss of more than 25 percent of the mussel species*. Negative effects will be assumed if subsequent sampling (sustained over two sampling periods) reveals a loss of more than 25 percent of the mussel species known to occur at the bed.

e. *No evidence of recent recruitment*. If there are no signs of recruitment for two consecutive sampling periods for five common-to-abundant species, negative affects will be assumed.

f. *Significant reduction in growth rates or increase in mortality*. If a significant reduction (0.05 level) at the affected site is identified, negative effects will be assumed.

Methods

Mussels were collected at a farshore (affected by commercial traffic) and a nearshore site (affected to a lesser degree by traffic) within each mussel bed. Divers were equipped with surface-supplied air and communication equipment. Qualitative samples were obtained by two to three divers working simultaneously who retrieved all live mussels encountered by touch, in increments of 5 or 20, until approximately 600 individuals were collected. Quantitative sampling consisted of having two divers retrieve all sand, gravel, and shells from within a 0.25-m^2 aluminum quadrat. At each site, 10 quantitative samples were obtained at each of three closely placed subsites; two sites were worked at each mussel bed. All material was sent to the surface in a 20-ℓ bucket, taken to shore, sieved through a nested screen series (finest screen with apertures of 6.4 mm), and picked for live organisms. All bivalves were identified, and total shell length (SL) was measured to the nearest 0.1 mm.

Criteria for Testing

The following is a summary of results and how they relate to the six criteria:

Decrease in density of five common-to-abundant species

This criterion was met (i.e., there was not a significant density decline at the 0.1 level for five common-to-abundant species that was sustained for 2 consecutive years) at mussel beds chosen for detailed study. The criterion was tested for *Amblema plicata plicata, Q. p. pustulosa*, *Truncilla truncata*, *Quadrula quadrula*, *Obliquaria reflexa*, *Ellipsaria lineolata*, and *Leptodea fragilis*. A total of 29 density evaluations in specific pools were possible (each species could not be tested at every bed). There was a significant density decline for eight species and a significant density increase for two species. However, the criterion was met since there was not a significant decline in density for five common-to-abundant species, sustained for at least 2 years, at a bed.

Absence of *L. higginsi*

The criterion stated that negative effects would be assumed if this species was not collected during two consecutive sampling periods. Based on this criterion, there were no negative effects at beds in Pools 10 and 14. At the beds in Pools 12 and 17, *L. higginsi* was much less common and was not collected each year. This criterion was met at the bed in Pool 12, but was not met at the bed in Pool 17. The bed in Pool 24 is outside the range of *L. higginsi*.

Decrease in live-to-recently dead ratios for dominant species

This criterion stated that negative effects would be assumed if there was a continual decrease in the ratio of live-to-recently dead organisms for three consecutive sampling periods. This criterion was met. Recently dead organisms were rarely collected during this survey and always made up less than 1 percent of the sample.

Loss of more than 25 percent of the mussel species

The criterion stated that negative effects would be assumed if there was a loss, sustained for two consecutive sampling periods, of over 25 percent of existing mussel species. Although there was some year-to-year variation in species richness, numbers remained relatively constant for each study year. At the bed in Pool 24, the number of species collected each year, based on qualitative and quantitative sampling was as follows: 18 (1988), 22 (1989), 22 (1991), 13 (1992), and 20 (1994); total species richness was 26. At the mussel bed in Pool 10, the total number of species collected each year was 27 (1988), 22 (1989), 25 (1991), 18 (1992), 26 (1993), and 25 (1994); total species richness was 31. Similar results were found for the other beds; although species richness varied among years, no dramatic changes were noted. The criterion for species richness was met at each bed; none experienced a sustained loss of any species. There were interbed differences in species richness, brought about by local physical and hydraulic conditions.

Evidence of recent recruitment

No indication of recruitment problems existed among UMR populations of mussels, in terms of either species or total individuals. There was always evidence of at least some recent recruitment. Depending on the pool, location of the site (nearshore or farshore), and year, between 10 and 55 percent of all individuals collected in quantitative samples were less than 30 mm long. Approximately 10 to 75 percent of species present showed evidence of recent recruitment in any particular pool, site, or year. Nearshore versus farshore comparisons did not yield any clear differences with respect to evidence of recent recruitment. No trend was evident in recent recruitment in terms of numbers of individuals. However, communitywide evidence of recent recruitment (i.e., percent of species) was consistently lower in 1989 than in 1990-1994.

Concluding Comments

Based on results of physical effects studies at these beds, periods of increased velocity, flow reversal, and elevated suspended solids do not affect mussels. Although there were annual fluctuations in specific biotic parameters, based upon pre-established criteria, these mussel populations appear stable and unaffected by movement of commercial traffic. Results of future studies, to be conducted after commercial traffic levels have increased as a result of construction of the second lock, will be used to further investigate the effects of movement of commercial navigation traffic.

1 Introduction

Background

Concern over the environmental effects of commercial vessel movement

In the United States, three projects are responsible for initiating concern over the environmental effects of commercial navigation traffic. These are the Tennessee-Tombigbee Waterway, a connecting link between the Tennessee and Tombigbee rivers in Alabama and Mississippi; the second lock at the Melvin Price Locks and Dam project near Alton, IL; and construction of a new lock in the Ohio River at Gallipolis between Ohio and West Virginia. During the last 15 years, environmental groups and State conservation agencies have expressed concern over the environmental effects of vessel movement. As a result, much speculation and discussion on this topic has appeared, most in the Government or nonrefereed literature (Virginia Polytechnic Institute and State University 1975; Academy of Natural Sciences of Philadelphia 1980; Berger Associates, Ltd. 1980; Sparks et al. 1979; U.S. Army Corps of Engineers 1980; Lubinski et al. 1980, 1981; Environmental Science and Engineering 1981, 1988; Kennedy, Harber, and Littlejohn 1982; Rasmussen 1983; Simons et al. 1981; Simons, Ghaboosi, and Chang 1987; Wuebben, Brown, and Zabilansky 1984; and Nielsen, Sheehan, and Orth 1986). Much of this writing has been considered speculative (Wright 1982). Regardless, the increasing use of inland waterways to transport bulk commodities (Dietz et al. 1983) and the recent articles on impacts of waterway use in Europe (Brookes and Hanbury 1990; Haendel and Tittizer 1990) suggest that this issue will remain important well into the 21st century.

Background on the Melvin Price Locks and Dam

In the late 1970s, the St. Louis District began to construct the Melvin Price Locks and Dam to replace Locks and Dam 26 located on the Mississippi River near Alton, IL. The new structure has two chambers, one 1,200 ft[1] long for

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page x.

commercial tows, and a second 600-ft auxiliary lock for smaller craft. Since the original structure consisted only of a 600-ft lock and a 360-ft auxiliary lock, the new facility will greatly reduce traffic congestion. Previously, delays up to 72 hr were common. Alton is at a critical segment of the waterway; 15 miles north is the confluence of the Illinois River, which leads through the Chicago Ship Canal to Lake Michigan, and 10 miles south is the confluence of the Missouri River. The locks are 200 miles upriver of the confluence of the Ohio River, which connects to the Tennessee, Cumberland, Allegheny, and Monongahela rivers.

Incidental take statement of the U.S. Fish and Wildlife Service

The U.S. Fish and Wildlife Service (FWS) evaluated the possible effects of increased traffic associated with the second lock on *Lampsilis higginsi*. On 20 November 1987, they transmitted their Biological Opinion on this subject to the U.S. Army Engineer District, St. Louis, which described possible physical and biological effects of commercial traffic. The Biological Opinion dealt primarily with possible effects of increased traffic on *L. higginsi*. The FWS determined that operation of the second lock would result in incidental take of *L. higginsi*.

Included with the Biological Opinion was an incidental take statement that dealt with *L. higginsi*. The statement concluded that it was not practical to monitor *L. higginsi* since it was in such low abundance. Therefore, it would be appropriate to monitor community conditions at beds where *L. higginsi* occurred and incidental take would not be defined in absolute numerical terms.

The incidental take statement defined level of take in terms of changes in community structure of a mussel bed. Level of take was defined as the following:

a. A continual decline in the density of the five most abundant mussel species, over three sampling periods (6 years), including both adults and juveniles (juvenile being defined as less than 30 percent of maximum size encountered, measured as total length) other than *Amblema plicata plicata*.

b. Failure to collect *L. higginsi* from a bed in which it is known to occur.

c. A continual decrease in the live-to-recently dead ratio over three sampling periods or 6 years (i.e., more dead-less live). Recently dead is defined as those shells still exhibiting some shininess of the nacre or approximately less than 1 year dead.

d. A one-time decline of 25 percent or more in the total number of species encountered per bed.

e. No evidence of recent recruitment of the five dominant species other than *A. p. plicata*.

f. A decline in the growth rate of two dominant species other than *A. p. plicata*.

These criteria were developed based upon meetings attended by individuals from the following agencies: U.S. Army Engineer Divisions, Lower Mississippi Valley and North Central; U.S. Army Engineer Districts, St. Paul and Rock Island; the U.S. Army Engineer Waterways Experiment Station (WES) and selected State conservation agencies. The criteria were used as a basis for designing this study of navigation effects in the upper Mississippi River (UMR). Minor modifications to these criteria for field testing were required and will be discussed in Chapter 2.

The St. Louis District was to implement reasonable and prudent measures to minimize impacts of taking. These would include the biological and physical monitoring program discussed in this document. In addition, the St. Louis District would conduct a feasibility study to determine how future activities could be modified to reduce harm. This final requirement of the Incidental Take Statement has not been completed yet, but will be prepared by the end of 1996.

Annual tow data for Locks 10, 12, 14, 17, and 24 were obtained from the St. Louis District and were converted to number of passages per day and plotted for years 1989-94 (U.S. Army Corps of Engineers 1995; see Figure 1 and Tables A1 and A2, Appendix A). Annual tow data are for total passages and include upriver and downriver movement at each lock. After 1990, there has been a gradual decline in events at all locks. Extremely low passage in 1993 is a result of temporarily suspending traffic during the extremely high-water period in the spring and summer.

The current study took place during a period when traffic levels were not expected to increase. After 1994, biological and physical data will be collected at each bed once every 5 years. This will be done until traffic levels have increased as a result of completion of the Melvin Price Locks and Dam, Second Lock Project, by an average of one tow per day above 1990 levels in the pool where monitoring took place. Studies will then resume at the original rate (annually) and continue until 2040, the economic life of the project. In 1990, the number of tows passing upriver and downriver per day was as follows: Lock 10 (7.5), Lock 12 (8.8), Lock 14 (12.3), Lock 17 (11.0), and Lock 24 (12.3).

Importance of freshwater mussels in rivers of the United States

Freshwater mussels (family: Unionidae) dominate the benthic biomass in most large rivers in the United States (Fuller 1974). Their sedentary lifestyle

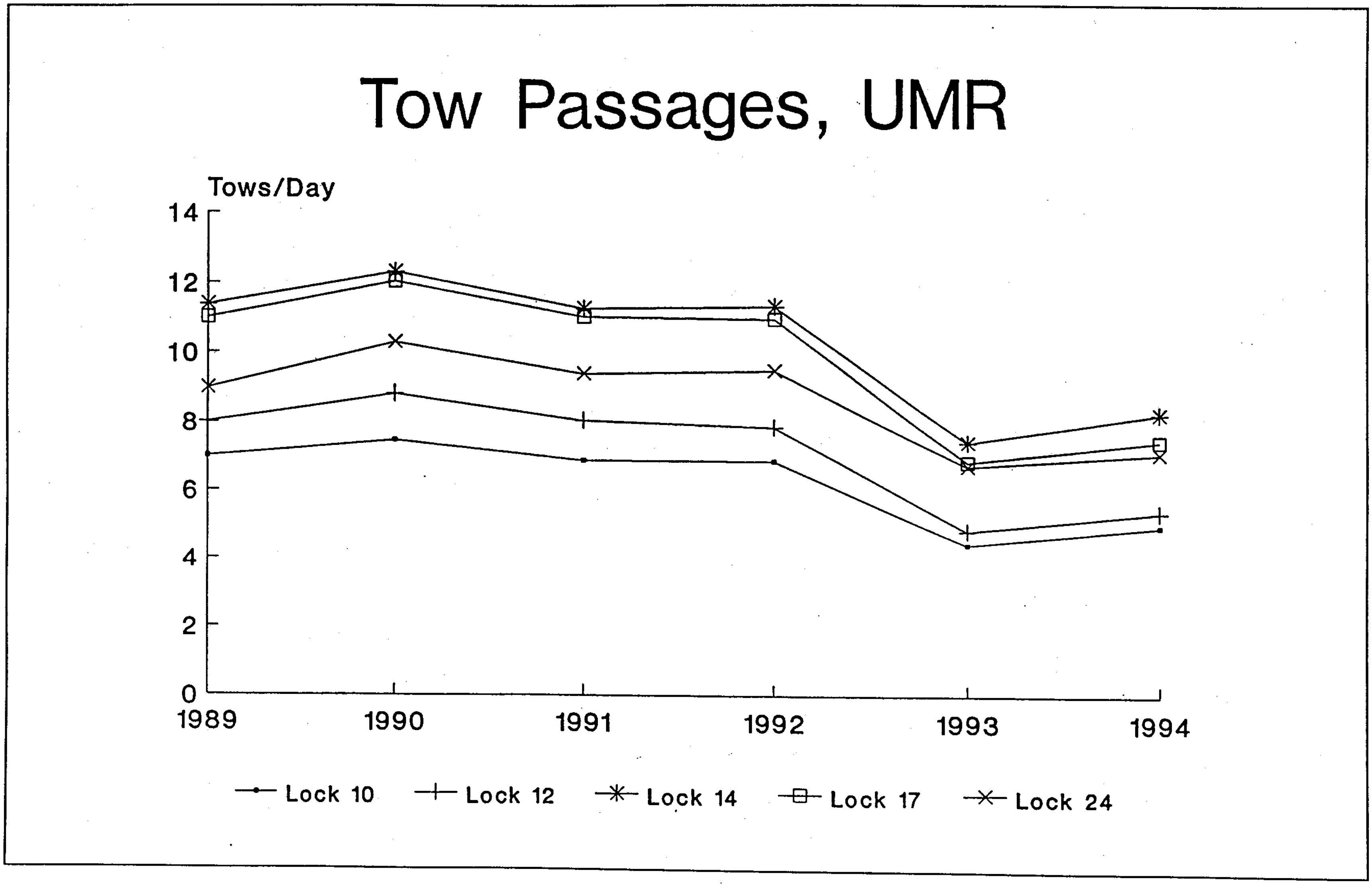


Figure 1. Number of tow passages per day at mussel beds in five pools of the UMR, 1989-94

and reliance on suspended particulate organic matter as food make them particularly susceptible to turbulence, sedimentation, and fluctuating water levels.

Shells of common unionids (principally *A. p. plicata*, *Megalonaias nervosa*, *Quadrula quadrula*, and *Fusconaia ebena*, which is no longer found in the UMR) are used in the cultured pearl industry (Fuller 1974; Sweaney and Latendresse 1982; Sitwell 1985). Commercially valuable species are collected by divers or with a brail (Coker 1919) and then shipped to the Orient and processed into inserts.

In the United States, approximately 50 unionid species are listed as endangered by the U.S. Fish and Wildlife Service (1994). Willful destruction of these endangered or threatened species or their habitat by a Federal agency is prohibited.

Need to monitor mussels in the UMR

In accordance with the Endangered Species Act, Section 7, Consultation Procedures, personnel from the St. Louis District and the FWS determined that a monitoring program should be initiated to assess the effects of projected traffic levels on freshwater mussels including *L. higginsi*. The monitoring plan would be designed to obtain data on physical effects of commercial vessel passage (changes in water velocity and suspended solids near the substratum-water interface) at dense and diverse mussel beds where *L. higginsi* was found. In addition, important biotic parameters (such as species richness, species diversity, density, growth rate, and population structure of dominant mussel species) would be monitored. Data collected on common mussels would be used to determine whether commercial navigation traffic is negatively affecting *L. higginsi*. This surrogate species concept was being used since it is extremely difficult to obtain information on density, recruitment, and other biotic parameters for uncommon species. In addition, intensive collections of this species would be detrimental to its continued existence.

Purpose and Scope

The purpose of this monitoring program (1988-94) was to obtain baseline data on physical (water velocity and suspended solids) and biological (density, species richness, relative species abundance, population demography of dominant species, etc.) conditions at five mussel beds between RM 299 and 635 in the UMR. This report contains a final synthesis of the complete study and evaluates the biological and physical effects of movement of commercial navigation traffic in large waterways.

2 Study Design, Study Area, and Methods

Development of the Study

In March 1987, the first two meetings of the consultation process on endangered species as part of the Melvin Price Locks and Dam, Second Lock Project, were held. In addition to personnel from the FWS, the St. Louis District, and WES, the following individuals attended the meetings: Alan Buchanan and Leroy Koch (Missouri Department of Conservation), Ed Cawley (Loras College), Kevin Cummings (Illinois Natural History Survey), Mike Knott (Stanley Consultants), and Marian Havlik (Malacological Consultants). The need to monitor mussel resources in the UMR, the environmental effects of commercial traffic, and methods for assessing environmental impacts to mussels were discussed. Attendees also developed the six criteria that could be used to assess changes in UMR mussel populations and made preliminary recommendations on locations of study sites. Information on study design, parameters that were measured, criteria for assessing change, and study-site location appear in the following sections.

Study Design

Research was designed to obtain information on changes in water velocity and suspended solids near the substratum-water interface when vessels pass. In addition to physical studies, important biotic parameters (species richness, species diversity, density, growth rate, and population structure of dominant mussel species) were monitored. Physical and biological data were collected at a farshore (experimental) and nearshore (reference) site within each mussel bed. Experimental sites were located close to the navigation channel (affected by vessel passage). Reference sites were located as far as possible from the channel (affected to a lesser extent by vessel passage) but still on the mussel bed. Research was designed to couple empirical data from physical and biological studies to predict effects of vessel passage on freshwater mussels.

Six criteria were chosen to evaluate the effects of commercial navigation traffic on freshwater mussels and *L. higginsi*. Criteria were developed by attendees at consultation meetings on endangered species as part of the Melvin Price Locks and Dam, Second Lock Project. The intent was to choose criteria that reflected the health of the mussel community and were relatively easy to measure and unambiguous to interpret.

Data collected during the preliminary study in 1988 plus 6 years of detailed study (1989-94) were required to interpret criteria. Information obtained from later studies would be compared with earlier results to make an assessment of negative effects. Personnel from the FWS, the St. Louis District, and WES met each year to discuss major findings. The following six criteria were considered indicative of the health of mussel beds and were used to determine if commercial navigation traffic negatively affected freshwater mussels:

a. *Decrease in density of five common-to-abundant species*. Negative effects will be assumed if there is a significant ($p < 0.1$) decline in density, sustained over each of at least two consecutive sampling periods (i.e., a study year), for at least five common-to-abundant species.

b. *Absence of Lampsilis higginsi*. If *L. higginsi* is not collected on two consecutive sampling periods, it will be assumed that this species is declining in abundance. This criterion applies only to beds in Pools 10, 12, and 14, which are within its range.

c. *Decrease in live-to-recently-dead ratios for dominant species*. Negative effects will be assumed if there is a continual decrease in the live-to-recently-dead ratio for three consecutive sampling periods.

d. *Loss of more than 25 percent of the mussel species*. Negative effects will be assumed if subsequent sampling (sustained over two sampling periods) reveals a loss of more than 25 percent of the mussel species known to occur at the bed.

e. *No evidence of recent recruitment*. If there are no signs of recruitment for two consecutive sampling periods for five common-to-abundant species, negative affects will be assumed.

f. *Significant reduction in growth rates or increase in mortality*. If a significant reduction (0.05 level) at the affected site is identified, negative affects will be assumed.

Quantitative techniques were used to collect mussels at each bed every second year. Qualitative methods were used every year or every second year to collect mussels and search for endangered species.

This study took place (1988-94) during a period when traffic levels were not expected to increase. After 1994, biological and physical data will be collected at each bed once every 5 years. This will be done until traffic levels have increased (as a result of completion of the second lock of the Melvin Price Locks and Dam Project) by an average of one tow per day above 1990 levels in the pool where monitoring took place. Studies will then resume at the original rate (annually) and continue until 2040, the economic life of the project. A summary of studies conducted at each mussel bed appears in Table 1.

Table 1
Summary of Tasks Associated With Biological and Physical Studies Conducted in the Navigation Traffic Effects Study, Upper Mississippi River, 1988-94

		Year						
Pool	RM	1988	1989	1990	1991	1992	1993	1994
24	299.6	Qual	Qual		Qual		ND	Qual
		Quant	Quant		Quant		ND	Quant
					Growth			Growth
					Phys			
17	450.4	Qual		Qual		Qual		Qual
		Quant		Quant		Quant		Quant
				Growth				
				Phys				
14	504.8	Qual	Qual		Qual		ND	Qual
		Quant	Quant		Quant		ND	Quant
			Growth					
			Phys		Phys			
12	571.5		Qual	Qual		Qual		Qual
				Quant		Quant		Quant
				Growth				
				Phys				
10	635.2-MC	Qual	Qual		Qual		Qual	Qual
			Quant		Quant		Quant	Quant
			Growth					
			Phys		Phys			

Note: Precise river miles (RMs) can differ in previous reports since exact location can vary slightly (0.1 to 0.4 miles) each year; Quant = Quantitative samples; Qual = Qualitative samples; Growth = Marked mussels were placed for analysis of rate of growth; Phys = Physical studies such as measures of water velocity and total suspended solids following passage of a commercial vessel; MC = Main channel; ND = No data because of high water.

The reconnaissance to choose sample sites and to conduct preliminary sampling was conducted in 1988 (Miller et al. 1990) and also in 1989 (Miller and Payne 1991). Information from each study year can be found for the following years: 1990 (Miller and Payne 1992), 1991 (Miller and Payne 1993), 1992 (Miller and Payne 1994a), 1993 (Miller and Payne (1995a), and 1994 (Miller and Payne 1995b). Results of laboratory studies designed to mimic the effects of commercial traffic on mussels are in Payne and Miller (1987) and Aldridge, Payne, and Miller (1987).

WES modified some of the criteria listed in the incidental take statement to make them more amenable to testing. The following is a description of how selected criteria were modified:

a. The modified criterion specified two consecutive sampling periods rather than three sampling periods. In addition, for this study negative effects would be assumed if there was a significant density decline at the 0.1 probability level. Changing from 2 to 3 years makes this criterion slightly more restrictive (i.e., in favor of protecting the resource) than originally stated. Specifying 0.1 (as compared with the more typically used 0.05 probability level) would likely increase the number of recognizable negative effects.

b. WES personnel modified this criterion to specify that negative effects would be assumed if *L. higginsi* were not collected for two consecutive sampling periods. Presumably if this species were collected only once in 10 years (per the incidental take statement), no negative effects would be assumed. WES modified this criterion to make it more restrictive and used intensive qualitative sampling to increase the probability of obtaining locally uncommon species.

c. This criterion was not modified.

d. This criterion was modified such that negative effects would be assumed if there was a 25-percent loss sustained for 2 years. Based on the incidental take statement, negative effects would be assumed if there was a one-time decline of at least 25 percent of the species at the bed. As modified, this criterion was less restrictive. Species richness is difficult to assess accurately due to the high number of locally uncommon species. Based on this modification, there would now be a reduced chance of erroneously considering loss of 25 percent of the species a negative effect caused by commercial traffic.

e. This criterion was modified such that negative effects would be assumed if there was no recruitment for five common-to-abundant species sustained for 2 years. The incidental take statement indicated that negative effects would be assumed if there was no evidence of recent recruitment for five common species (excluding the ubiquitous *A. p. plicata*). In the modified version, excluding *A. p. plicata* made this criterion slightly less restrictive; requiring a change to be sustained for 2 years was also slightly less restrictive. These modifications decreased the likelihood of erroneously considering lack of recruitment caused by commercial traffic. Quantitative sampling in large rivers indicates that recruitment at some viable beds does not occur each year.

f. This criterion was meant to apply to test organisms held in exclosures; as such, it was not modified.

The above modifications, which deviated slightly from the incidental take statement, were used to test for negative effects. Before this report was made final, each criterion was reviewed and it was determined that none of the modifications affected the outcome of the study.

Many other studies of mussels and physical effects of traffic have been conducted in the UMR (see References section). Unique aspects of this study were as follows:

a. Physical effects studies (changes in velocity and suspended sediments following vessel passage) were conducted immediately over beds that supported dense and diverse assemblages of mussels.

b. The study was designed to allow comparisons among years, among beds, and between nearshore and farshore sampling sites. Nearshore/farshore differences were most pronounced for density values and to some extent community composition; evidence of recent recruitment, size demography, growth rates, etc., did not differ greatly at different locations on the bed. Some of the comparisons were made by keeping nearshore and farshore sites separate; others were done by combining the two locations.

c. Field studies were designed based upon results of research on the effects of laboratory-induced intermittent turbulence and turbidity on various species of mussels. Results of these laboratory studies are discussed in this report.

d. Results of these studies were compared with a predetermined set of criteria established to judge the health of mussel beds. These criteria were used to assess temporal change during the study. However, their greatest utility will be for comparison with results of future studies.

Study Area

The UMR was once a free-flowing, braided, pool-riffle habitat with side channels, sloughs, and abandoned channels. This riverine habitat was altered as a result of passage of the Rivers and Harbors Act of July 1930, which authorized the U.S. Army Corps of Engineers to construct a navigation channel with a minimum depth of 9 ft and a minimum width of 300 ft. Development of this navigation channel, which included construction of locks, dams, dikes, wing dams, and levees, converted the river to a series of run-of-the-river reservoirs, characterized by relatively slow-moving water and extensive adjacent lentic habitats. Typically, the upper reaches of pools in the UMR have comparatively high water velocity and coarse substratum, whereas the lower reaches are more lake-like with deep, low-velocity water and fine-grained sediments (Eckblad 1986).

Prior to conducting any field work, WES personnel prepared a list of mussel beds in the UMR based upon data in Peterson (1984), other published reports, and information from individuals knowledgeable on the area. A selection process was used to identify medium-sized to large beds in stable areas of the main part of the river that were subject to at least some effects of traffic and did not appear to be subject to harvesting pressure. The intent was to choose sites that had dense and diverse mussel beds and supported at least some *L. higginsi*. Beds would not be located immediately downriver of existing or proposed developments such as ports, loading facilities, or waste discharges.

In 1988, preliminary data on physical and biological conditions were collected at candidate mussel beds in Pools 26, 25, 24, 19, 18, 17, 14, 10, and 7. In 1989, additional studies were conducted in Pools 12 and 13. Both qualitative and quantitative sampling techniques were employed to determine if chosen mussel beds were suitable for detailed study. Based on information collected in the field in 1988 and 1989, a list of suitable mussel beds was prepared. Personnel of the St. Louis District, WES, and FWS chose the most suitable beds for detailed study. Permanent study sites were located at the following river miles:

Pool	RM
24	299.6 RDB (right descending bank)
17	450.4 RDB
14	504.8 LDB (left descending bank)
12	571.5 RDB
10	635.2 RDB (main channel)

Each bed is several miles long; the exact location of sampling sites on beds often varies slightly from year to year (Figure 2). A brief description of study sites appears below.

Pool 24

The mussel bed in Pool 24 is located on the RDB approximately 1.5 miles downriver of Lock and Dam 22 (Figure 3). A series of wing dams on the LDB direct water across the channel and toward the mussel bed. Commercial traffic must move along the RDB when approaching or exiting the lock. Substratum at this location consists of slab rock, coarse gravel, and sand.

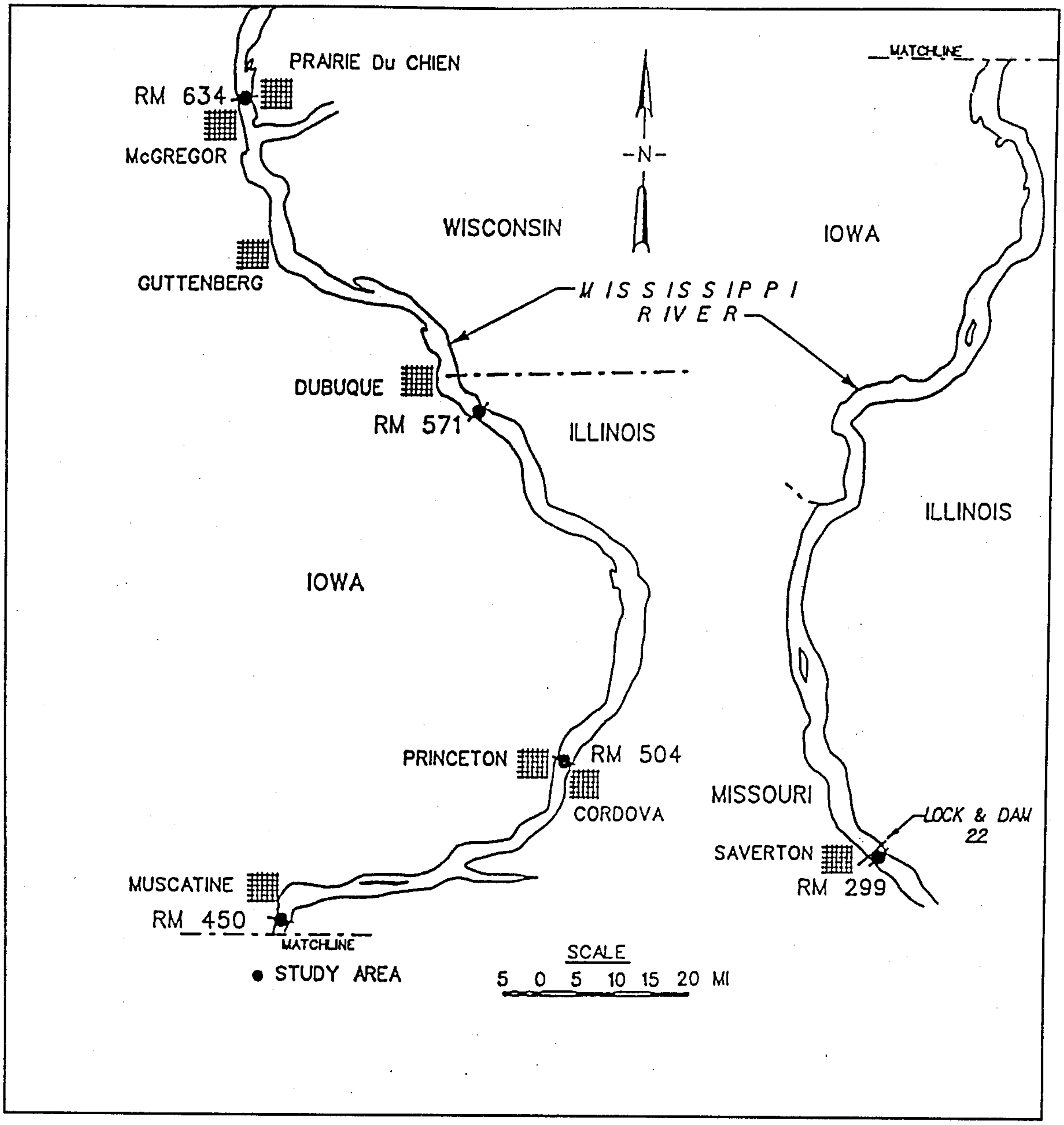


Figure 2. Location of five mussel beds chosen for detailed study in UMR

Although *L. higginsi* has never been found in Pool 24, this bed contains a dense and diverse assemblage of mussels. This location was included so that representative data would be collected in a lower reach of the UMR.

Pool 17

The mussel bed in Pool 17 is at River Mile (RM) 450.4 immediately downriver of a small creek (Figure 4). Quantitative samples were first collected here in 1988 (Table 2). The substratum is fine- grained material with little gravel and some detritus. There are commercial loading facilities

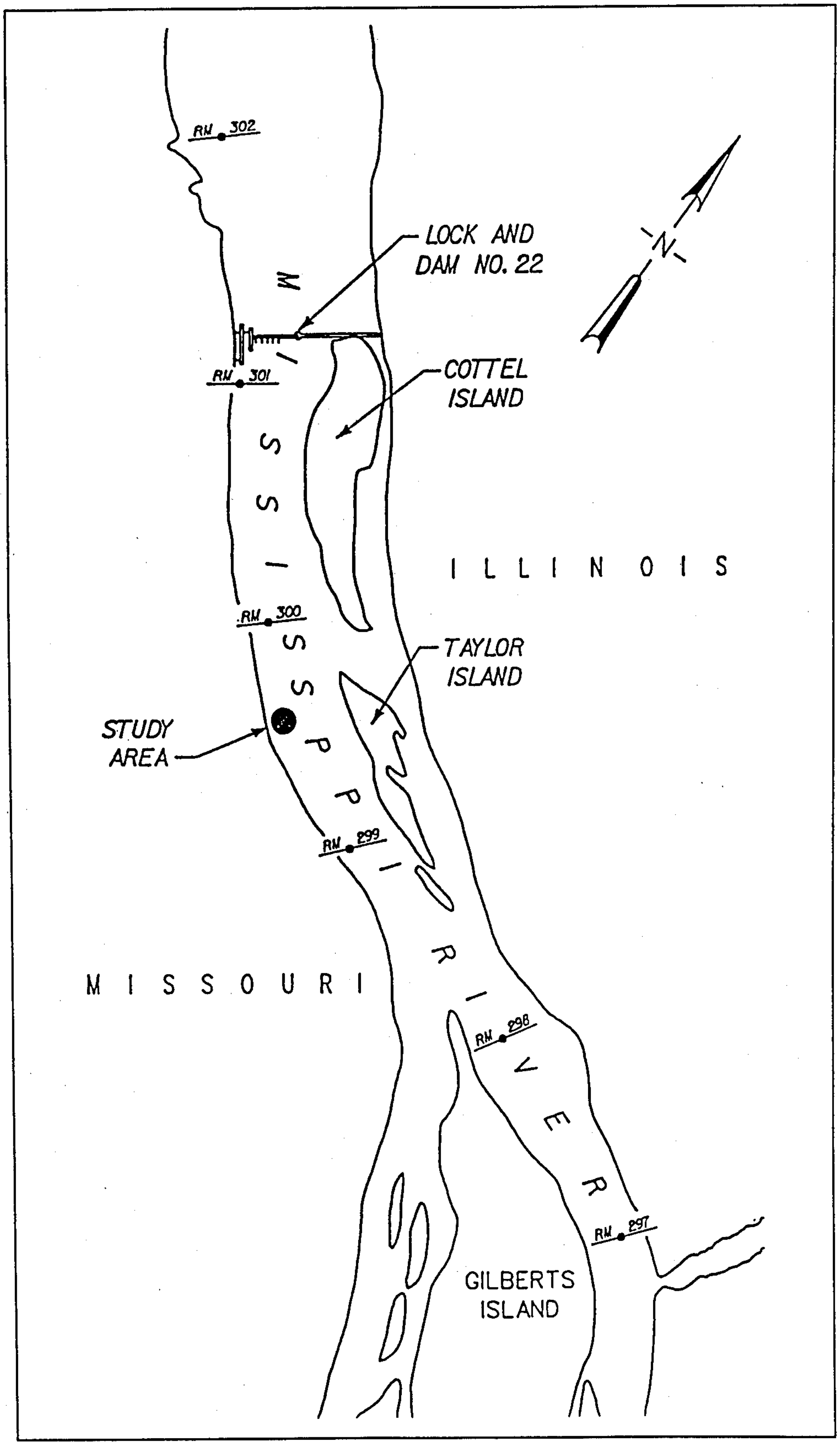


Figure 3. Location of mussel bed in Pool 24 of UMR

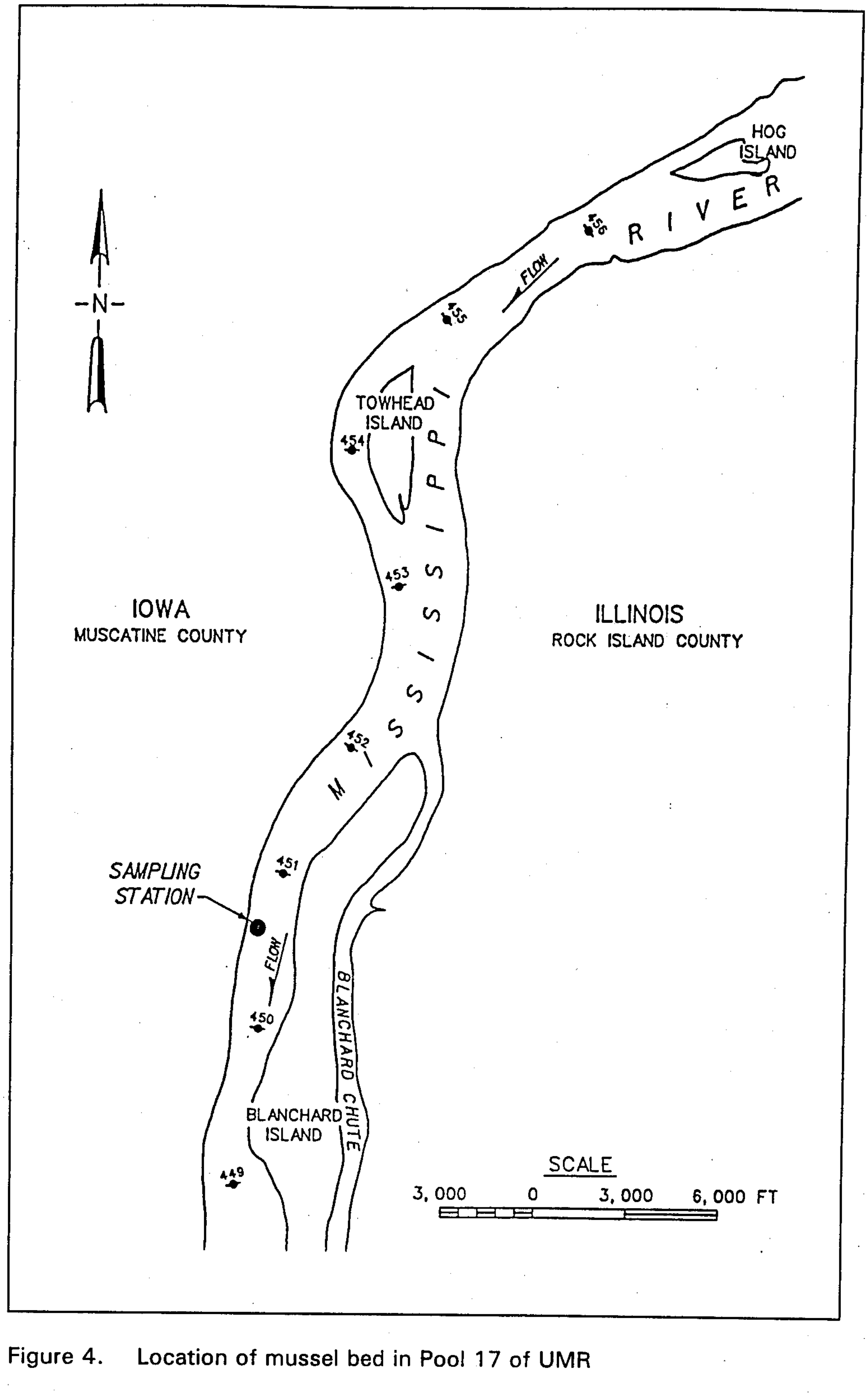


Figure 4. Location of mussel bed in Pool 17 of UMR

Table 2
Summary of Bivalve Collections Using Qualitative and Quantitative Methods in the UMR, 1988-94

Pool	RM	Year	No. of Quantitative Samples	No. of Qualitative Samples	No. of Bucket Samples
24	299.6	1988	10	18	--
		1989	60	42	--
		1990	--	--	--
		1991	60	24	--
		1992	--	12	10
		1993	--	--	--
		1994	60	24	--
17	450.4	1988	20	27	--
		1989	--	--	--
		1990	60	32	--
		1991	--	--	--
		1992	60	24	--
		1993	--	--	--
		1994	60	48	--
14	504.8	1988	20	27	--
		1989	60	59	--
		1990	--	--	--
		1991	60	48	--
		1992	60	36	--
		1993	--	--	--
		1994	60	48	--
12	571.5	1988	--	--	--
		1989	--	33	--
		1990	60	36	--
		1991	--	--	--
		1992	60	36	--
		1993	--	--	--
		1994	60	36	--

(Continued)

Note: High water in 1993 eliminated all sampling except in Pool 10. EC = East channel; MC = Main channel. In 1992, mussels were obtained at some sites by collecting total substratum without the 0.25-m^2 quadrats (= bucket samples).

Table 2 (Concluded)

Pool	RM	Year	No. of Quantitative Samples	No. of Qualitative Samples	No. of Bucket Samples
10	635.2	1988	--	43	--
		1989	40	14	--
		1990	--	--	--
		1991	60	48	--
		1992	--	24	40
		1993-MC	60	24	--
		1993-EC	60	60	--
		1994	60	--[1]	--

[1] No qualitative samples were collected in 1994 at this location. Instead, a total of 43 separate samples were collected with a suction dredge at a nearshore site in the main channel, two sites in the turning basin of the east channel, and a single site at the reference site in the east channel.

immediately upriver and downriver. *Lampsilis higginsi* was collected at the study site; however, it is very uncommon in this pool. This site was chosen to provide a mussel bed in the middle section of the UMR.

Pool 14

An extensive mussel bed is located in the lower portion of Pool 14 on the LDB (Figure 5). A summary of samples collected in previous years appears in Table 2. This bed supports a dense and diverse assemblage of mussels, including *L. higginsi*. Substratum consists of silt, sand, and gravel.

Pool 12

The site in Pool 12 is located at RM 571.5 on the RDB (Figure 6). The mussel bed is long and narrow and located on the RDB of the river immediately downriver of a sharp left turn (coming downriver). Commercial vessels moving either upriver or downriver must approach the RDB (where the mussel bed is located) as they enter or exit the turn.

Pool 10

Near Prairie du Chien, WI, the UMR splits into an east and west or main channel (Figure 7). The east channel is slightly less deep and not as wide as the main channel, although it is navigable. Substratum in both the east and

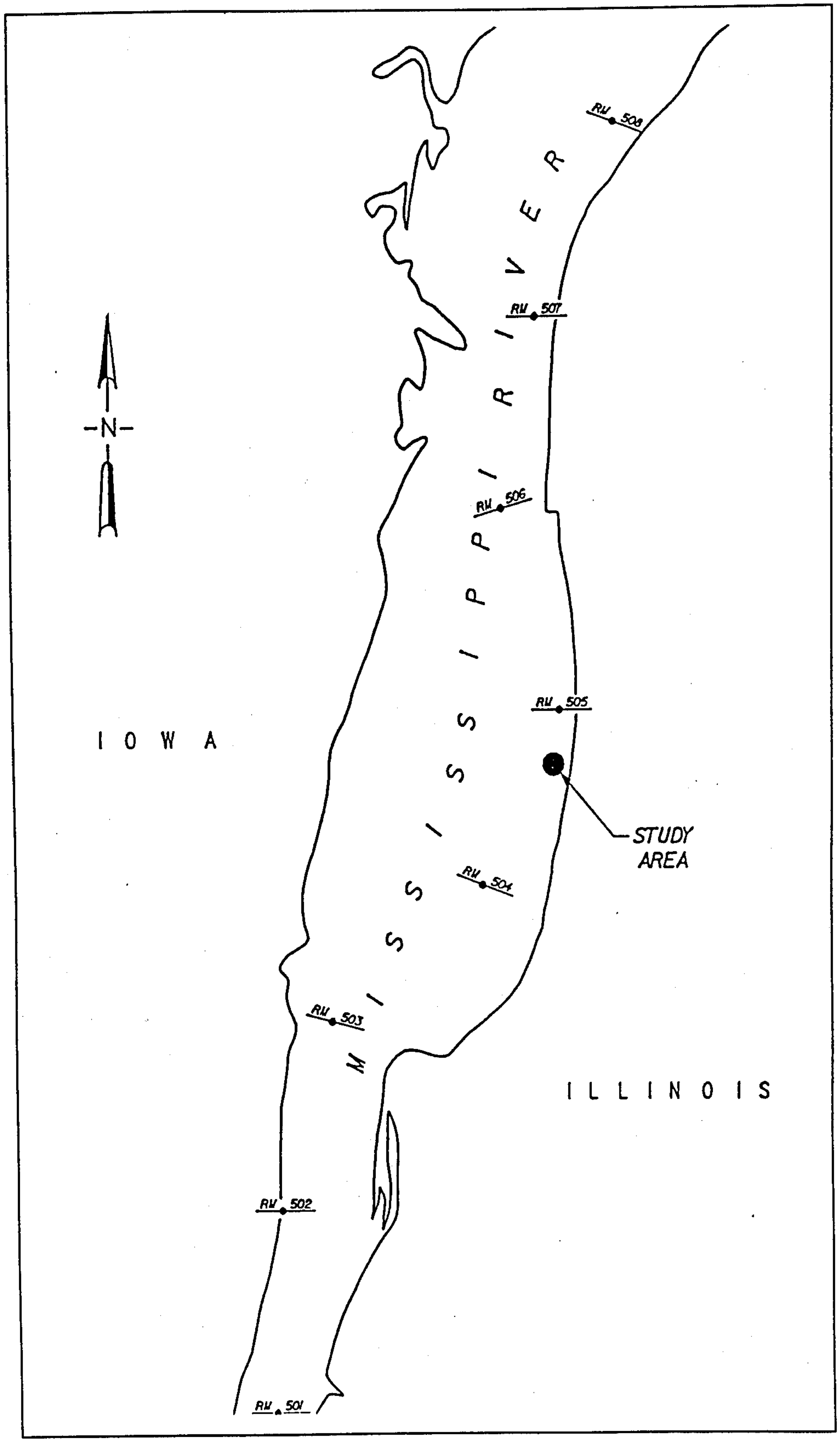


Figure 5. Location of mussel bed in Pool 14 of UMR

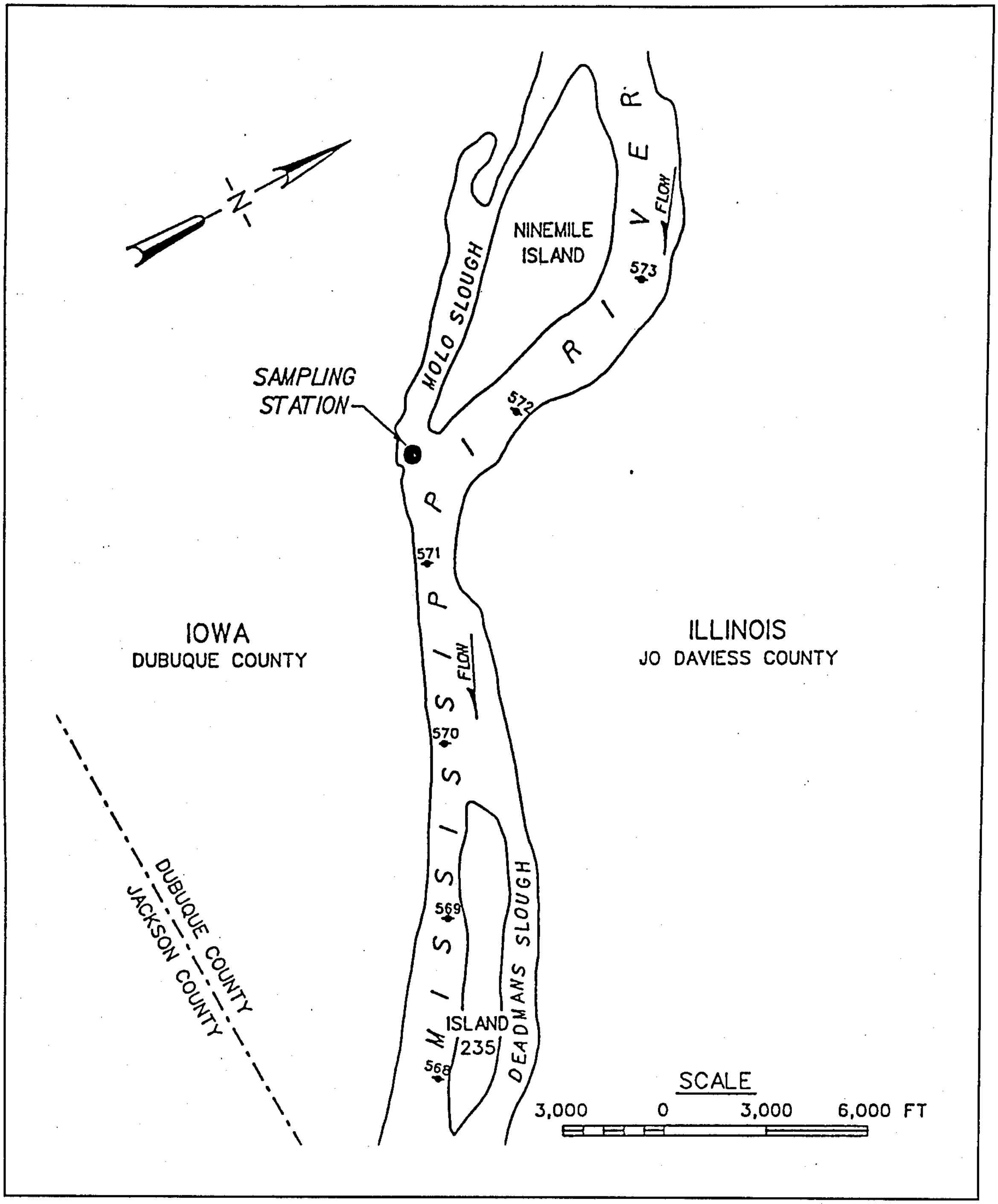


Figure 6. Location of mussel bed in Pool 12 of UMR

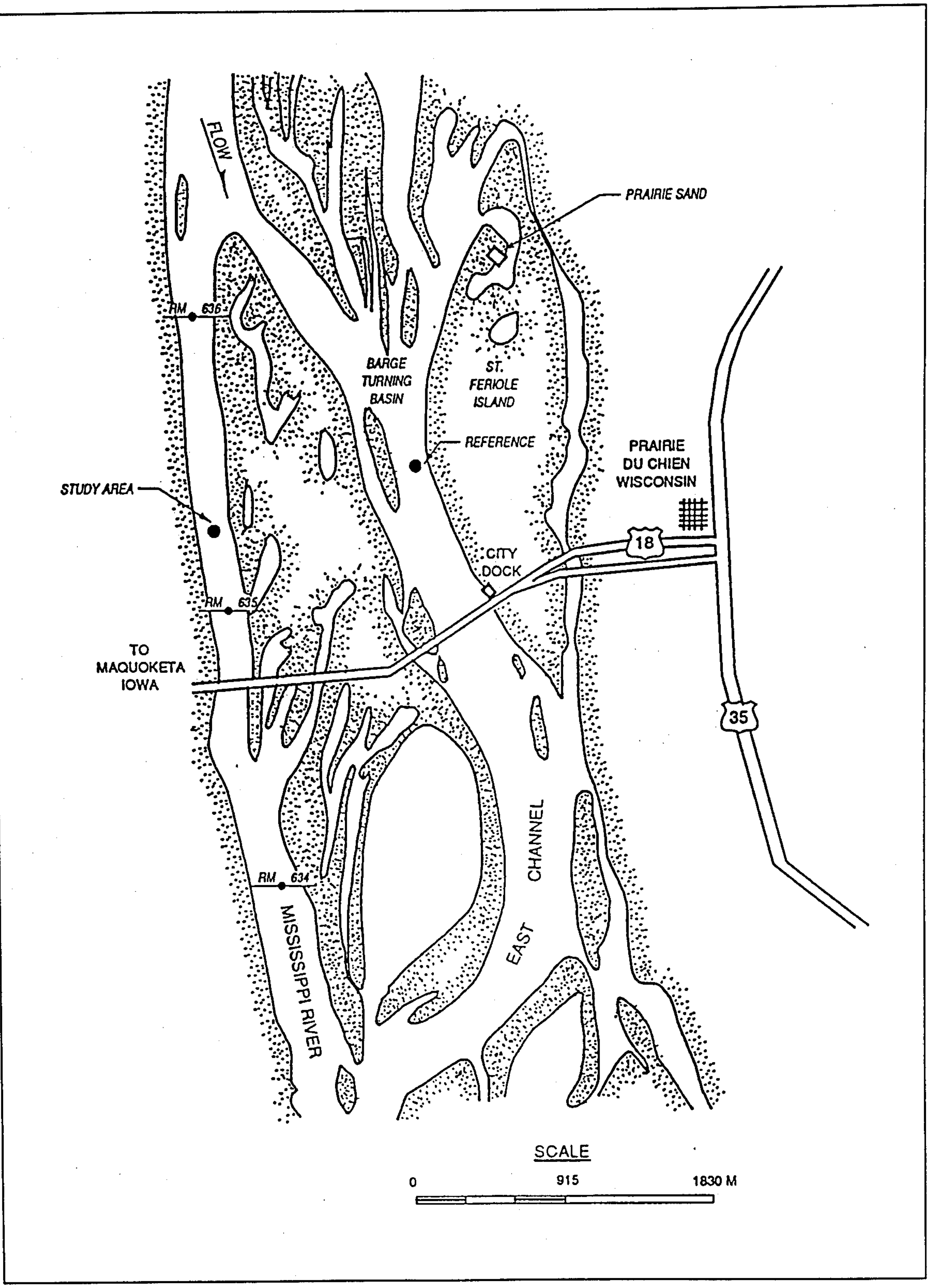


Figure 7. Location of mussel bed in Pool 10 of UMR

main channel consists of sand and silt with less than 5-percent gravel by weight. The study site is in the west or main channel of the UMR.

Sediment Characteristics

Grain-size distribution was analyzed from each sediment sample collected quantitatively and picked for live mussels on the shore (see Figures 8-12). The bed in Pool 24 was characterized by dominance of large-sized particles (>34.0 mm in diameter, see Figure 8). Coarse gravel and cobble represented approximately 40 to 50 percent of the sample. Fine-grained sediments, less than 6.35 mm in diameter, comprised 20 to 30 percent of the sample. Moderate mussel densities at this bed are probably the result of the higher percentage of larger particles, which reduce the available area of river bottom for large and small mussels.

In contrast to the mussel bed in the upper reach of Pool 24, the nearshore site at the mussel bed in Pool 17 was characterized by dominance of fine-grained particles, less than 6.35 mm (Figure 9). When compared with the nearshore site, the farshore location had greater concentration of large-sized particles. Fine sand and silt (less than 6.35 mm in diameter) comprised approximately 50 percent of the samples.

Sediment composition in mussel beds in Pools 14 and 12 were similar and dominated by fine-grained sands and silt (Figures 10 and 11). There were little to no differences in grain size based on distance to shore. Sand and silt comprised about 60 percent of the samples.

Approximately 60 percent of the sediments at the nearshore site in the main channel of Pool 10 consisted of gravel and cobble greater than 34 mm in diameter (Figure 12). Sediment at the farshore site consisted of approximately equal percentages of very small and very large particles.

Methods

Preliminary reconnaissance for mussels

A diver equipped with surface air supply and communication equipment made a preliminary survey of each sample site before detailed studies began. The diver obtained information on substrate type, water velocity, and presence of mussels. A fathometer was used to measure water depth, and distance to shore was determined with an optical range finder.

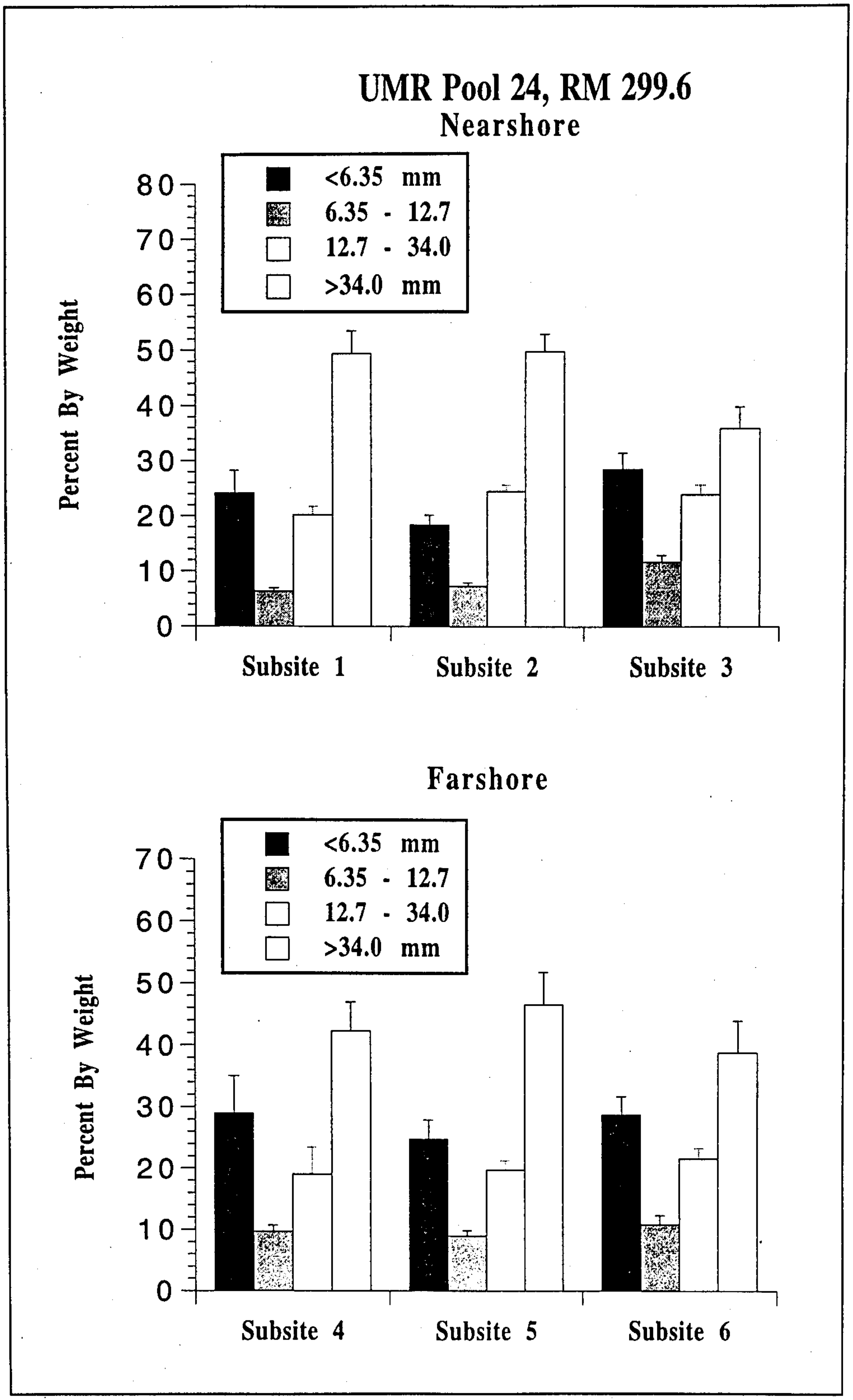


Figure 8. Sediment characteristics at a nearshore and farshore site at a mussel bed in Pool 24 of UMR, 1994

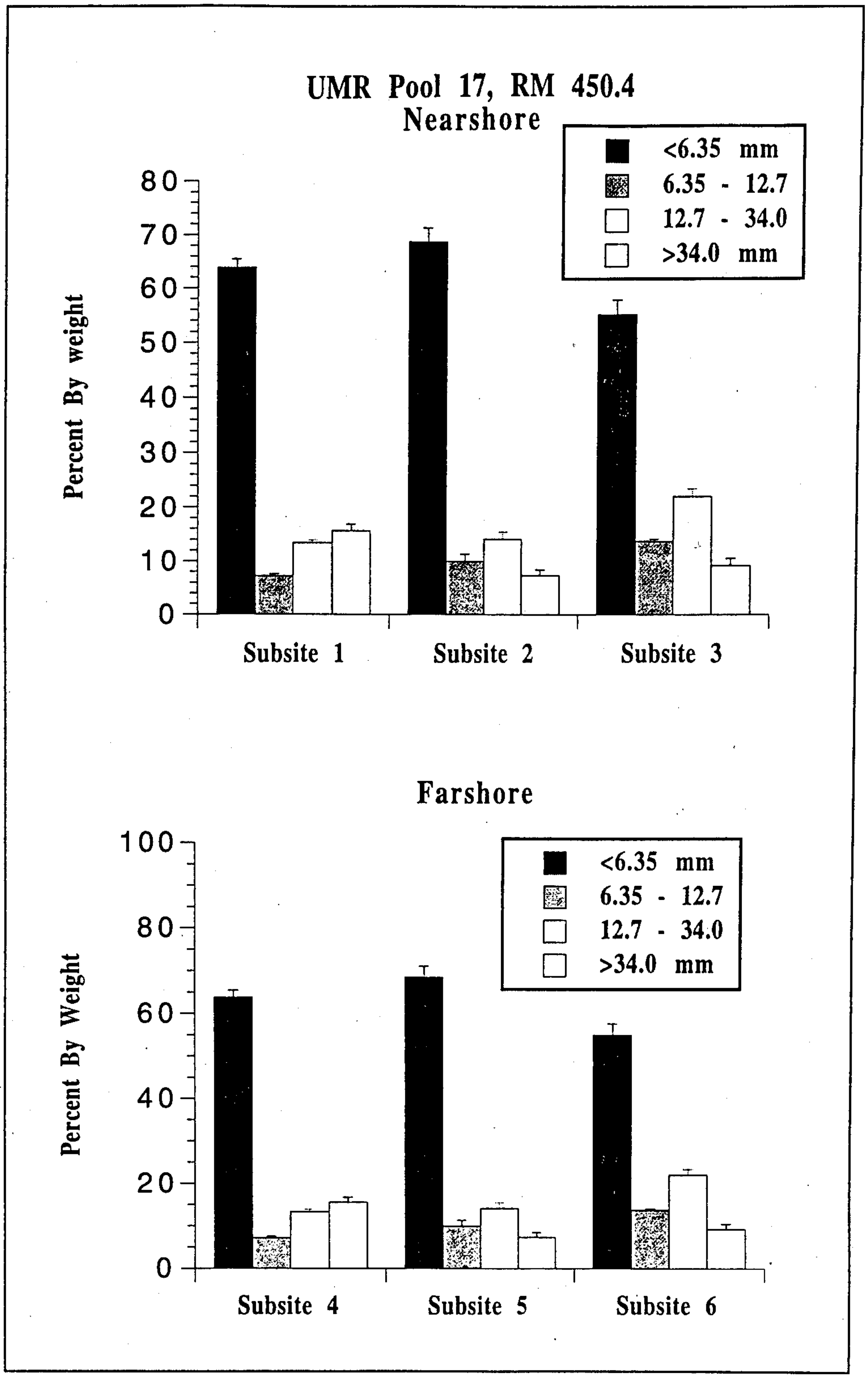


Figure 9. Sediment characteristics at a nearshore and farshore site at a mussel bed in Pool 17 of UMR, 1994

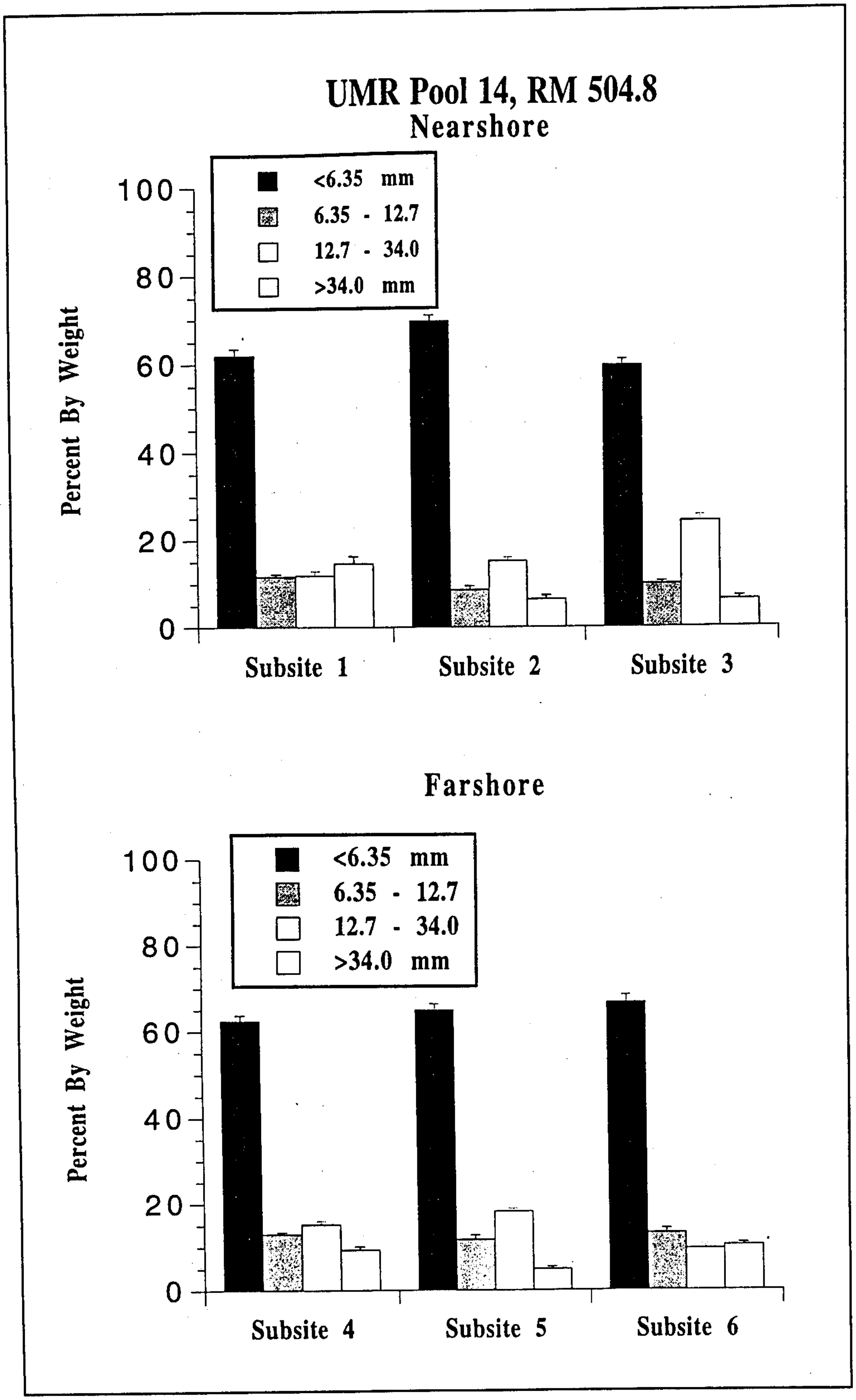


Figure 10. Sediment characteristics at a nearshore and farshore site at a mussel bed in Pool 14 of UMR, 1994

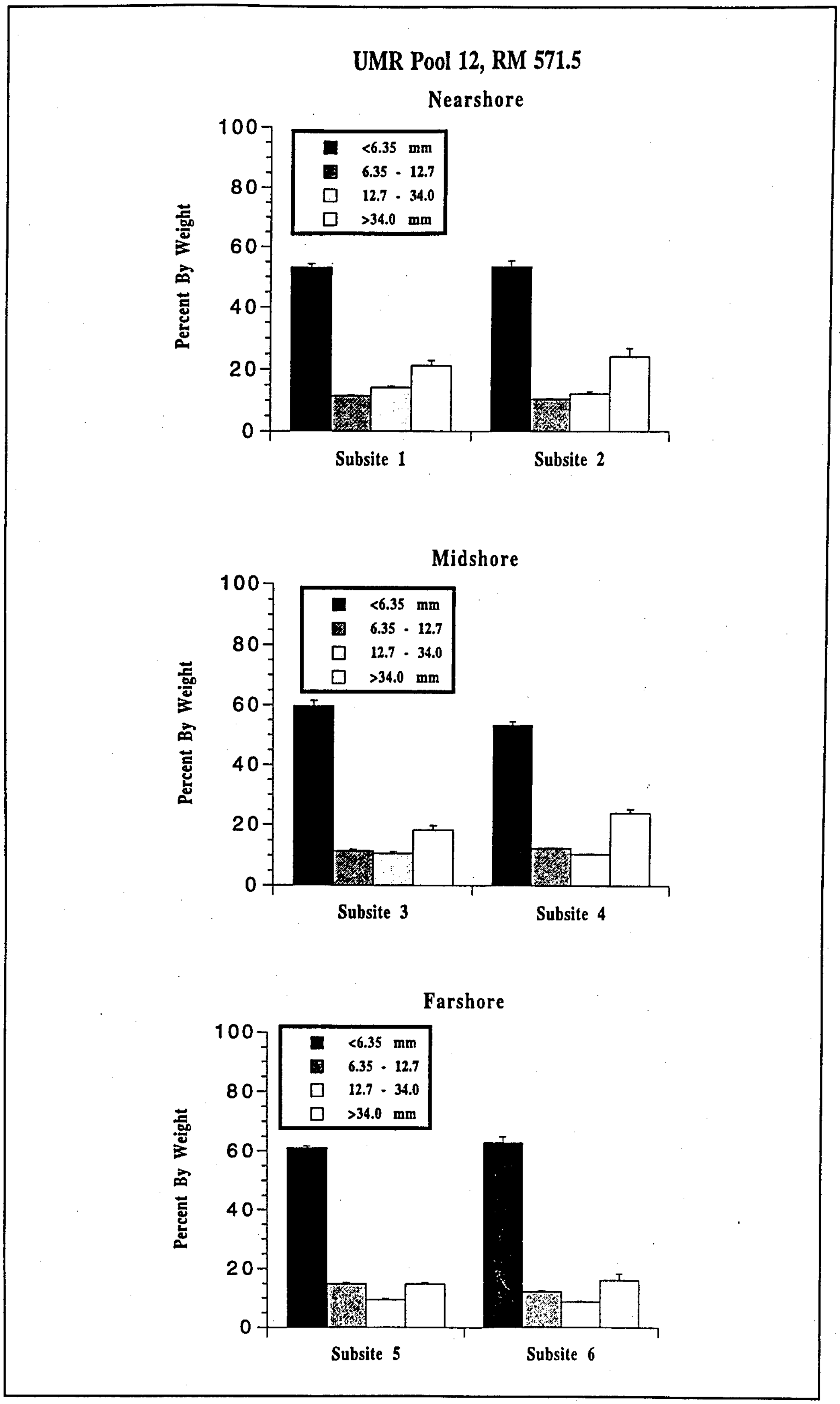


Figure 11. Sediment characteristics at a nearshore, midshore, and farshore site at a mussel bed in Pool 12 of UMR, 1994

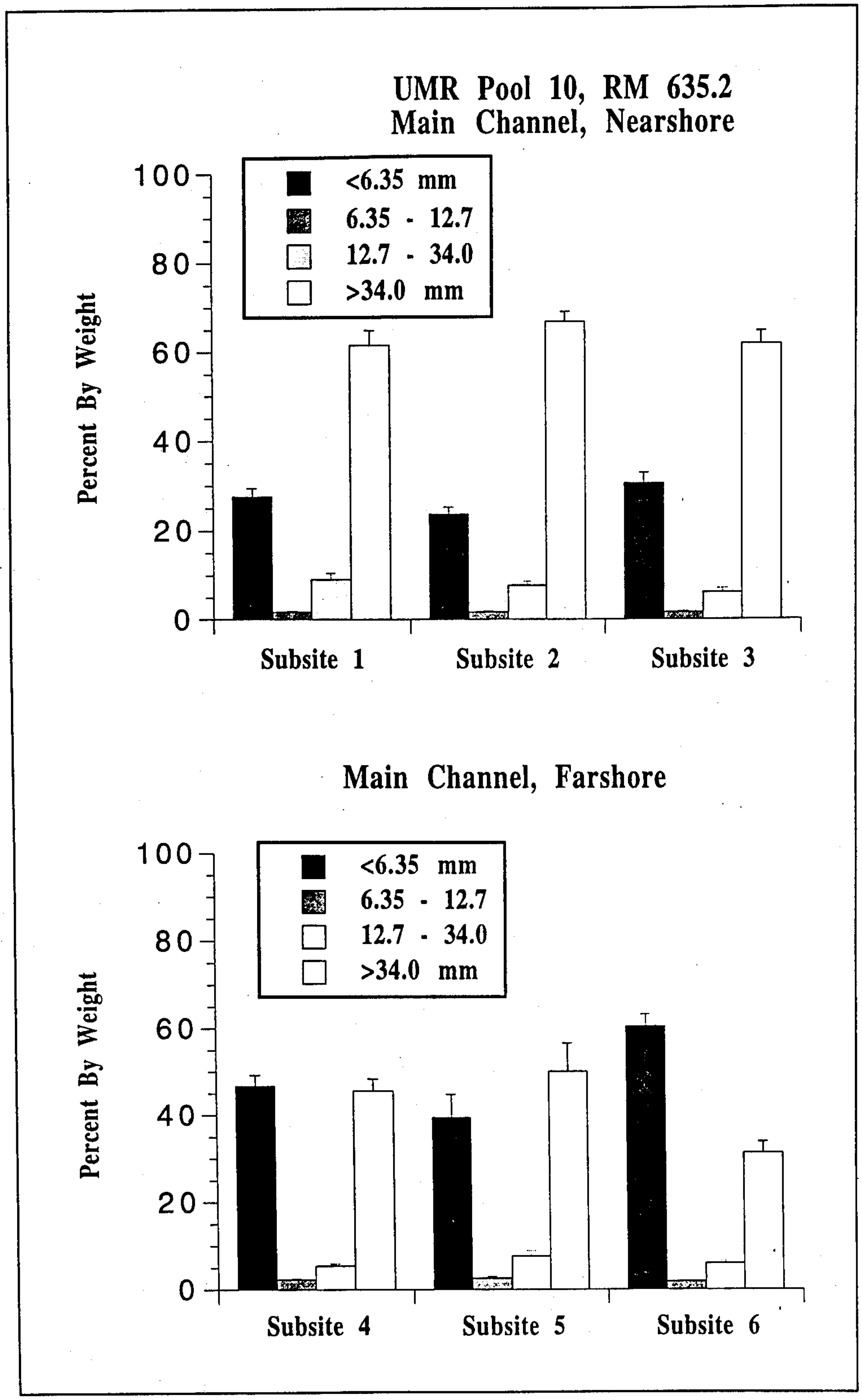


Figure 12. Sediment characteristics at a nearshore and farshore site at a mussel bed in Pool 10 of UMR, 1994

Qualitative mussel collections

Qualitative samples were obtained by two divers working simultaneously. Divers were given a total of 12 nylon bags and instructed to place about 5 mussels in 3 bags and 20 mussels in the remaining 9 bags. Divers attempted to collect only live mussels, although occasionally dead shells were taken that were later discarded. Collecting was done mainly by feel since water visibility was poor. Mussels were brought to the surface, identified, and counted. Selected mussels were shucked and retained for voucher. Additional specimens were preserved in 10-percent buffered formalin and returned to the laboratory for analysis of physical condition (ratios of shell length to tissue dry mass, etc.). Unneeded mussels and all *L. higginsi* were returned to the river unharmed. A list of the number of quantitative and qualitative samples collected at each location during the study appears in Table 2.

Quantitative sampling for mussels

At each nearshore or farshore site, ten 0.25-m^2 quadrat samples were obtained at each of three subsites separated by 5 to 10 m. At each subsite, quadrats were placed approximately 1 m apart and arranged in a 2 by 5 matrix. A diver removed all sand, gravel, shells, and live molluscs within the quadrat. It usually took 5 to 10 min to clear the quadrat to a depth of 10 to 15 cm. All material was sent to the surface in a 20-ℓ bucket, taken to shore, sieved through a nested screen series (finest screen with apertures of 6.4 mm), and picked for live organisms. All bivalves were identified, and total shell length (SL) measured to the nearest 0.1 mm. All *L. higginsi* were returned to the river unharmed. Some of the bivalves were measured in the evening, then returned to the river the next day. Bivalves that could not be processed during the survey were preserved in 10-percent buffered formalin and taken to WES for analysis. Notes were made on the number of "fresh dead mussels" (defined as dead individuals with tissue still attached to the valves).

Shells of voucher specimens collected using qualitative and quantitative methods were placed in plastic zipper-lock bags. Mussels not needed for voucher were returned to the river. Methods for sampling mussels are based on techniques described in Miller and Nelson (1983); Isom and Gooch (1986); Kovalak, Dennis, and Bates (1986); Miller and Payne (1988); and Miller et al. (1994). Mussel identification was based on taxonomic keys and descriptive information in Murray and Leonard (1962); Parmalee (1967); Starrett (1971); and Burch (1975). Taxonomy is consistent with Williams et al. (1992).

Data analysis

All bivalve data (lengths, weights, etc.) were entered on a spreadsheet and stored in ASCII files. Summary statistics were calculated using functions in the spreadsheets or with programs written in BASIC or SAS (Statistical Analysis System). All computations were accomplished with an IBM or compatible personal computer. Biological and physical data were plotted directly from ASCII files using a Macintosh SE computer and laser printer. Species diversity was determined with the following formula:

$$H' = - p_j \log p_j$$

where p_j is the proportion of the population that is of the j^{th} species (Shannon and Weaver 1949).

Mark and recapture studies

Growth studies were initiated at mussel beds in Pools 14 and 10 in 1989, in Pools 17 and 12 in 1990, and in Pool 24 in 1991. Approximately 25 individuals of common species (*A. p. plicata, Obovaria olivaria, Lampsilis cardium*, or *Fusconaia flava*) were collected as part of qualitative collections. Total length of each mussel was measured, and an identifying number was then etched into the shell with a dremal tool.

A set of three 0.25-m^2 aluminum quadrats was cabled together with 3/16-in. coated aluminum cable. Each set was secured to the substratum with a No. 4 Danforth anchor. One set was placed at a nearshore location, and one set was placed at a farshore location. All substratum was excavated from the quadrats, and the marked live mussels, along with clean sand gravel, were placed in each quadrat.

During subsequent years, sites were revisited in an attempt to relocate the quadrats and marked mussels. During the course of the study, approximately 50 percent of the quadrats were relocated. The majority of those not located were probably found by commercial shell fisherman or others. Some may have been moved by erosive flows during high water, or it is possible that divers were unable to locate cable and quadrats that had been placed during previous years. Because of the inconsistency of this phase of the work, and since good data were obtained on recruitment and growth for dominant species from the quantitative collections, this phase was abandoned.

3 Techniques to Assess the Environmental Impacts of Commercial Navigation Traffic

Use of Habitat Suitability Index Models to Assess Commercial Traffic Effects

Background

Models that evaluate quality of habitat for fish and wildlife populations are often used by State and Federal agencies to predict ecological consequences of water resource developments. Habitat Suitability Index (HSI) models have been used to analyze changes in habitat quality and quantity relative to populations of terrestrial and aquatic animals. The strength of these procedures lies in their ability to predict loss in value based upon with- and without-project conditions. Quantitative measures of the environmental effects of a water resource project can encourage consideration of less damaging alternatives. Consideration has been given to using HSI models, developed primarily for the Habitat Evaluation Procedures (U.S. Fish and Wildlife Service 1981), to predict the environmental effects of increased traffic.

Effects of traffic on riverine habitats

An increase in commercial navigation traffic does not affect basic attributes of habitat such as water depth and velocity, presence of cover, and substratum type. Additional traffic in a waterway causes an increase in relatively subtle and complex habitat factors, such as pulses of turbulence, suspended solids, wave wash, and drawdown. Changes that relate specifically to traffic cannot be readily predicted or measured. Furthermore, biological consequences of such habitat changes are not well known. Conversely, the major habitat conversions (i.e., changes in water depth or substrate type associated with reservoir construction) are easily predicted.

The magnitude and duration of navigation-related effects can vary drastically within and among sites because of variables such as bottom topography, sediment type, and discharge. Furthermore, concern is usually expressed over the incremental increases in traffic in a waterway that has supported commercial navigation for many years. The scouring of bottom sediments by propeller wash of passing tows in a newly completed waterway would drastically change sediment conditions. Soft-bottom habitats would be quickly converted to scoured clay or rock. However, following these initial changes, subsequent passages would have relatively minor effects. Increased traffic does not alter the basic aspects of physical habitat, such as water depth and velocity, cover, and sediment characteristics.

Schamberger and O'Neil (1986) enumerate the requirements that habitat variables must meet in order to be included in an HSI model. They state that variables must (a) be vulnerable to change during the course of a study, (b) be readily estimated or measured, (c) be predictably changed in value under future conditions, (d) elicit species responses, and (e) be influenced by project planning or management. Careful consideration of these requirements shows that satisfactory HSI models cannot be built to evaluate effects of an incremental increase in commercial navigation traffic.

Variables that are sensitive to an incremental increase in navigation traffic, such as periodic increases in turbulence and suspended solids, cannot be easily measured or estimated. Discharge, flow patterns, bottom topography of the navigation channel and adjacent areas, sediment characteristics, and tow passage characteristics have complex influences on navigation-effected variables. Results of the few field studies that have been conducted are characterized by extreme spatial and temporal variability, such that clear patterns of navigation effects often cannot be discerned (Bhowmik et al. 1981a,b; Eckblad 1981; Eckblad, Volden, and Weilgart 1984; Environmental Science and Engineering 1981). These studies do not suggest general relationships, and information on local physical conditions throughout large navigable rivers is insufficient to develop trustworthy models (Simons et al. 1981).

In addition, there are not enough data to predict when, where, and to what extent future navigation effects will be manifest. Since present conditions are so ill-defined, future habitat conditions cannot be predicted in terms of those variables that are sensitive to an incremental increase in navigation traffic. This holds true despite the fact that economically based forecasts can be used to predict future traffic rates.

The requirement that changes in habitat values elicit species responses must be carefully considered. Obviously, the responses elicited must clearly bear on the well-being of the population. Habitat suitability as predicted by an HSI model should relate to carrying capacity (Schamberger and O'Neil 1986). The biological consequences of intermittent increases in turbulence, suspended solids, and desiccation have been studied for larval and adult fishes. However, egg and larval fish mortality may have little bearing on the ultimate standing stock of adult fish. Water quality, spawning habitat, food availability, and predation are all factors that have overwhelming effects on carrying capacity for adult fish.

Finally, variables in an HSI model must be affected by planning and management. Realistically, short of setting limits on allowable rates of traffic (which is very unlikely), planning or management of commercial navigation traffic cannot reduce intermittent increases in turbulence, suspended solids, or drawdown events.

Summary

Habitat suitability modeling was not intended as a predictive technique for subtle, complex alterations of a habitat. Instead, HSI models have been developed for and applied to projects in which entire parcels of habitat are converted from one type to another type (e.g., Verner, Morrison, and Ralph 1986). It is reasonable to use simple, deterministic models of species-to-habitat relationships to quantify habitat conversions, although much uncertainty surrounds even these relatively straightforward analyses (O'Neil and Carey 1986). However, it is unreasonable to use HSI models to quantify the consequences of complex and subtle alterations of physical habitat that result from incremental increases in navigation traffic. The habitat variables that are vulnerable to incremental increases in traffic are not suitable for an HSI model. These variables are not easily estimated or measured, and they cannot be predicted for future conditions. In addition, the animal responses they elicit are vaguely understood, and planning and management options do not exist that can modify effects of traffic on these variables.

Value of Long-Term Field Studies

In 1987, a conference on long-term studies in ecology was held at the Institute of Ecosystem Studies, the New York Botanical Garden, New York. The goals of this conference were to (a) identify the roles of long-term ecological studies, (b) identify options for the study of long-term ecological phenomena, (c) evaluate strengths and weaknesses of various study approaches, (d) provide and clarify criteria for the most efficient and appropriate approaches to the study of long-term phenomena, and (e) examine how all approaches should be integrated to maximize understanding of long-term phenomena (Likens 1987). Ecological phenomena particularly amenable to long-term studies included the following: slow processes, rare events or episodic phenomena, processes with high variability, subtle processes, and complex phenomena (Likens et al. 1983; Strayer et al. 1986, as cited by Franklin 1987).

Freshwater mussels are long-lived (30 or more years in some species) and, because they are relatively nonmotile, are unable to change their surroundings if conditions become unsuitable. Their habitat is affected by local and upriver changes in climate, season, land use, edaphic conditions, and water level. Habitat conditions are also affected by source and nonsource pollution, commodity movement, and commercial developments in the watershed. It is clear that man-made and natural disturbances in large rivers are long term, complex, often subtle, and episodic. The characteristics of freshwater mussels can make them susceptible to these disturbances. Thus, these organisms and their habitats are particularly appropriate for long-term ecological studies.

The biological consequences of man-made and natural disturbances to habitat (specific physical and chemical conditions) can be measured on organisms held in the laboratory. Much can be learned about the physiological responses of organisms exposed to sublethal stress. However, caution must be used when extrapolating results of laboratory experiments to the field (Payne and Miller 1987) since physiological responses that occur in a laboratory often do not take place under natural conditions. Field studies are the best means of understanding effects of physical disturbances on naturally occurring populations. Studies can be designed to evaluate physical effects of water resource development on recruitment, rate of growth, density, species richness, and diversity. These parameters provide the most useful measures of the overall health and ultimate survival of a mussel community. Long-term studies on freshwater mussels in large rivers should not be discounted as "mere monitoring" (Taylor 1987). Instead, they provide an opportunity to investigate the effects of complex, episodic events on a resource with ecological, economic, and cultural value.

4 Studies on the Physical Effects of Vessel Passage

Effects of Commercial Vessel Passage on Water Velocity

Background

The effects of commercial vessel passage on ambient water velocity or suspended solids have been studied by Bhowmik et al. (1981a,b); Claflin et al. (1981); Eckblad (1981); Environmental Science and Engineering (1981); and Johnson (1976). Results from these studies have shown that physical effects of passage can be highly variable and dependent upon direction of travel, distance from shore, speed, and size of tow, as well as water depth, velocity, and substratum type. Regardless, previous workers did not conduct their experiments at known mussel beds. The present studies were designed to collect information on water velocity and resuspension of sediments at sites on stable sand/gravel shoals known to support dense and species-rich mussel communities.

Methods

Water velocity was measured approximately 9 in. (23 cm) above the substratum-water interface using a Marsh McBirney Model 527 current meter. The sensor for this instrument measures velocity in two directions (an X and Y component that are at right angles to each other) and is equipped with a compass. The compass, which is read from the meter, assists in positioning the sensor and can be used to calculate direction of flow. The meter sensor was mounted in a concrete block, positioned, and secured by divers. Two meters were equipped with 1,000 ft (305 m) of cable, and two were equipped with 200 ft (61 m) of cable. Water velocity in two directions and a compass reading were obtained at l-sec intervals and stored on a model CR10 data logger (Campbell Scientific, Inc., Logan, UT). Data were downloaded to a Toshiba lap-top personal computer for later analysis and plotting. Depending upon conditions, up to four sensors were deployed at distances ranging from approximately 50 to 500 ft (15 to 152 m) from the bank. Sensors were never placed in the navigation channel. Each sensor was positioned to obtain velocity readings parallel to (pointing upriver) and at right angles (pointing into the channel) to the direction of flow. In all cases, velocity sensors were placed directly over mussel beds.

The sensors were positioned at the beginning of the day and retrieved every evening. When a commercial vessel was sighted, the meters and data logger were turned on (usually about 250 or more sec before the vessel reached the sensors), and continuous data on water velocity and compass readings were obtained. Usually between 600 and 1,200 sec of data were collected for each vessel passage. Information on type of vessel, distance to shore, and direction were recorded.

Velocity data and compass readings were converted to ASCII files, and magnitude of flow was calculated from individual velocity components by the formula:

$$Magnitude = (X^2 + Y^2)^{0.5}$$

The resolved angle of water flow was determined by the formulae:

$$0 = TAN^{-1}\ (X/Y)\ if\ Y \geq 0,\ or$$

$$0 = TAN^{-1}\ (X/Y) + 180°,\ if\ Y < O$$

Summary statistics (mean, standard deviation, minima, and maxima) were calculated for a time interval immediately before and during each event. The time interval before the event included 100 to 200 sec that ended at least 50 sec before the vessel reached the site. The time interval that included the event usually began 50 sec before the vessel reached the sensors and continued for approximately 150 sec during and after vessel passage. The magnitude of physical change associated with each passage could then be evaluated by comparing summary statistics collected during the event with statistics obtained before the vessel passed. Changes in water velocity were measured for 60 commercial vessels during a 3-year period (1989-91) at the five mussel beds in the UMR (Table 3).

Results

Based on 60 events in which data were collected, 12 (20 percent) had a major effect on ambient water velocity (See Figures 13-16 for examples). Test 20 was from an upbound tow at RM 571.5, July 1990 (Figures 13-15). An upbound vessel causes an increase in ambient velocity because the mass of water displaced by the barges adds to the existing water movement. At a distance of 105 ft (32 m) from the RDB, ambient combined velocity prior to passage was 0.348 ft/sec (10.6 cm/sec). Maximum combined velocity

Table 3
Summary Information on Commercial Vessel Passages Studied in the UMR, 1989-90

Year	River Mile	No. of Commercial Vessels	No. of Events With No Effects	No. Of Events With Major Effects
1989	505.5	7	1	1
1989	634.7	4	1	3
1990	448.7	1	1	0
1990	450.4	9	1	8
1990	571.5	13	2	0
1991	299.4	14	10	0
1991	504.7	12	10	0
Total		60	26	12

following passage was almost double this value, 0.720 ft/sec (21.9 cm/sec). At distances 240, 305, and 410 ft (73, 93, and 125 m) from the shore, the changes in velocity following passage were similar and of the same magnitude.

An example of a major effect on velocity caused by a downbound tow, RM 634.7, 1989, can be found in Figure 16. On the X axis (longshore velocity, which is parallel to shore), minimum velocity changed from approximately 0.25 ft/sec before passage to -1.791 ft/sec after passage. Combined velocity increased by about three times, from approximately 0.5 ft/sec (15.2 cm/sec) to more than 1.5 ft/sec (45.7 cm/sec). Disruption to ambient water velocity lasted for about 1 min. A downbound vessel usually causes a decrease in velocity because the displaced water moves upriver following passage. This flow reversal is apparent in the bottom of Figure 16; water moves at 180 deg (south, or downriver) before the event and then abruptly shifts to 360 deg (north or upriver) as the vessel passes. Reversals in direction will occur only for downbound vessels.

Examples of measurable but minor effects of upbound and downbound vessels appear in Figures 17 and 18, respectively. During passage, combined velocity for Test 15 (Figure 17) was 0.80 ft/sec (24.4 cm/sec); following passage, velocity declined by less than 50 percent to 0.56 ft/sec (17.1 cm/sec). Test 17 depicts a minor change caused by a downbound vessel (Figure 18). Passage of the vessel caused a decrease of 0.10 ft/sec from 0.58 to 0.48 ft/sec.

Changes in mean downstream velocity for an upbound event with minor effects (Test 14) is depicted in Figure 19. For this test, mean velocity during passage was slightly greater at three of the four sensors. Velocity changes caused by a major event (Test 20, the complete plot is shown in Figures 13-15) were greater than those for Test 14. A comparison of summary statistics

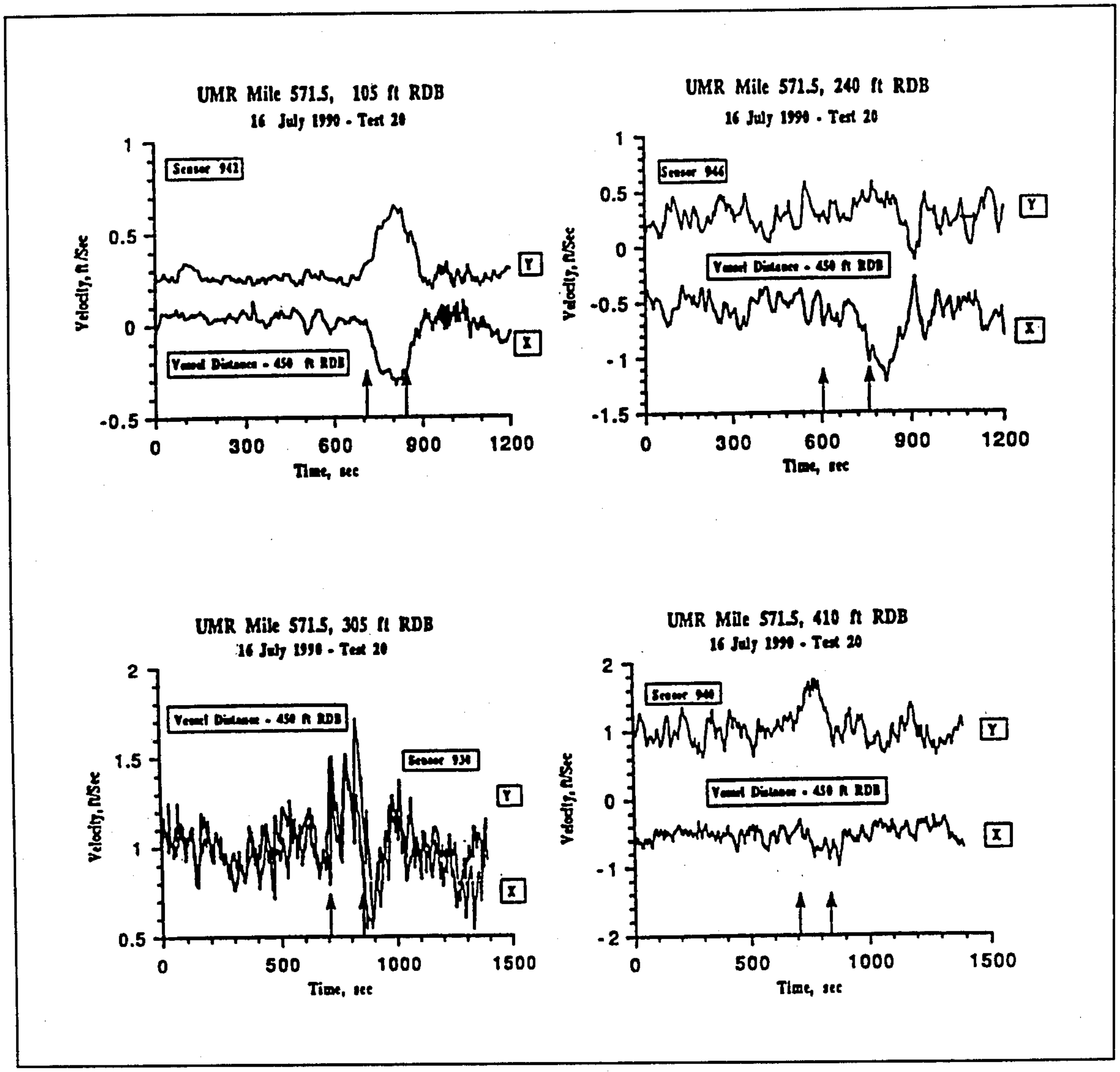


Figure 13. Changes in water velocity on X and Y axis caused by an upbound tow, RM 571.5, 1990

for the 200-sec increment before and during vessel passage provides a mechanism for assessing the physical effects of upbound versus downbound vessel passage. Maximum and minimum velocity readings for a 200-sec period are influenced by the direction of vessel movement. A summary of changes in minimum and maximum velocity for all 24 events monitored in 1991 and all sensors used for each event appears in Figure 20. Passage of an upbound vessel had little effect on minimum velocity; however, maximum velocity increased (compare top left with bottom left figures). When a vessel moves upriver, the displacement causes return flow, which increases ambient velocity. This increase has no effect on minimum velocity. When a vessel moves downriver, the return flow tends to reverse the current, thereby, reducing minimum velocity. The return flow from a downbound vessel has little or

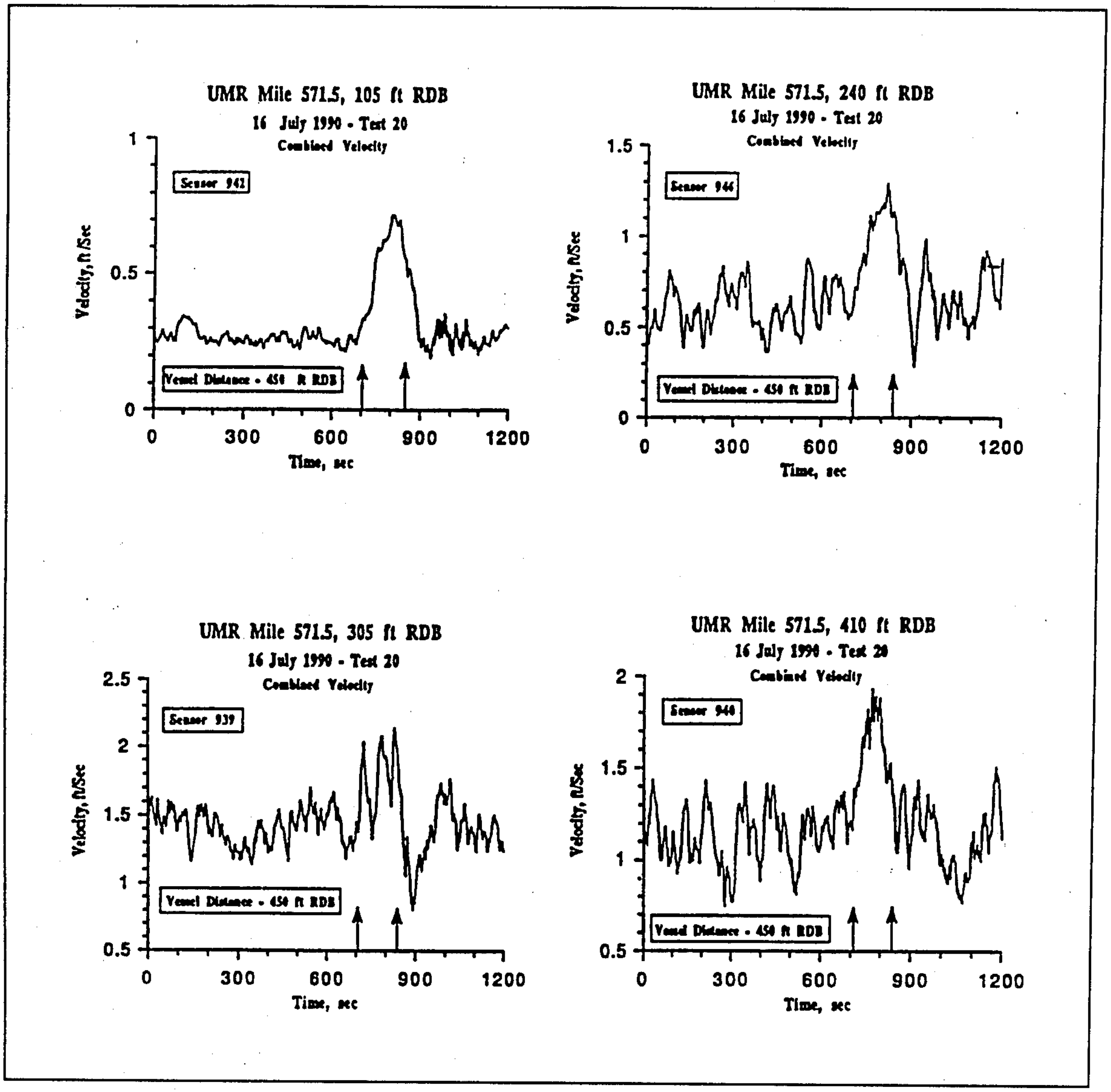


Figure 14. Changes in combined or net water velocity caused by an upbound tow, RM 571.5, 1990

no effect on maximum velocity (compare top right with bottom right plots of Figure 20).

Related studies

In the Illinois River, Environmental Science and Engineering (1981) showed that barge and tow passage on average caused 8- to 18-cm/sec (0.31- to 0.70-ft/sec) changes in the magnitude of longshore velocity vectors at both nearshore and farshore monitoring stations. As with results of the studies of these authors, tows moving upriver generated a downstream increase in velocity, and traffic moving downriver forced velocity changes in the reverse

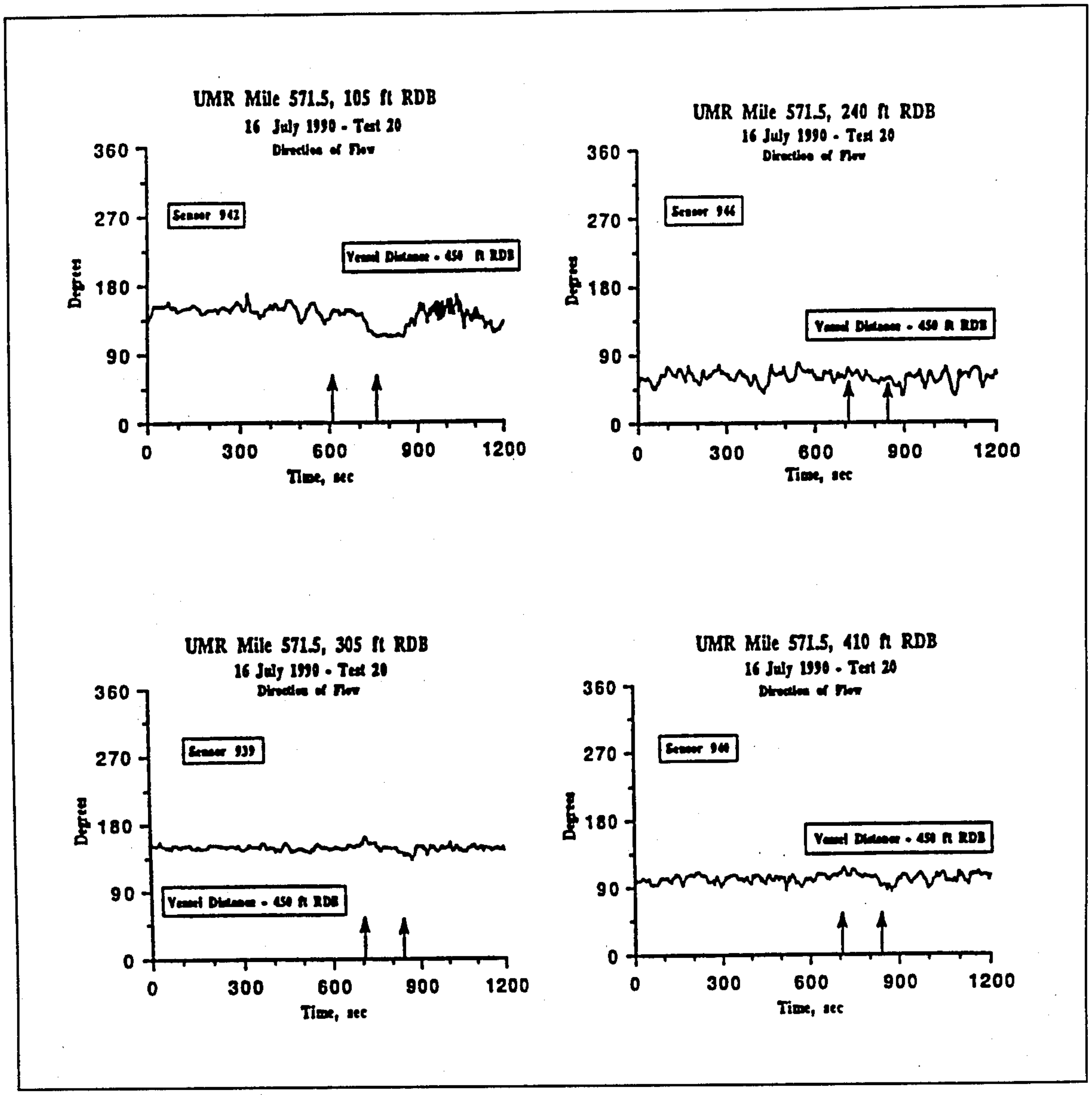


Figure 15. Changes in direction of water flow caused by an upbound tow, RM 571.5, 1990

direction. Because ambient flow was only about 6 cm/sec, most downriver traffic caused measurable velocity reversals.

Results of studies by Environmental Science and Engineering (1988) in the Mississippi River were more complex. As in the Illinois River, upbound tows caused ambient downriver velocities to increase at the farshore station, and downbound tows had an opposite effect. On average, the maximum change in velocity was about 20 cm/sec, compared with an average ambient flow of about 25 cm/sec. However, nearshore changes in velocity were different from farshore changes. For 8 of 23 events (34 percent), velocities immediately following passage could not be discerned from ambient velocity readings at the nearshore station. For events in which passage caused measurable differences, velocity changes at the nearshore station were opposite in direction and

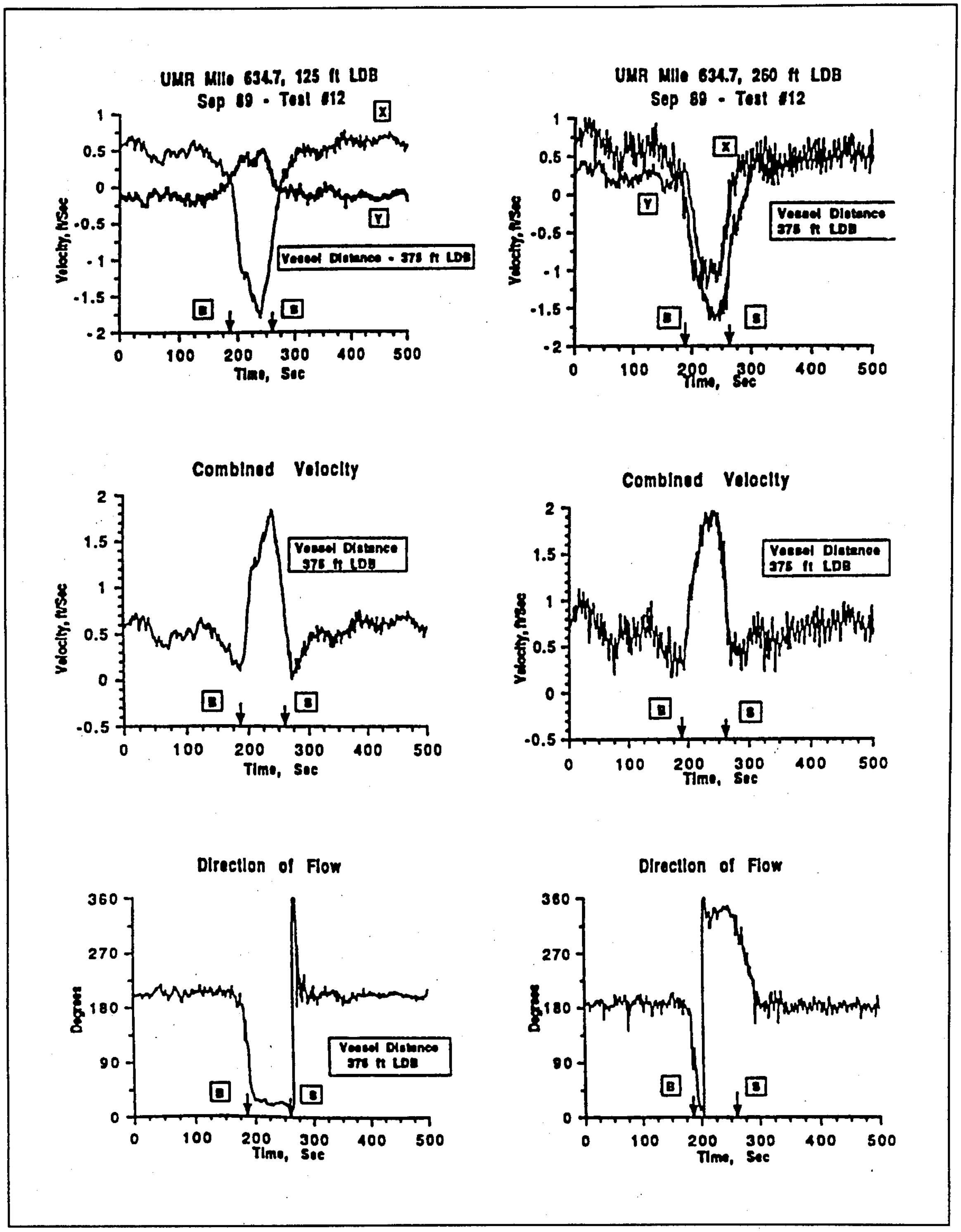


Figure 16. Changes in water velocity at X and Y axis, combined velocity, and direction of water flow caused by a downbound tow, RM 634.7, 1989

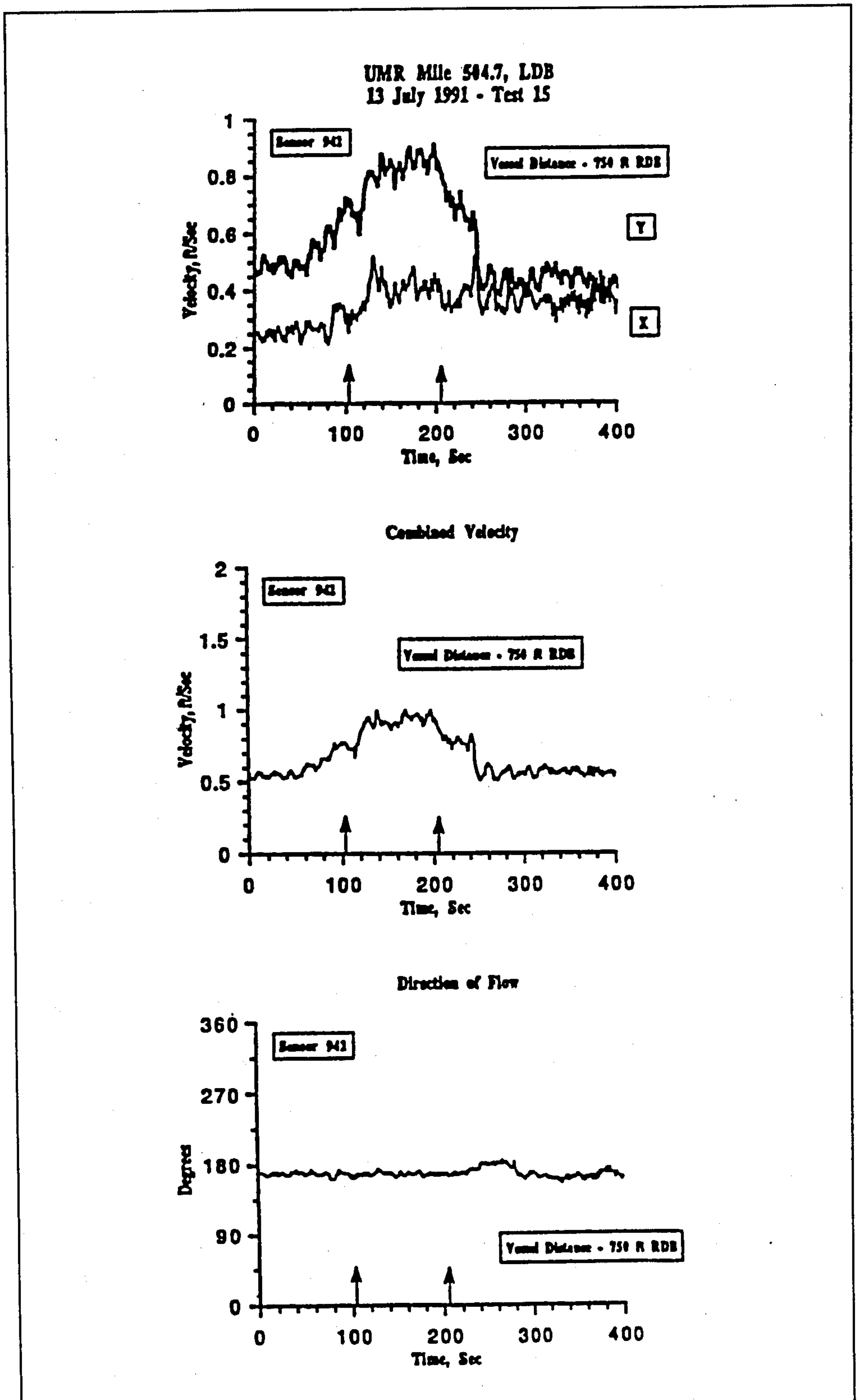


Figure 17. Changes in water velocity at X and Y axis, combined velocity, and direction of water flow caused by an upbound tow, RM 504.7, 1991

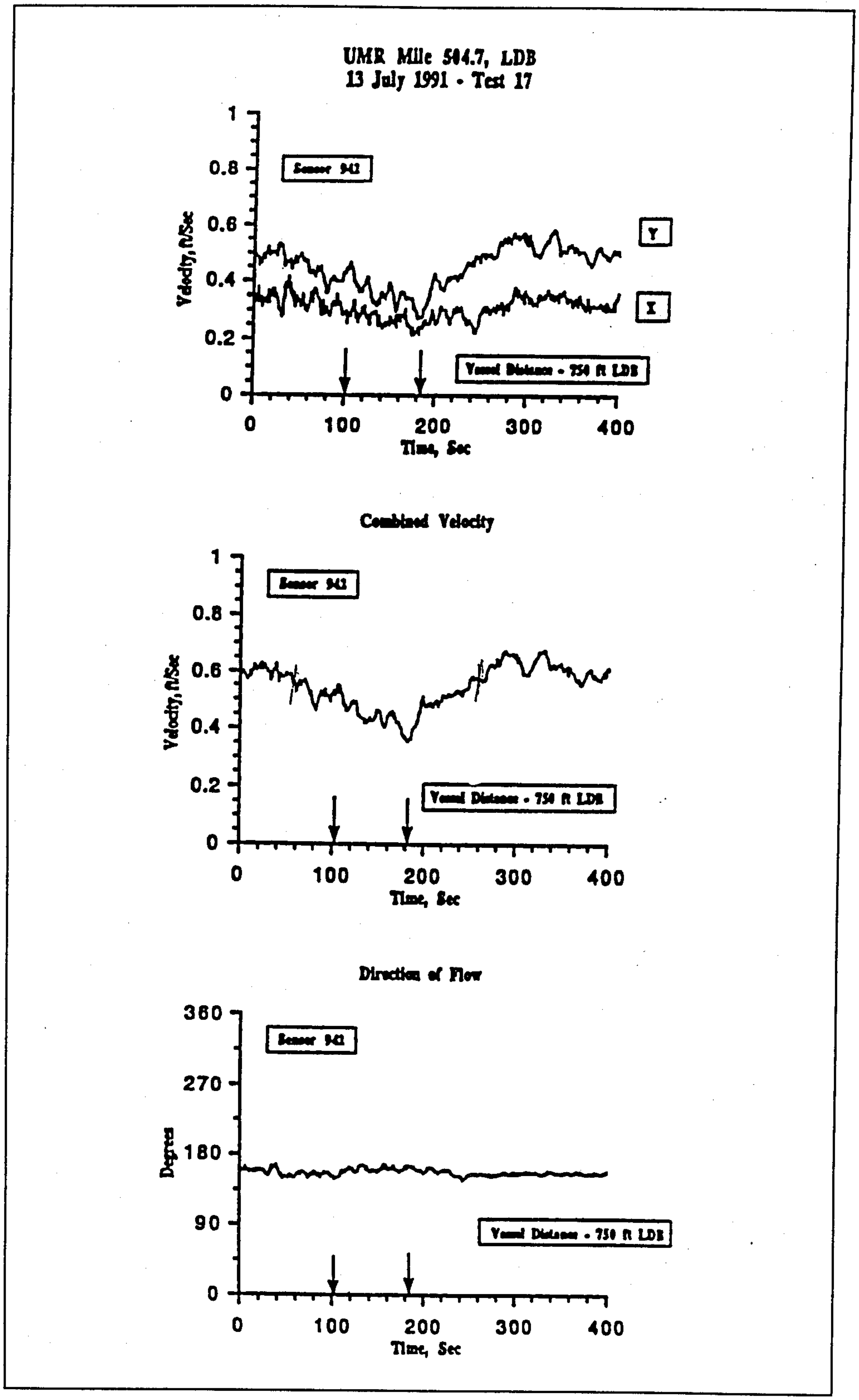


Figure 18. Changes in water velocity at X and Y axis, combined velocity, and direction of water flow caused by a downbound tow, RM 504.7, 1991

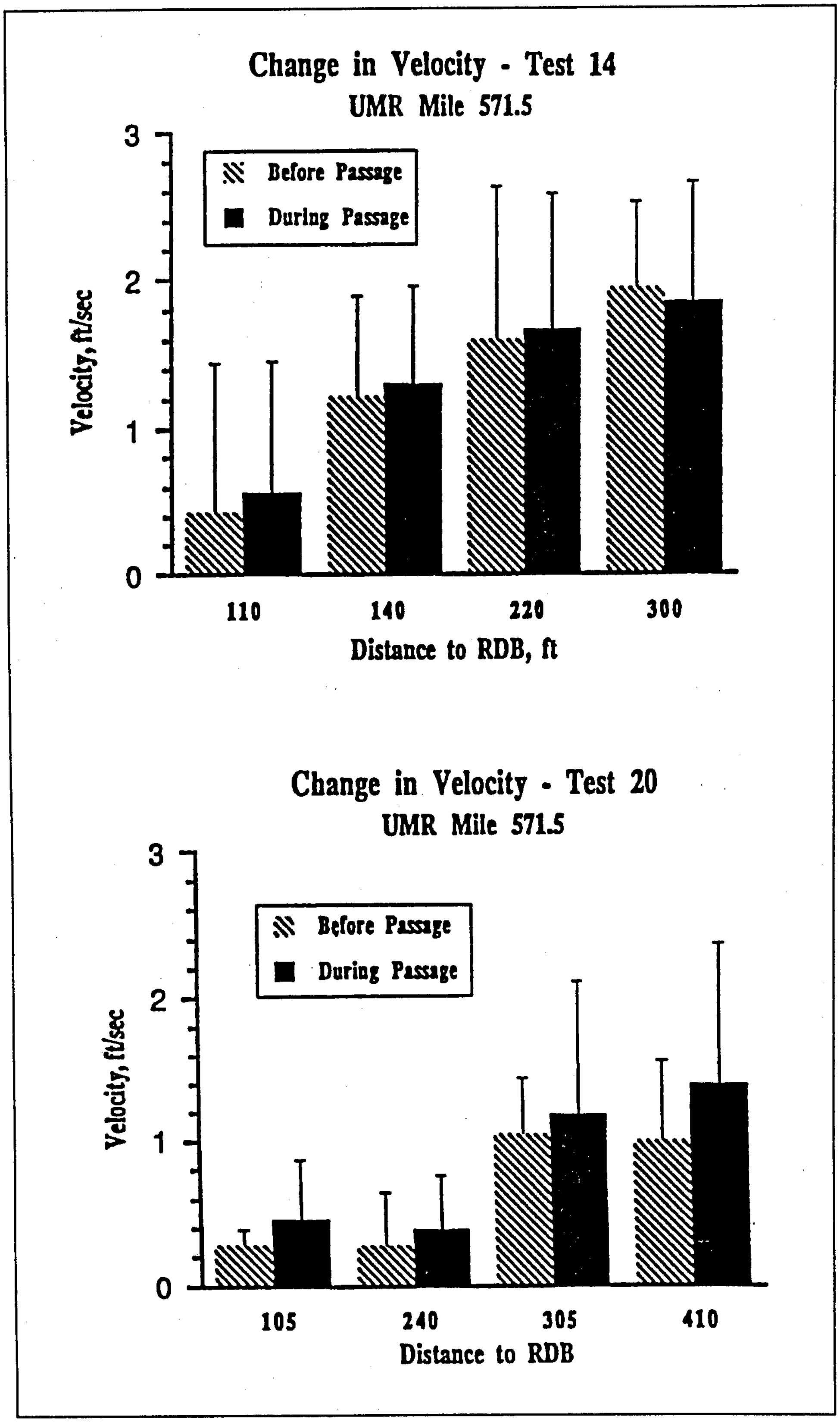


Figure 19. Mean and range in downstream velocity immediately before and during Tests 14 and 20, 1990

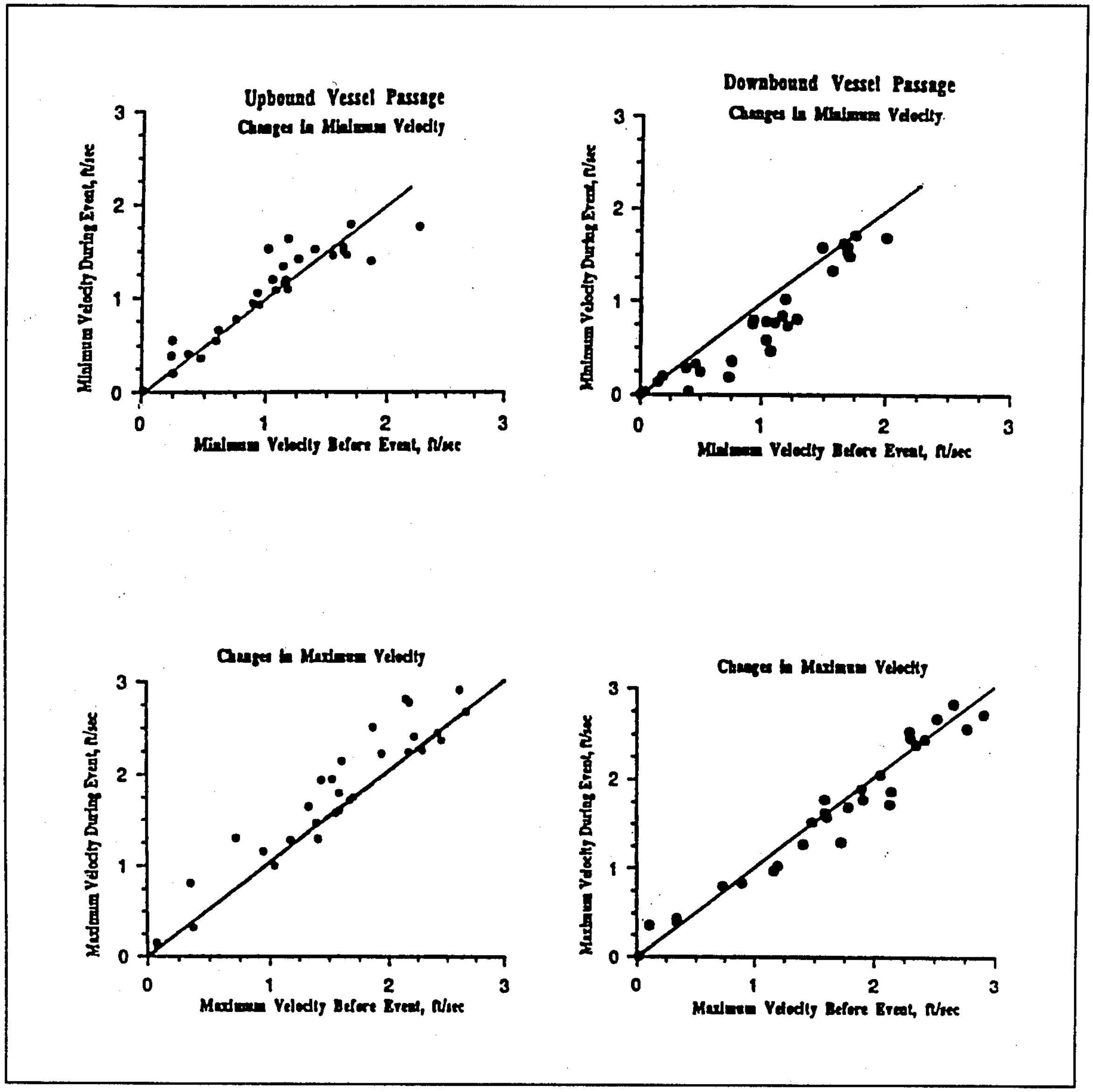


Figure 20. Effects of upbound and downbound vessels on minimum and maximum velocity (Data were compiled for all commercial vessel passages studied in July 1990)

less in magnitude than those at the farshore station. Nearshore velocities changed by an average of 10 cm/sec. Because ambient velocity at the nearshore station was usually near 0 cm/sec, upbound tows often caused brief upstream currents, and downbound tows caused significant downstream currents. The duration of changes in nearshore and farshore velocities averaged 1 to 2 min.

Concluding comments on the effects of vessels on water velocity

Ambient water velocity over mussel beds in the summer when these studies were conducted was usually 0.5 to 1.0 ft/sec (15.2 to 30.5 cm/sec). These velocities can be considered moderate. Between January and April of each year, sustained velocities of 2 to 3 ft/sec (61 to 91 cm/sec) are common. Vessel-induced disruptions to ambient conditions in the summer usually lasted no more than 1 min. Events that were considered major were characterized by velocity changes that were at least double ambient conditions. Rarely was an event recorded that brought about a change of greater than three times ambient velocity. Minor changes were those that were detectable but brought about changes less than double ambient conditions. A total of 60 commercial vessel passages were monitored for water velocity changes in the UMR. Velocity measurements were made directly over the mussel bed. Twenty percent of these events produced major effects. Thirty-seven percent produced a minor effect, and 43 percent produced no measurable change.

Typically, downbound vessels caused a decrease in velocity and a reversal in flow. Upbound vessels usually caused an increase in water velocity. Changes in ambient velocity immediately following vessel passage was caused by vessel displacement and not propeller wash. Propellers are designed to send water directly away from the vessel and not toward the substratum. As results of these and studies of others have shown, there is variability among events.

Much has been written about negative effects of changes in ambient water velocity caused by commercial vessel passage. However, at no time in the present study, or in the work of others, could velocity changes from a either single or multiple events be considered damaging to benthic organisms or their habitat.

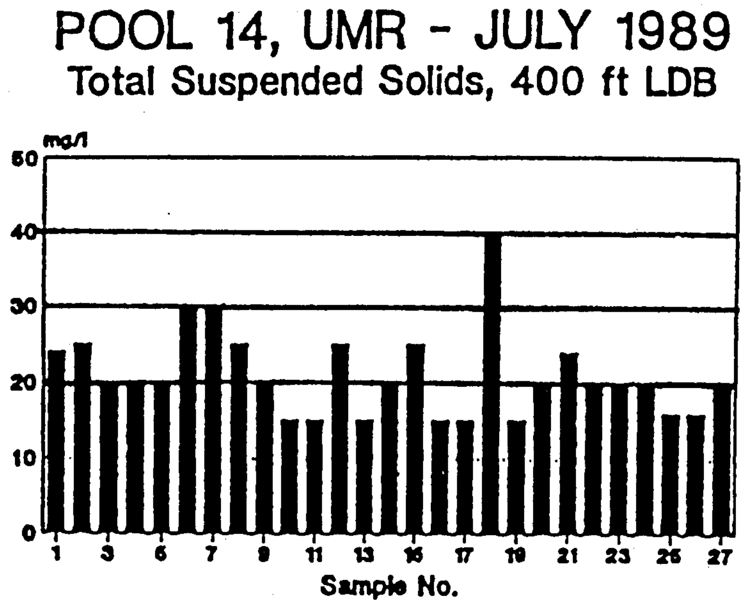
Effects of Commercial Vessel Passage on Water Turbidity

Methods

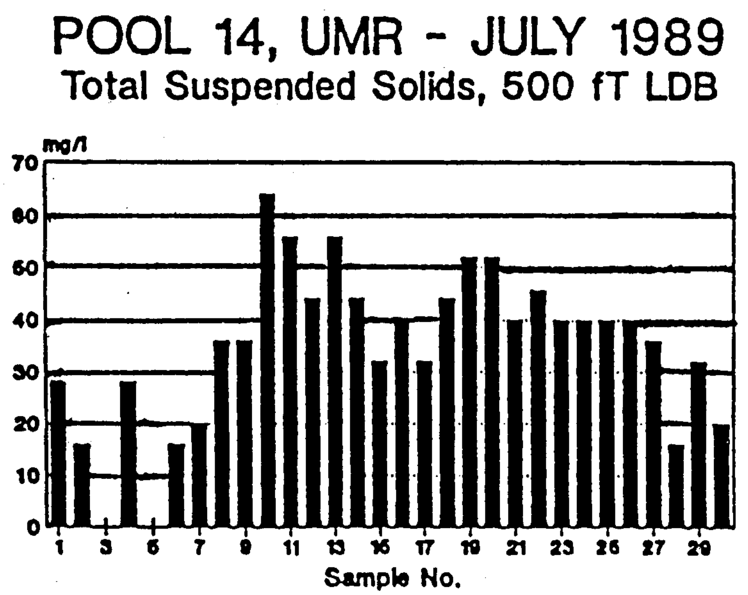
Water was collected 10 cm (4 in.) above the substratum-water interface at the locations where water velocity was measured. Water was brought to the surface through a 25-ft (7.6-m) length of rubber hose secured to a concrete block. Suction was provided by a 12-V Water Puppy pump. The pump ran continuously, and a 500-ml bottle was filled every 2 min. Turbidity was determined in the field with a Hach portable turbidimeter, and total suspended solids were determined in the laboratory using gravimetric procedures.

Results

In 1989, effects of vessel passage on changes in suspended solids associated with vessel passage were measured in Pool 14 (Figure 21). During ambient conditions (no vessels in the area), total suspended solids (TSS) ranged from 16.0 to 30.0 mg/ℓ (mean = 20.4 $\pm$ 5.3 (standard deviation)).



b. Nearshore site



c. Farshore site

Figure 21. Ambient total suspended solids immediately before and after passage of a commercial navigation vessel, 1989

Minor fluctuations in TSS in large rivers are expected and caused by minor fluctuations in water velocity and direction of flow. An upbound tow passed within 600 ft of the LDB after three samples had been collected. Following passage, mean velocity at the nearshore site was 21.1 $\pm$ 5.7 mg/ℓ (range = 15.0 to 40.0 mg/ℓ), and at the farshore site was 37.4 $\pm$ 12.4 mg/ℓ (range = 16.0 to 64.0 mg/ℓ).

Water samples were collected immediately before and after commercial vessels passed the collection site for Tests 23 and 24, July 1990 (Figure 22). Vessel passage is noted by an arrow. For Test 23, vessel passage caused a peak in turbidity immediately above the river bottom of approximately 90 Jackson Turbidity Units. After nearly 300 sec, this value decreased to slightly above ambient conditions. Turbidity had returned to ambient conditions after 750 sec had elapsed. For Test 24, a smaller peak in turbidity near the river bottom took place immediately before the vessel passed (Figure 22). Within 2 min, this comparatively high value decreased to near ambient conditions.

Summary

Vessel-induced changes in turbidity and suspended solids at mussel beds in the UMR were minor, of short duration, and usually lasted no more than several minutes. Vessel motion increased these values more at the substratum-water interface than the surface. Typically, a vessel caused an increase in velocity or total suspended solids of no more than one to two times over ambient conditions. Changes lasted for several minutes at the most.

In the UMR, mussels inhabit firmly packed substratum that is relatively free of recently settled sediments; therefore, movement of large vessels are likely to have minimal effects on ambient turbidity and suspended solids. Data from other surveys on large rivers are variable, dependent on local conditions, but are similar to results of these studies. In Pool 2 of the UMR, North Star Research Institute (1973) reported changes of 30 to 70 and 20 to 80 JTU in surface waters following vessel passage.

Herricks et al. (1982) collected samples in 1-m-deep water in a section of the Kaskaskia River. Following commercial vessel passage, suspended sediment values increased from 91 to 362 mg/ℓ and from 124 to 253 mg/ℓ in a section of the river that was 1 m deep. Bhowmik et al. (1981a) reported that tows increased suspended solids for 60 to 90 min in the Illinois River, which is comparatively slow moving, shallow, and carries a higher suspended solid load than the UMR.

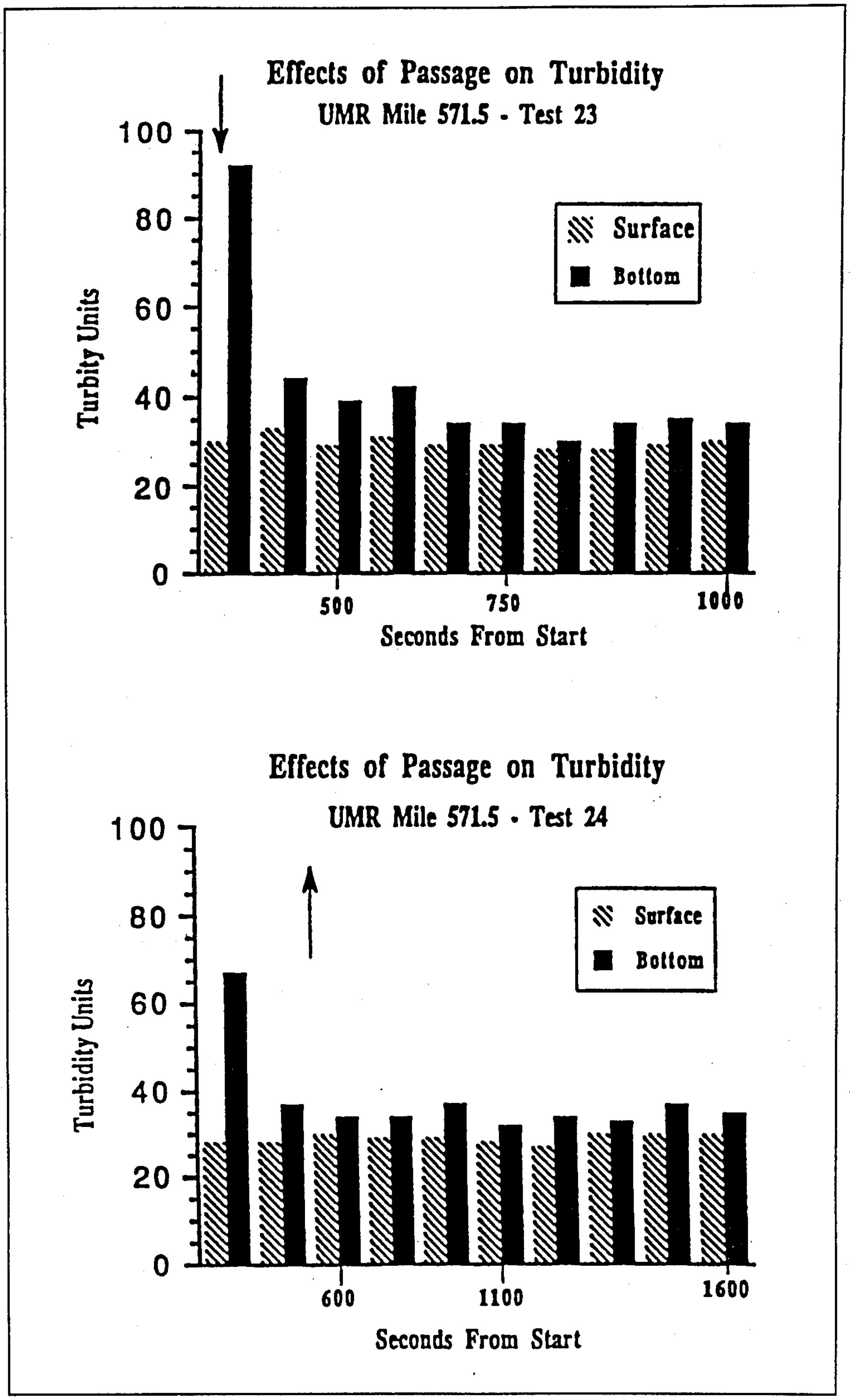


Figure 22. Effects of commercial vessel passage on turbidity in surface and bottom water (immediately above the substratum-water interface) for Tests 23 and 24, 1990

5 Results of Laboratory Studies Designed to Mimic the Effects of Commercial Traffic

Effects of Turbulence and Turbidity

In this study, metabolic rate and catabolic substrate shifts were measured for three species of mussels that were cyclically exposed to unnaturally high levels of turbulence and turbidity at two distinct frequencies (Aldridge, Payne, and Miller 1987). This experiment was designed both to evaluate the importance of frequency of cyclic exposure to physiologically disruptive changes in hydrologic conditions and to assess the utility of food clearance, respiration, and nitrogen excretion rate measurements as quantitative indices of stress.

Three species of mussels were used: *Q. p. pustulosa*, *Fusconaia cerina* (Conrad), and *Pleurobema beadleanum* (Lea). Mussels were subjected to one of four treatments for 10 days:

a. *Infrequent turbulence and suspended solids*. Mussels were exposed to suspended solids (average maximum value of 750 mg/ℓ) created by low levels of turbulence maintained for 7 min every 3 hr.

b. *Infrequent turbulence*. This treatment was a control for the previous experimental treatment where the mussels were exposed to low levels of turbulence but not suspended solids for 7 min every 3 hr.

c. *Frequent turbulence and suspended solids*. Mussels were exposed to suspended solids (average maximum value of 600 mg/ℓ) created by low levels of turbulence maintained for 7 min every 0.5 hr.

d. *Frequent turbulence*. This treatment was a control for the third experimental treatment where mussels were exposed cyclically to low levels of turbulence but not suspended solids for 7 min every 0.5 hr.

Diatomaceous earth, washed several times so that only intact diatom tests remained, was used as the suspended solid in these experiments.

Following turbulence, the suspended solid concentrations in treatments *a* and *c* reached their peak of 750 and 600 mg/ℓ, respectively, and fell to 10 percent of that peak value within 15 min after the end of turbulence. Minimum suspended solids concentration for treatments *a* and *c* were 25 and 125 mg/ℓ, respectively. The inability to achieve zero levels of suspended solids between successive episodes of turbulence is a typical problem in these types of studies (Moore 1977). The peak suspended solids concentrations used would be expected only in areas affected severely by dredging and navigation impacts (Wilbur 1983; Robinson, Wehling, and Morse 1984).

The following physiological rates were assessed: food clearance, oxygen uptake, and nitrogen excretion. Atomic ratios of O:N were used to assess shifts in catabolic substrates used by mussels. Tissue dry mass was also monitored. A detailed account of methods can be found in Payne and Miller (1987) or Aldridge, Payne, and Miller (1987).

Three paired comparisons were made of treatments. First the effect of the periodicity of two levels of physical disturbance (turbulence) was assessed by comparing the physiological condition of mussels in the infrequent versus the frequent turbulence treatments (*b* and *d*). In the other two comparisons, the combined effects of suspended solids and turbulence exposure were assessed by comparing treatments *a* and *b* as well as *c* and *d*. No differences between replicate aquaria were seen ($p > 0.05$, two-tailed t-test).

While acknowledging that there is no zero level control for assessing turbulence effects, a comparison of treatments *b* and *d* is useful in assessing the relative effects of varying the time interval between brief periods of turbulence (Table 4). All three species responded to more frequent turbulence by lowering nitrogen excretion rates and hence increasing O:N. Values for O:N were derived from each pair of rate determinations made on an individual mussel. The O:N ratio provides an assessment of the relative contribution of protein to total catabolism (Corner, Cowey, and Marshall 1975; Ikeda 1977; Widdows 1978; Russell-Hunter et al. 1983; Bayne and Newell 1983). Protein-based catabolism is indicated by O:N values less than 30 (Bayne and Widdows 1978). Infrequent exposure to turbulence had no major effect. All three species yielded O:N values averaging 13, that reflected their ability to base their metabolism on almost total reliance on the proteinaceous food ration of yeast. Only *P. beadleanum* showed higher values of O:N with more frequent exposure to turbulence. This species showed a change in O:N from 11 to 62, reflecting a shift to catabolism based mainly on nonproteinaceous body stores.

The effects of infrequent exposure to elevated suspended solids were evaluated by comparing them with the effects of infrequent exposure to turbulence alone. When exposed infrequently to suspended solids and turbulence

Table 4
Tissue Dry Mass (TDM), Food Clearance Rates (FCR), Oxygen Uptake Rates (VO), Nitrogen Excretion Rates (NE), and O:N Ratios for Mussels Exposed to Infrequent Turbulence and Those Exposed to Frequent Turbulence

Species	Physiology Monitor	Treatment		Student's t-Test		
		Infrequent	Frequent	df	t	Significance
Quadrula pustulosa	TDM, g	1.05 ± 0.23	1.13 ± 0.44	22	1.24	NS[1]
	FCR, mg yeast.g.h	7.86 ±5.63	8.93 ± 7.00	24	0.43	NS
	VO, mol O.g.h	18.20 ± 5.75	15.52 ± 4.16	20	1.25	NS
	NE, mol N.g.h	2.61 ± 0.78	1.66 ± 0.61	24	3.46	p < 0.01
	O:N	14.00 ± 4.38	17.22 ± 4.22	20	1.76	NS
Fusconaia cerina	TDM	0.98 ± 0.37	1.02 ± 0.36	32	0.33	NS
	FCR	11.56 ± 8.80	8.00 ± 3.59	32	1.54	NS
	VO	16.82 ± 5.62	14.81 ± 3.86	27	1.13	NS
	NE	2.42 ± 1.18	1.49 ± 0.80	32	2.63	p < 0.05
	O:N	13.86 ± 4.04	32.42 ± 38.67	27	1.79	NS
Pleurobema beadleanum	TDM	0.36 ± 0.07	0.36 ± 0.09	28	0.16	NS
	FCR	7.92 ± 8.83	9.71 ± 7.99	28	0.59	NS
	VO	20.81 ± 6.41	22.02 ± 9.80	28	0.13	NS
	NE	3.96 ± 1.11	2.17 ± 1.85	28	3.16	p < 0.01
	O:N	11.30 ± 4.73	62.34 ± 92.78	28	2.05	p < 0.05

Note: Data taken from Aldridge, Payne, and Miller (1987).
[1] NS = Not significant at p < 0.05 level.

(treatment *a*), all three species showed significant and substantial reductions in food clearance rates. In addition, *Q. p. pustulosa* and *P. beadleanum* showed reduced oxygen uptake and nitrogen excretion rates (Table 5). However, shifts in O:N were not observed.

The combined effects of suspended solids and turbulence exposure were more severe at high frequencies of exposure (treatment *c*). *Quadrula p. pustulosa, F. cerina*, and *P. beadleanum* all showed significant reductions in food clearance and nitrogen excretion rates (Table 6). Major shifts in O:N were made by all mussels exposed to frequent turbidity to the extent that their catabolism had become entirely based on nonproteinaceous body stores as indicated by O:N ratios in excess of 145.

Intermittent exposure of freshwater mussels to high levels of suspended solids disrupted feeding and caused shifts to catabolism of endogenous nonproteinaceous energy reserves. Exposure of all three species of unionid

Table 5
Tissue Dry Mass (TDM), Filter Clearance Rates (FCR), Oxygen Uptake Rates (VO), Nitrogen Excretion Rates (NE), and O:N Ratios for Mussels Exposed to Infrequent Turbulence and Those Exposed to Infrequent Turbulence Plus Turbidity

		Treatment		Student's t-Test		
Species	Physiology Monitor	Turbulence	Turbulence Plus Turbidity	df	t	Significance
Quadrula pustulosa	TDM	1.05 ± 0.23	1.19 ± 0.44	24	1.00	NS[1]
	FCR, mg yeast.g.h	7.86 ± 5.63	3.35 ± 2.74	24	2.76	$p < 0.05$
	VO, mol O.g.h	18.20 ± 5.75	12.48 ± 4.75	20	2.10	$p < 0.05$
	NE, mol N.g.h	2.61 ± 0.78	1.51 ± 0.38	24	4.54	$p < 0.001$
	O:N	14.00 ± 4.38	16.34 ± 6.42	20	1.00	NS
Fusconaia cerina	TDM	0.98 ± 0.37	0.99 ± 0.29	32	0.06	NS
	FCR	11.56 ± 8.80	5.07 ± 3.51	32	2.82	$p < 0.02$
	VO	16.82 ± 5.62	13.55 ± 4.69	27	1.71	NS
	NE	2.42 ± 1.18	1.73 ± 0.75	32	1.99	NS
	O:N	13.86 ± 4.05	19.40 ± 11.86	27	1.66	NS
Pleurobema beadleanum	TDM	0.36 ± 0.07	0.36 ± 0.06	26	0.12	NS
	FCR	7.92 ± 8.83	3.28 ± 1.49	26	2.28	$p < 0.05$
	VO	20.81 ± 6.42	12.15 ± 6.43	26	3.44	$p < 0.01$
	NE	3.96 ± 1.11	2.37 ± 1.06	26	3.90	$p < 0.001$
	O:N	11.30 ± 4.73	15.21 ± 15.87	26	0.88	NS

Note: Data taken from Aldridge, Payne, and Miller (1987).
[1] NS = Not significant at $p < 0.05$ level.

mussels to infrequent (once every 3 hr) and frequent turbidity (once every 0.5 hr) at levels of 750 and 600 mg/ℓ, respectively, caused reduced food clearance rates. Frequent exposure to turbidity resulted in reduced nitrogenous excretion rates in all three species and higher O:N ratios. The response to infrequent exposure to turbidity was more variable with only *Q. p. pustulosa* and *P. beadleanum* showing major responses. Both reduced oxygen uptake and nitrogenous excretion rates in tandem. The fact that the animals exposed to turbidity infrequently showed no shift in catabolic substances (O:N ratio) suggests that they were less seriously affected than mussels exposed frequently to turbidity.

High levels of turbidity have an additive effect to turbulence. However, field studies of navigation effects on turbidity show that levels of suspended solids (600 to 750 mg/ℓ) used in the laboratory experiments designed to elicit physiological stress responses will rarely be encountered by natural populations of mussels during periods of normal flow as a result of navigation

Table 6
Tissue Dry Mass (TDM), Filter Clearance Rates (FCR), Oxygen Uptake Rates (VO), Nitrogen Excretion Rates (NE), and O:N Ratios for Mussels Exposed to Frequent Turbulence and Those Exposed to Frequent Turbulence Plus Turbidity

Species	Physiology Monitor	Treatment		Student's t-Test		
		Turbulence	Turbulence Plus Turbidity	df	t	Significance
Quadrula pustulosa	TDM, g	1.13 ± 0.44	1.10 ± 0.27	24	0.17	NS[1]
	FCR, mg yeast.g.h	8.93 ± 7.00	2.36 ± 2.19	24	3.23	$p < 0.01$
	VO, mol O.g.h	15.52 ± 7.00	13.42 ± 3.75	19	1.22	NS
	NE, mol N.g.h	1.66 ± 0.61	0.11 ± 0.07	24	9.09	$p < 0.001$
	O:N	17.22 ± 4.22	233.50 ± 69.04	18	9.95	$p < 0.001$
Fusconaia cerina	TDM	1.02 ± 0.36	0.97 ± 0.30	32	0.41	NS
	FCR	8.03 ± 3.59	5.12 ± 4.37	32	2.10	$p < 0.001$
	VO	14.82 ± 3.86	15.80 ± 3.73	24	0.71	NS
	NE	1.49 ± 0.80	0.24 ± 0.31	32	6.01	$p < 0.001$
	O:N	32.42 ± 38.67	216.78 ± 112.91	24	6.05	$p < 0.001$
Pleurobema beadleanum	TDM	0.36 ± 0.09	0.33 ± 0.07	29	0.76	NS
	FCR	9.71 ± 7.99	3.34 ± 2.74	29	2.76	$p < 0.05$
	VO	22.02 ± 9.80	16.64 ± 4.78	29	1.92	NS
	NE	2.17 ± 1.85	0.23 ± 0.11	29	4.05	$p < 0.001$
	O:N	62.34 ± 92.78	149.19 ± 50.50	28	6.88	$p < 0.001$

[1] NS = Not significant at $p < 0.05$ level.

traffic (Bhowmik et al. 1981a; Claflin et al. 1981; Eckblad 1981; Johnson 1976). Nonetheless, laboratory studies at least indicate the potential for disruption of normal feeding and metabolism due to exposure to high levels and frequencies of turbulence and suspended solids. The ecological significance of any shifts from food to body-storage-based metabolism associated with stressful conditions of turbulence and suspended-solids exposure ultimately depends on these shifts being translated into reduced growth, reproduction, or survival of individuals in naturally occurring populations.

Effects of Intermittent Exposure to Water Velocity Pulses

This study dealt with the effects of continuous versus intermittent exposure to turbulence on the freshwater bivalve *F. ebena*. Seventy-two mussels were divided into three groups of approximately equal size distribution. Each group was exposed to one of three conditions: continuous-low, continuous-high, and cyclic-high water velocity. The three conditions were created by manipulating the magnitude and duration of velocities of water flowing over gravel in which mussels were positioned (Table 7). Low-velocity flow (7 cm/sec) was created by continuous operation of a small centrifugal water pump submersed in each tank. A larger pump ran continuously in the continuous-high velocity treatment, creating a 27-cm/sec flow. In the cyclic-high velocity treatment, the larger pump was activated for 5 min each hour with a programmable electronic timer.

Table 7
Means and Standard Deviations of Water Velocity Exposure, Tissue Condition Index, and Respiration Rate Measurements of Juvenile *Fusconaia ebena* in Three Velocity Exposure Treatments

Variable	Velocity Exposure Treatment		
	Continuous Low	Cyclic High	Continuous High
Water velocity, cm/sec			
Low	7.11 ± 1.02[a]	6.60 ± 1.02[a]	
High	26.42 ± 1.27[a]	27.18 ± 3.56[a]	
Tissue Condition Index[1]			
(TDM/SDM) X 100	1.72 ± 0.19[a]	1.69 ± 0.30[a]	1.43 ± 0.27[b]
Percent Reduction	19.73 ± 8.39[a]	22.39 ± 13.84[a]	34.48 ± 12.50[b]
Respiration Rate			
μmoles 02/(mg x hr)	1.45 ± 0.27[a]	1.46 ± 0.55[a]	1.75 ± 0.58[a]

Note: TDM stands for tissue dry mass, SDM for shell dry mass. Superscript letters a and b indicate which means were not significantly different at the 0.05 level using Duncan's Multiple Range Test. Mussels in the cyclic-high treatment were exposed to 5 min of high followed by 55 min of low velocity flow per hour.
[1] Percent reduction is relative to the TCI of juvenile *F. ebena* fixed in the field upon collection on 27 August.

Water was maintained at 18 to 26 °C and contained an ad libitum but nonfouling suspension of brewer's yeast for the duration of the 37-day experiment. Nutritionally adequate feeding of filter-feeding bivalves in a small, closed system is not possible. The yeast suspension was provided for simplicity and because previous studies in the laboratory have shown that the yeast cells are ingested and used in partial support of maintenance metabolism.

On Days 33, 35, and 37, a batch of eight mussels was removed from each of the three treatments to measure respiration and tissue condition. Following determination of respiration, soft tissue was removed from the shell, and all tissues and shells were dried for 48 hr at 65 °C and separately weighed. A tissue condition index (TCI) was obtained by dividing tissue dry mass (TDM) by shell dry mass (SDM), both in milligrams, and multiplying the quotient by 100. A batch of juveniles fixed in 12-percent neutral formalin upon collection from the Ohio River in late August was treated in an identical manner to estimate initial TCI.

The TCI of juvenile *F. ebena* in the continuous-low and cyclic-high velocity treatments was 20 and 22 percent less than the TCI of field-fixed juveniles. Continuous exposure to high-velocity water caused a 34-percent reduction in TCI. Comparison of the mean TCI by Duncan's multiple range test indicated that weight loss was not significantly different ($p < 0.05$) between continuous-low and cyclic-high velocity treatments, but weight loss was significantly less in these two treatments than in the continuous-high velocity group (Table 7). Respiration rates, measured in still water, did not differ significantly among mussels from the three treatments.

To recapitulate, juvenile *F. ebena* were not affected by 5-min exposure to high-velocity flow once per hour, a result directly relevant to evaluating the environmental effects of commercial navigation traffic. Commercial traffic rates do not often exceed one tow per hour. Thus, turbulence caused by routine traffic is not likely to deleteriously affect mussels. Conversely, at sites where barges are fleeted, towboats sometimes work essentially continuously. Potential impacts to mussels by abrupt water velocity changes in fleeting areas need to be evaluated on a site-specific basis.

The level of velocity change used in this laboratory study falls within the range of changes observed in the field by Environmental Science and Engineering (1981) or Miller and Payne (1991), (1992), and (1993). The laboratory study of *F. ebena* showed that a 5-min increase in velocity of 18 cm/sec once per hour did not significantly reduce the tissue condition index relative to mussels continuously exposed to a velocity of 8 cm/sec. Thus, laboratory data suggest that a species such as *F. ebena* is not likely to be deleteriously affected by velocity changes induced by routine traffic.

6 Presence of *Dreissena polymorpha* in the UMR

Background

The first report of the zebra mussel (*Dreissena polymorpha*) in North America was from Lake St. Clair in June 1988 (Hebert, Muncaster, and Mackie 1989; Roberts 1990). By late summer 1989, zebra mussels had spread downstream into the Detroit River, Lake Erie, Niagara River, and western Lake Ontario (Griffiths, Kovalak, and Schloesser 1989). By late September 1990, zebra mussels had spread through Lake Ontario and down the St. Lawrence River to Massena, NY. In June 1991, biologists from the Illinois Natural History Survey found adult zebra mussels at Illinois River Miles 50, 60, and 110 (Moore 1991; Sparks and Marsden 1991).

By early January 1993, zebra mussels had spread throughout most of the inland waterway system. They probably reached upriver sites on hulls of commercial navigation vessels (Keevin, Yarbrough, and Miller 1992). They were found in the lower Mississippi River as far south as Vicksburg, MS, and in the Upper Mississippi River near St. Paul, MN (*Dreissena polymorpha* Information Review 1992). Although commercial vessels are important in the dissemination of zebra mussels, high-density populations can reach areas by water. For example, densities of zebra mussels in the Illinois and lower Mississippi rivers are several orders of magnitude greater than in the UMR. There is every reason to believe that *D. polymorpha* will continue to spread throughout North America where suitable habitat exists (Strayer 1990).

Effects of Introduction of *D. polymorpha* on Results of this Study

Zebra mussels were first collected during this survey in 1993 in Pool 10. In 1994, zebra mussels were collected at all mussel beds surveyed. Zebra mussels were most common at the bed in Pool 14 where their density was 8.2 individuals/m^2 in 1994. However, these low densities had no measurable effects on native mussels during the study.

Zebra mussels will become more common at these beds in the UMR and will likely have an adverse affect on native fauna. When interpreting results of future studies, it will be important to consider the likely effects of zebra mussels. This will be especially important if they reach high densities, greater than 10,000 individuals/m^2, which have been reported from the Illinois River.[1] Effects of high densities of zebra mussels on native mussels in this country and Europe have been thoroughly documented (Lewandowski 1976; Nalepa 1995). Zebra mussels will have adverse affects on native mussels, unlike the case of the Asiatic clam, *Corbicula fluminea*, where sustained co-existence with native mussels in the lower Ohio River has been documented (Miller and Payne 1994b).

1 Personal Communication, 1995, Blodgett, Illinois Natural History Survey.

7 An Assessment of the Health of the Five Mussel Beds in the UMR

Background

The purpose of these field studies was to document important biotic attributes of five prominent mussel beds in the UMR from 1988 to 1994. Data will characterize baseline conditions for future studies and can be used to test for negative effects during the study period, 1988-94. In the following section, the health of these mussel beds will be examined using results of this study.

Possible Effects of Commercial Clamming on UMR Mussel Populations

In 1989, 7.1 million pounds of mussels were harvested from the Illinois and Mississippi rivers and had an average value of $3.2 million. Over 7.7 million pounds were harvested in 1990 and were valued at $6.1 million (Thiel and Fritz 1993). The specific quantity of mussels harvested commercially from each bed studied during this survey cannot be determined. For the most part, beds were chosen because it appeared that they had minimal harvesting pressure. An exception could be the bed in Pool 10 near Prairie du Chien, WI.

There is no doubt that commercial harvesting pressure could negatively affect results of this survey. Declines in density of *A. p. plicata* and other thick-shelled species (*M. nervosa* and *Quadrula* spp.) could be attributable to harvest. Although density can be affected by commercial harvest, other parameters measured during this survey (recruitment and growth rates, species richness, and presence of *L. higginsi*) should be unaffected by harvest.

Temporal Trends in Six Parameters That Characterize the Relative Health of Mussel Beds

Decrease in density of five common-to-abundant species

Based on results of quantitative sampling in 1994, percent abundance of the five most common species at each mussel bed in each navigation pool appear below:

Percent Abundance of the Five Most Abundant Species at Mussel Beds in Five Navigation Pools of the UMR, 1994

Species	Pool				
	24	17	14	12	10
T. truncata	36.2	24.6	25.1	22.8	19.9
E. lineolata	11.9	21.2	--	--	--
A. p. plicata	11.1	13.6	17.9	24.0	49.0
Q. p. pustulosa	9.1	15.0	15.5	--	--
O. reflexa	19.8	6.3	12.0	10.5	3.5
L. fragilis	--	--	7.4	11.3	8.4
Q. quadrula	--	--	--	6.2	3.4

Change in density of five of these species appears in Figures 23-39 and Tables B1-B7, Appendix B. Mean density for total mussels at these beds appears in Table B8. The criterion stated that negative effects will be assumed if there is a significant ($p < 0.1$) decline in density, sustained over each of at least two consecutive sampling periods, for at least five common-to-abundant species. Appendix B contains results of Duncan's analysis at the 0.1 as well as the 0.5 level. Analysis at the 0.1 level is more conservative; typically, a larger number of significant differences will be found among a set of means than when comparisons are made at the 0.05 level. The intent was to take a conservative approach to searching for differences, but to require that this change hold for at least two sampling periods for at least five species. This criterion probably does not apply well to short-lived species (*Truncilla* spp.) whose complete life cycle could include the period of study.

A total of 29 density comparisons were made. There were eight significant density declines ($p < 0.1$) and two significant density increases. The criterion for density was met since there was not a significant density decline for all five species at any one bed. Density declines for *A. p. plicata* and possibly *Q. quadrula* and *Q. pustulosa* could be the result of commercial harvest. Changes in density of *T. truncata*, *E. lineolata*, *L. fragilis*, and *O. reflexa* are not related to commercial harvest. A summary of trends for 1988-94 appear below:

Summary of Density Changes of Five Common Species at Five Locations in the UMR, 1988-94					
	Pool				
Species	24	17	14	12	10
T. truncata	NC	D*	I*	NC	I
E. lineolata	NC	NC	--	--	--
A. p. plicata	NC	D*	NC	NC	D*
Q. p. pustulosa	D*	NC	NC	I	NC
O. reflexa	D*	D*	I	NC	D
L. fragilis	--	--	--	I	I*
Q. quadrula	D	NC	NC	D*	D*

Note: D = General decline in density; I = General increase in density; NC = No distinct density trend. Those marked with an asterisk are significant at the 0.1 level for two consecutive years (Duncan's Multiple Range Test).

Absence of *L. higginsi*

The range in abundance of *L. higginsi* at the four beds in the UMR that are within its range varied from 0.09 percent (quantitative samples in 1989 from Pool 14) to 1.72 percent (qualitative samples in 1988 from Pool 10) (Table 8). Because this species is uncommon, at least several hundred mussels have to be collected before it is likely to obtain one individual. At the bed in Pool 17, this species was collected twice, in 1988 and again in 1994, and was not collected in 1990 and 1992. *Lampsilis higginsi* was collected in 2 of 4 sample years at the bed in Pool 12. At the beds in Pools 10 and 14, this species was collected during each survey year.

The criterion stated that negative effects would be assumed if this species was not collected during two consecutive sampling periods. Based on this criterion, there are no negative effects at beds in Pools 10 and 14. At the beds in Pools 12 and 17, *L. higginsi* was much less common and was not collected each year. This criterion was just met at the bed in Pool 12, but was not met at the bed in Pool 17 (Table 9).

Decrease in live-to-recently dead ratios for dominant species

This criterion stated that negative effects would be assumed if there was a continual decrease in the ratio of live-to-recently-dead organisms for three consecutive sampling periods. This criterion was easily met; recently dead mussels were rarely collected during this survey, and always made up less than 1 percent of the sample.

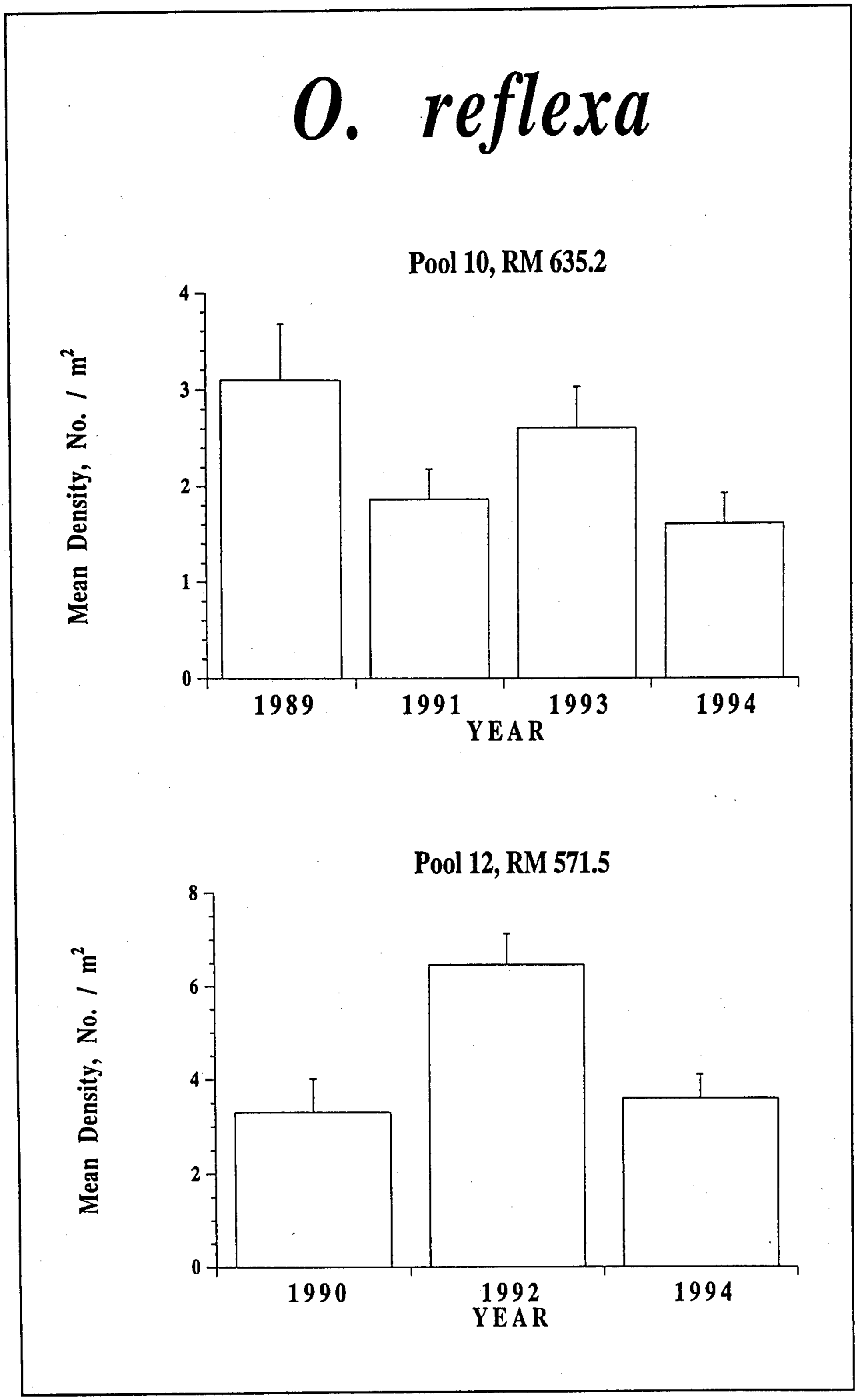


Figure 23. Total density of *O. reflexa*, RM 635.2 and 571.5

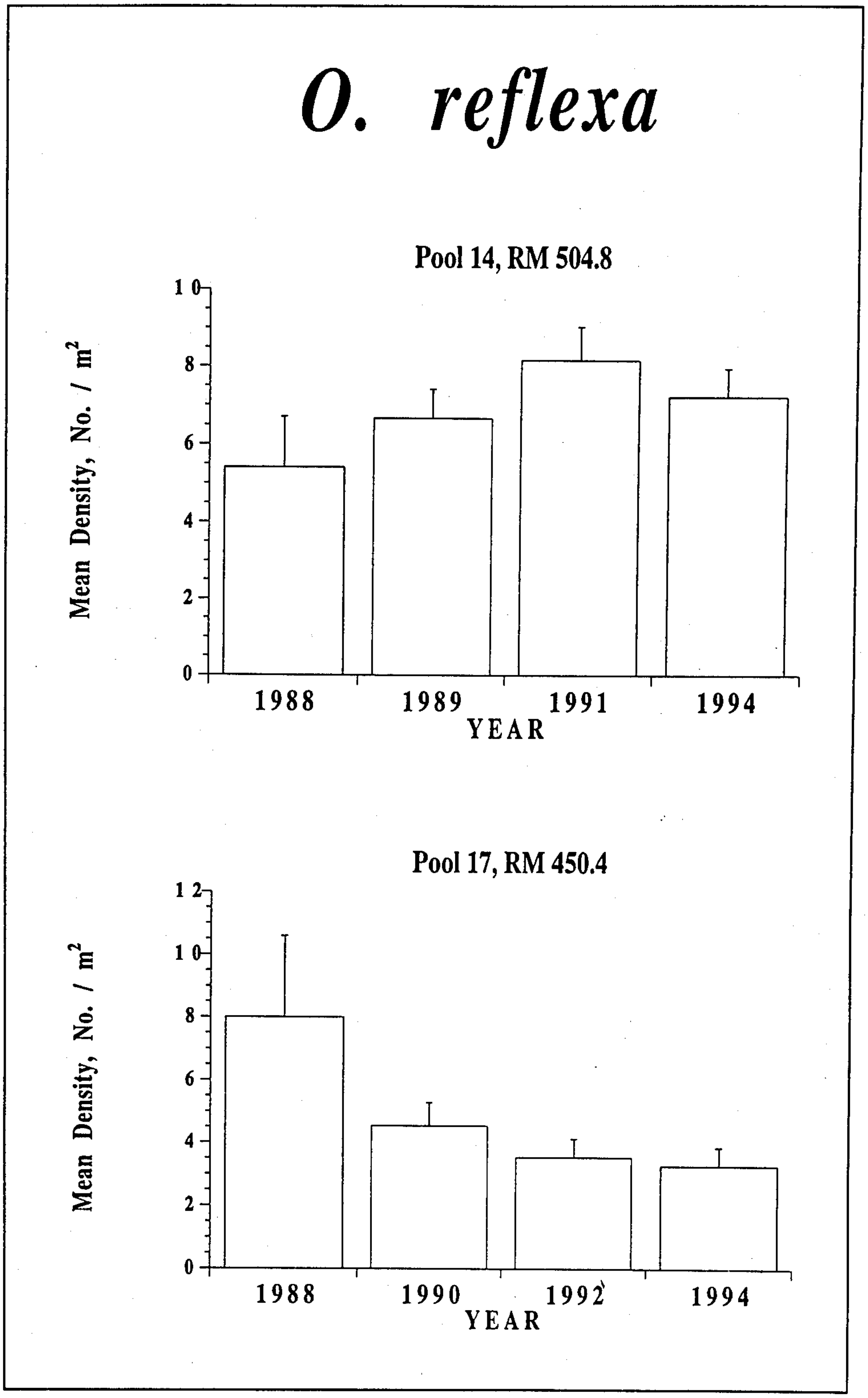


Figure 24. Total density of *O. reflexa*, RM 504.8 and 450.4

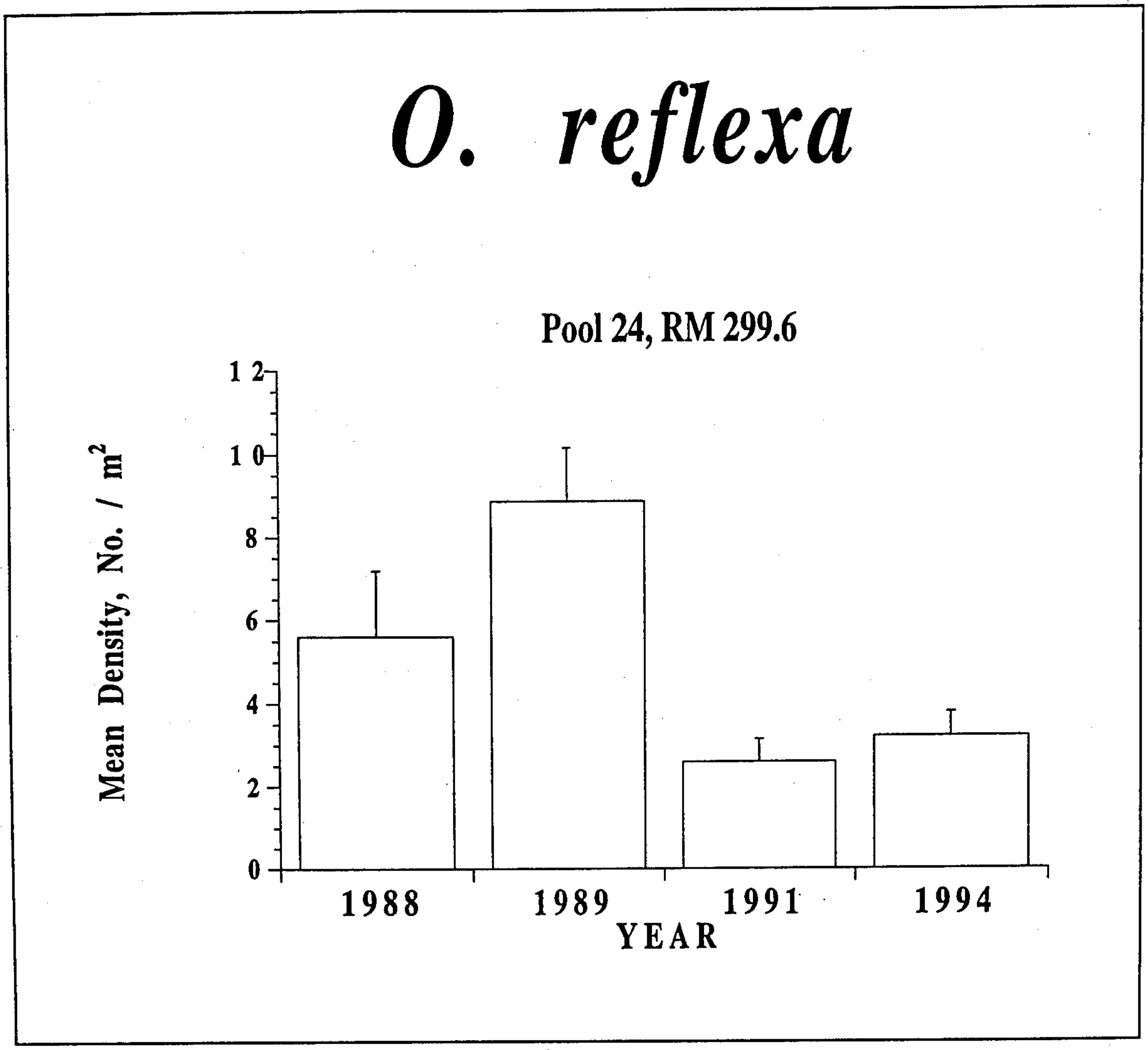


Figure 25. Total density of *O. reflexa*, RM 299.6

Loss of more than 25 percent of the mussel species

This criterion stated that negative effects would be assumed if there was a loss, sustained for two consecutive sampling periods, of over 25 percent of existing mussel species. In mussel beds that support 20 to 32 species, this would require a sustained loss of 5 to 8 species. A complete species list for each year at each bed, which includes total individuals and total species collected, appears in Appendix C, Tables C1-C6.

Although there is some year-to-year variation in species richness, numbers remain relatively constant for each study year. At the bed in Pool 24, the number of species collected each year, based on qualitative and quantitative sampling was 18 (1988), 22 (1989), 22 (1991), 13 (1992), and 20 (1994) for a total species richness of 26 (Table B1). At the mussel bed in Pool 10, the

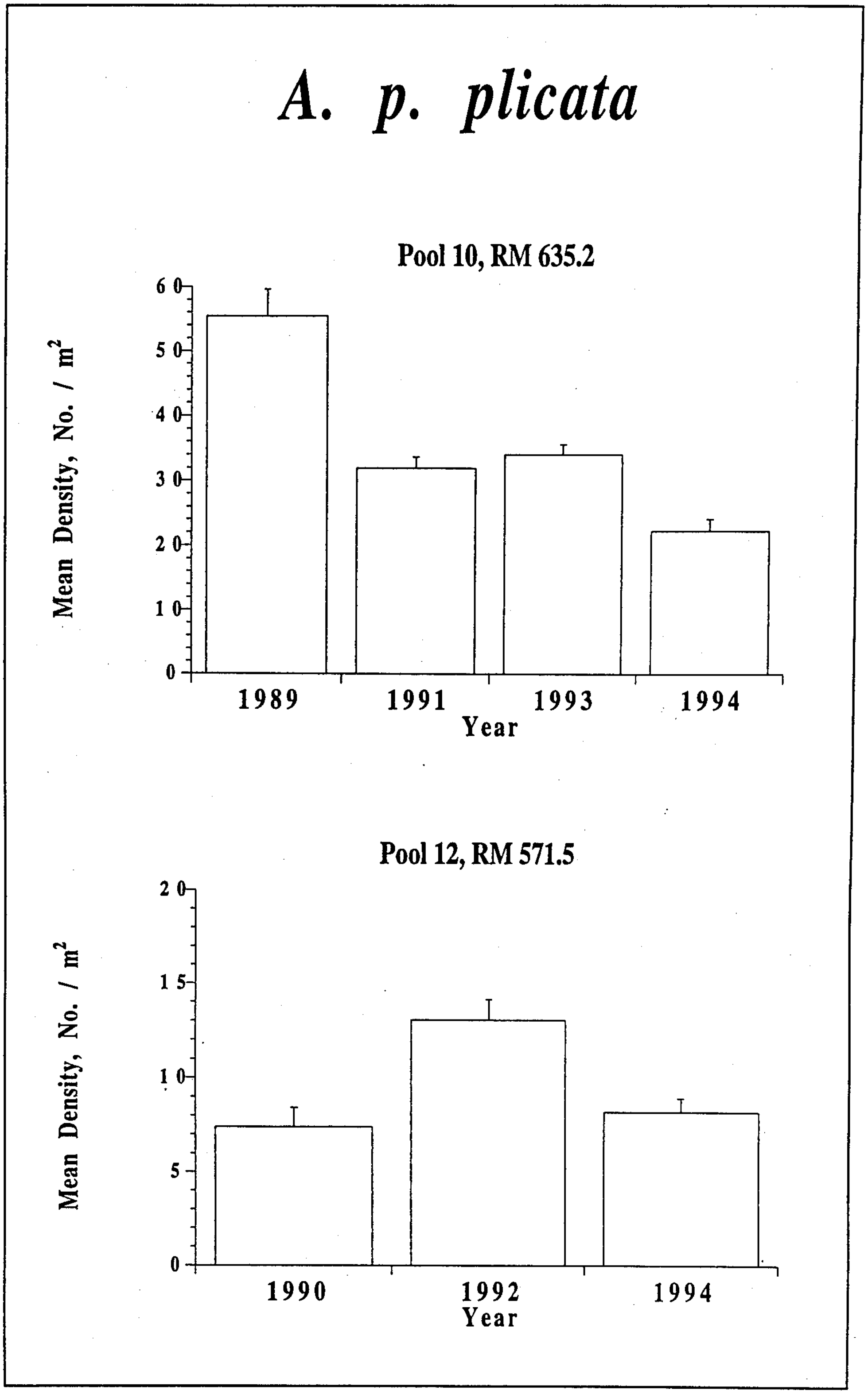


Figure 26. Total density of *A. p. plicata*, RM 635.2 and 571.5

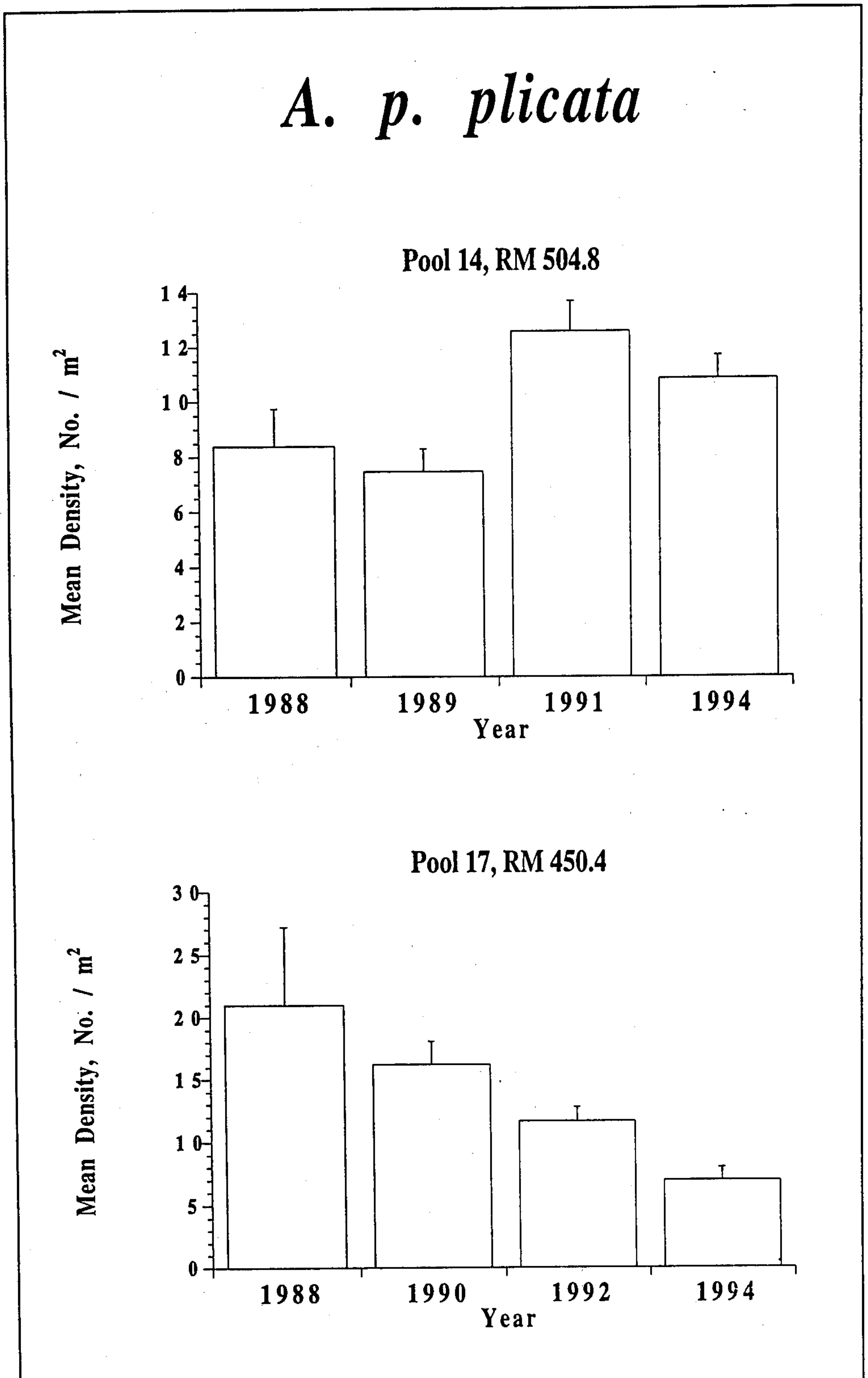


Figure 27. Total density of *A. p. plicata*, RM 504.8 and 450.4

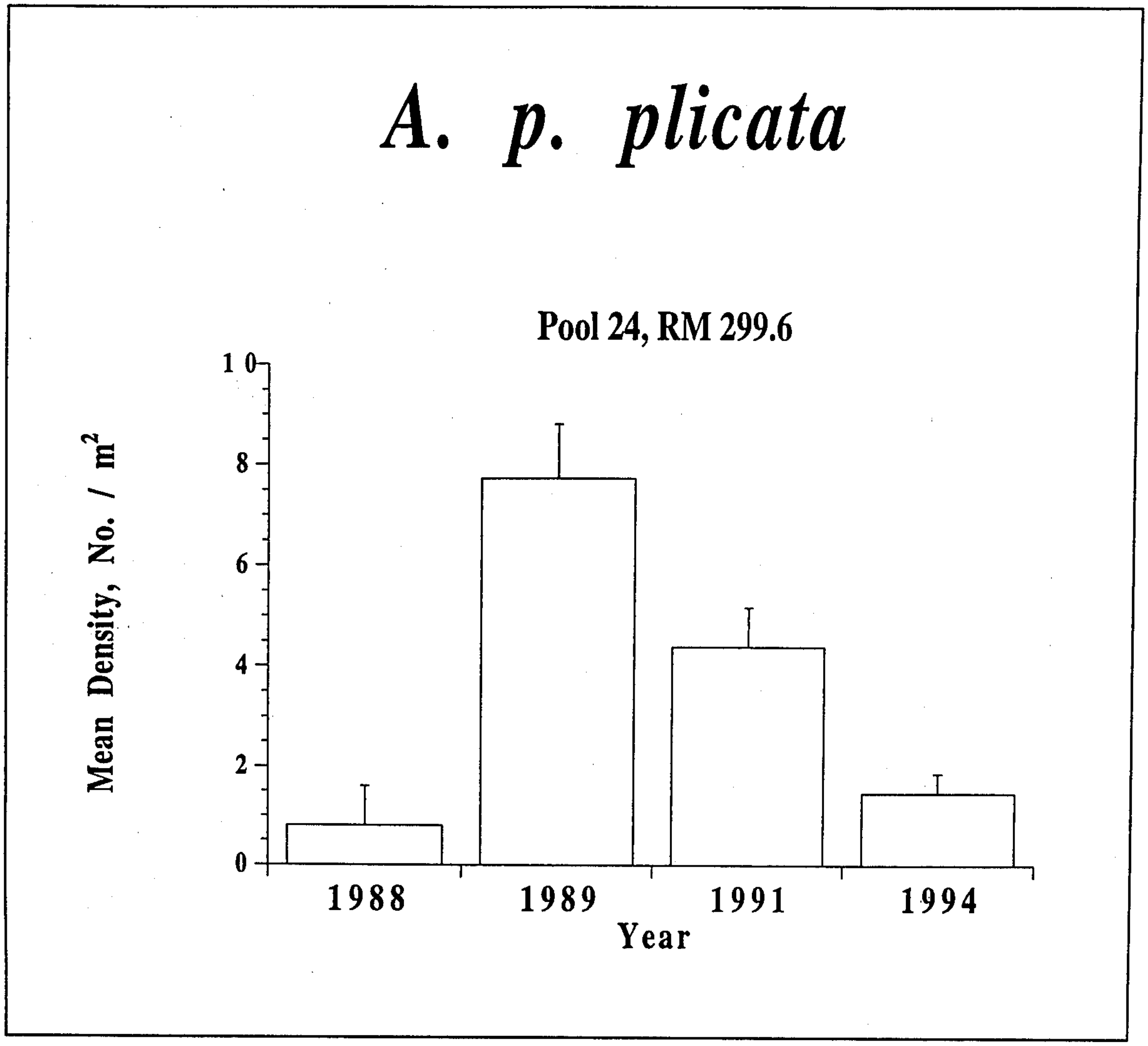


Figure 28. Total density of *A. p. plicata*, RM 299.6

total number of species collected each year was 27 (1988), 22 (1989), 25 (1991), 18 (1992), 26 (1993), and 25 (1994), for a total species richness of 31 (Table C5).

Species diversity and Menhinick's Index are plotted for each mussel bed for each survey year, based on quantitative sampling. Species diversity ranged from slightly less than 1.5 to nearly 2.5, and was variable among years (Figures 40-42). The lowest diversity values come from the bed in Pool 10. High dominance of the commercially valuable *A. p. plicata* caused low-diversity values.

Menhinick's Index (total species/square root of total individuals) provides a measure of richness that is less dependent on the number of individuals collected. Based upon data from quantitative samples, this index ranged from 0.7 (data from nearshore subsites, RM 450.4, 1994) to a high of nearly 1.5 at farshore subsites, RM 299.6, 1994 (Figures 43-45). Unlike diversity and

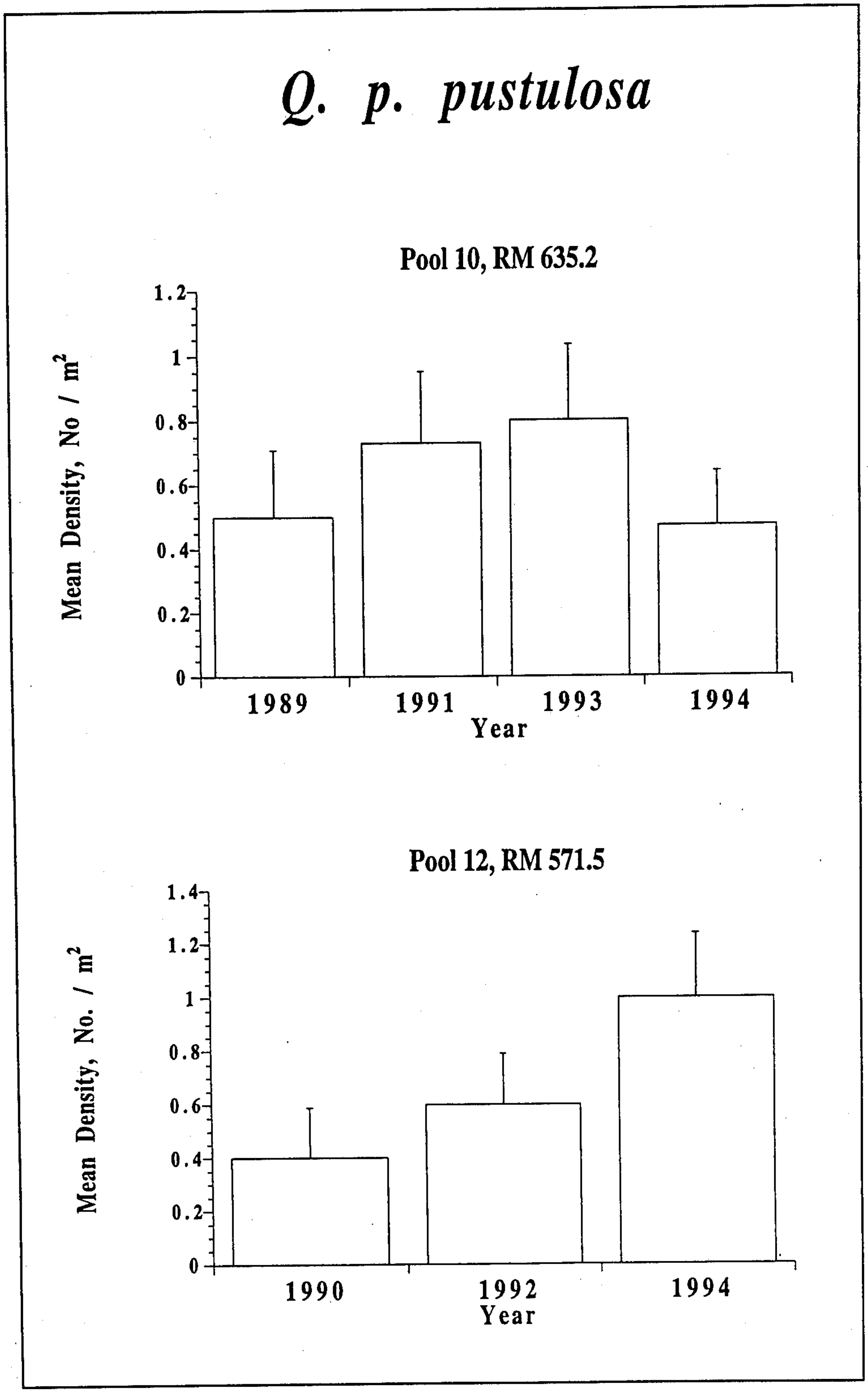


Figure 29. Total density of *Q. p. pustulosa*, RM 635.2 and 571.5

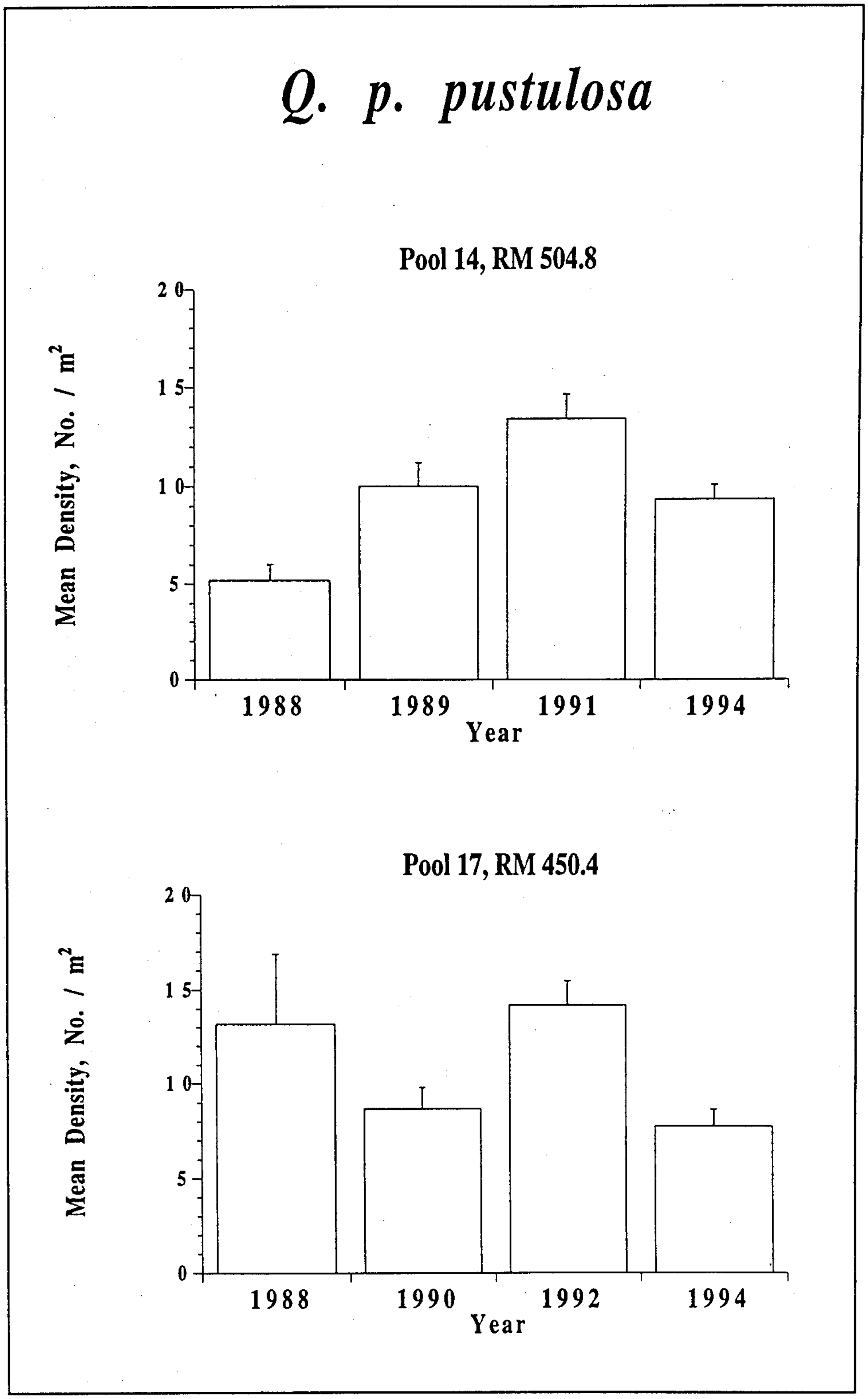


Figure 30. Total density of *Q. p. pustulosa*, RM 504.8 and 450.4

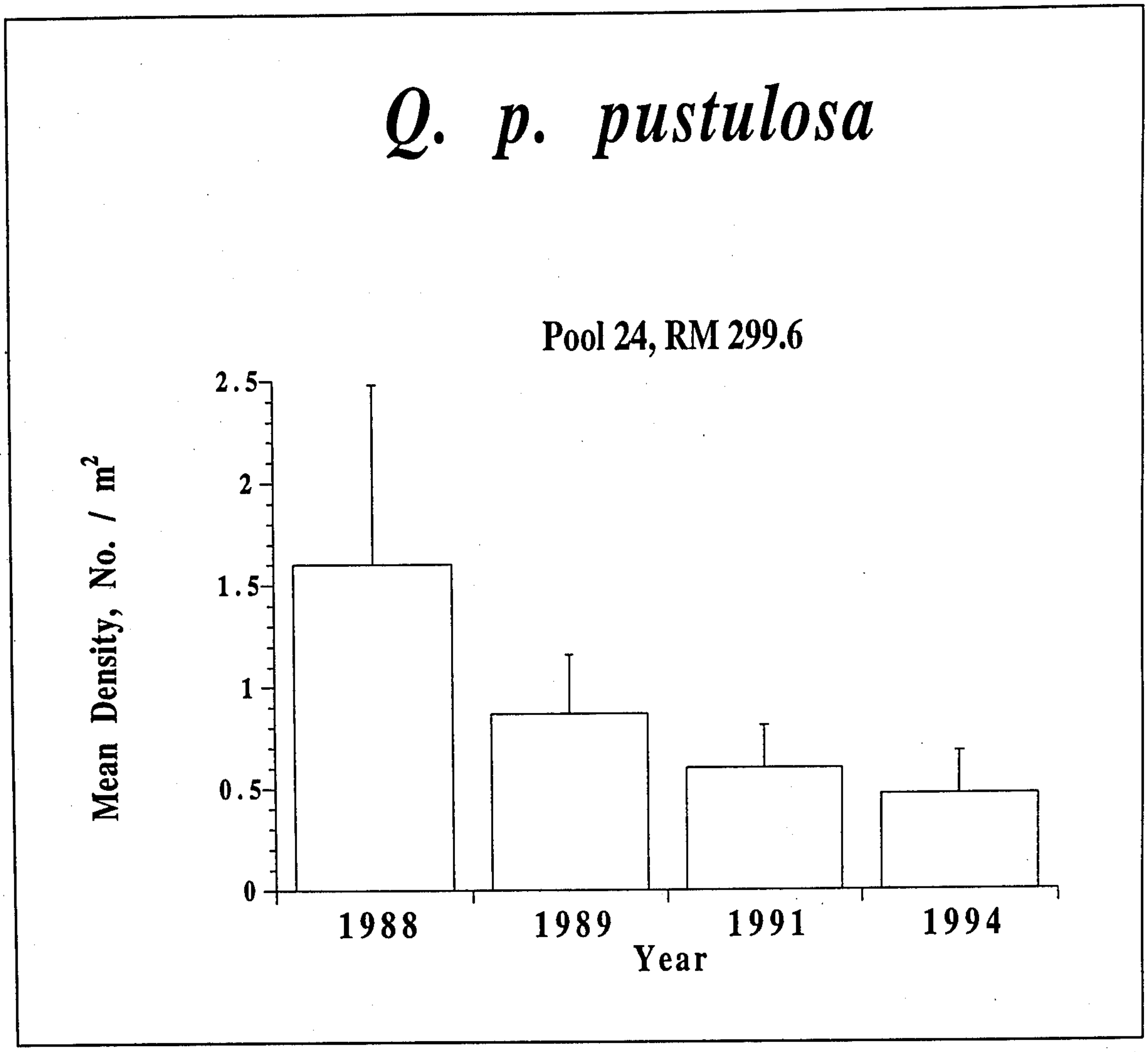


Figure 31. Total density of *Q. p. pustulosa*, RM 299.6

evenness indices, Menhinick's Index is dependent upon the relationship between number of species and individuals present and is not directly related to distribution of species within the community. However, if a large number of species are collected within a sample of relatively few individuals (high diversity), then Menhinick's Index will be high. Conversely, if the same number of species are collected in a sample of very many individuals, then the index will be low.

The nearshore station at RM 299.6 shows considerable interyear variation and no specific temporal trend; the farshore station shows a gradual increase in Menhinick's Index (Figure 43). However, as noted above, total species for these 3 years (22, 22, and 20 for 1989, 1991, and 1994, respectively) are similar. The increase in the index through time is probably a result of the increase in community-wide recruitment through time, which resulted in an increased ability to collect uncommon species. The burst of recruitment of *A. p. plicata* in 1989 had little effect on Menhinick's Index.

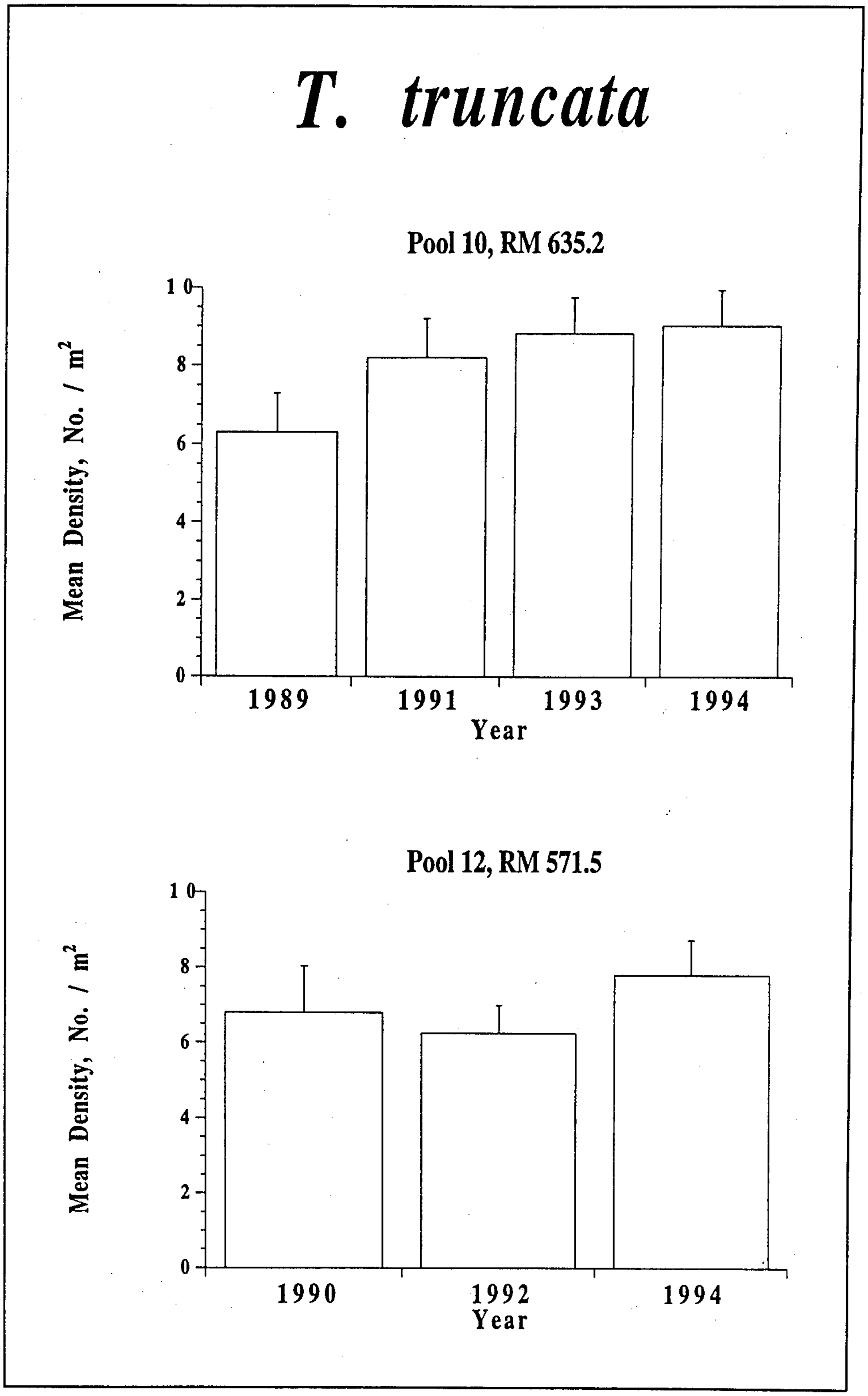


Figure 32. Total density of *T. truncata*, RM 635.2 and 571.5

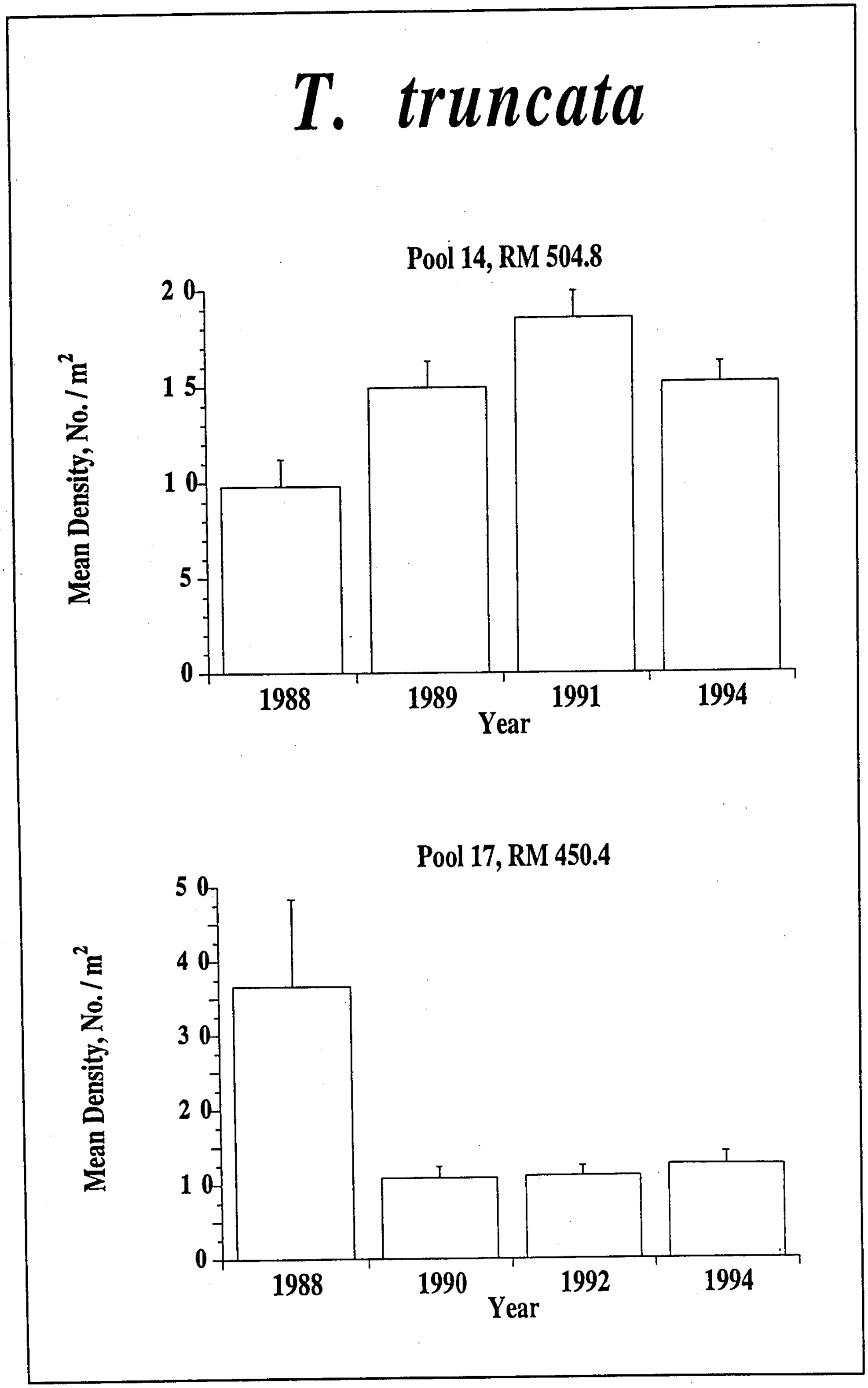


Figure 33. Total density of *T. truncata*, RM 504.8 and 450.4

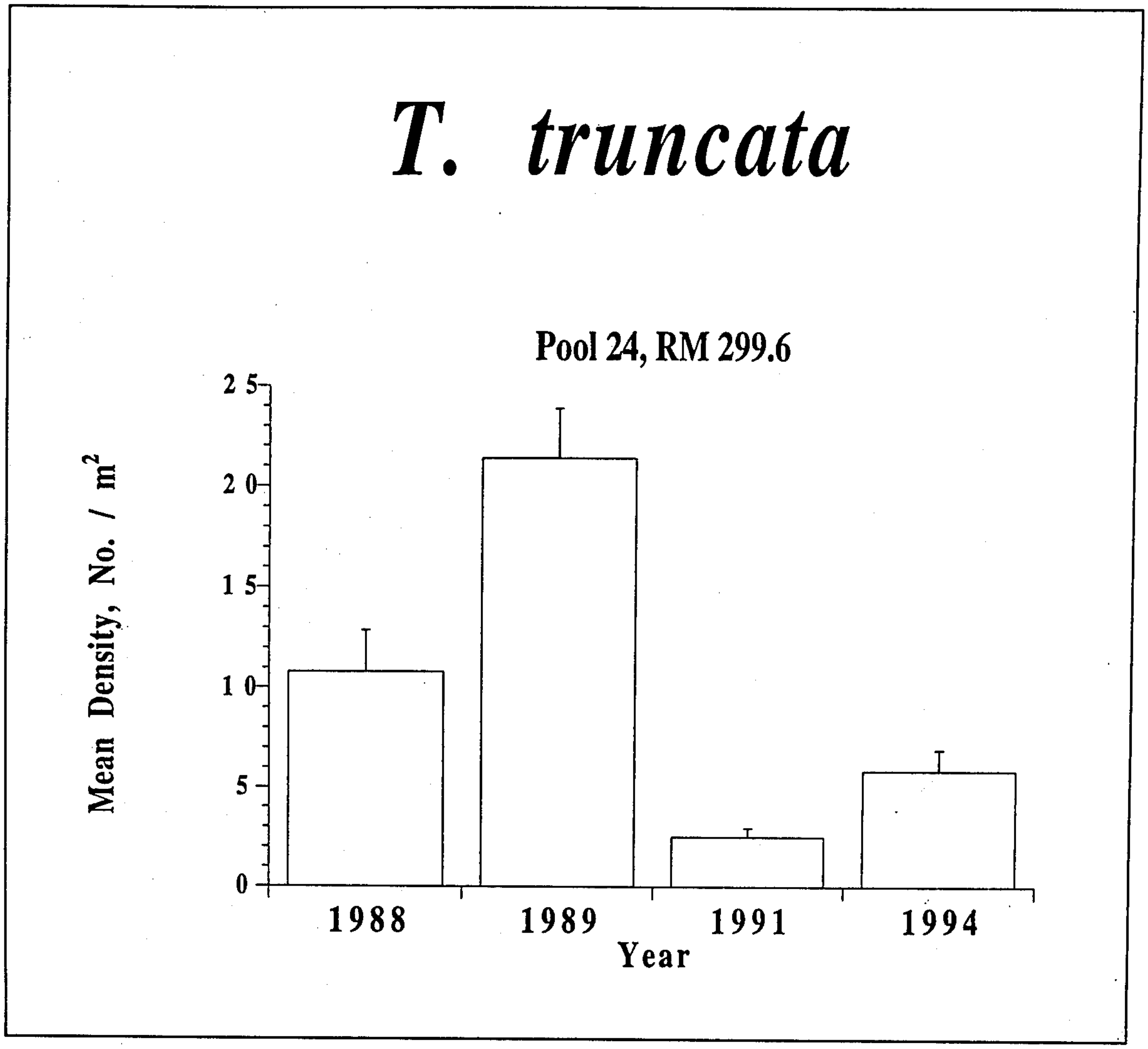


Figure 34. Total density of *T. truncata*, RM 299.6

Menhinick's Index remained stable through time at RM 450.4 (Figure 43), and no specific trends for the index were seen at RM 504.8 or 571.5 (Figure 44). The gradual decrease in the index at the farshore site at RM 504.8 was not observed at the nearshore site. At RM 635.2, there were no specific temporal trends; a gradual increase in the index was noted at the farshore location and a gradual increase at the nearshore location (Figure 45).

To summarize, the criterion for species richness was met at each bed; none experienced a sustained loss of any species. There are interbed differences in species richness, brought about by local physical and hydraulic conditions, and distribution of species. Menhinick's Index and Shannon's diversity index are variable among years; however, no specific negative or positive trends were noted.

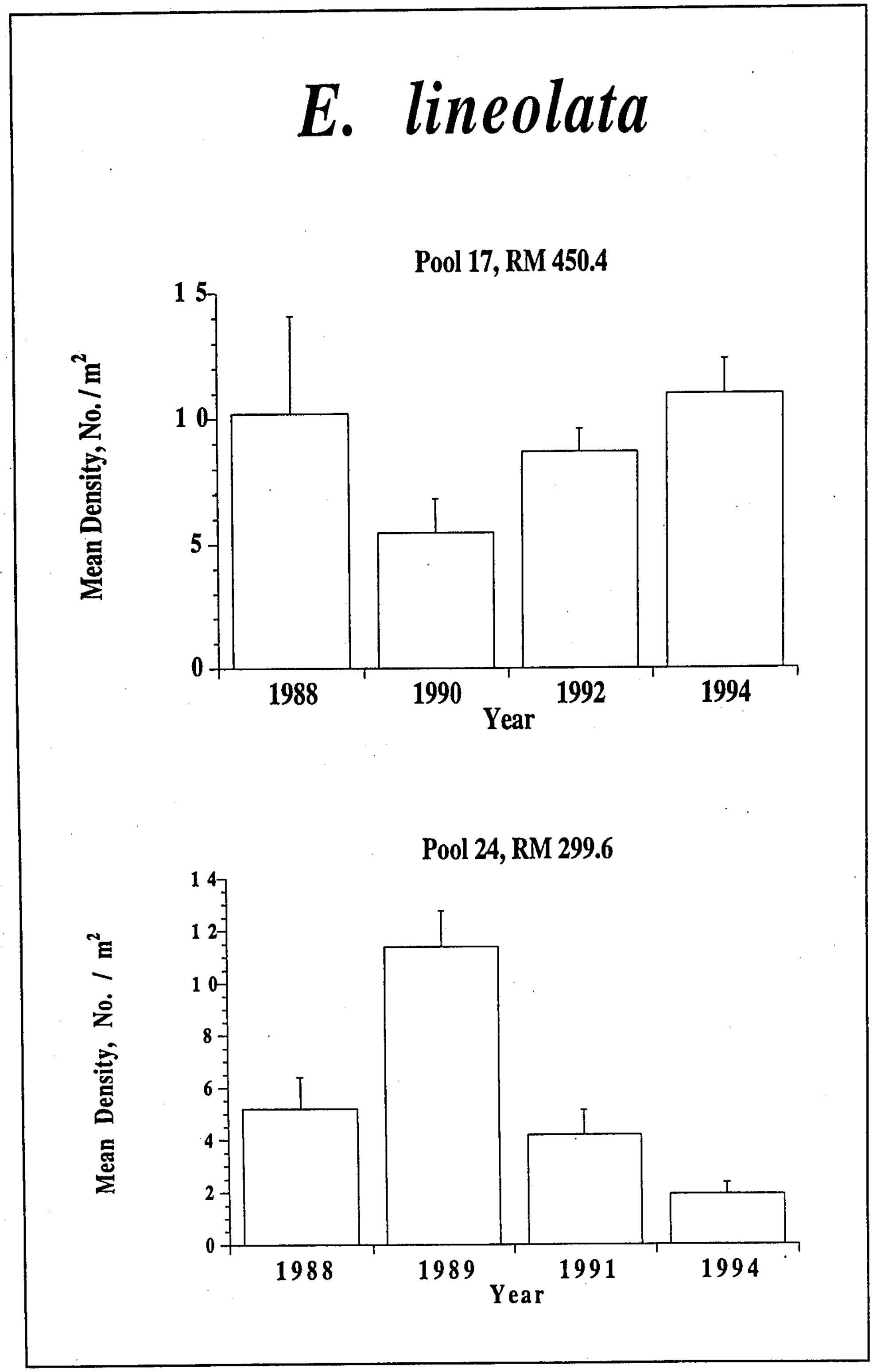


Figure 35. Total density of *E. lineolata*, RM 450.4 and 299.6

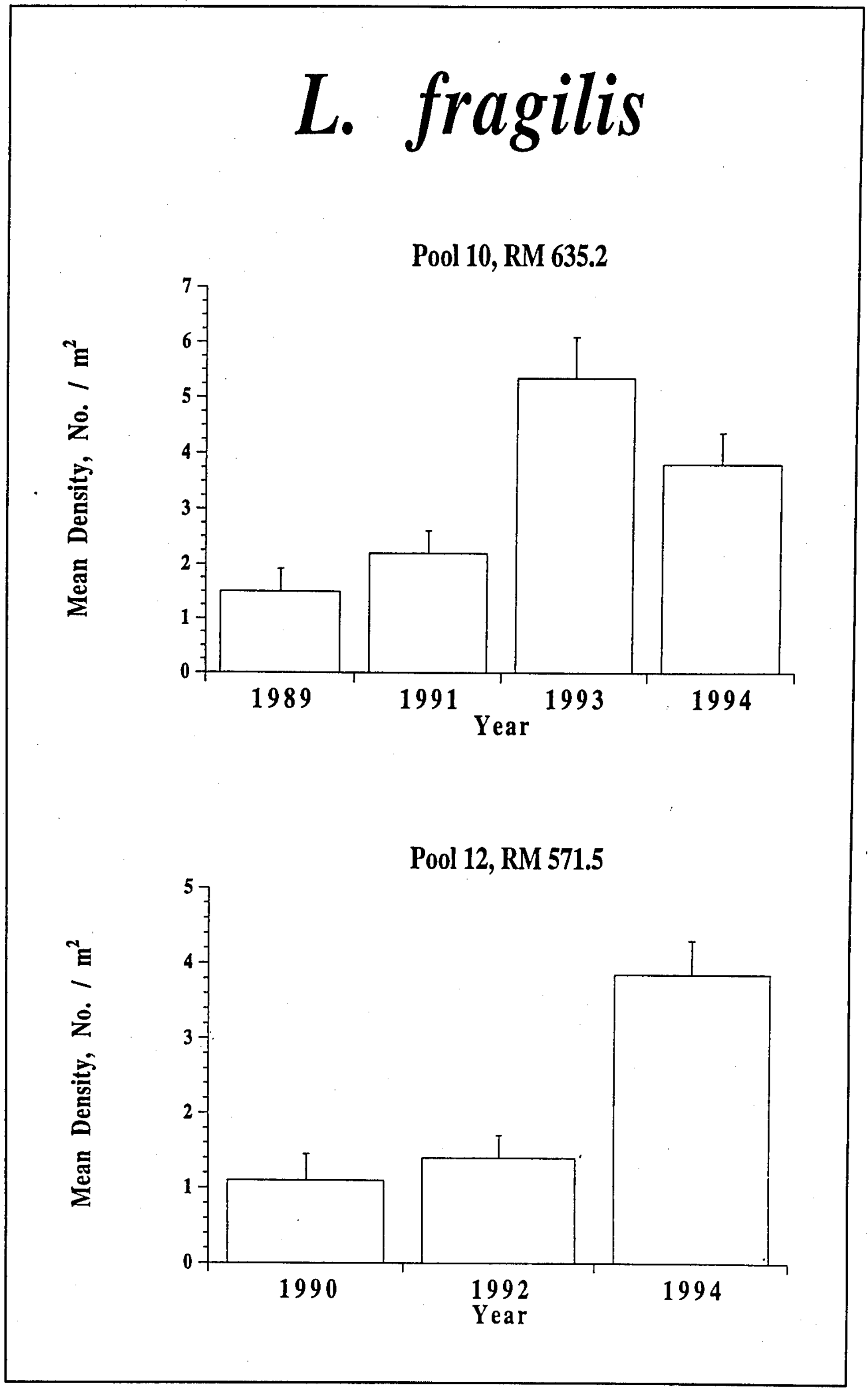


Figure 36. Total density of *L. fragilis*, RM 635.2 and 571.5

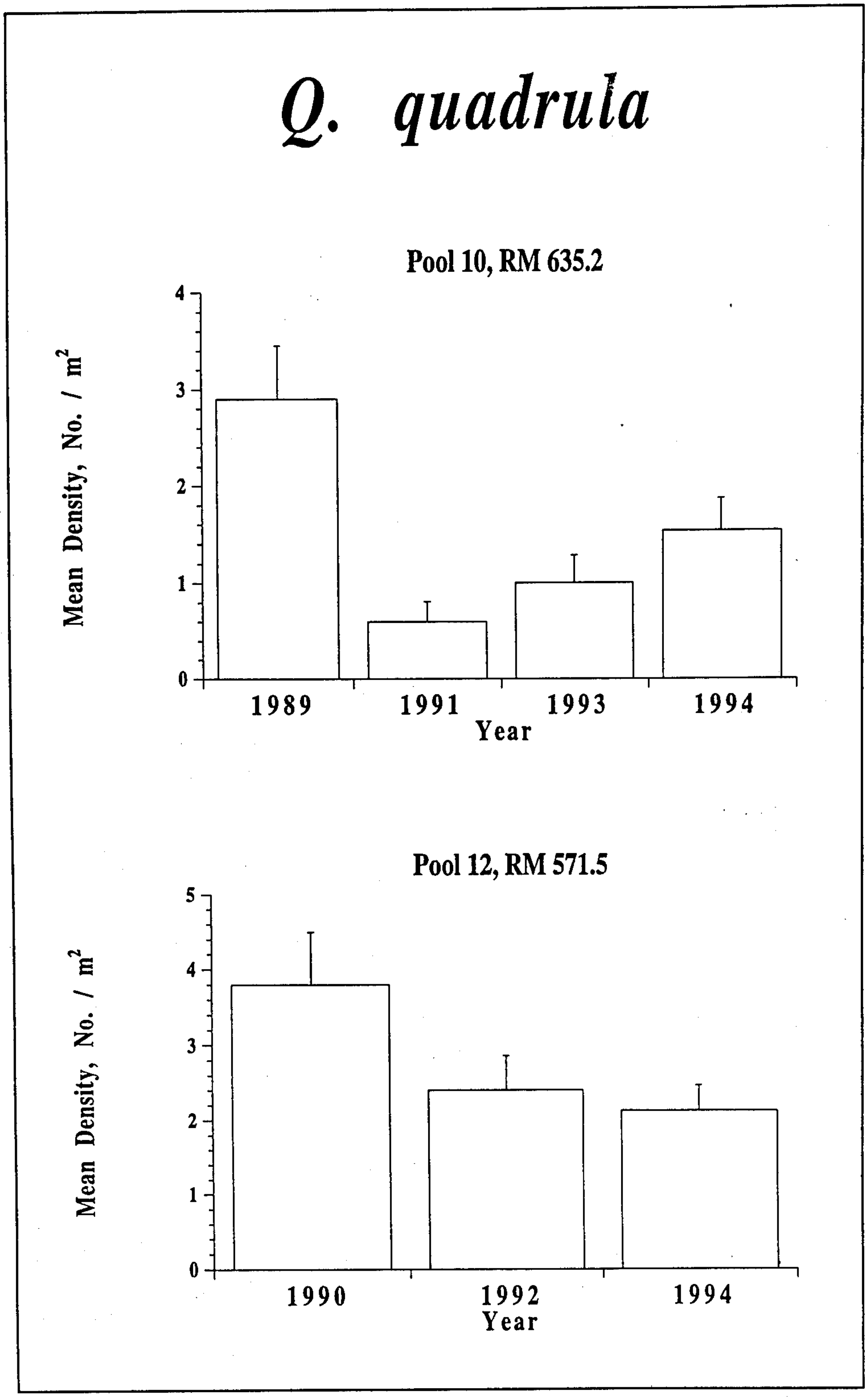


Figure 37. Total density of *Q. quadrula*, RM 635.2 and 571.5

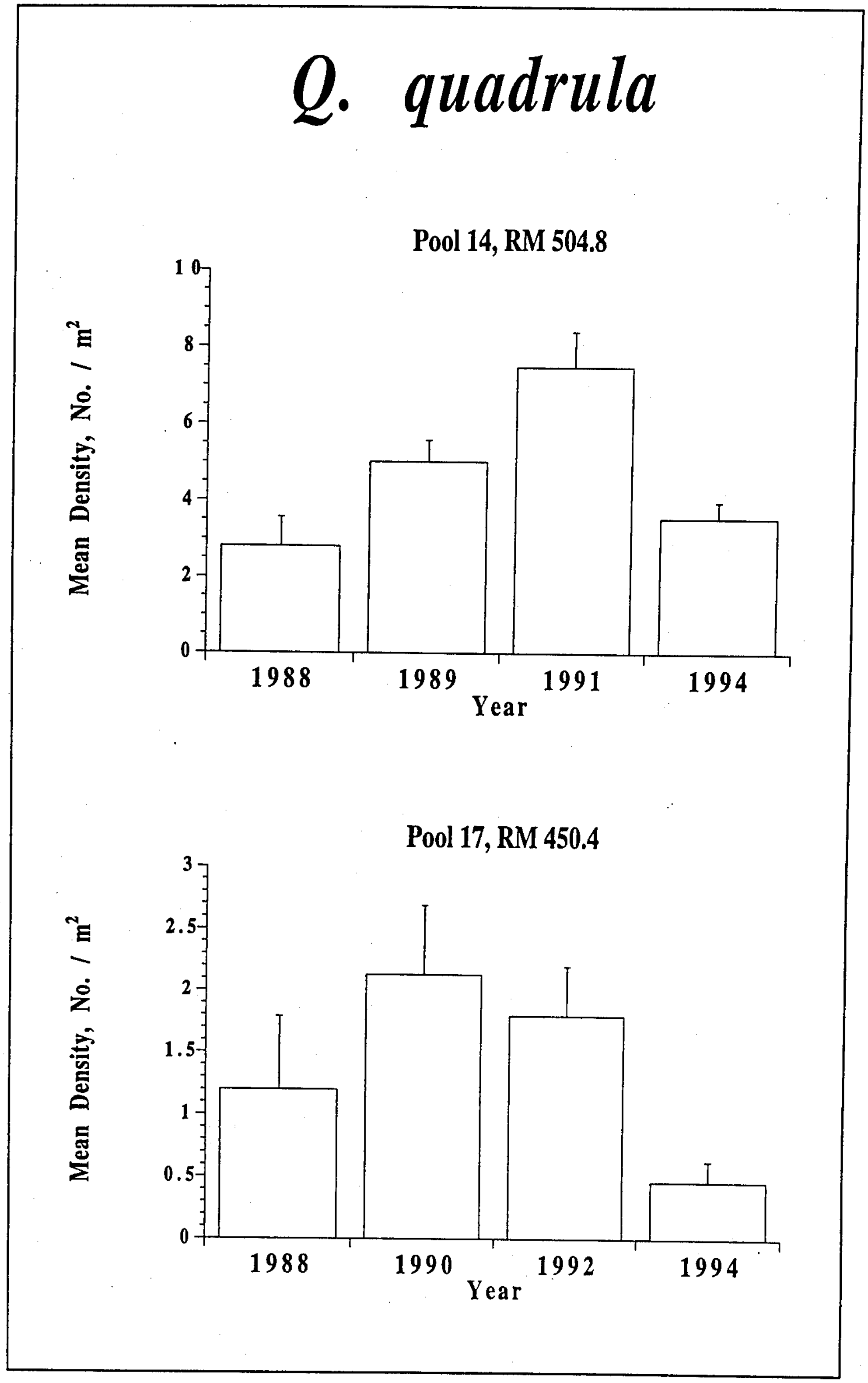


Figure 38. Total density of *Q. quadrula*, RM 504.8 and 450.4

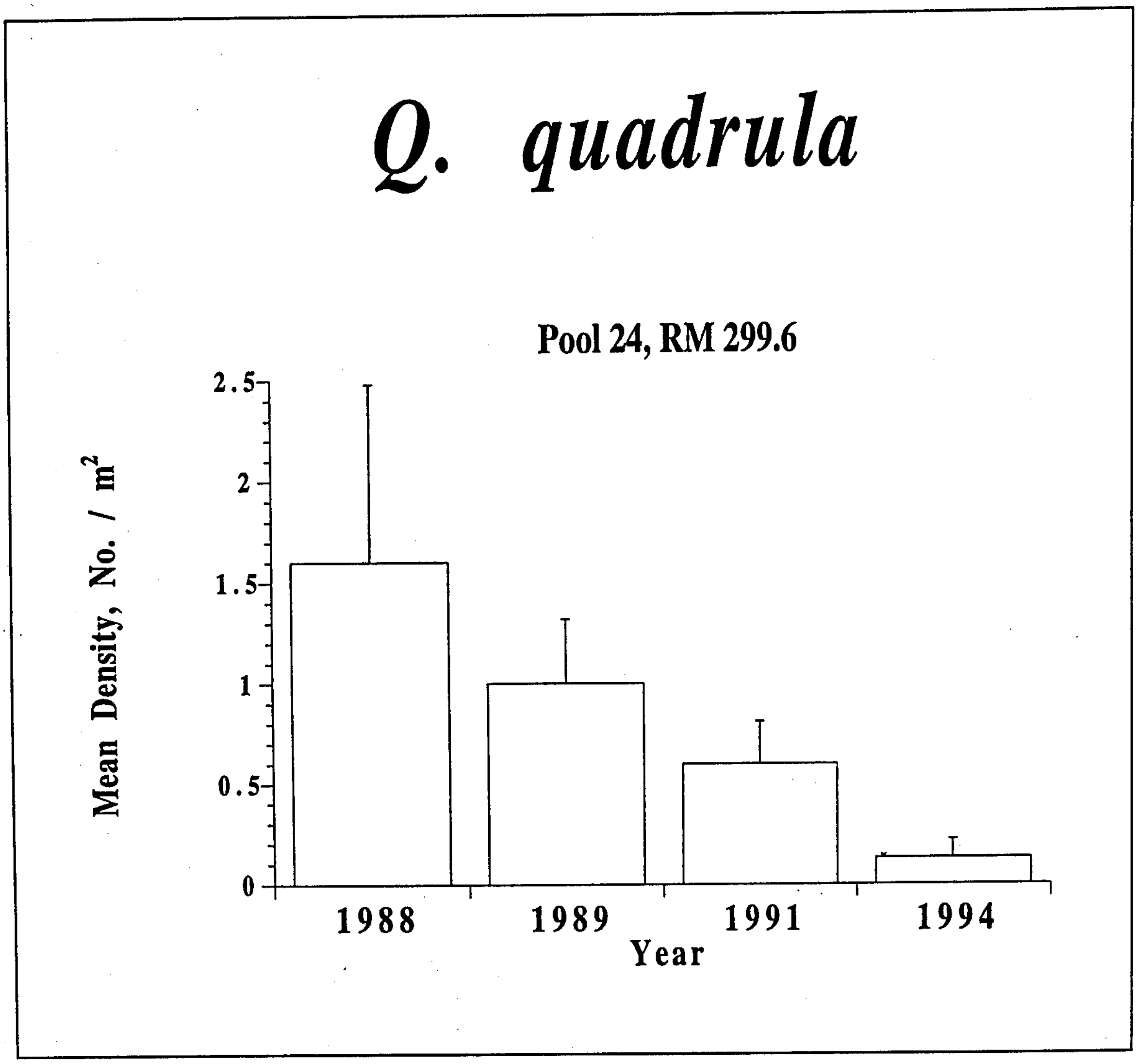


Figure 39. Total density of *Q. quadrula*, RM 299.6

Evidence of recent recruitment

No indication of recruitment problems exists among UMR populations of mussels, in terms of either species or total individuals (Figures 46-52). There was always evidence of at least some recent recruitment. Depending on the pool, site (nearshore or farshore), and year, between 10 and 55 percent of all individuals collected in quantitative samples were less than 30 mm long. Approximately 10 to 75 percent of species present showed evidence of recent recruitment in any particular pool, site, or year. Nearshore versus farshore comparisons did not yield any clear differences with respect to evidence of recent recruitment. No trend was evident in recent recruitment in terms of numbers of individuals.

Table 8
Numbers of *Lampsilis higginsi* Taken in Qualitative and Quantitative Samples in the UMR, 1988-94

Year	Quantitative Samples			Qualitative Samples		
	Total Mussels	*L. higginsi*		Total Mussels	*L. higginsi*	
		Total	Percent		Total	Percent
Pool 24 (RM 299.6)						
1988	78	0	0.00	326	0	0.00
1989	1,143	0	0.00	648	0	0.00
1991	301	0	0.00	465	0	0.00
1992	107	0	0.00	184	0	0.00
1994	243	0	0.00	390	0	0.00
Pool 17 (RM 450.4)						
1988	1,176	0	0.0	567	1	0.18
1990	651	0	0.00	506	0	0.00
1992	954	0	0.00	402	0	0.00
1994	773	0	0.00	801	1	0.12
Pool 14 (RM 504.8)						
1988	253	1	0.4	734	8	1.09
1989	1,131	1	0.09	961	5	0.52
1991	1,247	6	0.49	815	6	0.74
1992	800	2	0.25	386	3	0.78
1994	903	4	0.44	789	6	0.76
Pool 12 (RM 571.5)						
1989	--	--	--	98	0	0.00
1990	408	5	1.22	518	5	0.98
1992	558	1	0.18	376	0	0.00
1994	509	0	0.00	579	0	0.00
Pool 10 (RM 635.2 - Main Channel)						
1988	845	2	0.24	699	12	1.72
1989	1,616	11	0.68	212	0	0.00
1991	861	2	0.23	690	4	0.58
1992	700	3	0.43	376	1	0.27
1993	905	4	0.11	404	1	0.25
1994	680	1	0.15	--	--	--

Table 9
Presence (+) and Absence (-) of *Lampsilis higginsi* at Five Mussel Beds in the UMR (1988-94) Based on Qualitative (Qual) and Quantitative (Quant) Sampling

Location	Year						
	1988	1989	1990	1991	1992	1993	1994
Pool 24							
Qual	-	-	NS[1]	-	-	NS	-
Quant	-	-	NS	-	-	NS	-
Pool 17							
Qual	+	NS	-	NS	-	NS	+
Quant	-	NS	-	NS	-	NS	-
Pool 14							
Qual	+	+	NS	+	+	NS	+
Quant	+	+	NS	+	+	NS	+
Pool 12							
Qual	NS	-	+	NS	-	NS	-
Quant	NS	NS	+	NS	+	NS	-
Pool 10							
Qual	+	-	NS	+	+	+	-
Quant	+	+	NS	+	+	+	+

[1] NS = No samples taken.

Significant reduction in growth rates or increase in mortality

Growth studies were initiated at mussel beds in Pools 14 and 10 in 1989, in Pools 17 and 12 in 1990, and in Pool 24 in 1991. Approximately 25 individuals of common species (*A. p. plicata, O. olivaria, L. cardium*, or *F. flava*) were collected, total length of each was measured, and an identifying number was then etched into the shell with a dremal tool. During subsequent years, sites were revisited to relocate the quadrats and marked mussels. Approximately 50 percent of the quadrats were relocated. The majority of those not located were probably found by commercial shell fishermen; some could have been moved by erosive flows during high water; or it is possible that divers were unable to locate them. Because of the inconsistency of this phase of the work, and since very good data on recruitment and growth was obtained from the quantitative collections, this phase of the work was abandoned.

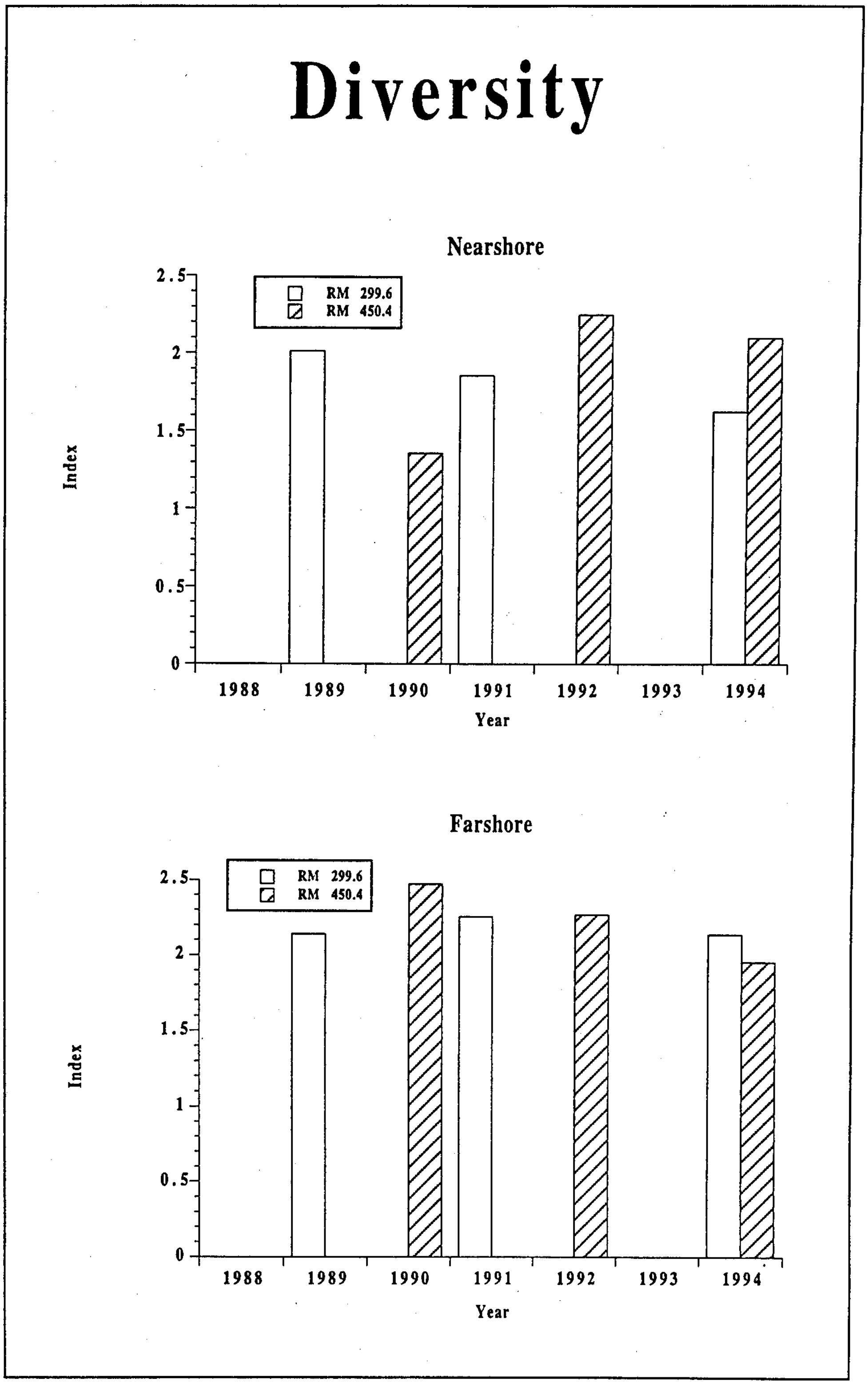


Figure 40. Species diversity for nearshore and farshore sites, RM 299.6 and 450.4

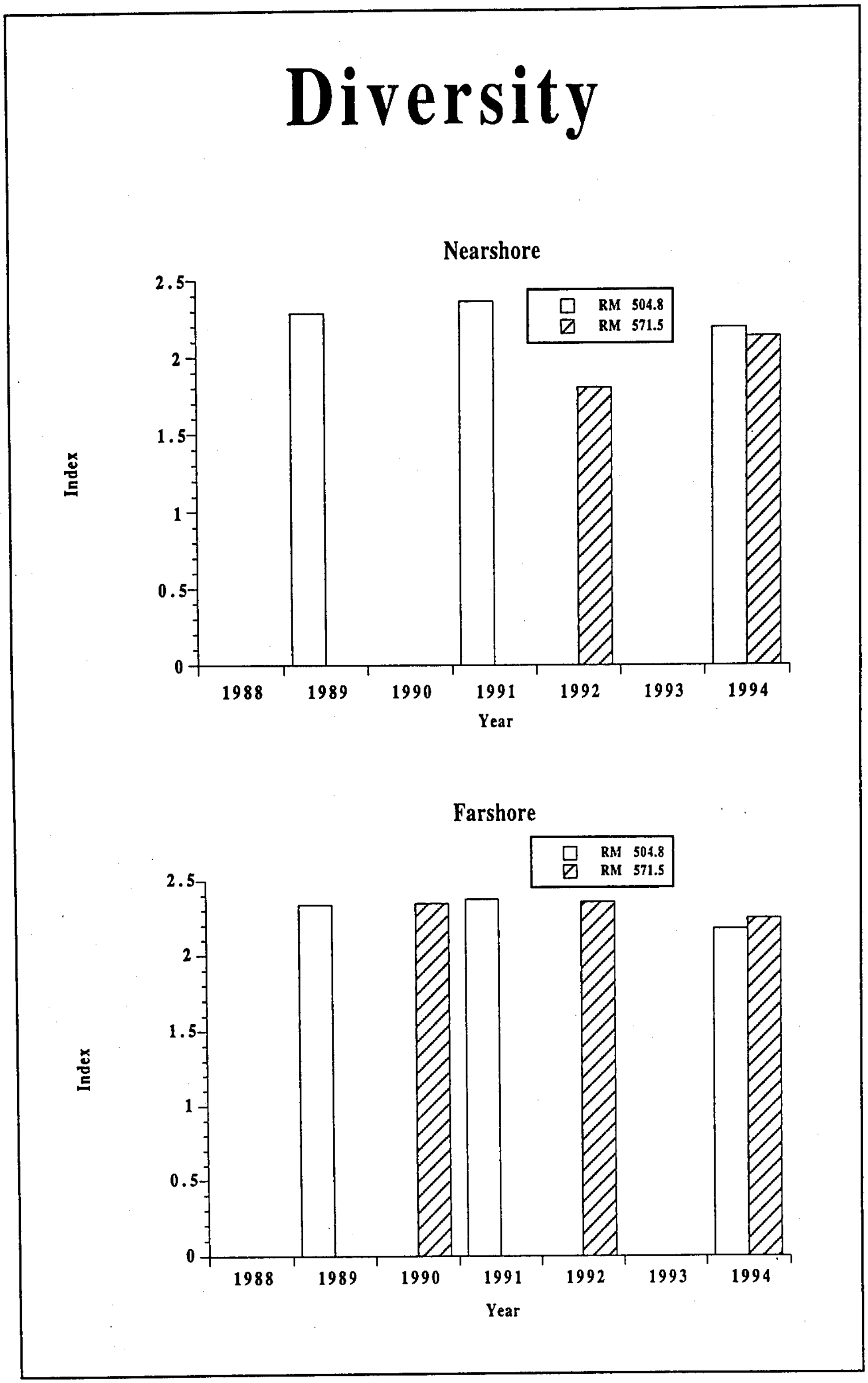


Figure 41. Species diversity for nearshore and farshore sites, RM 504.8 and 571.5

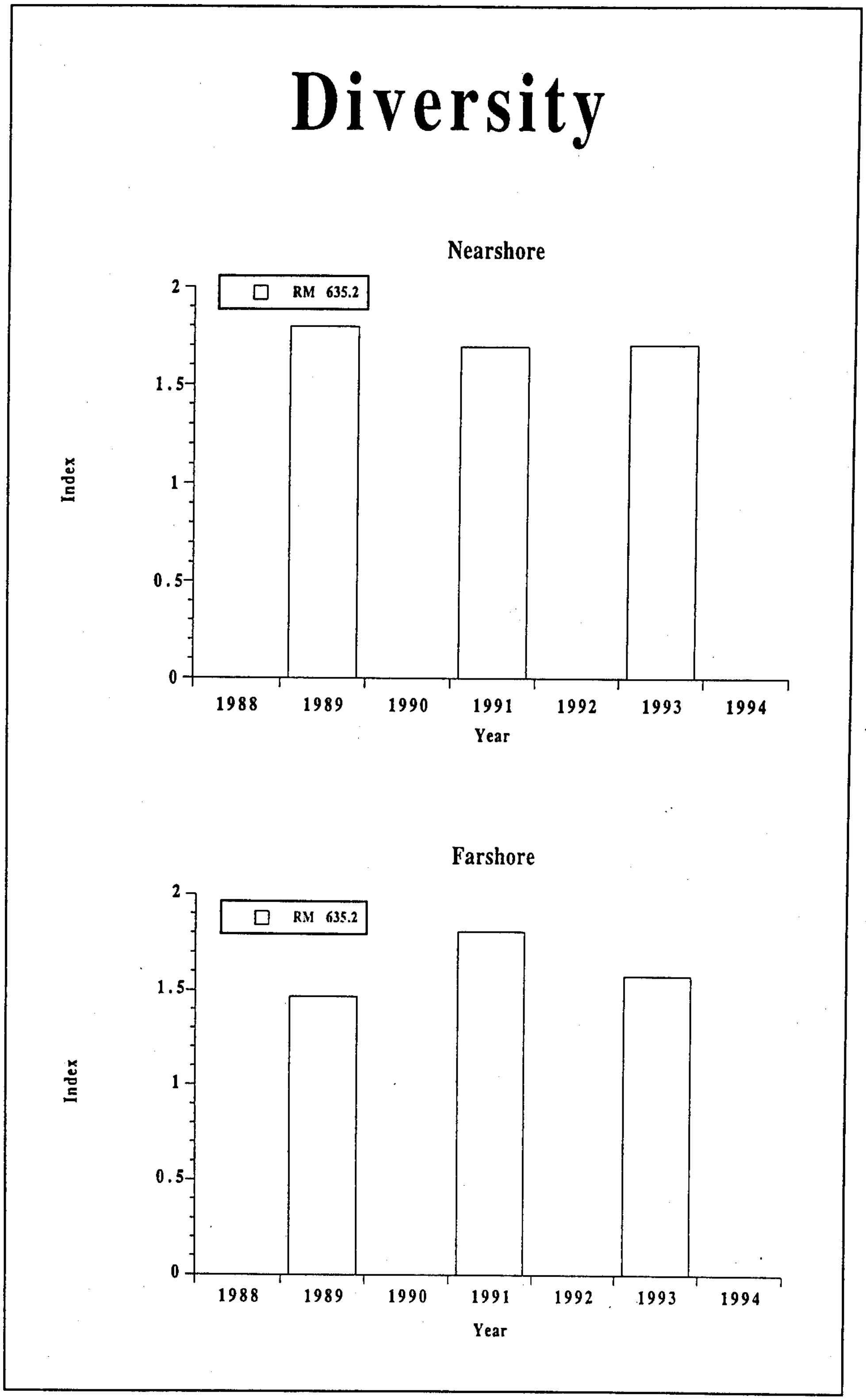


Figure 42. Species diversity for nearshore and farshore sites, RM 635.2

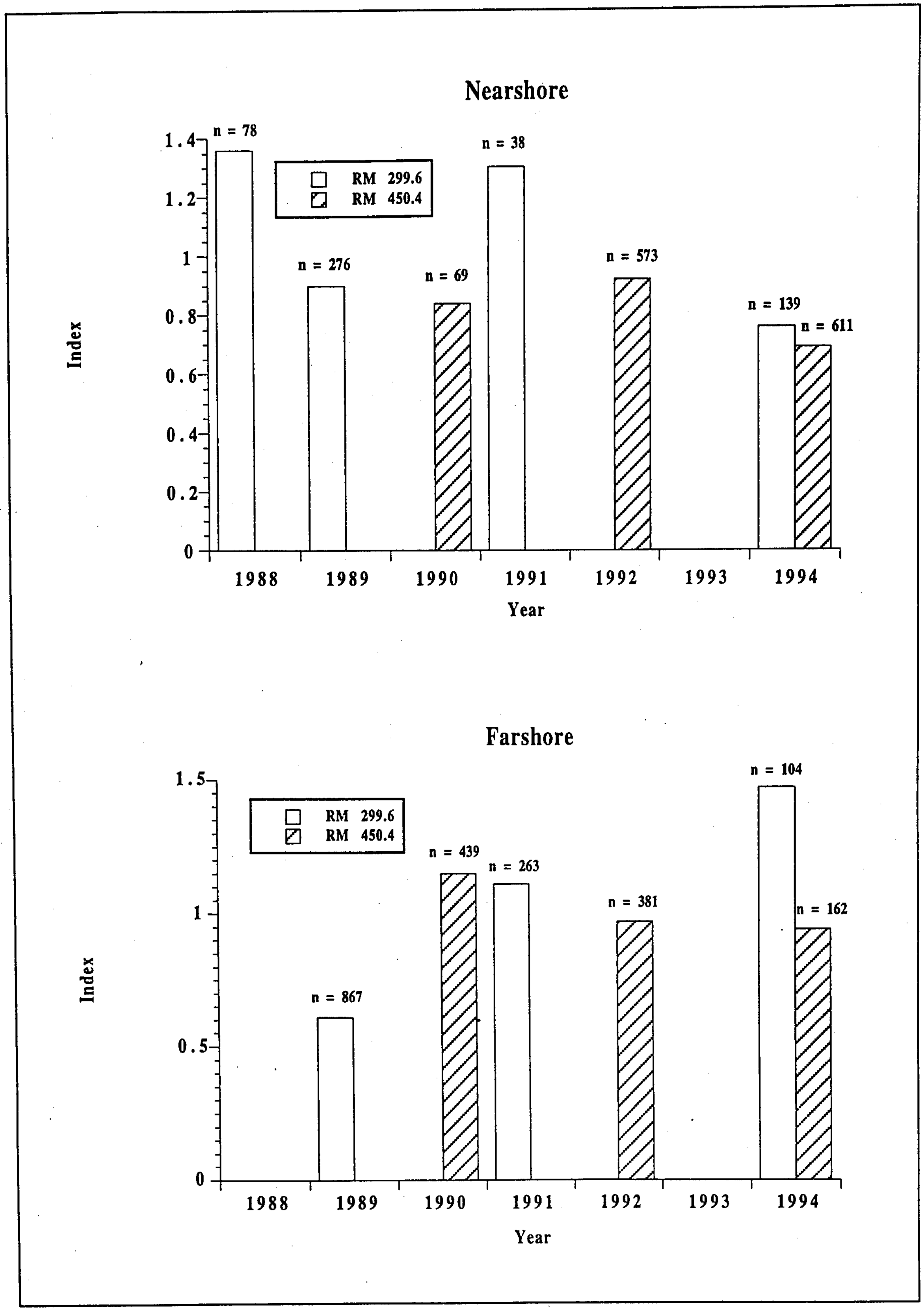


Figure 43. Menhinick's Index for nearshore and farshore sites, RM 299.6 and 450.4

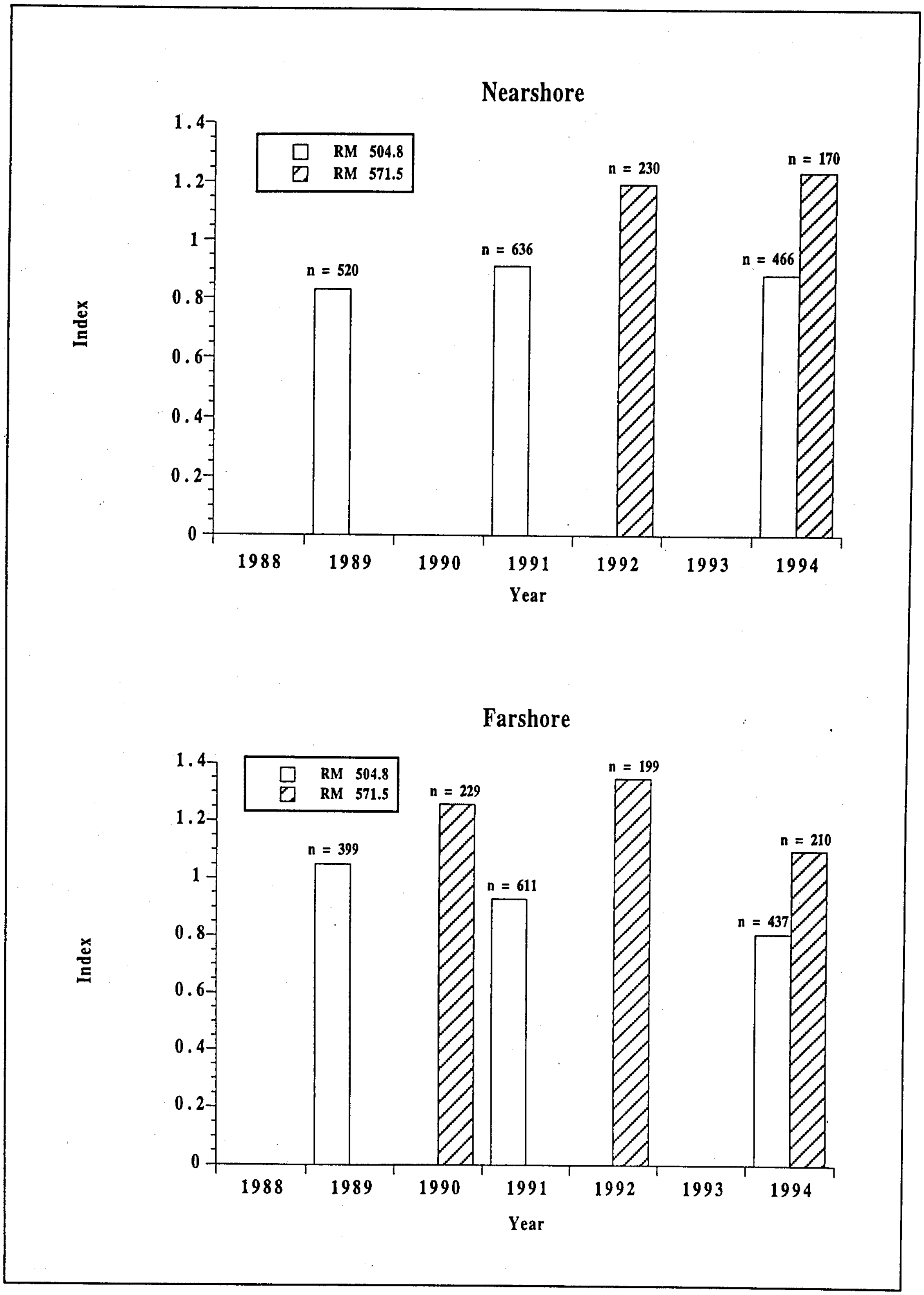


Figure 44. Menhinick's Index for nearshore and farshore sites, RM 504.8 and 571.5

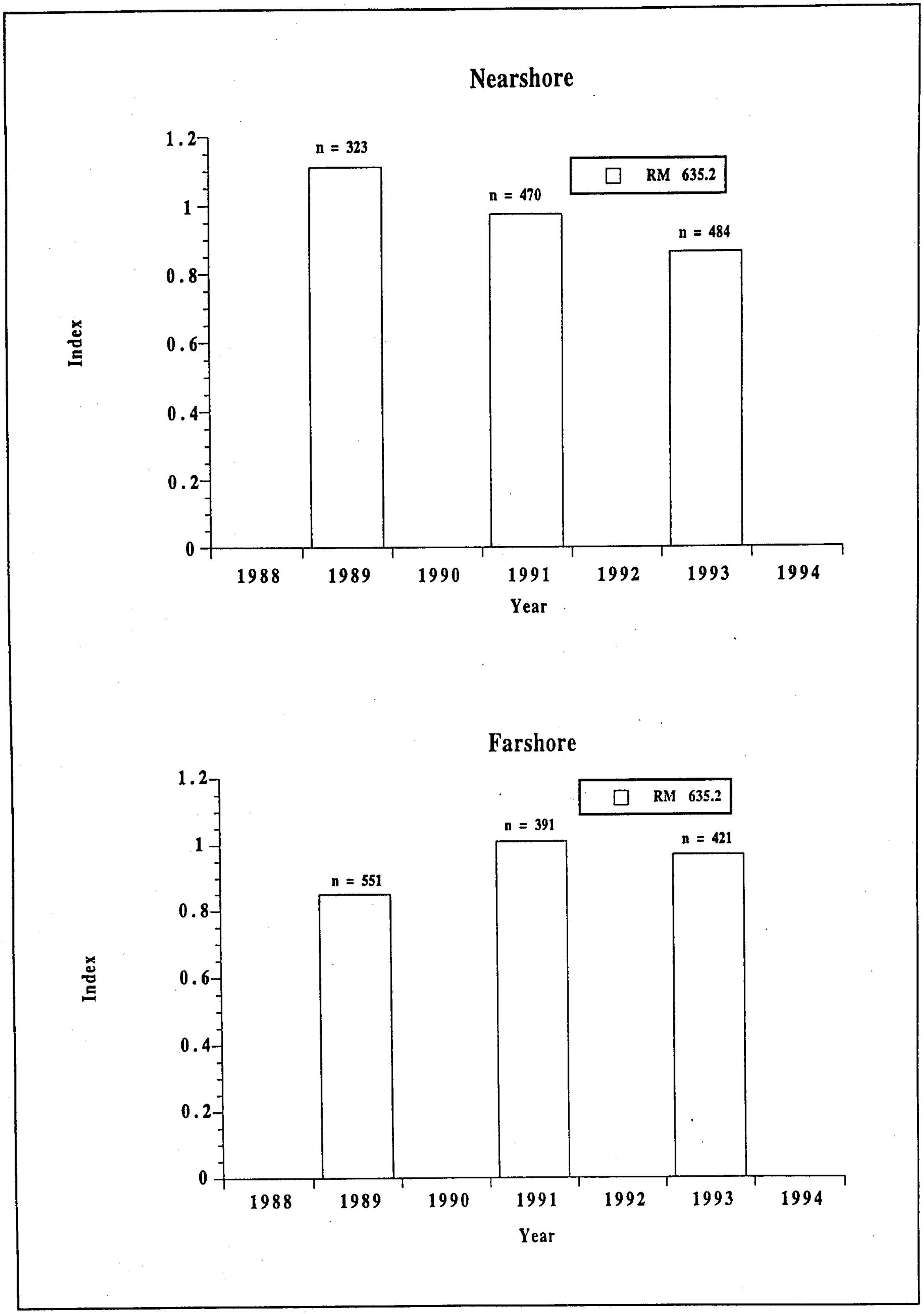


Figure 45. Menhinick's Index for nearshore and farshore sites, RM 635.2

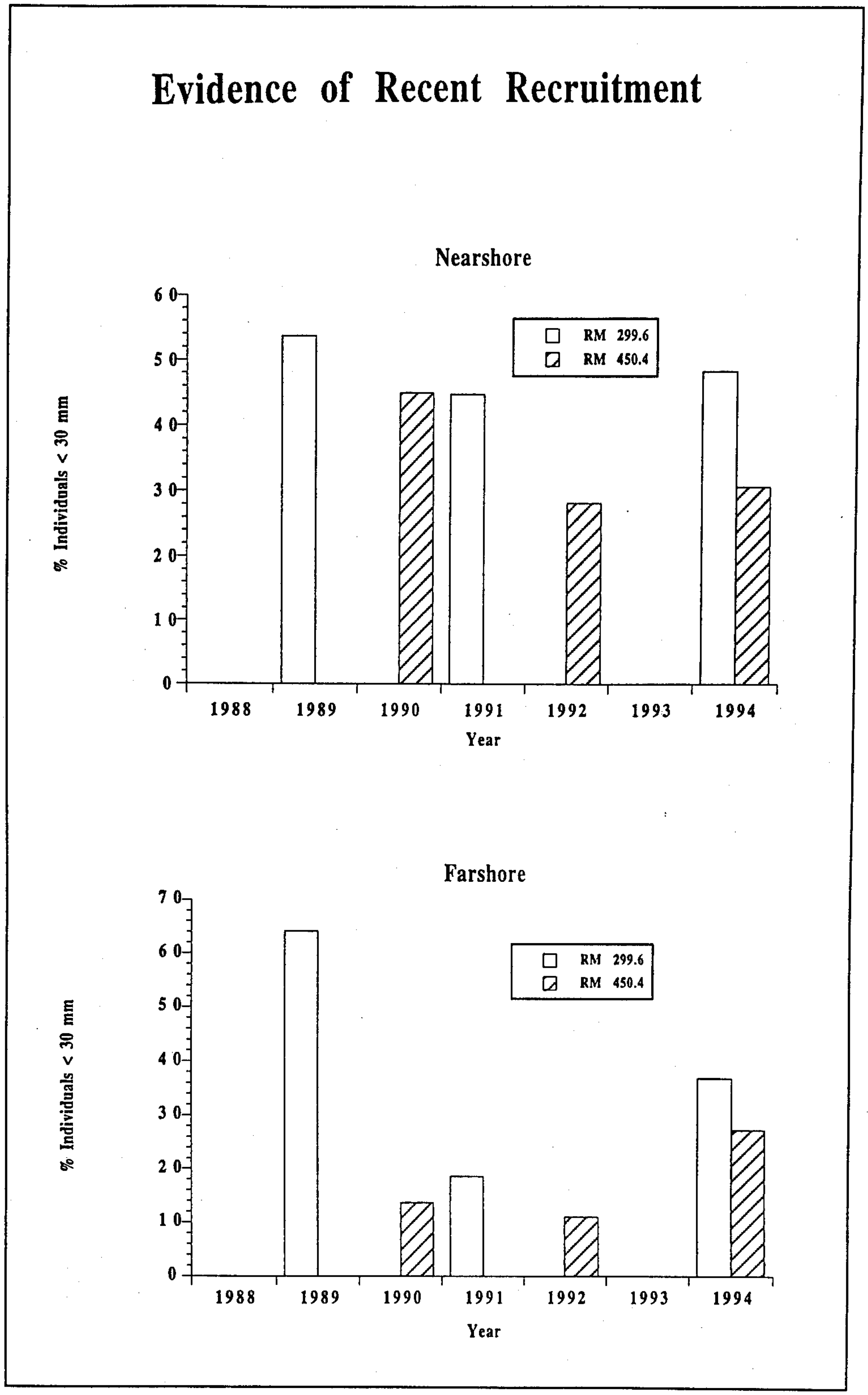


Figure 46. Percent individuals less than 30 mm total shell length for nearshore and farshore sites, RM 299.6 and 450.4

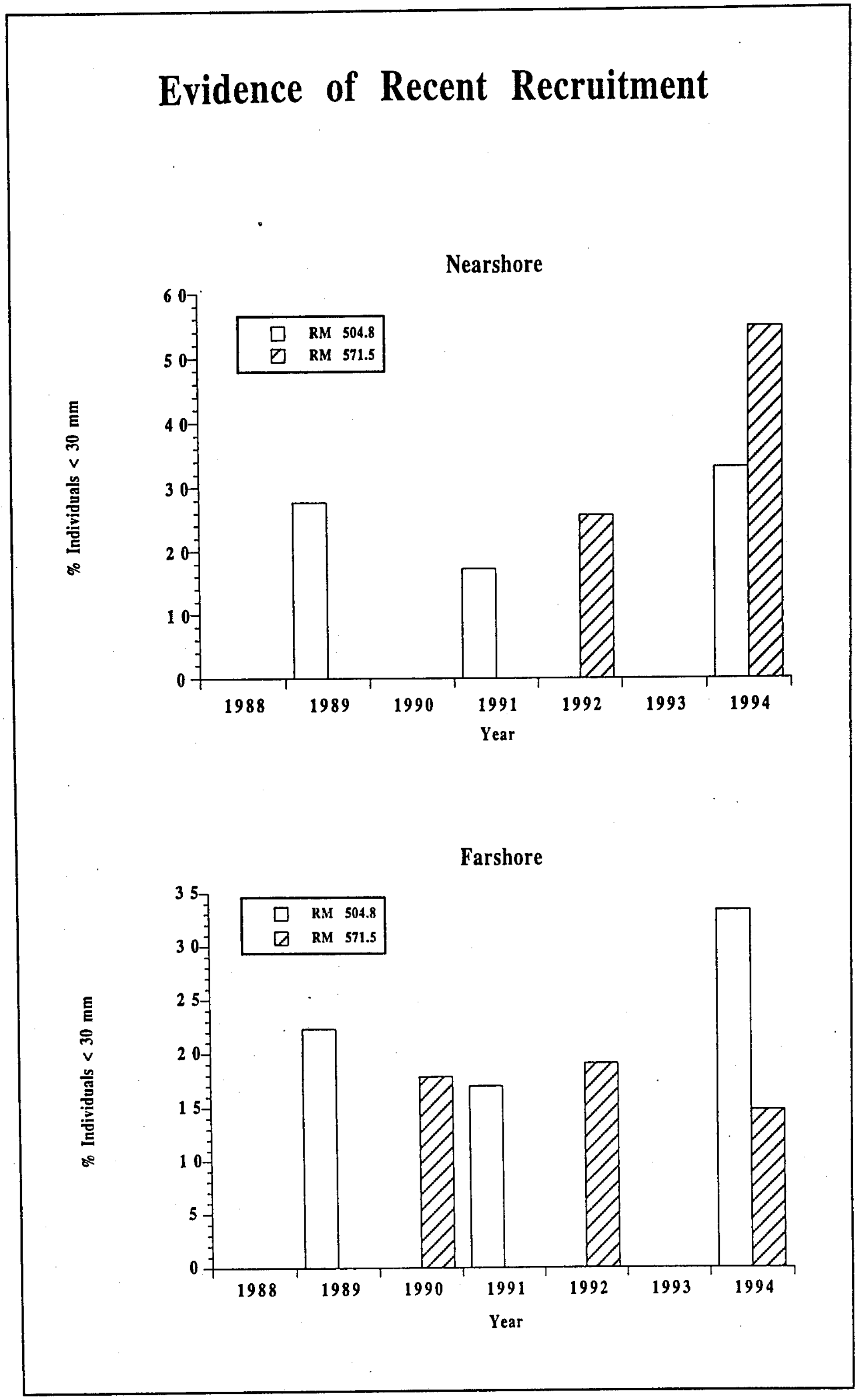


Figure 47. Percent individuals less than 30 mm total shell length for nearshore and farshore sites, RM 504.8 and 571.5

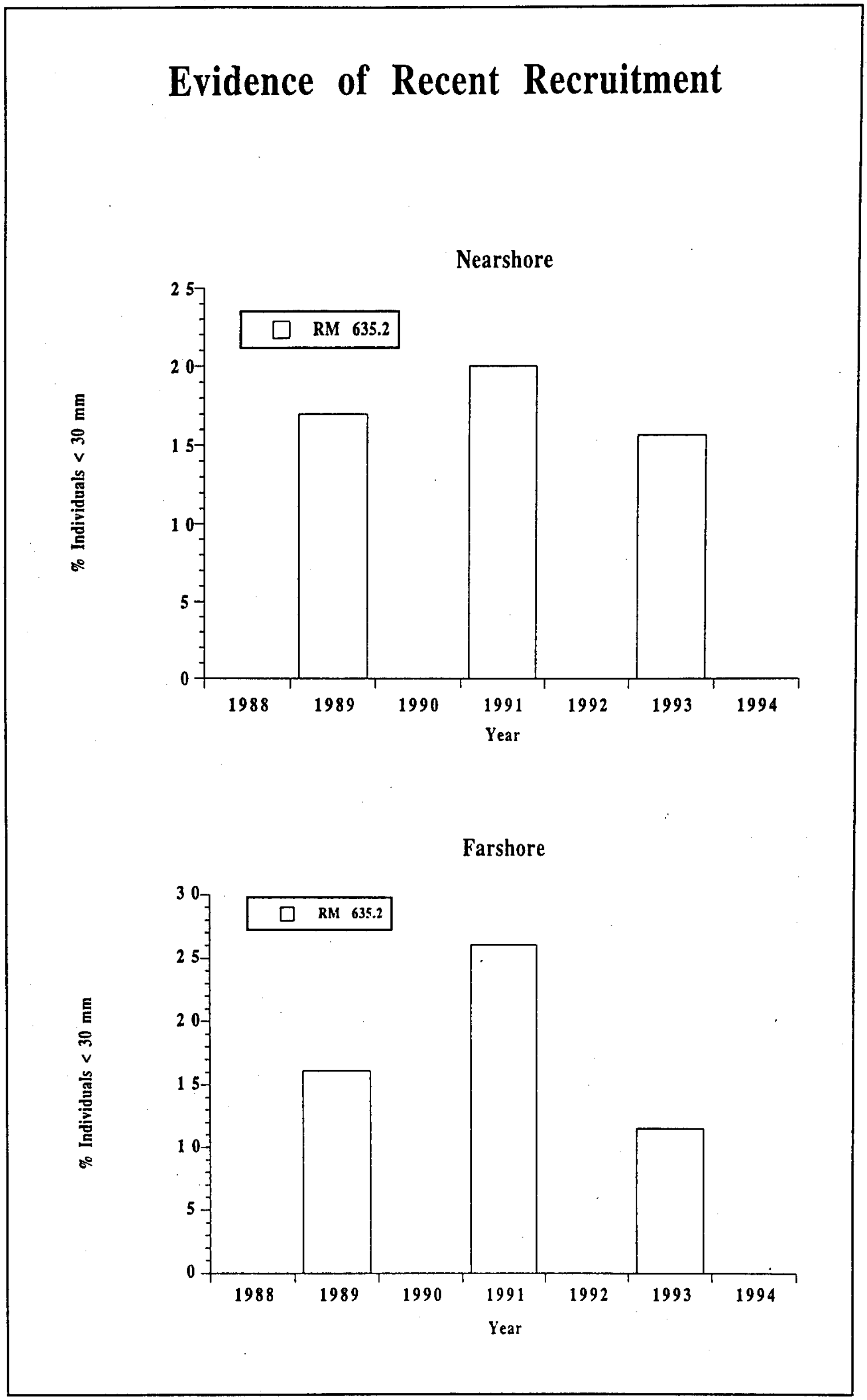


Figure 48. Percent individuals less than 30 mm total shell length for near-shore and farshore sites, RM 635.2

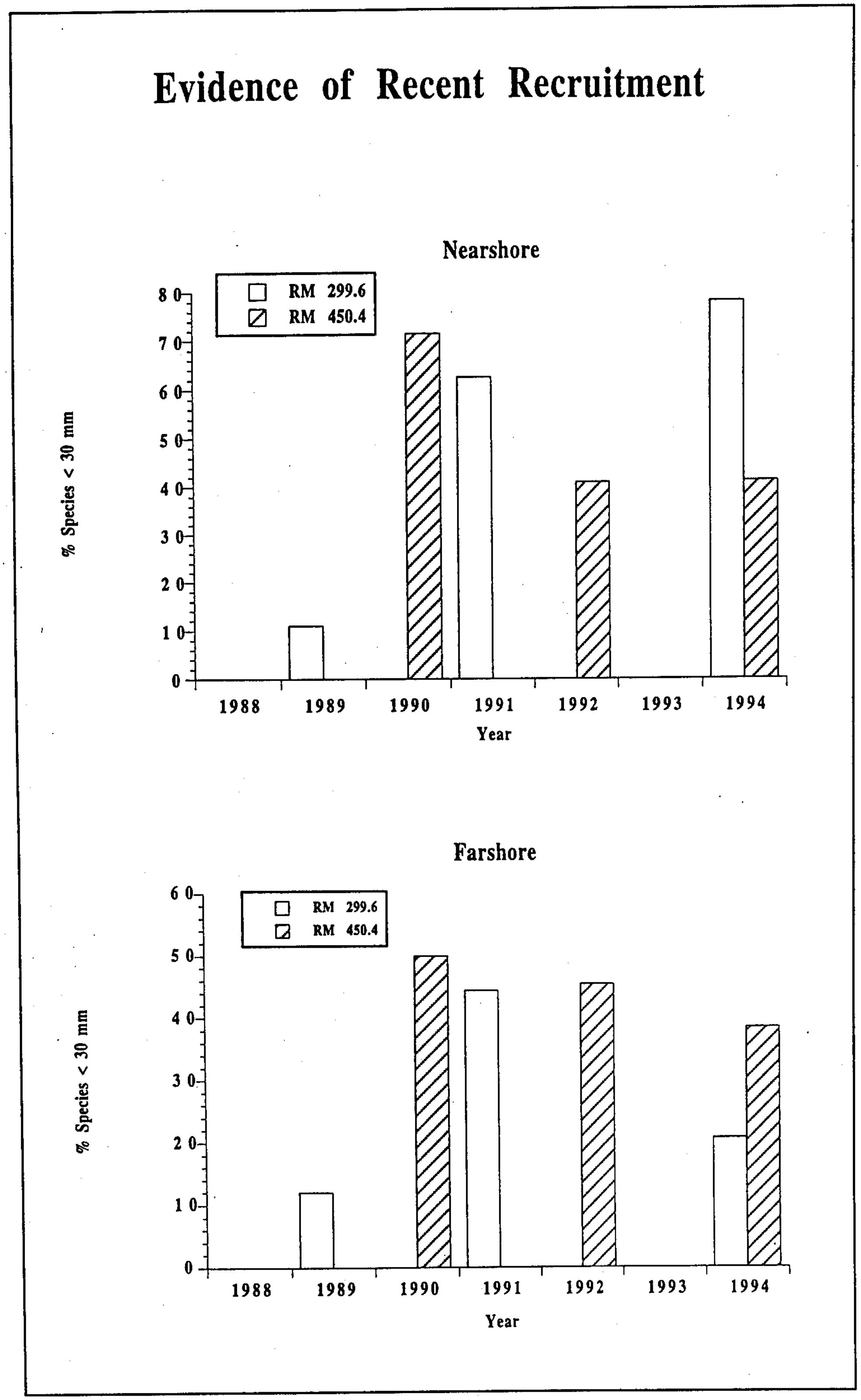


Figure 49. Percent species less than 30 mm total shell length for nearshore and farshore sites, RM 299.6 and 450.4

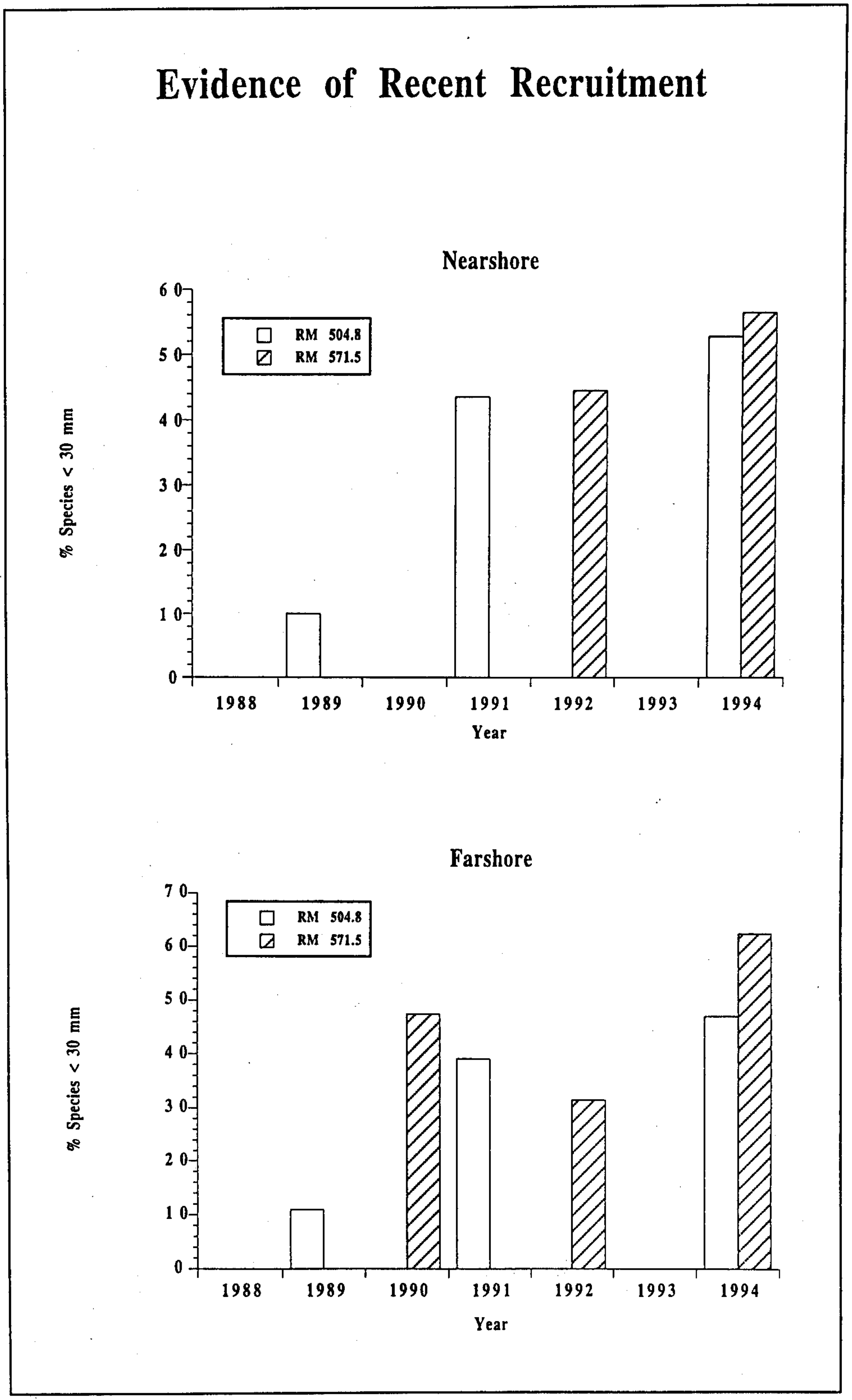


Figure 50. Percent species less than 30 mm total shell length for nearshore and farshore sites, RM 504.8 and 571.5

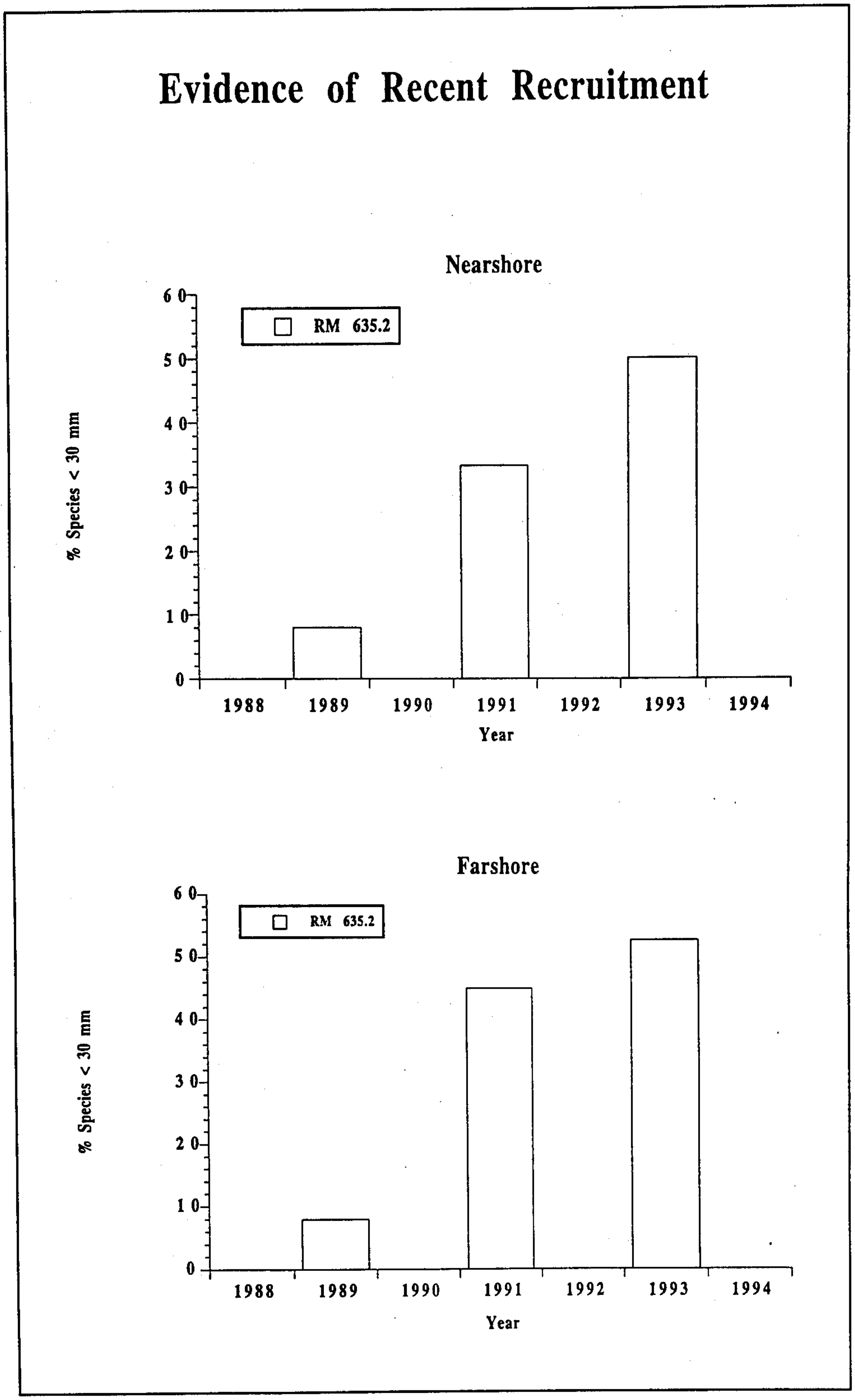


Figure 51. Percent species less than 30 mm total shell length for nearshore and farshore sites, RM 635.2

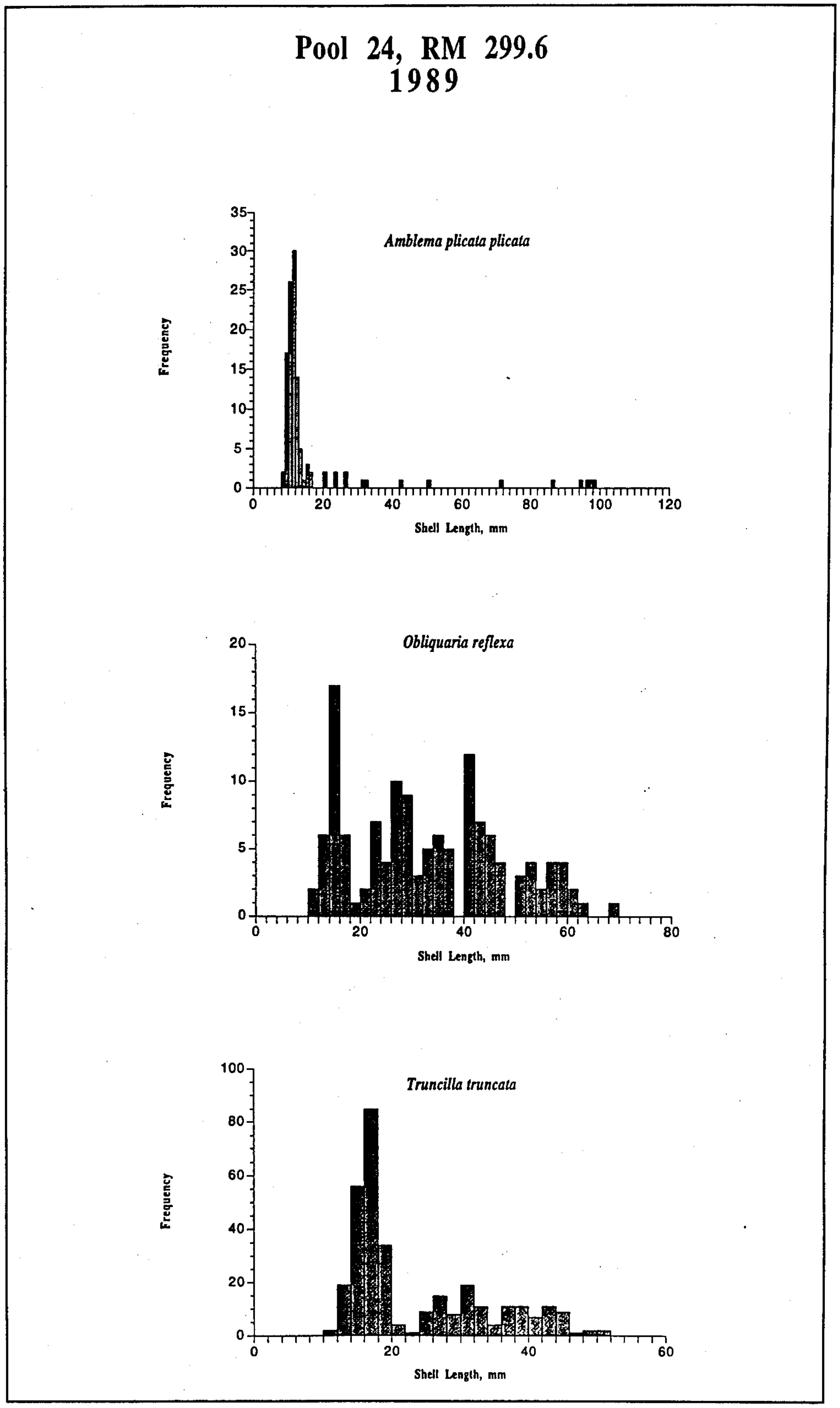


Figure 52. Length frequency histograms for three species of mussels, RM 299.6

The number of fresh dead mussels in quantitative samples was counted each year of the survey. Typically, only a few fresh dead native mussels were found each year. No evidence of large-scale mortality of native mussels was found during this survey.

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Appendix A
Data on Number of Commercial Tows Using Five Pools in the Upper Mississippi River (UMR), 1989-94

Table A1
Number of Commercial Tows/Year Using Five Navigation Pools in the UMR, 1989-94

Lock	Direction	1989	1990	1991	1992	1993	1994	Min	Max	Range	Mean
10	Up	940	995	914	918	597	674	597	995	398	840
	Down	948	1,019	941	930	595	661	595	1,019	424	849
	Total	1,888	2,014	1,855	1,848	1,192	1,335	1,192	2,014	822	1,689
12	Up	1,074	1,179	1,083	1,047	636	729	636	1,179	543	958
	Down	1,088	1,201	1,090	1,072	663	7182	663	1,201	538	972
	Total	2,162	2,380	2,173	2,119	1,299	1,447	1,299	2,380	1,081	1,930
14	Up	1,521	1,645	1,504	1,507	981	1,109	981	1,645	664	1,378
	Down	1,551	1,680	1,540	1,548	1,018	1,113	1,018	1,680	662	1,408
	Total	3,072	3,325	3,044	3,055	1,999	2,222	1,999	3,325	1,326	2,786
17	Up	1,452	1,591	1,473	1,461	902	999	902	1,591	689	1,313
	Down	1,517	1,656	1,506	1,497	940	1,008	940	1,656	716	1,354
	Total	2,969	3,247	2,979	2,958	1,842	2,007	1,842	3,247	1,405	2,667
24	Up	1,606	1,840	1,668	1,685	1,189	1,269	1,189	1,840	651	1,543
	Down	1,668	1,917	1,754	1,772	1,258	1,309	1,258	1,917	659	1,613
	Total	3,274	3,757	3,422	3,457	2,447	2,578	2,447	3,757	1,310	3,156

Table A2
Number of Commercial Tows/Day Using Five Navigation Pools in the UMR, 1989-94

Lock	Direction	1989	1990	1991	1992	1993	1994	Min	Max	Range	Mean
10	Up	3.48	3.69	3.39	3.40	2.21	2.50	2.21	3.69	1.47	3.11
	Down	3.51	3.77	3.49	3.44	2.20	2.45	2.20	3.77	1.57	3.14
	Total	6.99	7.46	6.87	6.84	4.41	4.94	4.41	7.46	3.04	6.25
12	Up	3.98	4.37	4.01	3.88	2.36	2.70	2.36	4.37	2.01	3.55
	Down	4.03	4.45	4.04	3.97	2.46	2.66	2.46	4.45	1.99	3.60
	Total	8.01	8.81	8.05	7.85	4.81	5.36	4.81	8.81	4.00	7.15
14	Up	5.63	6.09	5.57	5.58	3.63	4.11	3.63	6.09	2.46	5.10
	Down	5.74	6.22	5.70	5.73	3.77	4.12	3.77	6.22	2.45	5.22
	Total	11.38	12.31	11.27	11.31	7.40	8.23	7.40	12.3	4.91	10.32
17	Up	5.38	5.89	5.46	5.41	3.34	3.70	3.34	5.89	2.55	4.86
	Down	5.62	6.13	5.58	5.54	3.48	3.73	3.48	6.13	2.65	5.01
	Total	11.00	12.03	11.03	10.96	6.82	7.43	6.82	12.0	5.20	9.88
24	Up	4.40	5.04	4.57	4.62	3.26	3.48	3.26	5.04	1.78	4.23
	Down	4.57	5.25	4.81	4.85	3.45	3.59	3.45	5.25	1.81	4.42
	Total	8.97	10.29	9.38	9.47	6.70	7.06	6.70	10.3	3.59	8.65

Note: Usage per day for Locks 10-17 was determined by dividing annual usage by 270; for Lock 24, annual usage was divided by 365.

Appendix B
Mean Density of Total Mussels and Selected Species of Mussels, Upper Mississippi River (UMR), 1988-94

Table B1
Mean Density of *O. reflexa* at Five Locations in the UMR, 1988-94

Pool	RM	Year	N	*O. reflexa* Mean	*O. reflexa* SE	Probability Level 0.1	Probability Level 0.05	Significant Decrease?
10	635.2	1989	40	3.10	0.58	a	a	No
		1991	60	1.86	0.32	b	b	
		1993	60	2.60	0.42	ab	ab	
		1994	60	1.60	0.32	b	b	
12	571.5	1990	40	3.30	0.71	b	b	No
		1992	60	6.46	0.67	a	a	
		1994	60	3.60	0.51	b	b	
14	504.8	1988	20	5.40	1.31	b	a	No
		1989	60	6.66	0.74	ab	a	
		1991	60	8.13	0.87	a	a	
		1994	60	7.20	0.73	ab	a	
17	450.4	1988	20	8.00	2.59	a	a	Yes
		1990	60	4.53	0.76	b	b	
		1992	60	3.53	0.60	b	b	
		1994	60	3.26	0.60	b	b	
24	299.6	1988	10	5.60	1.60	b	ab	Yes
		1989	60	8.86	1.27	a	a	
		1991	60	2.60	0.54	b	b	
		1994	60	3.20	0.58	b	b	

Table B2
Mean Density of *A. p. plicata* at Five Locations in the UMR, 1988-94

Pool	RM	Year	N	*A. p. plicata*		Probability Level		Significant Decrease?
				Mean	SE	0.1	0.05	
10	635.2	1989	40	55.40	4.23	a	a	Yes
		1991	60	31.93	1.65	b	b	
		1993	60	34.00	1.58	b	b	
		1994	60	22.26	1.83	c	c	
12	571.5	1990	40	7.40	1.03	b	b	No
		1992	60	13.06	1.08	a	a	
		1994	60	8.20	0.74	b	b	
14	504.8	1988	20	8.40	1.36	bc	bc	No
		1989	60	7.47	0.81	c	c	
		1991	60	12.53	1.10	a	a	
		1994	60	10.80	0.84	ab	ab	
17	450.4	1988	20	21.00	6.22	a	a	Yes
		1990	60	16.20	1.90	ab	ab	
		1992	60	11.67	1.15	bc	bc	
		1994	60	7.00	1.00	c	c	
24	299.6	1988	10	0.80	0.80	c	c	No
		1989	60	7.73	1.08	a	a	
		1991	60	4.40	0.77	b	bc	
		1994	60	1.47	0.40	c	bc	

Table B3
Mean Density of *Q. p. pustulosa* at Five Locations in the UMR, 1988-94

Pool	RM	Year	N	*Q. p. pustulosa*		Probability Level		Significant Decrease?
				Mean	SE	0.1	0.05	
10	635.2	1989	40	0.50	0.21	a	a	No
		1991	60	0.73	0.22	a	a	
		1993	60	0.80	0.23	a	a	
		1994	60	0.47	0.17	a	a	
12	571.5	1990	40	0.40	0.19	a	a	No
		1992	60	0.60	0.19	ab	a	
		1994	60	1.00	0.24	b	a	
14	504.8	1988	20	5.20	0.83	c	c	No
		1989	60	10.00	1.21	b	ab	
		1991	60	13.40	1.24	a	a	
		1994	60	9.33	0.73	b	b	
17	450.4	1988	20	13.20	3.69	a	a	No
		1990	60	8.67	1.12	b	b	
		1992	60	14.20	1.28	a	a	
		1994	60	7.73	0.90	b	b	
24	299.6	1988	10	1.60	0.88	a	a	Yes
		1989	60	0.87	0.29	ab	ab	
		1991	60	0.60	0.21	b	ab	
		1994	60	0.47	0.21	b	b	

Table B4
Mean Density of *T. truncata* at Five Locations in the UMR, 1988-94

Pool	RM	Year	N	*T. truncata*		Probability Level		Significant Decrease?
				Mean	SE	0.1	0.05	
10	635.2	1989	40	6.30	0.99	b	a	No
		1991	60	8.20	0.99	ab	a	
		1993	60	8.80	0.93	a	a	
		1994	60	9.00	0.92	a	a	
12	571.5	1990	40	6.80	1.24	a	a	No
		1992	60	6.26	0.74	a	a	
		1994	60	7.80	0.95	a	a	
14	504.8	1988	20	9.80	1.40	b	b	No
		1989	60	14.93	1.34	a	a	
		1991	60	18.46	1.41	a	a	
		1994	60	15.13	1.03	a	a	
17	450.4	1988	20	36.60	11.75	a	a	Yes
		1990	60	10.86	1.51	b	b	
		1992	60	11.13	1.30	b	b	
		1994	60	12.66	1.66	b	b	
24	299.6	1988	10	10.80	2.07	b	b	No
		1989	60	21.40	2.50	a	a	
		1991	60	2.53	0.47	c	c	
		1994	60	5.86	1.06	bc	bc	

Table B5
Mean Density of *E. lineolata* at Mussel Beds in Pools 17 and 24, UMR, 1988-94

Pool	RM	Year	N	*E. Lineolata* Mean	SE	Probability Level 0.1	0.05	Significant Decrease?
17	450.4	1988	20	10.20	3.89	a	ab	No
		1990	30	5.46	1.36	b	b	
		1992	60	8.66	0.89	ab	ab	
		1994	60	10.93	1.39	a	a	
24	299.6	1988	10	5.20	1.20	b	b	No
		1989	60	11.40	1.37	a	a	
		1991	60	4.20	0.94	b	b	
		1994	60	1.93	0.44	b	b	

Table B6
Mean Density of *L. fragilis* at Mussel Beds in Pools 10 and 12, UMR, 1988-94

Pool	RM	Year	N	*L. fragilis* Mean	SE	Probability Level 0.1	0.05	Significant Decrease?
10	635.2	1989	40	1.50	0.42	c	c	No
		1991	60	2.20	0.41	c	bc	
		1993	60	5.33	0.74	a	a	
		1994	60	3.80	0.55	b	ab	
12	571.5	1990	40	1.10	0.35	b	b	No
		1992	60	1.40	0.31	b	b	
		1994	60	3.86	0.45	a	a	

Table B7
Mean Density of *Q. quadrula* at Five Locations in the UMR, 1988-94

				Q. quadrula		Probability Level		
Pool	RM	Year	N	Mean	SE	0.1	0.05	Significant Decrease?
10	635.2	1989	40	2.90	0.55	a	a	Yes
		1991	60	0.60	0.21	c	b	
		1993	60	1.00	0.28	bc	b	
		1994	60	1.53	0.33	b	b	
12	571.5	1990	40	3.80	0.70	a	a	Yes
		1992	60	2.40	0.46	b	b	
		1994	60	2.13	0.34	b	b	
14	504.8	1988	20	2.80	0.77	c	b	No
		1989	60	5.00	0.57	b	b	
		1991	60	7.46	0.92	a	a	
		1994	60	3.53	0.43	bc	b	
17	450.4	1988	20	1.20	0.59	ab	ab	No
		1990	60	2.13	0.56	a	a	
		1992	60	1.80	0.40	a	ab	
		1994	60	0.46	0.17	b	b	
24	299.6	1988	10	1.60	0.88	a	a	No
		1989	60	1.00	0.32	ab	ab	
		1991	60	0.60	0.21	b	ab	
		1994	60	0.13	0.09	b	b	

Table B8
Mean Density of Total Mussels at Five Locations in the UMR, 1988-94

Pool	RM	Year	N	Total Mussels		Probability Level		Criterion Met
				Mean	SE	0.1	0.05	
10	635.2	1989	40	87.40	5.48	a	a	No
		1991	60	57.40	2.47	b	b	
		1993	60	60.33	2.99	b	b	
		1994	60	45.47	2.60	c	c	
12	571.5	1990	40	33.90	2.76	a	a	Yes
		1992	60	37.20	2.06	a	a	
		1994	60	34.80	1.80	a	a	
14	504.8	1988	20	50.60	3.50	c	b	Yes
		1989	60	61.27	3.56	b	b	
		1991	60	83.13	3.37	a	a	
		1994	60	60.20	2.48	b	b	
17	450.4	1988	20	235.20	61.50	a	a	Yes
		1990	60	72.67	6.21	b	b	
		1992	60	63.60	3.97	b	b	
		1994	60	51.53	4.98	b	b	
24	299.6	1988	10	31.20	4.34	b	b	Yes
		1989	60	74.40	8.09	a	a	
		1991	60	20.07	2.69	b	b	
		1994	60	16.20	1.90	b	b	

Appendix C
Species List for Each Mussel Bed Surveyed in the Upper Mississippi River (UMR), 1988-94

Table C1
List of Bivalves Collected at RM 299.6, Pool 24, UMR 1988-94

Species	1988	1989	1991	1992	1994
Actinonaias ligamentina (Lamarck)				1	
Amblema p. plicata (Say)	1	1	1	1	1
Arcidens confragosus (Say)		1	1		1
Corbicula fluminea (Mueller)	1	1	1		
Cumberlandia monodonta (Say)		1			
Dreissena polymorpha (Pallas)					1
Ellipsaria lineolata (Rafinesque)	1	1	1	1	1
Elliptio dilatata (Rafinesque)					
Fusconaia ebena (I. Lea)	1		1		
Fusconaia flava (Rafinesque)	1	1	1	1	1
Lampsilis cardium (Rafinesque)[1]	1	1	1	1	1
Lampsilis higginsi (Lea)					
Lampsilis siliquoidea (Barnes)					
Lampsilis teres (Rafinesque)					1
Lasmigona c. complanata (Barnes)		1	1		1
Lasmigona costata (Rafinesque)					
Leptodea fragilis (Rafinesque)	1	1	1		1
Ligumia recta (Lamarck)	1	1	1		1
Megalonaias nervosa (Rafinesque)[2]	1	1	1	1	1
Obliquaria reflexa (Rafinesque)	1	1	1	1	1
Obovaria olivaria (Rafinesque)	1	1	1	1	1
Plethobasus cyphyus (Rafinesque)					
Pleurobema coccineum (Conrad)					
Potamilus alatus (Say)	1	1	1		1
Potamilus ohiensis (Rafinesque)					
Pyanodon grandis (Say)[3]		1	1		
Quadrula metanevra (Rafinesque)	1	1	1	1	1
Quadrula nodulata (Rafinesque)	1	1	1	1	1
Quadrula p. pustulosa (I. Lea)	1	1	1	1	1
Quadrula quadrula (Rafinesque)	1	1	1	1	1
Strophitus undulatus (Say)					
Toxolasma parvus (Barnes)					
Truncilla donaciformis (I. Lea)	1	1	1		1
Truncilla truncata (Rafinesque)	1	1	1	1	1
Utterbackia imbecillis (Say)[4]		1	1		
Total individuals - Quantitative	78	1,143	301		243
Total individuals - Qualitative	326	648	465	184	390
Total collected	404	1,791	766	184	633
Total species	18	22	22	13	20

Note: In previous reports, these species were occasionally referred to as indicated below:
[1] Either *L. ovata* or *L. ventricosa*.
[2] *Megalonaias gigantea*.
[3] *Anodonta grandis*.
[4] *Anodonta imbecillis*.

Table C2
List of Bivalves Collected at RM 450.4, Pool 17, UMR 1988-94

Species	1988	1990	1992	1994
Actinonaias ligamentina (Larmack)	1	1	1	1
Amblema p. plicata (Say)	1	1	1	1
Arcidens confragosus (Say)	1	1	1	1
Corbicula fluminea (Mueller)		1		
Cumberlandia monodonta (Say)			1	
Dreissena polymorpha (Pallas)				1
Ellipsaria lineolata (Rafinesque)	1	1	1	1
Elliptio dilatata (Rafinesque)				
Fusconaia ebena (I. Lea)				
Fusconaia flava (Rafinesque)	1	1	1	1
Lampsilis cardium (Rafinesque)[1]	1	1	1	1
Lampsilis higginsi (Lea)	1			1
Lampsilis siliquoidea (Barnes)				
Lampsilis teres (Rafinesque)				
Lasmigona c. complanata (Barnes)	1	1	1	1
Lasmigona costata (Rafinesque)				
Leptodea fragilis (Rafinesque)	1	1	1	1
Ligumia recta (Lamarck)	1	1	1	1
Megalonaias nervosa (Rafinesque)[2]	1	1	1	1
Obliquaria reflexa (Rafinesque)	1	1	1	1
Obovaria olivaria (Rafinesque)	1	1	1	1
Plethobasus cyphyus (Rafinesque)		1		
Pleurobema coccineum (Conrad)		1		
Potamilus alatus (Say)	1	1	1	1
Potamilus ohiensis (Rafinesque)	1	1		
Pyanodon grandis (Say)[3]	1	1	1	1
Quadrula metanevra (Rafinesque)	1	1	1	1
Quadrula nodulata (Rafinesque)	1	1	1	1
Quadrula p. pustulosa (I. Lea)	1	1	1	1
Quadrula quadrula (Rafinesque)	1	1	1	1
Strophitus undulatus (Say)	1	1	1	1
Toxolasma parvus (Barnes)		1		
Truncilla donaciformis (I. Lea)	1	1	1	1
Truncilla truncata (Rafinesque)	1	1	1	1
Utterbackia imbecillis (Say)[4]	1	1	1	
Total individuals - Quantitative	833	1,080	954	732
Total individuals - Qualitative	567	506	402	801
Total collected	1,400	1,586	1,356	1,533
Total species	24	27	23	23

Note: In previous reports, these species were occasionally referred to as indicated below:
[1] Either *L. ovata* or *L. ventricosa*.
[2] *Megalonaias gigantea*.
[3] *Anodonta grandis*.
[4] *Anodonta imbecillis*.

Table C3
List of Bivalves Collected at RM 504.8, Pool 14, UMR 1988-94

Species	1988	1989	1991	1992	1994
Actinonaias ligamentina (Larmack)	1				
Amblema p. plicata (Say)	1	1	1	1	1
Arcidens confragosus (Say)	1	1	1	1	1
Corbicula fluminea (Mueller)	1		1		
Cumberlandia monodonta (Say)					
Dreissena polymorpha (Pallas)					1
Ellipsaria lineolata (Rafinesque)	1	1	1	1	1
Elliptio dilatata (Rafinesque)		1	1		1
Fusconaia ebena (I. Lea)					
Fusconaia flava (Rafinesque)	1	1	1	1	1
Lampsilis cardium (Rafinesque)[1]	1	1	1	1	1
Lampsilis higginsi (Lea)	1	1	1	1	1
Lampsilis siliquoidea (Barnes)					
Lampsilis teres (Rafinesque)					
Lasmigona c. complanata (Barnes)	1	1	1	1	1
Lasmigona costata (Rafinesque)		1			
Leptodea fragilis (Rafinesque)	1	1	1	1	1
Ligumia recta (Lamarck)	1	1	1	1	1
Megalonaias nervosa (Rafinesque)[2]	1	1	1	1	1
Obliquaria reflexa (Rafinesque)	1	1	1	1	1
Obovaria olivaria (Rafinesque)	1	1	1	1	1
Plethobasus cyphyus (Rafinesque)					
Pleurobema coccineum (Conrad)					
Potamilus alatus (Say)	1	1	1	1	1
Potamilus ohiensis (Rafinesque)		1			
Pyanodon grandis (Say)[3]	1	1	1	1	1
Quadrula metanevra (Rafinesque)	1	1	1	1	1
Quadrula nodulata (Rafinesque)	1	1	1	1	1
Quadrula p. pustulosa (I. Lea)	1	1	1	1	1
Quadrula quadrula (Rafinesque)	1	1	1	1	1
Strophitus undulatus (Say)			1		
Toxolasma parvus (Barnes)	1	1			
Truncilla donaciformis (I. Lea)	1	1	1		1
Truncilla truncata (Rafinesque)	1	1	1	1	1
Utterbackia imbecillis (Say)[4]	1		1		1
Total individuals - Quantitative	253	919	1,247		903
Total individuals - Qualitative	734	961	815	386	789
Total collected	987	1,880	2,062	386	1,692
Total species	24	24	24	19	23

Note: In previous reports, these species were occasionally referred to as indicated below:
[1] Either *L. ovata* or *L. ventricosa*.
[2] *Megalonaias gigantea*.
[3] *Anodonta grandis*.
[4] *Anodonta imbecillis*.

Table B4
Mean Density of *T. truncata* at Five Locations in the UMR, 1988-94

Pool	RM	Year	N	*T. truncata*		Probability Level		Significant Decrease?
				Mean	SE	0.1	0.05	
10	635.2	1989	40	6.30	0.99	b	a	No
		1991	60	8.20	0.99	ab	a	
		1993	60	8.80	0.93	a	a	
		1994	60	9.00	0.92	a	a	
12	571.5	1990	40	6.80	1.24	a	a	No
		1992	60	6.26	0.74	a	a	
		1994	60	7.80	0.95	a	a	
14	504.8	1988	20	9.80	1.40	b	b	No
		1989	60	14.93	1.34	a	a	
		1991	60	18.46	1.41	a	a	
		1994	60	15.13	1.03	a	a	
17	450.4	1988	20	36.60	11.75	a	a	Yes
		1990	60	10.86	1.51	b	b	
		1992	60	11.13	1.30	b	b	
		1994	60	12.66	1.66	b	b	
24	299.6	1988	10	10.80	2.07	b	b	No
		1989	60	21.40	2.50	a	a	
		1991	60	2.53	0.47	c	c	
		1994	60	5.86	1.06	bc	bc	

Table B5
Mean Density of *E. lineolata* at Mussel Beds in Pools 17 and 24, UMR, 1988-94

Pool	RM	Year	N	*E. Lineolata* Mean	*E. Lineolata* SE	Probability Level 0.1	Probability Level 0.05	Significant Decrease?
17	450.4	1988	20	10.20	3.89	a	ab	No
		1990	30	5.46	1.36	b	b	
		1992	60	8.66	0.89	ab	ab	
		1994	60	10.93	1.39	a	a	
24	299.6	1988	10	5.20	1.20	b	b	No
		1989	60	11.40	1.37	a	a	
		1991	60	4.20	0.94	b	b	
		1994	60	1.93	0.44	b	b	

Table B6
Mean Density of *L. fragilis* at Mussel Beds in Pools 10 and 12, UMR, 1988-94

Pool	RM	Year	N	*L. fragilis* Mean	*L. fragilis* SE	Probability Level 0.1	Probability Level 0.05	Significant Decrease?
10	635.2	1989	40	1.50	0.42	c	c	No
		1991	60	2.20	0.41	c	bc	
		1993	60	5.33	0.74	a	a	
		1994	60	3.80	0.55	b	ab	
12	571.5	1990	40	1.10	0.35	b	b	No
		1992	60	1.40	0.31	b	b	
		1994	60	3.86	0.45	a	a	

Table C6
Summary Information on Bivalves Collected at Five Locations in the UMR 1988-94

Species	RM 229.6	RM 450.4	RM 504.8	RM 571.5	RM 635.2	Total
Actinonaias ligamentina (Larmack)	1	4	1	4	4	14
Amblema p. plicata (Say)	5	4	5	4	6	24
Arcidens confragosus (Say)	3	4	5	4	5	21
Corbicula fluminea (Mueller)	3	1	2	1	1	8
Cumberlandia monodonta (Say)	1	1	0	0	0	2
Dreissena polymorpha (Pallas)	1	1	1	1	2	6
Ellipsaria lineolata (Rafinesque)	5	4	5	4	4	22
Elliptio dilatata (Rafinesque)	0	0	3	0	6	9
Fusconaia ebena (I. Lea)	2	0	0	0	0	2
Fusconaia flava (Rafinesque)	5	4	5	4	6	24
Lampsilis cardium (Rafinesque)[1]	5	4	5	4	6	24
Lampsilis higginsi (Lea)	0	2	5	3	6	16
Lampsilis siliquoidea (Barnes)	0	0	0	1	2	3
Lampsilis teres (Rafinesque)	1	0	0	0	1	2
Lasmigona c. complanata (Barnes)	3	4	5	4	3	19
Lasmigona costata (Rafinesque)	0	0	1	0	0	1
Leptodea fragilis (Rafinesque)	244	4	5	4	6	23
Ligumia recta (Lamarck)	4	4	5	4	6	23
Megalonaias nervosa (Rafinesque)[2]	5	4	5	4	6	24
Obliquaria reflexa (Rafinesque)	5	4	5	4	6	24
Obovaria olivaria (Rafinesque)	5	4	5	4	5	23
Plethobasus cyphyus (Rafinesque)	0	1	0	0	0	1
Pleurobema coccineum (Conrad)	0	1	0	0	2	3
Potamilus alatus (Say)	4	4	5	4	6	23
Potamilus ohiensis (Rafinesque)	0	2	1	0	2	5
Pyanodon grandis (Say) [3]	2	4	5	4	6	21
Quadrula metanevra (Rafinesque)	5	4	5	3	6	23
Quadrula nodulata (Rafinesque)	5	4	5	4	5	23
Quadrula p. pustulosa (I. Lea)	5	4	5	4	6	24
Quadrula quadrula (Rafinesque)	5	4	5	4	6	24
Strophitus undulatus (Say)	0	4	1	3	5	13
Toxolasma parvus (Barnes)	0	1	2	1	2	6
Truncilla donaciformis (I. Lea)	4	4	4	4	6	22
Truncilla truncata (Rafinesque)	5	4	5	4	6	24
Utterbackia imbecillis (Say)[4]	2	3	3	2	4	14
Total individuals - Quantitative	1,765	3,599	3,322	1,475	4,165	14,326
Total individuals - Qualitative	2,013	2,276	3,685	2,838	2,832	13,644
Total collected	3,778	5,875	7,007	4,313	6,997	27,970
Total years	5	4	5	4	6	
Total species	26	30	29	27	31	35

Note: In previous reports, these species were occasionally referred to as indicated below:
[1] Either *L. ovata* or *L. ventricosa*.
[2] *Megalonaias gigantea*.
[3] *Anodonta grandis*.
[4] *Anodonta imbecillis*.

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13. ABSTRACT *(Maximum 200 words)*

Studies on the physical and biological effects of commercial navigation traffic at five historically prominent mussel beds in the upper Mississippi River (UMR) were conducted from 1988-94. The purpose was to analyze the effects of movement of commercial navigation vessels on ambient water velocity, suspended solids, and freshwater mussels, including the endangered Higgins eye mussel, *Lampsilis higginsi* (Lea). Mussel beds were located at the following river miles: 299.6 (Pool 24), 450.4 (Pool 17), 504.8 (Pool 14), 571.5 (Pool 12), and the main channel of the UMR at 635.2 (Pool 10). Studies were conducted as part of the Melvin Price Locks and Dam, Second Lock Project (formerly known as the Locks and Dam 26 Replacement Project), which will increase the capacity of the UMR for commercial navigation vessels. Data collected during this survey will be used to evaluate the health of mussel communities for the study period, 1988-94. In addition, these data will be compared with results from future studies to assess the long-term effects of commercial navigation traffic on mussels in the UMR.

Based upon 60 passages of commercial vessels that were studied, 20 percent had a major effect, 37 percent produced a minor effect, and 43 percent produced no measurable effect on ambient water velocity. A major effect was defined as an increase in velocity two to three times ambient levels (approximately 0.5 ft (15.2 cm/sec)).

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Vessel-induced changes in turbidity and suspended solids at mussel beds were minor and usually lasted 2 to 3 min. Pulses of increased velocity, turbidity, and suspended solids associated with vessel passage had little or no effect on mussels.

Each year divers collected qualitative and quantitative (0.25-m^2 total substratum) samples to assess temporal trends in mussel density, population demography, and other community and population parameters. Specific criteria, chosen to reflect the overall health of mussel beds, were established to provide a basis for detecting change. Although there was year-to-year variation in species richness, evidence of recent recruitment, growth rates, and mortality, pre-established criteria for these parameters were met at each bed. *Lampsilis higginsi* was regularly collected at beds on Pools 10, 12, and 14, which are within its range. The criterion for density stated that there should not be a significant decline, using the conservation p level of 0.1, sustained for two or more sampling periods, of five common-to-abundant species at each bed. Out of 29 possible evaluations at five beds, there were eight instances of significant decline and two instances of significant increase. However, at no beds was there a significant decline, sustained for 2 or more years, for five common-to-abundant species.

Although selected biotic parameters varied among years, based upon pre-established criteria, these mussel populations appear stable and unaffected by movement of commercial traffic. Results of future studies, to be conducted after commercial traffic levels have increased as a result of completion of the second lock at Melvin Price Locks and Dam, can be used to further investigate the environmental effects of movement of commercial navigation traffic.