

ENVIRONMENTAL IMPACT  
RESEARCH PROGRAM

TECHNICAL REPORT EL-90-10



US Army Corps  
of Engineers

TECHNIQUES FOR STUDYING THE PHYSICAL  
EFFECTS OF COMMERCIAL NAVIGATION  
TRAFFIC ON AQUATIC HABITATS

AD-A229 834

by

Nani G. Bhowmik

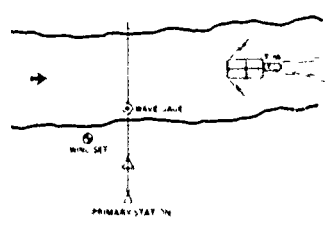
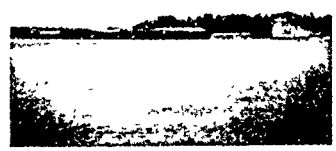
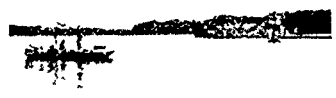
Illinois Department of Energy and Natural Resources  
State Water Survey Division  
Champaign, Illinois 61820

and

Andrew C. Miller, Barry S. Payne

Environmental Laboratory

DEPARTMENT OF THE ARMY  
Waterways Experiment Station, Corps of Engineers  
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199



DTIC  
ELECTE  
DEC 05 1990  
S B D

November 1990  
Final Report

Approved For Public Release; Distribution Unlimited



Prepared for DEPARTMENT OF THE ARMY  
US Army Corps of Engineers  
Washington, DC 20314-1000

Destroy this report when no longer needed. Do not return  
it to the originator.

The findings in this report are not to be construed as an official  
Department of the Army position unless so designated  
by other authorized documents.

The contents of this report are not to be used for  
advertising, publication, or promotional purposes.  
Citation of trade names does not constitute an  
official endorsement or approval of the use of  
such commercial products.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION Unclassified		1b. RESTRICTIVE MARKINGS			
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION / AVAILABILITY OF REPORT			
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE		Approved for public release; distribution unlimited.			
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Technical Report EL-90-10		5. MONITORING ORGANIZATION REPORT NUMBER(S)			
6a. NAME OF PERFORMING ORGANIZATION USAEWES Environmental Laboratory		6b. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION		
6c. ADDRESS (City, State, and ZIP Code) 3909 Halls Ferry Road Vicksburg, MS 39180-0631		7b. ADDRESS (City, State, and ZIP Code)			
8a. NAME OF FUNDING / SPONSORING ORGANIZATION US Army Corps of Engineers		8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code) Washington, DC 20314-1000		10. SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
11. TITLE (Include Security Classification) Techniques for Studying the Physical Effects of Commercial Navigation Traffic on Aquatic Habitats					
12. PERSONAL AUTHOR(S) Bhowmik, Nani G.; Miller, Andrew G.; and Payne, Barry S.					
13a. TYPE OF REPORT Final report		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) November 1990	15. PAGE COUNT 133
16. SUPPLEMENTARY NOTATION Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	Commercial navigation traffic		
			Laboratory simulation		
			Physical effects studies		
19. ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>The physical effects of commercial navigation traffic that can be studied in the field include: (a) resuspension and lateral transport of sediment; (b) sedimentation rates at specific habitats; (c) scour and disruption of substrates caused by tow passage; (d) altered velocity regimen including increased turbulence and reversal of flows; (e) pressure fluctuations, shear force, wave heights, wave wash, and drawdown; (f) changes in water quality parameters; and (g) wave generation.</p> <p>Studies on the physical effects of commercial traffic should be designed to obtain background data and physical effects data as a vessel passes. Background data collection should include ambient velocity and sediment concentration at the site for low, medium, and high flow conditions; hydraulic, hydrologic, and morphometric characteristics of the site; historical characteristics of the site including sedimentation patterns; wind and wave</p> <p style="text-align: right;">(Continued)</p>					
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED / UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL			22b. TELEPHONE (Include Area Code)		22c. OFFICE SYMBOL

19. ABSTRACT (Continued).

characteristics; bed and bank material characteristics; basic water quality parameters and other site-specific characteristics such as presence or absence of side channels, backwaters, or tributaries. Historical data on any of these parameters should also be obtained.

Information collected as a vessel passes should include <sup>several pore meters</sup> (a) detailed velocity data at a sufficient number of locations to determine the areal distribution of the altered velocity regimen; (b) suspended sediment samples at a sufficient number of locations to determine sediment concentration and particle size distribution; (c) pressure fluctuations; (d) waves and drawdown; (e) changes in water quality parameters; (f) pulse input of water and sediment into sensitive side channels and backwaters; (g) bank erosion rates; and (h) a detailed quantification of the traffic including various vessel characteristics. Data analyses should include basic graphical and regression analyses supplemented with standard statistical analyses. Analyses should be designed to determine and separate effects of navigation traffic from the normal seasonal variations.

This report briefly describes basic hydraulic and sediment transport characteristics of open channels. In addition, various equipment and techniques to measure physical forces are described. Information and procedures in this report can be used by biological or physical scientists in the planning and execution of a physical effects study.

*Keywords: \* navigation \* commerce \* sediment transport  
\* backwaters \* water quality  
waterways; \* wave; \* water quality  
LEMK*

B

PREFACE

In October 1985, the US Army Engineer Waterways Experiment Station (WES) initiated a multi-year study on the environmental effects of navigation traffic in large waterways. This work is part of the Environmental Impact Research Program (EIRP) at WES. In January 1988, Dr. Nani G. Bhowmik, Illinois Department of Energy and Natural Resources, met with WES personnel to review and analyze appropriate techniques for studying the physical effects of commercial navigation traffic. As a result of that meeting, this report was prepared by Dr. Bhowmik. Drs. Andrew C. Miller and Barry S. Payne of the WES Environmental Laboratory (EL) prepared selected sections and reviewed the report. The report was edited by Ms. Gail Taylor of the Illinois Water Survey, and Mrs. Janean Shirley of the WES Information Technology Laboratory. The report was also reviewed by Messrs. Steve Maynard and N. R. Oswalt of the Hydraulics Laboratory at WES, and by Messrs. Terry Siemsen and Dave Beatty of the US Army Engineer District, Louisville. Technical Monitors for the study were Dr. John Bushman, Mr. David P. Buelow, and Mr. Dave Mathis, Headquarters, US Army Corps of Engineers. Mr. Edwin Theriot was Chief, Aquatic Habitat Group, EL; Dr. Conrad J. Kirby was Chief, Environmental Resources Division, EL; Dr. John Harrison was Chief, EL; and Dr. Roger Saucier was Program Manager of the EIRP during the preparation of this report.

Commander and Director of WES was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

This report should be cited as follows:

Bhowmik, N. G., Miller, A. C., and Payne, B. S. 1990. "Techniques for Studying the Physical Effects of Commercial Navigation Traffic on Aquatic Habitats," Technical Report EL-90-10, US Army Engineer Waterways Experiment Station, Vicksburg, MS.



<b>Accession For</b>	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

## CONTENTS

	<u>Page</u>
PREFACE.....	1
CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT.....	4
PART I: INTRODUCTION.....	5
Background.....	5
Purpose and Scope.....	6
Recent Studies on Navigation Traffic Effects.....	6
PART II: HYDRAULICS OF FLOW.....	14
Background.....	14
Physical Characteristics of Large Rivers.....	14
Flow Characteristics.....	20
Sediment Transport.....	28
Vessel-Induced Effects Versus Natural Effects.....	34
PART III: INITIAL CONSIDERATIONS.....	40
Objectives.....	40
The Need for Site-Specific Studies.....	40
Site Selection.....	44
Existing Physical and Hydrologic Characteristics.....	44
Areas With Biological Importance.....	48
Seasonal Variation.....	49
Consideration of Replicates.....	50
PART IV: MEASUREMENT OF PHYSICAL EFFECTS.....	51
Suspended Sediment.....	51
Bed Load.....	60
Sedimentation Rates.....	61
Bed Material Sampling.....	67
Velocity Measurements.....	72
Pressure Fluctuations and Water Quality.....	79
Waves and Drawdown.....	81
PART V: FIELD DATA COLLECTION TECHNIQUES.....	95
Initial Considerations.....	95
Baseline Data.....	96
Field Studies.....	101
Traffic Characteristics.....	105
Backwater Lakes and Side Channels.....	109
Data Collection at Backwater Lakes and Side Channels.....	111
Impact of Recreational Traffic.....	115
Conducting Studies of Recreational Traffic.....	117
Bank Erosion.....	118
PART VI: DATA ANALYSIS.....	119
Site Characteristics.....	119
Flow Characteristics.....	120
Sediment Transport Characteristics.....	120

CONTENTS (Continued)

	<u>Page</u>
Recreational Traffic.....	123
Bank Erosion.....	124
PART VII: CONCLUDING REMARKS.....	126
REFERENCES.....	127

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

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

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
degrees (angle)	0.0745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
inches	2.54	centimetres
pints (US liquid)	0.4731765	cubic decimetres
square miles	2.589998	square kilometres
tons (2,000 pounds, mass)	907.1847	kilograms

---

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



TECHNIQUES FOR STUDYING THE PHYSICAL EFFECTS OF COMMERCIAL  
NAVIGATION TRAFFIC ON AQUATIC HABITATS

PART I: INTRODUCTION

Background

1. Movement of commercial or recreational traffic in a large waterway usually causes physical disturbances. These disturbances can include increased turbulence, altered velocity, changed flow pattern, resuspended sediment, increased turbidity, waves and wave wash, and drawdown. These physical effects are temporary, and will be minor or major depending on the size, shape, and speed of the tow, and its proximity to areas of concern. The physical characteristics of the waterway (including size, shape, and bed and bank material size distributions), and hydraulic characteristics (including ambient velocity and suspended sediment concentration), are vital in determining the magnitude of navigation effects.

2. Periods of turbulence or of elevated suspended solids can stress pelagic fish eggs and larvae and bottom-dwelling organisms such as mussels, aquatic insects, worms, and crustaceans. In addition to short-term disturbances, movement of commercial vessels can cause long-term effects. Over a period of time commercial vessels can scour shoals and erode natural banks. These effects can bring about sustained physical changes to main channel borders, slackwater habitats, and natural banks that are part of the riparian zone. Resource agency personnel often express concern over the effects of a sustained increase in traffic, or over relatively localized effects that could be the result of construction of a port or of a barge-loading facility. Engineers, biologists, and planners in Federal, state, and other organizations often must assess the effects of commercial navigation traffic on aquatic resources.

3. Although a number of field and laboratory investigations have been conducted on the physical effects of commercial traffic, there are no published methods for planning and studying commercial navigation effects. This report has been prepared to address this lack of information. It is not meant to be a comprehensive review of past studies.

## Purpose and Scope

4. The purpose of this document is to describe procedures for conducting field experiments on the physical effects of commercial navigation traffic. Topics include site selection criteria, evaluation of the hydraulics of flow, initial considerations before data collection, measurement of physical impacts, needed equipment, data collection techniques, and procedures for data analysis.

## Recent Studies on Navigation Traffic Effects

5. Studies on the physical effects of commercial traffic are usually conducted to obtain information for environmental assessments and impact statements. This section briefly reviews some of these studies (Johnson 1976; Sparks, Thomas, and Schaeffer 1980; Environmental Science and Engineering 1981; Simons et al. 1981; Simons, Ghaboosi, and Chang 1987; Bhowmik et al. 1981b; Bhowmik, Demissie, and Osakada 1981; Bhowmik, Demissie, and Guo 1982; Kincaid 1987; Bogner, Soong, and Bhowmik 1988; and Alavain and Furry 1988). In most of these studies the purpose was to obtain physical data on commercial traffic effects. The studies by Simons et al. (1981) and Simons, Ghaboosi, and Chang (1987) have been included to illustrate the use of numerical models (which can be verified by techniques described in this report) to analyze commercial navigation traffic effects.

### Johnson (1976)

6. Johnson (1976) measured dissolved oxygen and collected water samples for suspended sediments following passage of commercial vessels in upper, middle, and lower reaches of the Illinois and upper Mississippi rivers. The objectives of his study were to: (a) determine if tow traffic significantly increased suspended solids and turbidity; (b) determine if appreciable concentrations of tow-generated suspended solids entered side channels and backwaters; (c) determine if multiple tow events had an additive effect on elevating concentrations of suspended solids and turbidity; (d) estimate the time required for suspended solids and turbidity to return to ambient concentrations; and (e) estimate the magnitude and duration of the oxygen demand exerted by resuspended sediments.

7. At each of six study sites, boats were positioned along a transect across the river with a station on the left bank, main channel, and right

bank. A fourth station was located just inside the upriver entrance of a nearby side channel. Three replicate composite water-column samples for sediments were collected simultaneously at each station. Samples were collected by sending a 15.2-m-long, 0.64-cm-diam nylon tube to the bottom and then starting a water pump. Samples were collected immediately before passage of a tow and at 10, 20, 40, 60, 90, 120, 150, and 180 min after the tow passed. The following information was obtained: name of towboat and company, number of loaded and empty barges, draft depth, tow velocity, and engine horsepower.

8. Results from the upper Mississippi River indicated that tow-induced elevated suspended solids during normal pool levels were small compared with ambient levels during flood stage. Except in the case of one multiple tow (which consisted of the largest number of loaded barges encountered during the study) suspended solids caused by tow passage in the Illinois River were not elevated above those that occur during flood stage. There were no observed additive effects due to the passage of multiple tows on the Mississippi River, although additive effects were observed during three of the six traffic events on the Illinois River. The most important difference between those events that produced additive effects and those that did not appeared to be related to the number of barges being transported. Recovery time (time required for a return to ambient levels) varied considerably with each event in both rivers. This response appeared to be related to shoreline waves produced by smaller tows. Faster-moving tows had a greater effect on resuspending sediments than did slower tows.

9. Three replicate dissolved oxygen measurements were made in situ for each of three strata (surface, mid-depth, and near-bottom) in the main channel. In most cases, tow passage did not reduce dissolved oxygen concentrations in the main channel of either river.

Sparks, Thomas, and Schaeffer (1980)

10. Sparks, Thomas, and Schaeffer (1980) conducted studies in the Illinois River to determine if cessation of navigation traffic (caused by closure of a lock for repair) was associated with changes in ambient concentration of suspended solids. Their results showed that suspended sediment concentrations in the Illinois River were higher during periods with traffic than in those without. However, a review of these studies (Sparks, Thomas, and Schaeffer 1980) revealed that discharge was lowest when barge traffic had ceased and highest when barge traffic was present. Thus, from these results it is

impossible to assign tow traffic, as opposed to discharge, as the variable responsible for increased suspended solids concentration.

Environmental  
Science and Engineering (1981)

11. In the Illinois River, Environmental Science and Engineering (1981) measured tow-induced changes in longshore (parallel to the shore) and onshore (perpendicular to the shore) water velocity vectors at nearshore and near-channel stations at 15-sec intervals. Data loggers were coupled to electromagnetic velocity probes positioned 0.3 m above the bottom at two stations. The results demonstrated that tow passage caused 8- to 18-cm/sec changes in the magnitude of longshore velocity vectors at both nearshore and near-channel stations. Tows moving upriver generated a downriver increase in velocity, but traffic moving downriver caused velocity changes in the reverse direction. Because the ambient flow was only about 6 cm/sec, most downriver traffic caused a flow reversal. Longshore velocity changes were greater and in a consistent direction relative to onshore changes.

12. Results from the Mississippi River were more complex. In an assessment of longshore velocity changes at the near-channel monitoring station, upbound tows were found to cause an increase in ambient currents at the near-channel station. 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 near-channel changes. These velocity patterns could not easily be interpreted with respect to tow passage. The data in Appendix A of the report by Environmental Science and Engineering (1981) illustrate that at least 8 of 23 tow passage events did not affect water velocity at the nearshore station. Those measurements that showed a fairly clear relationship with tow passage events demonstrated that velocity changes at the nearshore station were opposite in direction and lower in magnitude than those at the near-channel station. Nearshore velocities changed by an average of 10 cm/sec. Because ambient velocity at the nearshore station was generally near 0 cm/sec, upbound tows often caused brief upriver currents and downbound tows caused significant downriver currents. The duration of changes in nearshore or near-channel velocities averaged 1 to 2 min.

13. Field studies by Environmental Science and Engineering illustrated that barge and tow traffic could cause intermittent changes in velocity at shallow areas tens of metres from the sailing line (on the average, 180 and

75 m in the Illinois and Mississippi studies, respectively). The same studies also demonstrated that site-specific conditions determined to what extent and direction velocity vectors could be changed.

Simons et al. (1981);  
Simons, Ghaboosi, and Chang (1987)

14. Simons et al. (1981) modeled backwater sedimentation and increases in suspended solids caused by commercial navigation vessels in selected pools of the upper Mississippi River. Although these predictions have been used to evaluate the effects of incremental increases in traffic in large reaches of the Illinois and Mississippi rivers, application of site-specific information to a river system is probably not valid. Data on physical effects should be obtained at sites likely to be affected by commercial traffic (See Part II). The predictions by Simons et al. (1981) were based on existing hydrologic, hydraulic, geomorphic, and suspended sediment data. The model estimated the effects of tow passage on water velocity in the main channel. Predicted changes in suspended sediment concentrations were made using equations that related concentrations of four sizes of suspended particles to velocity. Water velocity was assumed to return to ambient levels immediately after tow passage. According to the model, the sediment resuspended by the tows settled in the same manner as did naturally suspended sediments. Suspended sediments were carried into side channels and backwaters at a rate directly dependent on water velocity and suspended sediment concentration. Baseline levels of sediment volume entering backwaters under natural conditions (i.e., no tow traffic) were predicted using existing hydrologic, hydraulic, geomorphic, and sediment data.

15. Simons et al. (1981) were especially careful to point out a number of limitations and assumptions in their general predictive model. Among the most crucial of these is that hydrologic and sediment data from cross sections are generally insufficient to allow confident prediction of sediment resuspension and sedimentation in backwaters due to ambient conditions or navigation-related phenomena. Simons conducted additional research (Simons, Ghaboosi, and Chang 1987) on this problem using slightly different techniques.

Bhomik et al. (1981a,b)

16. Bhowmik et al. (1981a,b) conducted field studies on the Illinois and Mississippi rivers in 1980-81 to determine the resuspension and lateral movement of sediment due to tow traffic. Sampling was done at three sites on each cross section. Immediately after passage of a tow, one sample boat was

aligned with the sailing line, one was positioned about one half the distance between the sailing line and the shoreline, and one was positioned close to the shore. Simultaneously depth-integrated suspended sediment samples were obtained with isokinetic suspended sediment samplers from each sample boat. Sampling continued for 90 min after passage of the tow. Data were collected for both loaded and unloaded barges. Information was also obtained on hydraulic characteristics including velocity structure and bed and bank material characteristics. The ambient suspended sediment concentration varied from a low of 100 ppm to a high of about 500 ppm.

17. This study indicated that tow passages increased suspended sediment concentrations. The increase was greater in the channel border than in the navigation channel, and the increase was more significant when the ambient suspended sediment concentration was low. The concentration was increased for 60 to 90 min after tow passage. Following multiple tow passages there were periods of increased sediment concentration, although the average increase for a multiple event was less than the average increase for an isolated event. The effects of tow passage were greater on the Illinois than on the Mississippi River, which was consistent with the differences in channel dimensions. In addition, the ambient suspended sediment concentration was higher in the channel than in the channel border when the sediment load was increased by upriver runoff or flood flows.

18. No information on the redistribution of the resuspended or laterally displaced sediment was obtained. Data on the Illinois River (Schnepper et al. 1981) indicated that fine sand and silt were present in channel border areas but not in the navigation channel. It was concluded that additional data and much more detailed analyses were needed to establish a model for the resuspension and movement of sediment caused by vessel traffic on inland waterways.

19. Bhowmik et al. (1981b) also investigated the effects of tow traffic on the input of sediment at the inlet and outlet of a side channel, including changes in velocity structures. The study site was on the Illinois River in a relatively large side channel. The channel could convey up to 3 percent of the total flow when the flow in the river was 283 cm/sec to a maximum of 18.2 percent of the total flow when the flow was 2,831 cm/sec. Data on water levels, velocity, and suspended sediment concentrations were collected for 24 tow passage events, and all three of these physical parameters showed changes during the passage of tows with barges. Sediment input to the side channel

increased from 9 to 136 metric tons\* because of tow passage. However, the range of data collected at this location was not sufficient to extrapolate the extent of sediment input to other side channels. A physically based analytical model would be needed to quantify the impacts of navigation on a specific side channel.

Bhowmik, Demissie, and Osakada  
(1981); Bhowmik, Demissie, and Guo (1982)

20. Bhowmik, Demissie, and Osakada (1981) and Bhowmik, Demissie, and Guo (1982) also collected wave and drawdown data from the Illinois and Mississippi rivers in 1981. Six field trips were taken to collect wave and drawdown data: four to the Illinois River and two to the Mississippi River. Wave data were collected for a total of 59 tow passage events, and drawdown data were collected for 27 events. Additional wave data were collected during the passage of a towboat without barges and the passage of a cabin cruiser.

21. The maximum wave heights measured in the field ranged from a low of 3 cm to a high of 32.9 cm, while the maximum drawdown ranged from 1.5 cm to 21 cm. A comparison of the measured maximum wave heights and drawdowns with those predicted from existing equations showed low correlations between the measured and calculated wave heights and drawdowns. A multivariate regression analysis was then used to predict wave heights and drawdowns. In the equation for maximum wave height, the non-dimensional wave height was found to be a function of the draft Froude number only. In the equation for maximum drawdown, the non-dimensional drawdown was a function of the Froude number based on the hydraulic depth minus draft, blockage factor, and a dimensionless distance from the sailing line to the wave gage.

22. Significant wave heights for wind-generated waves were also calculated at the four study sites for 2- and 50-year return periods and 6-hr-duration winds. On the Illinois River, the significant wave heights were found to be in the range of 27.4 cm and 48.8 cm for the 2-year and 50-year winds of 6-hr duration, respectively, whereas on the Mississippi River the corresponding values were 39.6 cm and 73.2 cm, respectively.

23. The significance of waves generated by traffic in comparison with those generated by wind could not be determined qualitatively because of the difference in frequency, duration, and magnitude between the two types of

---

\* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

waves. Further research on this topic would be needed before a definite conclusion can be made.

Bogner, Soong, and Bhowmik (1988)

24. Bogner, Soong, and Bhowmik (1988) collected field data on sediment resuspension, altered and ambient velocity structure, and waves and drawdown on the Ohio River during a field experiment conducted by the US Army Corps of Engineers. For this experiment, one empty barge with a single tugboat was allowed to run a set of predetermined courses with varying degrees of speed and distances from the sample sites. Physical and water quality data were collected for a period of three weeks. The techniques that were used for this experiment are given by Bogner, Soong, and Bhowmik (1988).

Alavain and Furry (1988)

25. Alavain and Furry (1988) described a study conducted for the Huntington District in the Marmet Pool, Kanawha River, West Virginia. The work was undertaken to evaluate the environmental effects of commercial traffic and to examine the mechanism of water jets induced by vessel movement. At each station, longitudinal and transverse velocities, temperature, turbidity, and suspended solids concentration were measured. In addition, data on pool level, vessel-induced waves, and ambient weather were obtained. Physical measurements were made at three vertical locations on the sailing line (1.5, 8, and 16 ft from the bottom), at mid-depth one quarter of the distance from the bank, and at mid-depth near the shore in 1.5 ft of water.

26. Sensors were secured on an adjustable aluminum support structure with lead weights. A magnetic compass was used to orient the sensors in each package. Data from each tow event were collected for up to 30 min and stored in a data logger.

27. The investigators found that a drawdown of 0.1 ft was created by most vessels. Bow- and stern-generated waves arrived at the shore within 14.5 min of the test. Water level fluctuations were lessened after 18 min and returned to normal after 25 min. Water velocity fluctuations were usually less than 1.5 ft/sec; ambient velocity ranged from 0.25-0.5 ft/sec.

Kincaid (1987)

28. Kincaid (1987) described a study conducted on the Ohio River in the early 1980's. Data were collected on size, type, and speed of tows, and their distance from the shore. Single-axis velocity sensors were secured to concrete blocks to record changes in water velocity following tow passage. This project was part of a larger study that involved collecting data on sediment



types, aquatic biota, and chemical parameters. The work was done for the preparation of an Environmental Impact Statement for the Gallipollis Lock and Dam Replacement project for the Huntington District.

29. The most prominent feature of all field studies of navigation-induced resuspension of sediments is the large variation within or among studies. Simple generalizations about tow-induced resuspension of sediments do not always realistically portray the complex results of field observations. No field studies have been conducted to determine the impacts of tow movement on drawdown, waves (if present), and resuspension and deposition of sediment in backwater lakes.

## PART II: HYDRAULICS OF FLOW

### Background

30. The existing planform, shape, size, hydraulic geometry, and cross-section of a river are the result of existing and past physical conditions. In addition to natural conditions, human alterations also impact rivers. Realignment of river channels, construction of locks and dams and dikes, and the closing of dams have affected many rivers. These actions can alter the future planforms of many river reaches (Bhowmik, Demissie, and Adams, 1988; Bhowmik, Adams, and Sparks 1986; Demissie and Bhowmik 1985, 1987; Demissie, Bhowmik, and Adams 1983).

31. A site evaluation should be performed for river reaches where physical impacts of traffic will be studied. This evaluation should be based on an understanding of the hydraulic and sediment transport characteristics of the river. This section describes techniques that can be used for these preliminary evaluations. For detailed discussions of hydraulics of flow and sediment transport in an open channel, the reader is referred to publications by Chow (1959, 1964), Einstein (1950), Graf (1971), and Simons and Senturk (1977).

### Physical Characteristics of Large Rivers

32. Natural rivers are neither straight nor sinuous. In almost all cases, rivers in planform consist of a series of bends and straight reaches interconnected by transition zones and as Figure 1 illustrates, these bends and straight reaches vary in size and shape. In Figure 1,  $W_T$  is the top width of the channel at the bank-full discharge, which is defined as the discharge that has a return period of 2.33 years. This is also called channel-forming discharge and is the flow that is normally used in hydraulic geometry analyses of rivers (Bhowmik and Stall 1979).

33. The radius of curvature ( $R_c$  in Figure 1) is the distance from the center line of the channel to a point where an arc can be drawn (approximately) following the center line of the river, and  $\Delta$  deg is the angle (deflection angle) in degrees that is subtended at the center line by the bend. Characteristics of a bend can be defined as follows:

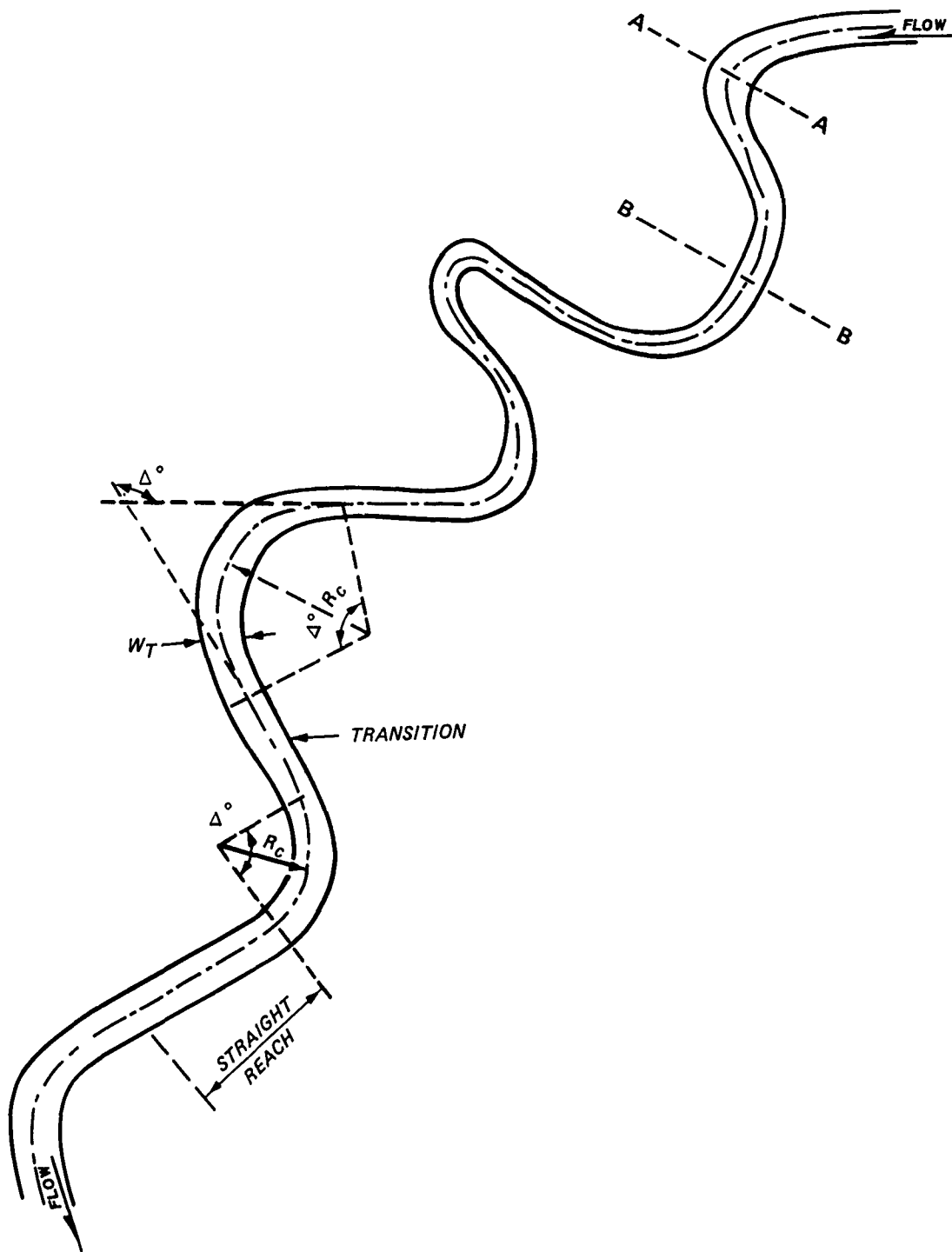


Figure 1. Generalized form of river channels

- $0 < \Delta \text{ deg} < 15 \text{ deg} = \text{mild bend}$   
 $15 \text{ deg} < \Delta \text{ deg} < 35 \text{ deg} = \text{average bend}$   
 $35 \text{ deg} < \Delta \text{ deg} = \text{sharp bend}$

34. When the value of  $\Delta \text{ deg}$  approaches or exceeds 180 deg, cutoffs become imminent unless prevented by intervening non-erodible land masses or artificial barriers.

35. Characteristics of the bends can also be defined on the basis of the relative magnitudes of the ratio of  $R_c/W_T$ , which can vary from 2 to 20 or more (Bhowmik and Simons 1969; Simons and Senturk 1977; ASCE 1975). Another important morphometric factor that must be considered in the analyses of rivers is sinuosity. Sinuosity ( $S_s$ ) is the ratio of the river length along its center line to its downvalley length. An analysis of nine river basins in Illinois showed that  $S_s$  can vary from about 1.05 to 2.0 for reaches where stream order varies from 3 to 7 (Bhowmik and Stall 1979; Bhowmik 1984). Similar variations can be expected for other rivers.

36. Cross-sectional shapes in any river channel change from one section to another, and from one river to another. However, an evaluation of the cross-sectional shapes of a river depends on whether the section is located within a straight or curved reach. In Figure 1 the cross-sectional shape at section A-A will be different from that present at B-B. Figures 2 through 7 depict some typical river cross sections. Figures 2 and 3 show a set of cross sections from the Kaskaskia River (Bhowmik 1979), the planform of which is shown in Figure 8. In general, cross-sectional shapes in straight reaches can be approximated by a trapezoidal shape (Figure 2), and those within a bend can be approximated by an extremely skewed shape (Figure 3). Research on the Kaskaskia River has also shown that the maximum depth ( $D_{\text{max}}$ ) in the straight reach is about 20 percent more than the average depth, and within the bend the maximum depth is about 50 percent more than the average depth.

37. The cross-sectional shapes in large rivers such as the Mississippi and Illinois may or may not be similar to the shapes shown for the Kaskaskia River. Figures 4 through 7 show four other cross sections from the Mississippi and Illinois rivers. The locations of cross sections C, D, and E are given on Figure 9. In these large river systems, low water depths have been increased and the channels normally have two to three distinct zones. These may include two major zones called "channel borders" and a single zone termed

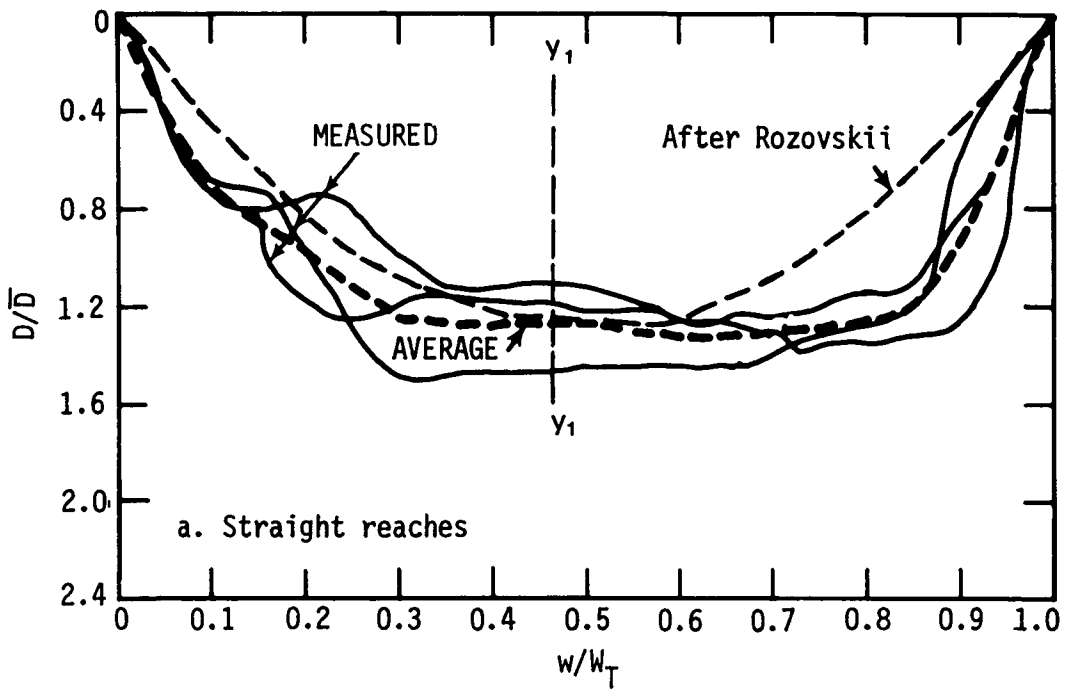


Figure 2. Cross section of straight reach of the Kaskaskia River (after Bhowmik 1979)

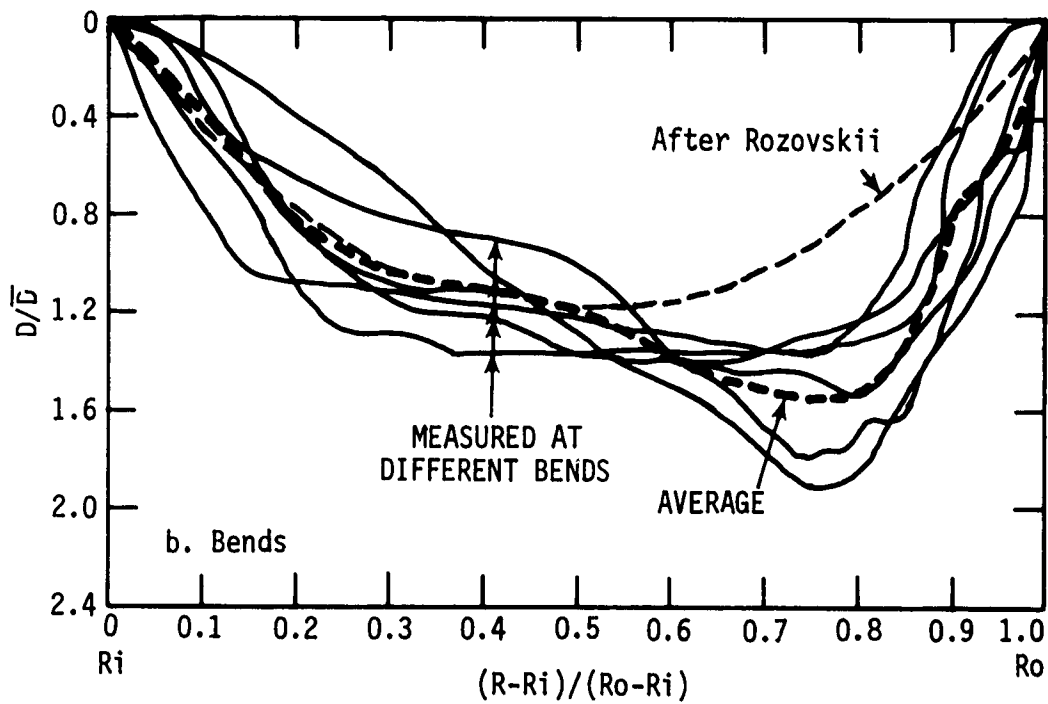


Figure 3. Cross section of a bend of the Kaskaskia River (after Bhowmik and Adams 1986)

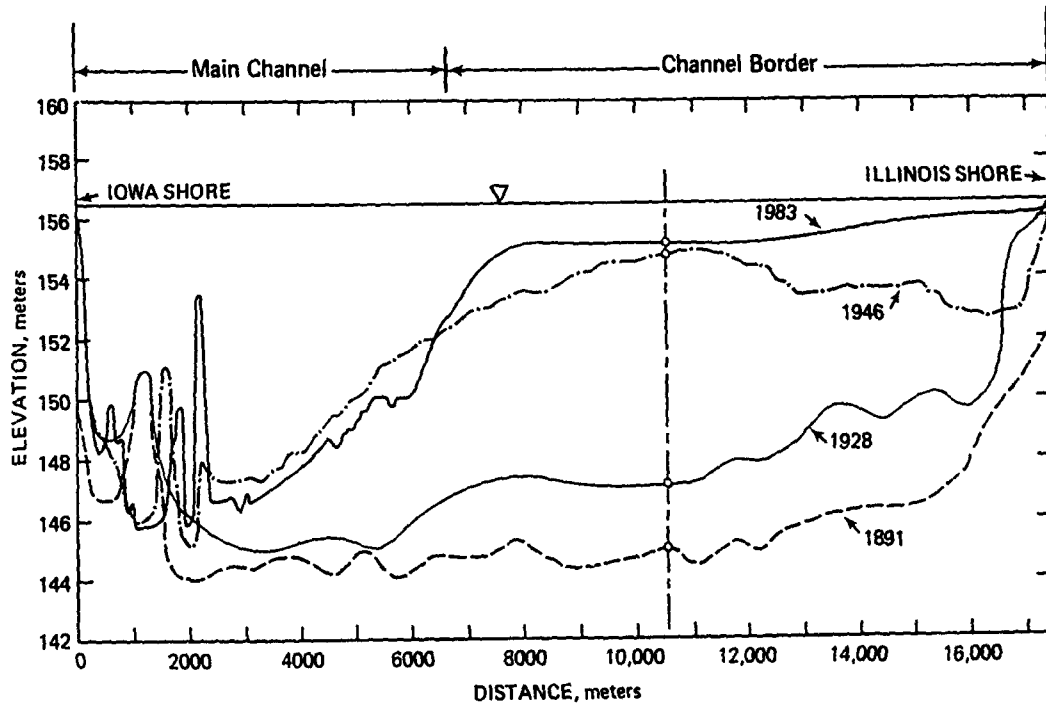


Figure 4. Cross section of the Mississippi River at RM 364.7, cross section C (see Figure 9)

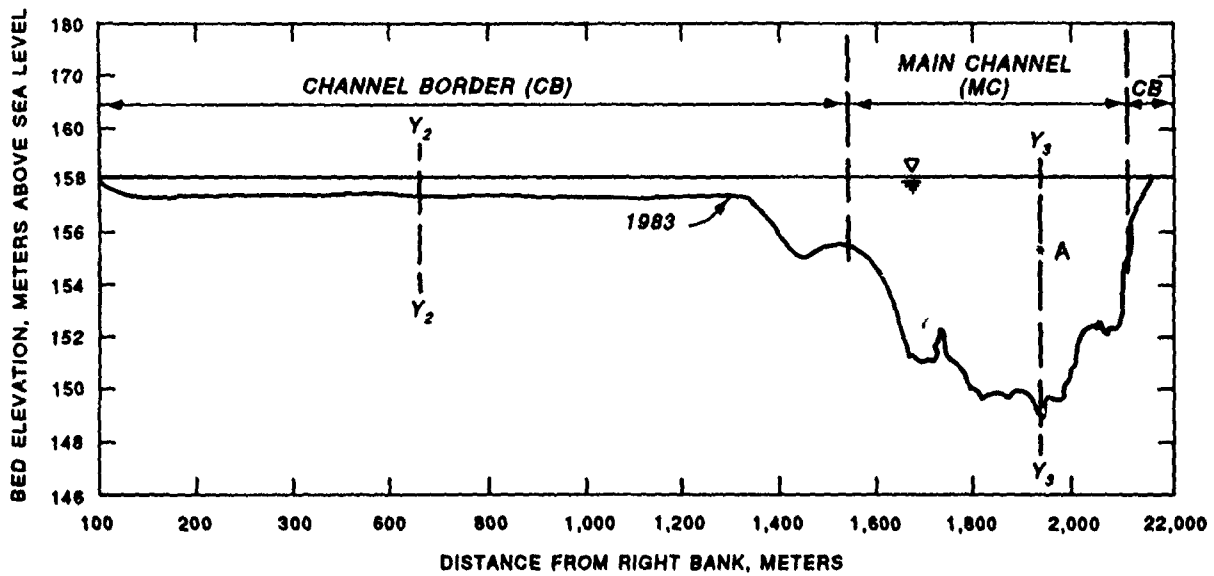


Figure 5. Cross section of the Mississippi River at RM 375.7, cross section D (see Figure 9)

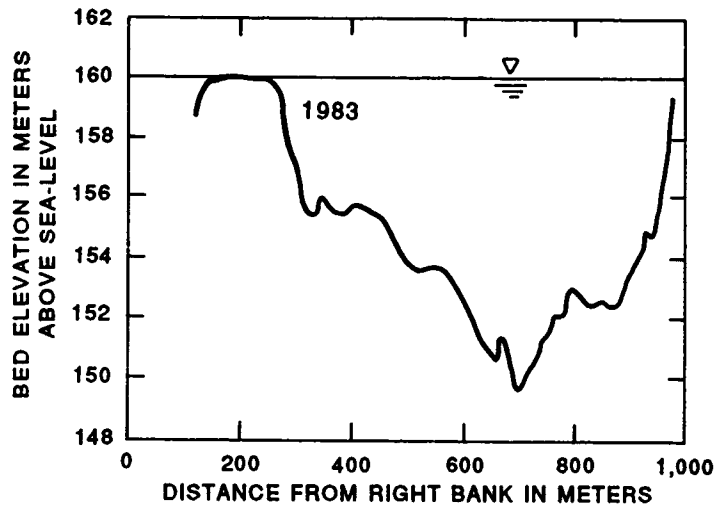


Figure 6. Cross section of the Mississippi River at RM 410, cross section E (see Figure 9)

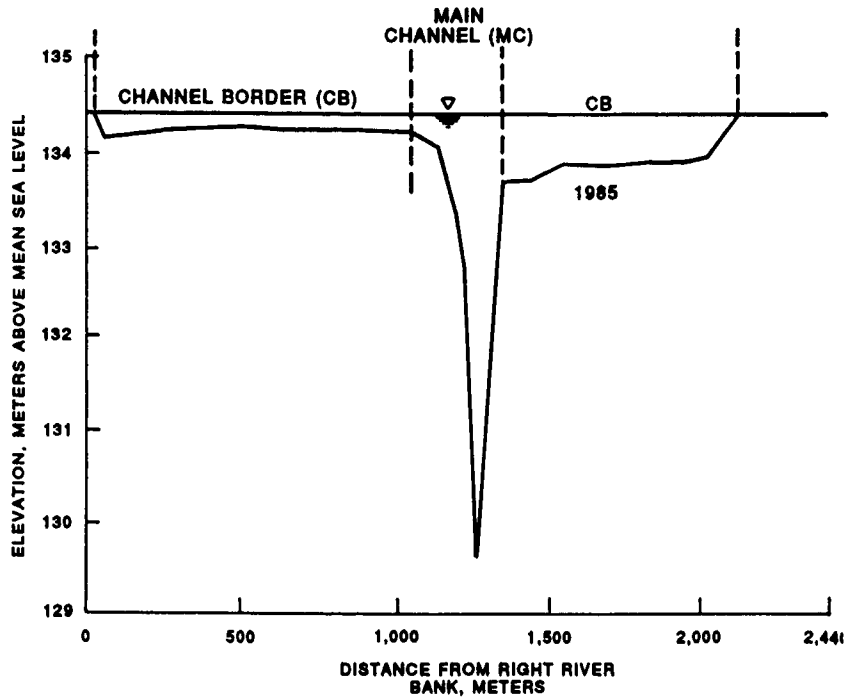


Figure 7. Cross section of the Illinois River at RM 175 (Peoria Lake)

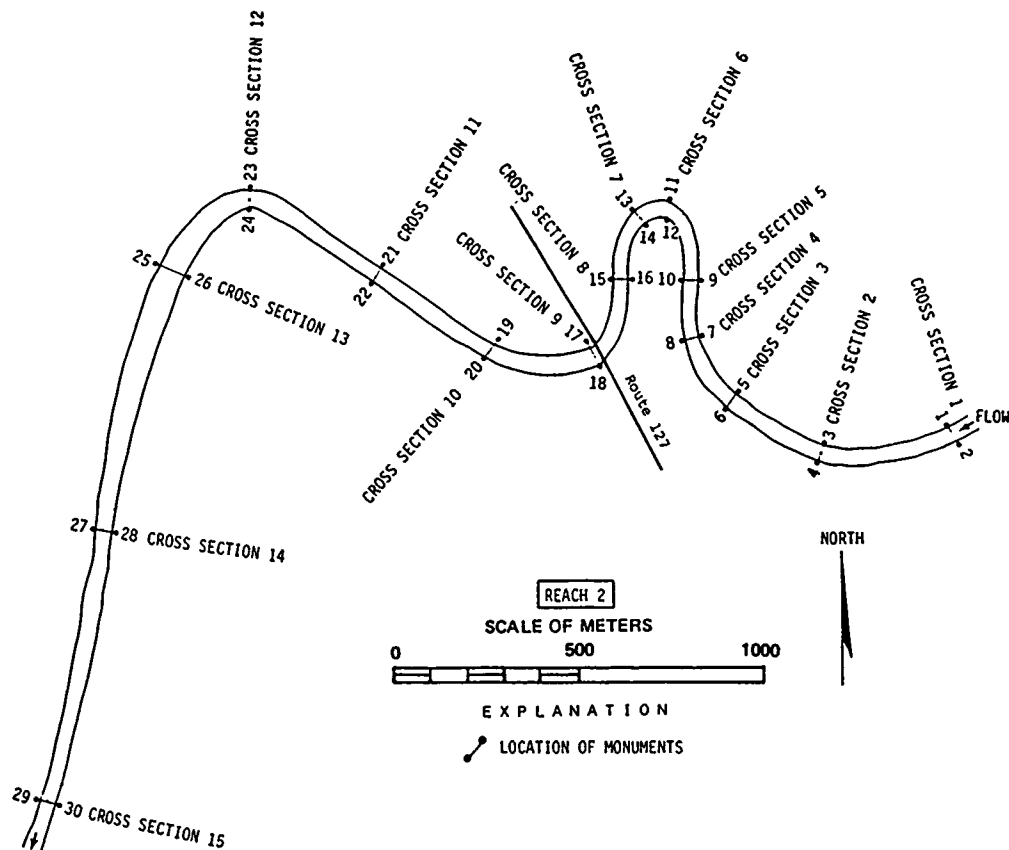


Figure 8. Planform of Reach 2 of the Kaskaskia River (after Bhowmik 1979)

the "main channel." Flow characteristics will be different within these zones, which can create specific types of aquatic habitats.

### Flow Characteristics

38. Reference materials on the hydraulics of flow and its characteristics in a natural river are extensive. The present shape, size, and morphometric features of a water body are the result of all constraints imposed on it by flow, geologic features, man-made alterations, land-use patterns, sediment inflow characteristics, and other physical factors. A detailed discussion of these hydraulic and sediment transport characteristics of an open channel is beyond the scope of this report although more information can be found in Chow (1959, 1964), Einstein (1950), Graf (1971), Simons and Senturk (1977), and ASCE (1975). Bhowmik (1979) and Bhowmik et al. (1986) summarized research conducted on the hydraulics of flow and sediment transport characteristics in open channels.



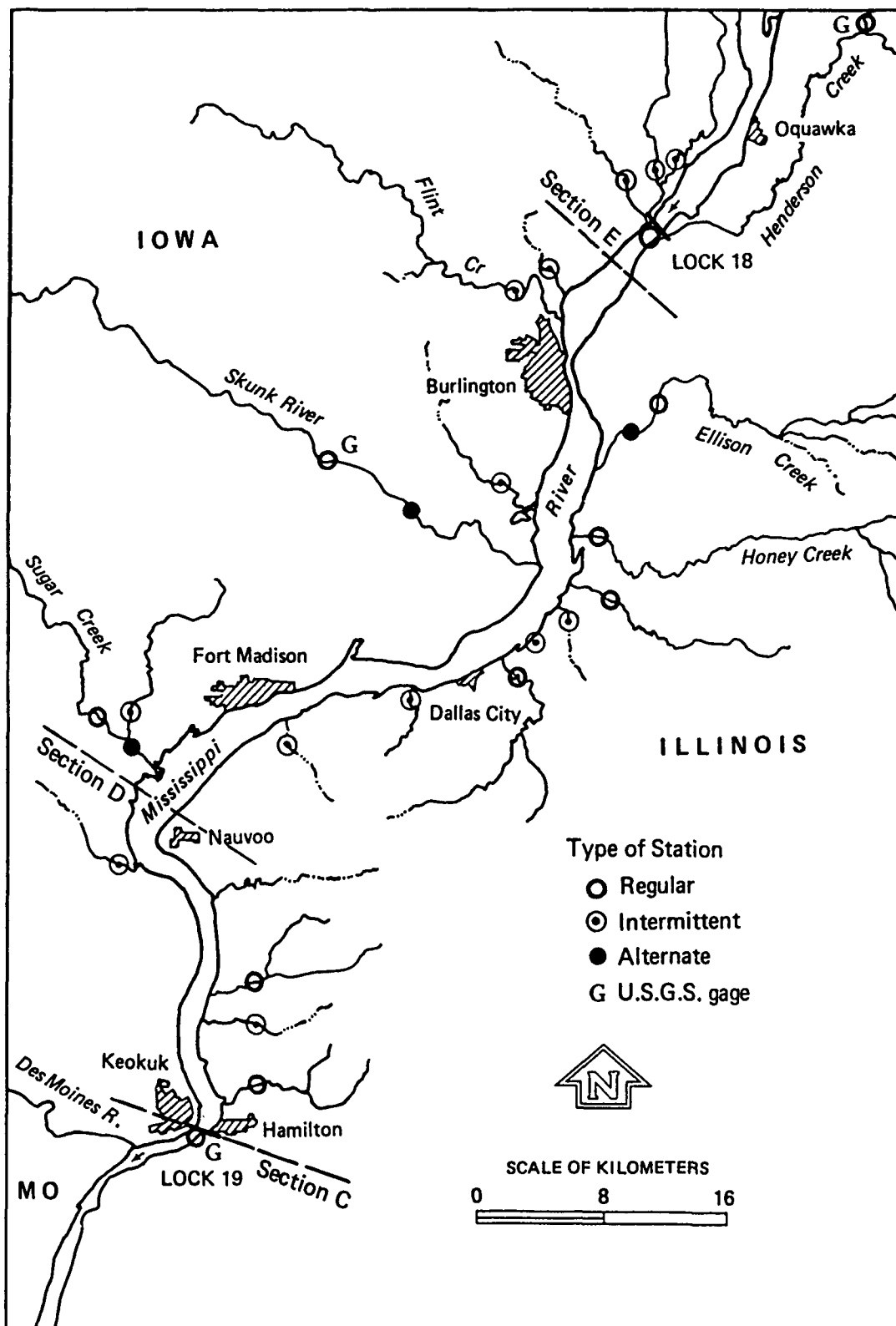


Figure 9. Planform of a reach of the Mississippi River upriver of Lock and Dam 19 (after Bhowmik and Adams 1986)

39. Selection of a site for an evaluation of navigation impacts should be based on historical variation of flow. This will enable a comparative analysis of the study site with similar sites in the basin. Analysis of historical flows requires the development of a flow-duration curve if sufficient gaging records are available. A flow-duration curve depicts the relationship between flows at a certain location and their respective probable frequencies of occurrences. Flows can be ordered either in ascending or descending order. Figure 10 shows flow-duration curves for the Kankakee River at Wilmington (drainage area = 12,823 sq km), the Illinois River near Marseilles and Meredosia (drainage area = 55,188 and 444,185 sq km, respectively) and the Mississippi River at Keokuk (drainage area = 308,210 sq km) and Lock and Dam 26 near St. Louis (drainage area = 444,185 sq km). The purpose of showing these five flow-duration curves is to demonstrate variations from one river to another. The flow-duration curves shown in Figure 10 do not depict the effects of seasonal variability or the changes in flow that occur from one year to another. Therefore, if data are available, an analysis should also be made of the historical changes in discharge. Figure 11 illustrates the results of this analysis for the Mississippi River near Keokuk, Iowa.

40. Flow in a river varies within and between years. Seasonal variations in flow are important in the development of aquatic habitats. Thus, a site evaluation should also incorporate an analysis of seasonal variations (low, medium, and high) in flows as shown for the Mississippi River at Keokuk (Figure 12). The relationship between the ambient and historical flow characteristics when field measurements are made (Figures 10 through 12) will determine if studies were conducted during typical flow conditions.

41. Field sites may not be located near gaging stations; therefore it will be necessary to determine flow where physical effects are to be studied. This is accomplished by obtaining information from a nearby gaging station and transposing it to the study site (Figures 10-12). This can be accomplished by developing a relationship between average flows and basin characteristics (Figure 13).

42. The effects of traffic on the velocity structure at a river cross section should be measured; however, velocities at any point in a vertical, such as at point A in Figure 5, are never constant. A single component of the velocity in the longitudinal direction (the dominant direction of the flow), if measured by a continuously recording current meter, produces a time-series

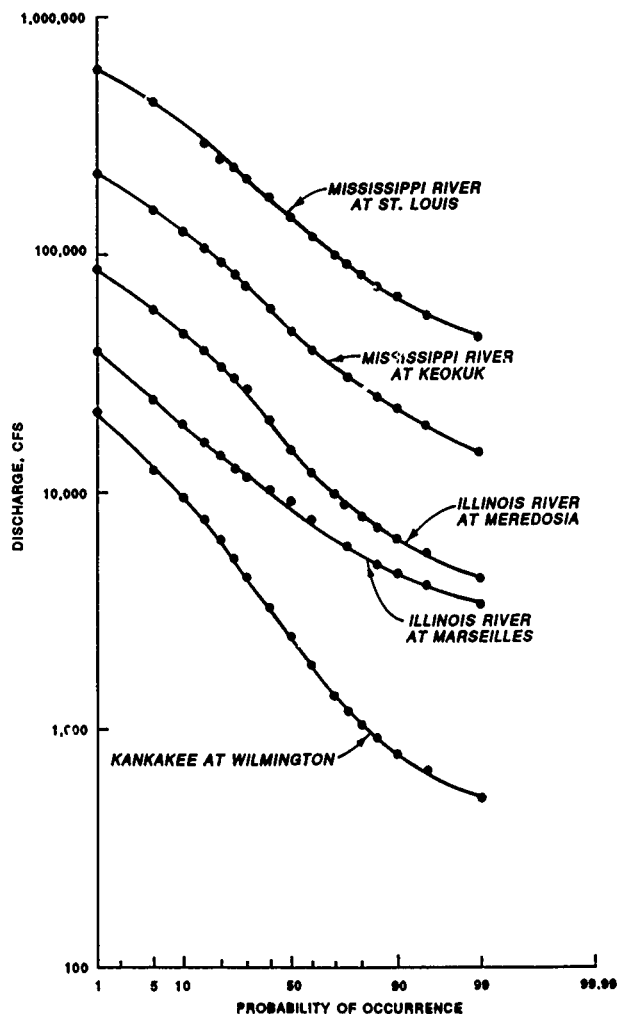


Figure 10. Typical flow duration curves

plot of instantaneous velocity (Figure 14). The velocity data reported in the literature are normally the average at a cross section. Data collected in the field demonstrate that the maximum instantaneous velocity at any point can be from 2 to 3 times greater than average velocities.

43. Measurement of velocities in the field can also be used to predict turbulence intensity. Continuous measurement of the velocity in the longitudinal direction will show a variation similar to that shown in Figure 14. Statistical analysis for any time series includes a determination of the standard deviation,  $\sigma$ , variance, skewness, and kurtosis. Computation of  $\sigma$  is essential for the determination of turbulence intensity, which is defined by the following equation:

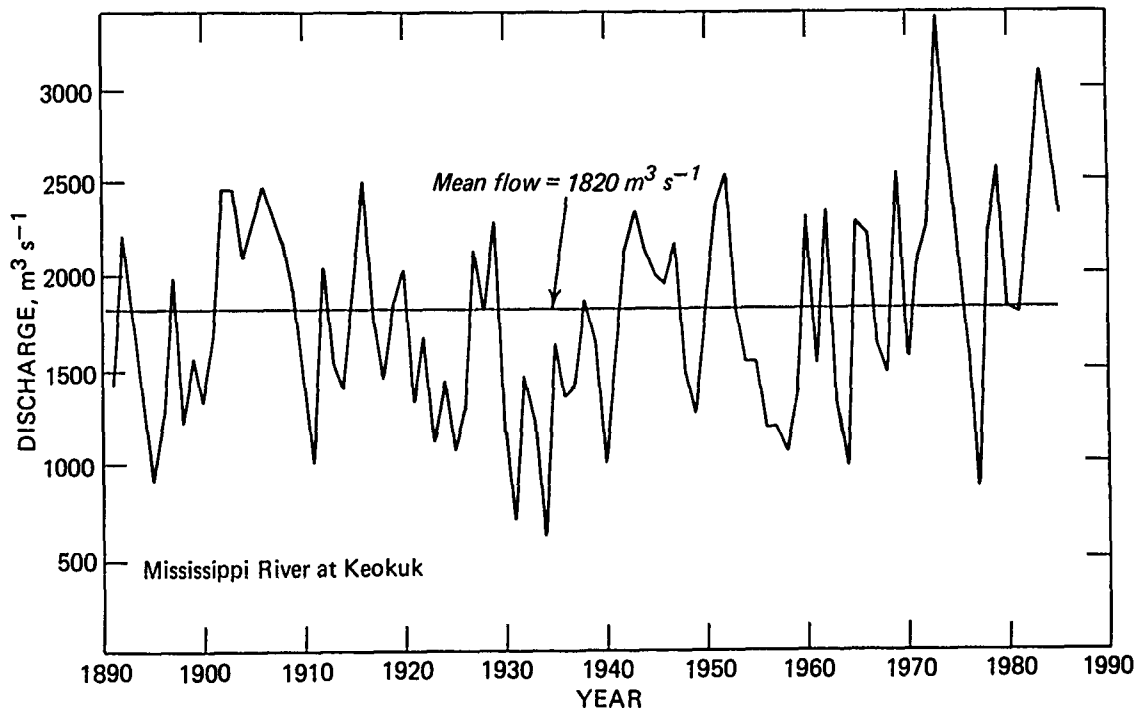


Figure 11. Average annual flows of the Mississippi River near Keokuk, IA

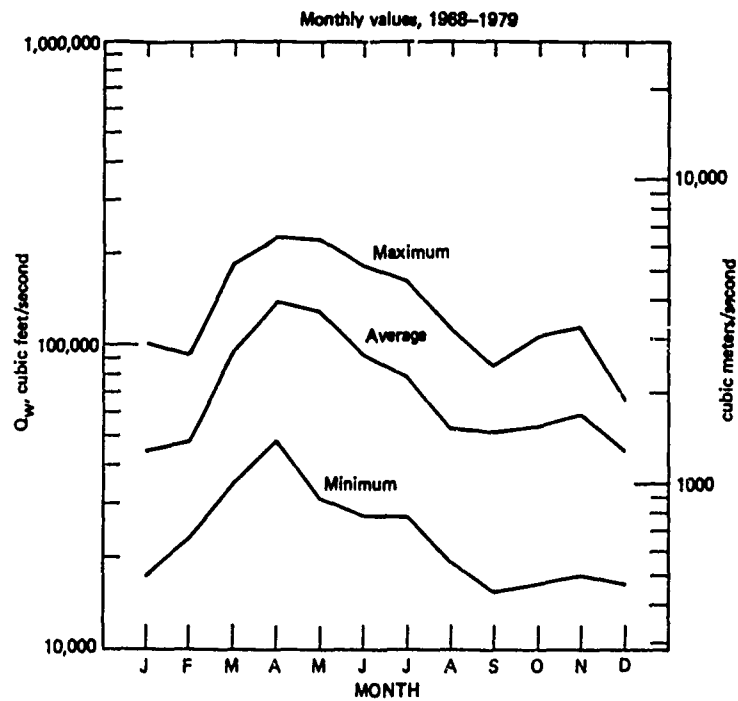


Figure 12. Historical seasonal variation of flow for the Mississippi River near Keokuk, IA

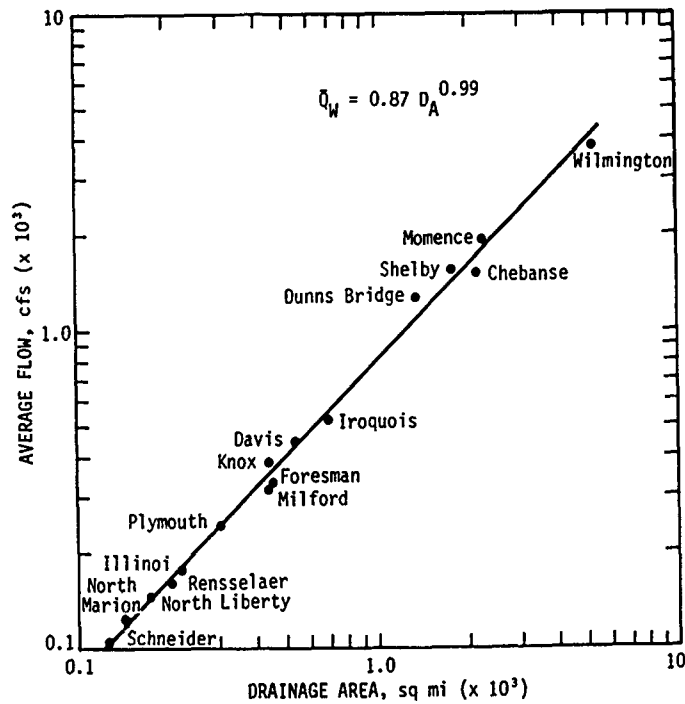


Figure 13. Relationship between average discharge and drainage area for the Kankakee River, IL (after Bhowmik et al. 1980)

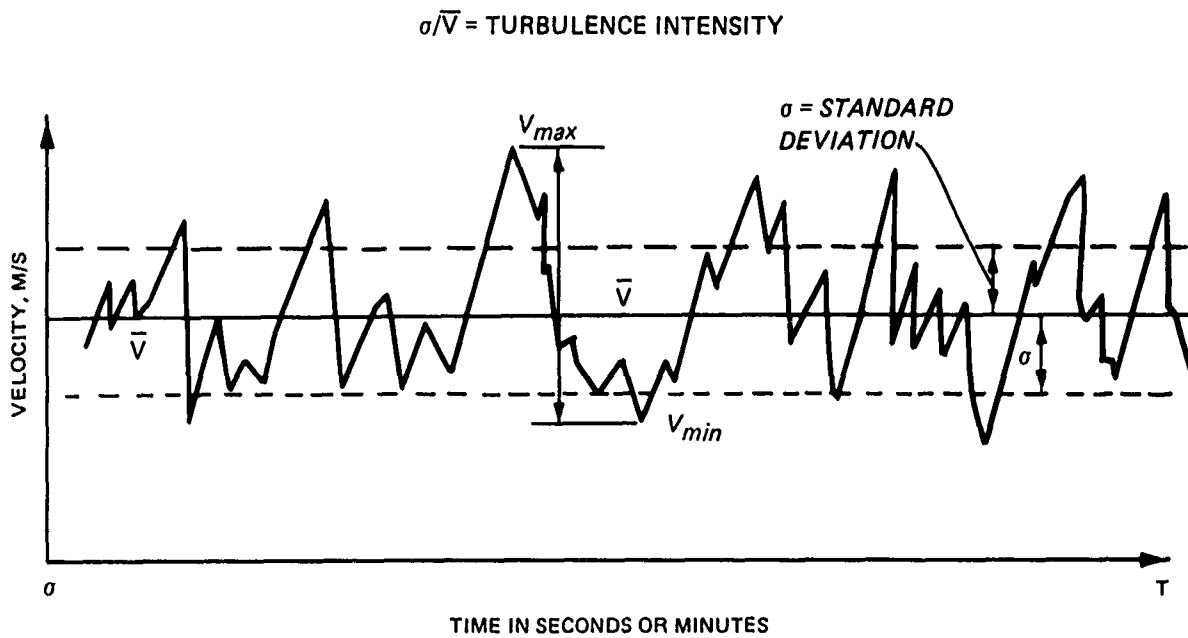


Figure 14. Schematic representation of velocity measured continuously at a point

$$\sigma/\bar{V} = \text{turbulence intensity} \quad (2)$$

where  $\bar{V}$  is the average velocity as shown in Figure 14. Since fluctuating velocity is used as a measure of turbulence, the ratio  $\sigma/\bar{V}$  is used to compute turbulence magnitude. Continuous measurements of velocity coupled with statistical analysis can be used to determine turbulence intensity.

44. Sufficient velocity measurements at points along a vertical such as  $y_1$ -  $y_1$  in Figure 2 can be plotted against depth (Figure 15). Normally the maximum velocity is located near or at the water surface and zero velocity occurs at the substrate-water interface. In large rivers, measurement of velocities closer than a few centimetres from the bed is difficult using available instrumentation. When plotted on semi-logarithm paper, the velocity distribution given in Figure 15 will appear as a straight line (Figure 16). Field data and theoretical analyses have shown that this vertical velocity distribution (from Bhowmik 1979) can be expressed as:

$$u/V_* = 4.65 \log (y/d_{95}) + 3.35 \quad (3)$$

where  $u$  is the point velocity,  $V_*$  is the shear velocity, and  $d_{95}$  is the size of the bed materials at which 95 percent of the bed materials are finer. The above equation is valid for turbulent flows only.

45. Determination of bottom velocity  $V_b$  (Figure 15) is important for the evaluation of biological habitats. Usually  $V_b$  cannot be measured in the field because it is difficult to position the sensor close to the bottom without interfering with water movement. Bottom velocity is normally considered to be about 70 to 80 percent of the average velocity in each vertical. Average velocities in each of the verticals such as those shown in Figure 2 are not the same for all parts of the channel. Thus, a determination of the average velocities across a channel is needed to evaluate habitat along the river cross section.

46. The lateral distributions of the velocities within a straight reach and a curved reach are different. In a straight reach, the lateral distribution of velocity is normally parabolic, with the maximum velocity occurring

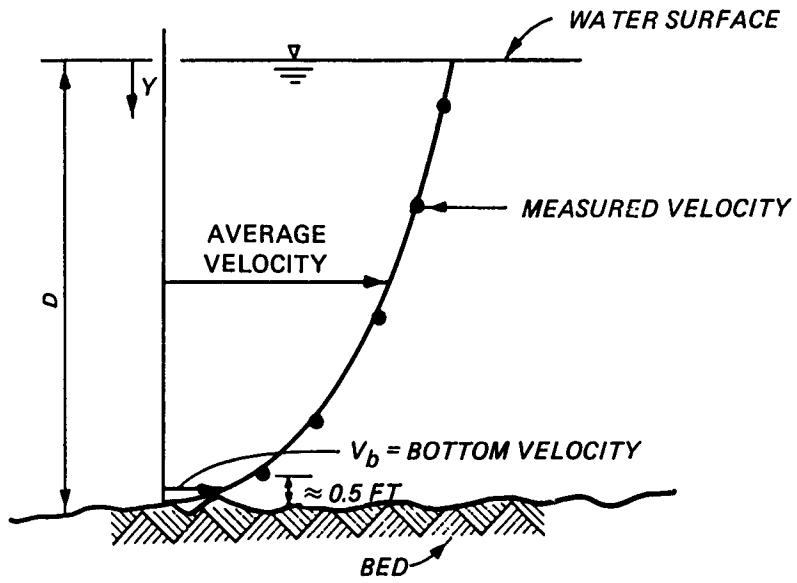


Figure 15. Normal vertical velocity distribution in a river channel

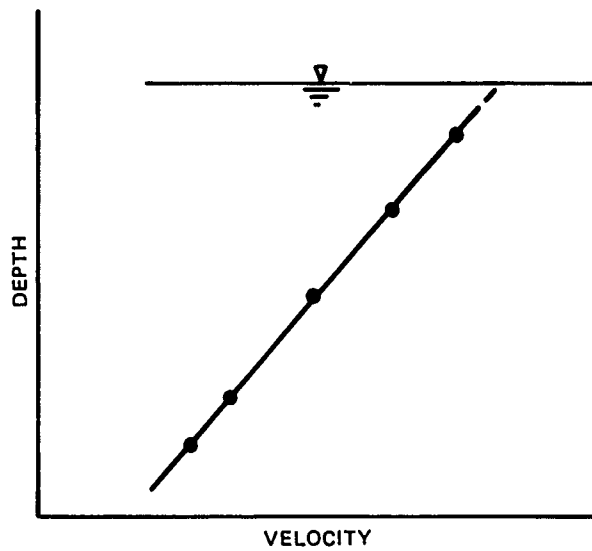


Figure 16. Velocity distribution plotted on semi-logarithmic paper

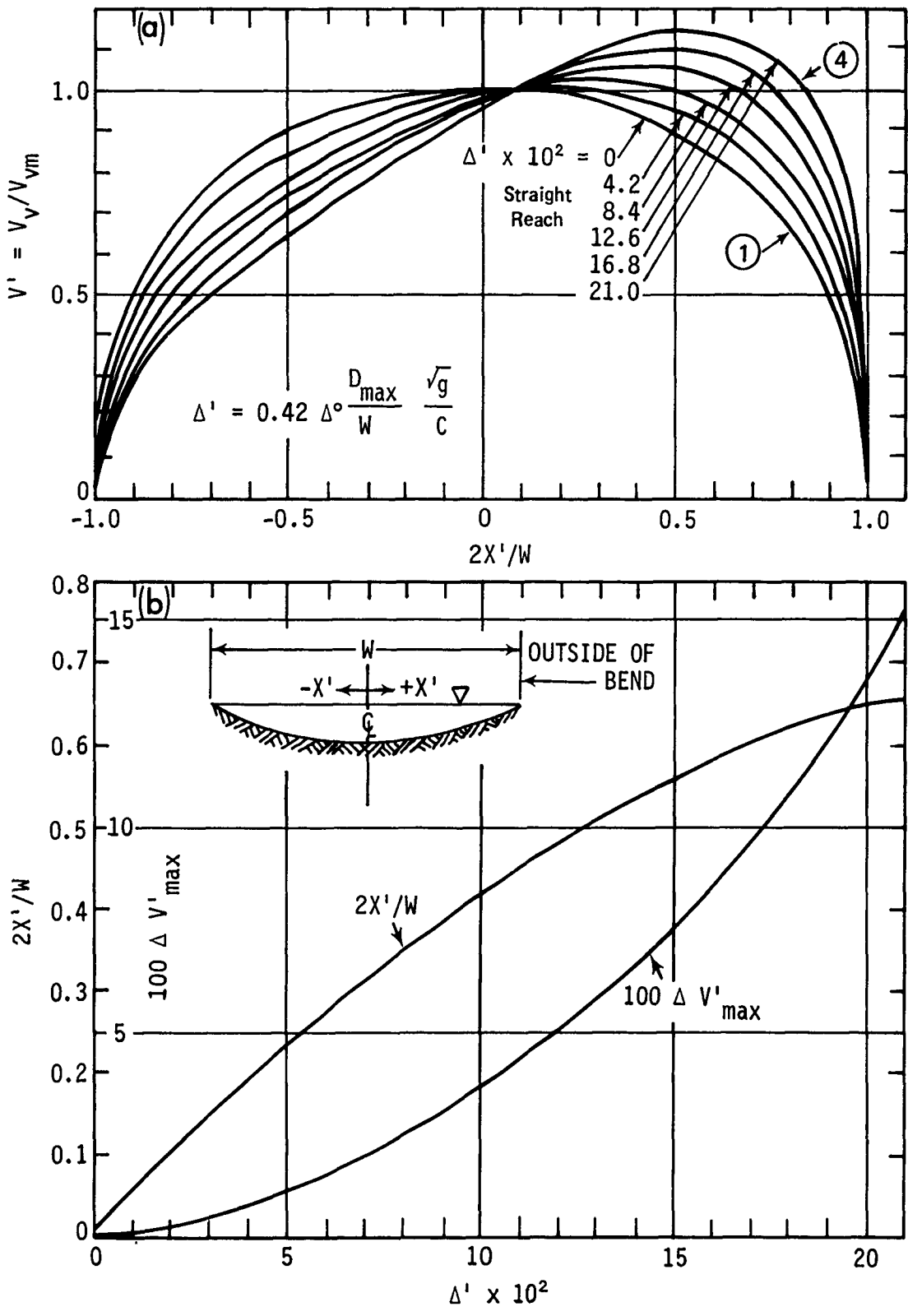


Figure 17. Lateral velocity distribution in a river bend (after Bhowmik 1979)



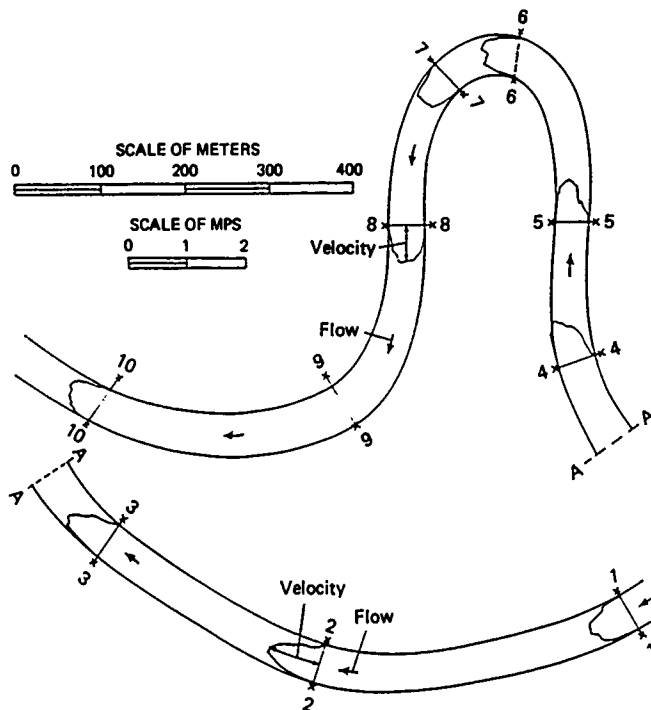


Figure 18. Depiction of velocity distribution in a river bend (after Bhowmik 1979)

near the center of the channel. In a curved reach, the lateral velocity distribution is skewed, with the maximum velocity occurring near the outside of the bend. Such a dimensionless lateral velocity distribution is shown in Figures 17 and 18 (Bhowmik 1979). As the deflection angle of the bend increases from line a-c to b-c (Figure 19), the lateral velocity distribution changes from 1 to 4 (Figure 17a), with the maximum skewness occurring at or near the end of the bend. Therefore, it is imperative that the characteristics of the bends and the associated velocity distributions be determined before a site near a bend is selected for study.

#### Sediment Transport

47. Sediment transported by rivers can be divided into two categories; suspended load and bed load. Suspended load is defined as that sediment surrounded by fluid that stays in suspension for an appreciable length of time. Sediment particles settle because of their weight, but fluid turbulence will resuspend them. Just as there exists an active exchange between bed material and bed load, there is an active exchange between bed load and suspended load.

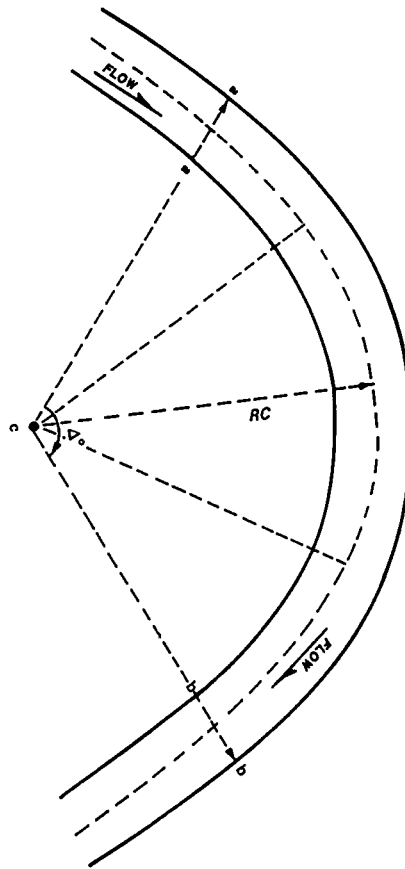


Figure 19. Depiction of river bend characteristics

Figure 20 illustrates bed load, suspended load, and the vertical velocity distribution in a river cross section. Bed load is defined as that sediment in the bed layer moved by saltation (jumping), rolling, or sliding. The bed layer is a flow layer several grain diameters thick immediately above the substrate. The bed layer thickness is usually taken as 2 grain diameters (Einstein 1950).

48. There is no sharp division between saltation and suspension. The distinction is made between the two different methods of hydraulic transport: movement due to shear force, and movement due to suspension (Simons and Senturk 1977). The total load in a river can be determined from the sum of the bed load and the suspended load. Some researchers have attempted to calculate total load directly. The total load that can be predicted is the total bed material load, which is composed of the particles that are found on the bed. The wash load is made up of particles finer than those in the bed and is dependent on the supply available from the watershed. Equipment and

instrumentation that are available for the measurement of bed load and suspended load (to be described later) are capable only of measuring suspended load about 8 cm from the bed. The bed load sampler that is presently available (Helley and Smith 1971) is the only equipment suitable for measuring coarse-grained bed loads.

49. The suspended sediment concentration in a river normally varies in such a way that the highest concentration is located close to the bed, and the lowest concentration is close to the surface (Figure 20a). In some instances, the vertical concentration profile has been shown to vary uniformly over the whole depth of flow. The sediment load ( $Q_s$ ) transported by any river is computed by multiplying the sediment concentration ( $C_s$ ) by water discharge (velocity ( $V$ ) times area ( $A$ )), and a coefficient to convert final values into tons per hour or day (Bhowmik et al. 1980, Figures 20b and 20c). For further description and evaluation of this procedure, the reader is referred to publications by ASCE (1975), Simons and Senturk (1977), and Bhowmik et al. (1980) and to the description later in this report.

50. Suspended sediment load transported by a river at any point in a vertical is not steady or constant, but varies with time and within the cross section. Figure 21 shows a hypothetical fluctuating sediment concentration plot typical of any large river cross section. A time-averaged and depth-averaged suspended sediment sample will integrate this variation and produces an acceptable and fairly accurate determination of the suspended sediment load within a cross section. The suspended sediment load carried by a river varies not only during storm hydrographs (Figure 22; Makowski, Lee, and Grinter 1986), but also during the year (Figure 23; Demissie, Bhowmik, and Adams 1983). This variation makes it imperative that a well-planned data collection program be developed to determine the changes in suspended sediment loads associated with the movement of the navigation traffic.

51. In addition to the physical flow parameters that impact the suspension and transport of sediment particles such as water discharge, channel width and depth, bed roughness, fall velocity, and size and shape of the particles, another important factor that should be considered is ambient water temperature. Water temperatures in most navigable rivers in the United States vary among years and seasons (see Figure 24 for the Illinois River at Havana, from Kothandaraman and Evans 1973). Lower temperatures increase the viscosity of the water and enable the same flow to transport higher percentages of suspended sediment than during higher temperatures. Therefore, data collection

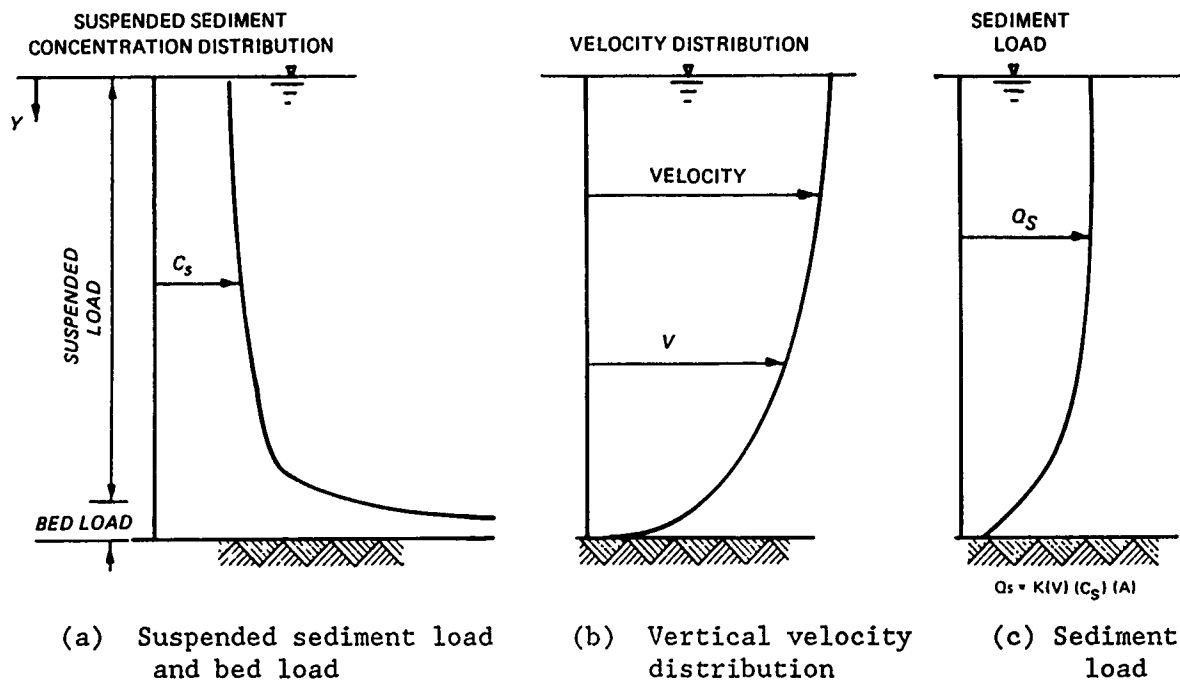


Figure 20. Vertical distribution of selected physical parameters with respect to depth in a river

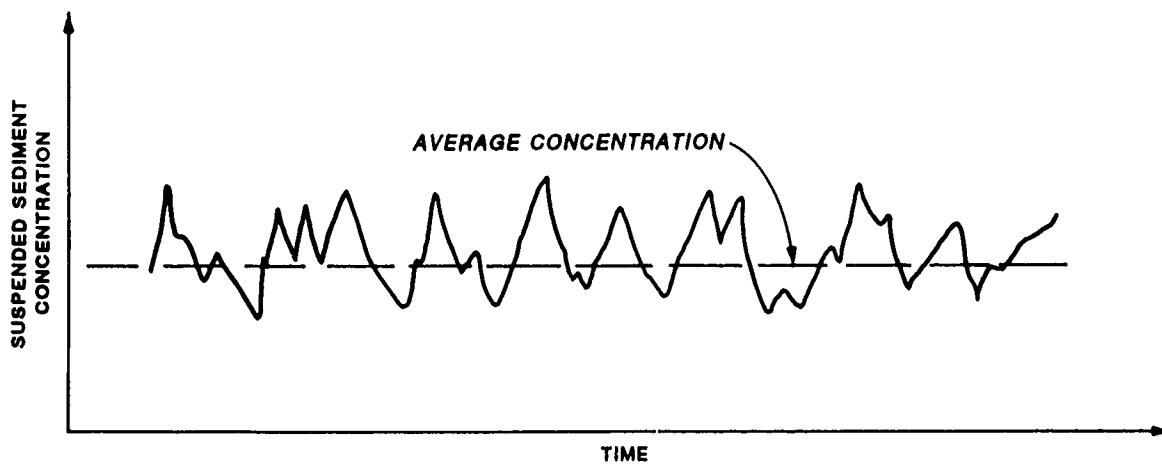


Figure 21. Changes in suspended sediment concentration with time

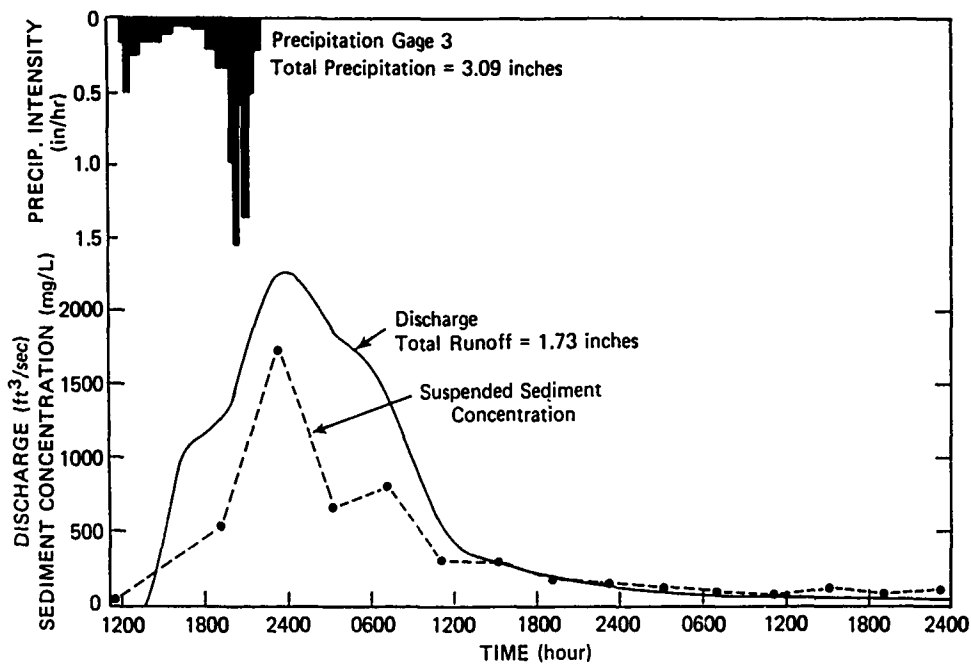


Figure 22. Changes in suspended sediment load during a storm (after Makowski, Lee, and Grinter 1986)

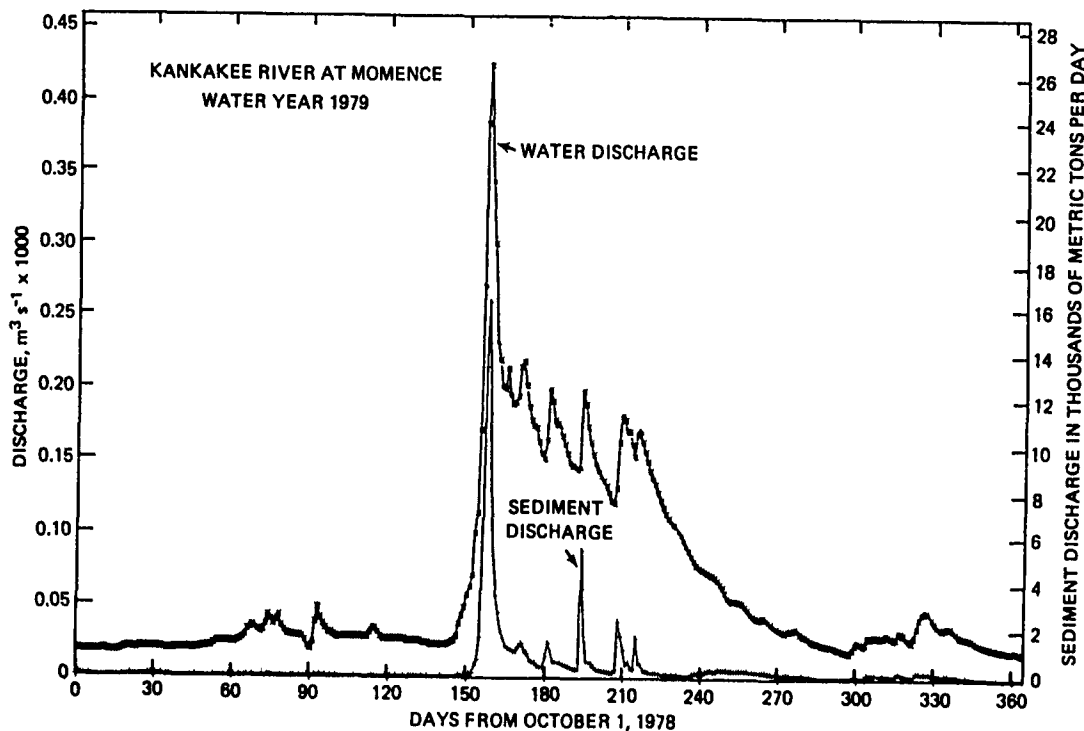


Figure 23. Annual variation in suspended sediment load for the Kankakee river at Momence, IL (after Demissie, Bhowmik, and Adams 1983)

programs should consider the impacts of ambient water temperatures on sediment transport characteristics.

### Vessel-Induced Effects Versus Natural Effects

52. The general nature of the flow field around a barge tow or other vessel was described by Karaki and Van Hoften (1974). Figure 25 shows the patterns that are generated around and under a barge for typical deep, normal, and shallow water flows. Not only does the field change near the barge, but the movement accelerates flow below the main body of the barge. The amount of this acceleration will be greatest when water depth is shallow relative to vessel draft.

53. Detailed flow field around a moving vessel is given by Blaauw et al. (1984) and an illustration of this flow field is shown in Figure 26. Movement of the tows can generate bow, stern, and transverse waves, drawdown, return flow, slope supply flow, and propeller wash. All of these physical alterations in the flow field can impact the bed and bank of the waterway by displacing or rearranging bed and bank materials and temporarily increasing the suspended sediment concentrations and turbidity.

54. Field data collection programs must ensure that proper techniques are used to separate the effects of navigation traffic from the normal flow and sediment transport characteristics of the river. Depending upon the relative blockage of the navigation channel, the size and speed of tows, and the distance and speed of the traffic, the traffic in a navigable channel will alter the near flow field. The alterations will include an increase in the suspended sediment concentration and a change in the velocity structure (Environmental Science and Engineering 1981; Johnson 1976; Bhowmik et al. 1981a; Bhowmik, Demissie, and Osakada 1981; Bhowmik et al. 1981b).

55. Separation of navigation-induced impacts such as the alteration of the velocity structure or an increase in the suspended sediment concentration will require the collection and analysis of data on velocity and suspended sediment concentration before, during, and after vessel passage. Figure 27 shows a set of velocity data that was collected with two Marsh-McBirney current meters placed at a distance of 12 and 72 m from the shore in Pool 26 of the Illinois River (Environmental Science and Engineering 1981). The

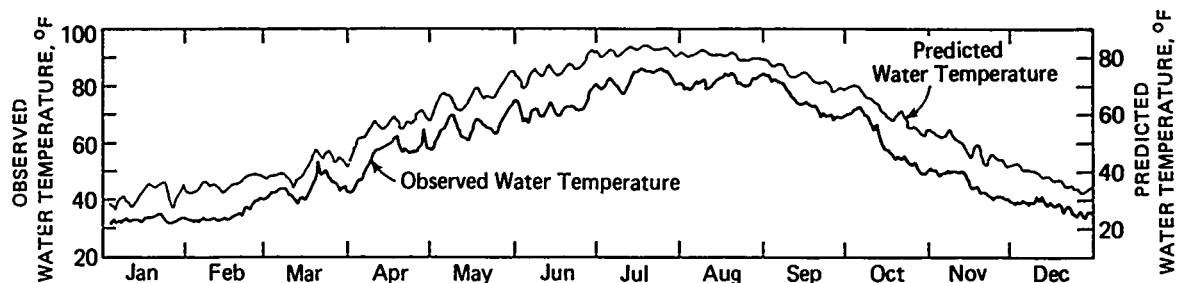


Figure 24. Annual fluctuation in water temperature in the Illinois River near Havana, Il (after Kothandaraman and Evans 1973)

sailing line was approximately 177 m from shore and the meters were placed approximately 30.5 cm above the riverbed. An examination of these two velocity vector lines for two separate tow events and also for the 8-min time span from point A to B (Figure 27) shows that the impact of the tow lasted for approximately 5 to 6 min. Thus velocity data collected at fixed locations before, during, and after the passage of tows or recreational vessels can be used to determine the effects of the tow movement on velocity structure. Two or more meters may be needed to determine the areal extent of the velocity changes at or within specific habitats. Illustrations similar to Figure 27, as well as statistical analyses, may be needed to separate the impact of vessel movement from ambient conditions.

56. The effects of commercial or navigational traffic on suspended sediment can be determined by collecting suspended sediment samples at selected locations throughout the day. These data should be obtained when a vessel passes the site. Figure 28 shows a plot of depth-integrated suspended sediment concentration data for September 23, 1980, at Hadley's Landing on the Illinois River, RM 13.2 (Bhowmik et al. 1981a). Whenever a tow passed the site, there was a brief lag, then sediment concentration increased over the ambient level. This was maintained briefly, then the concentration declined. This increase in suspended sediment concentration can be seen, although there is normal fluctuation in ambient sediment concentrations.

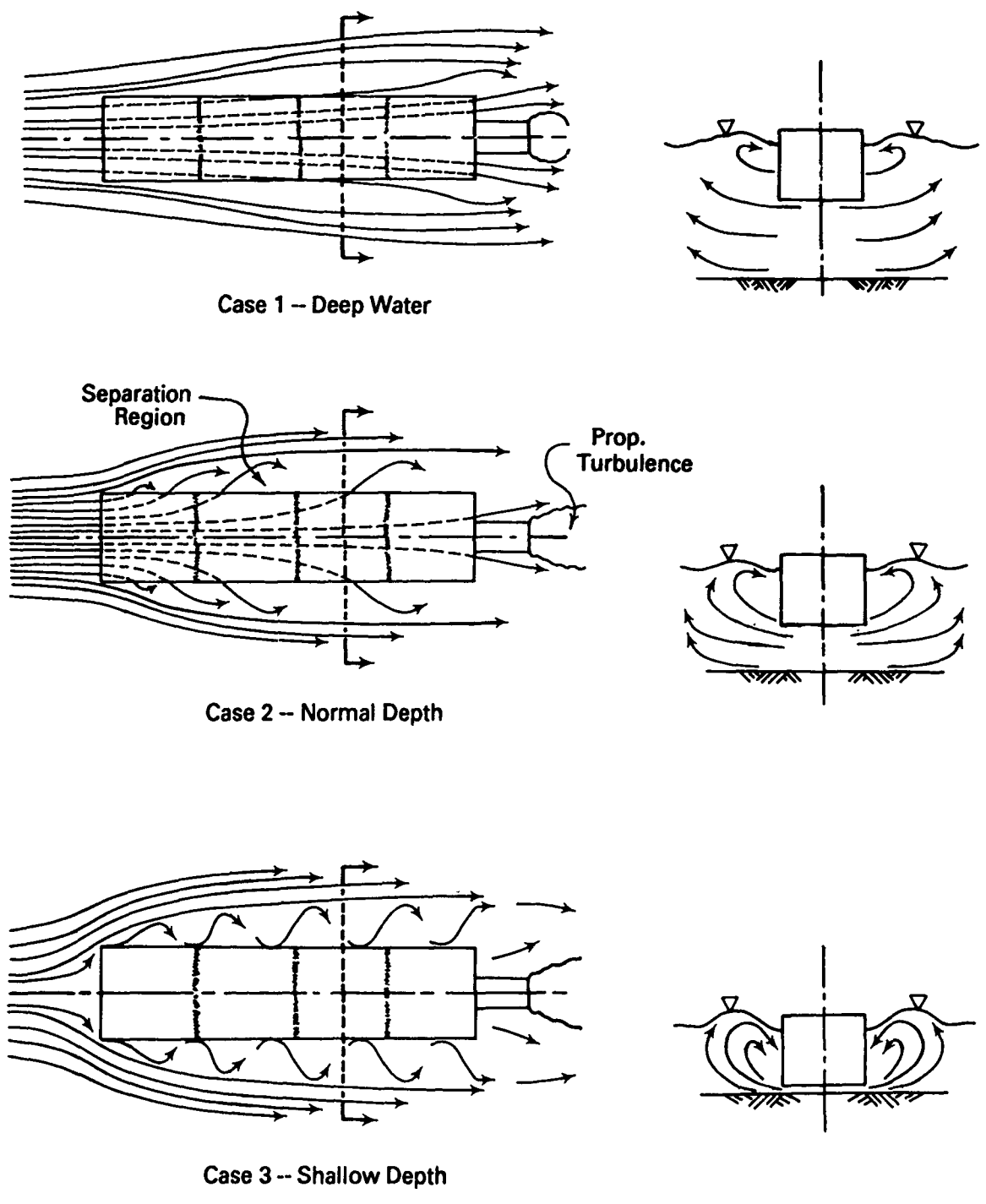


Figure 25. Flow and turbulence created by towboats (after Karaki and Van Hoften 1974)



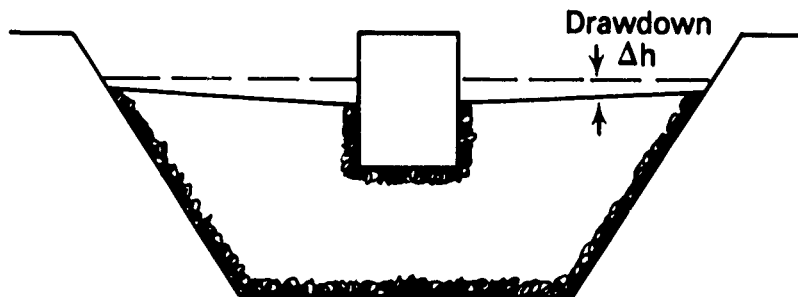
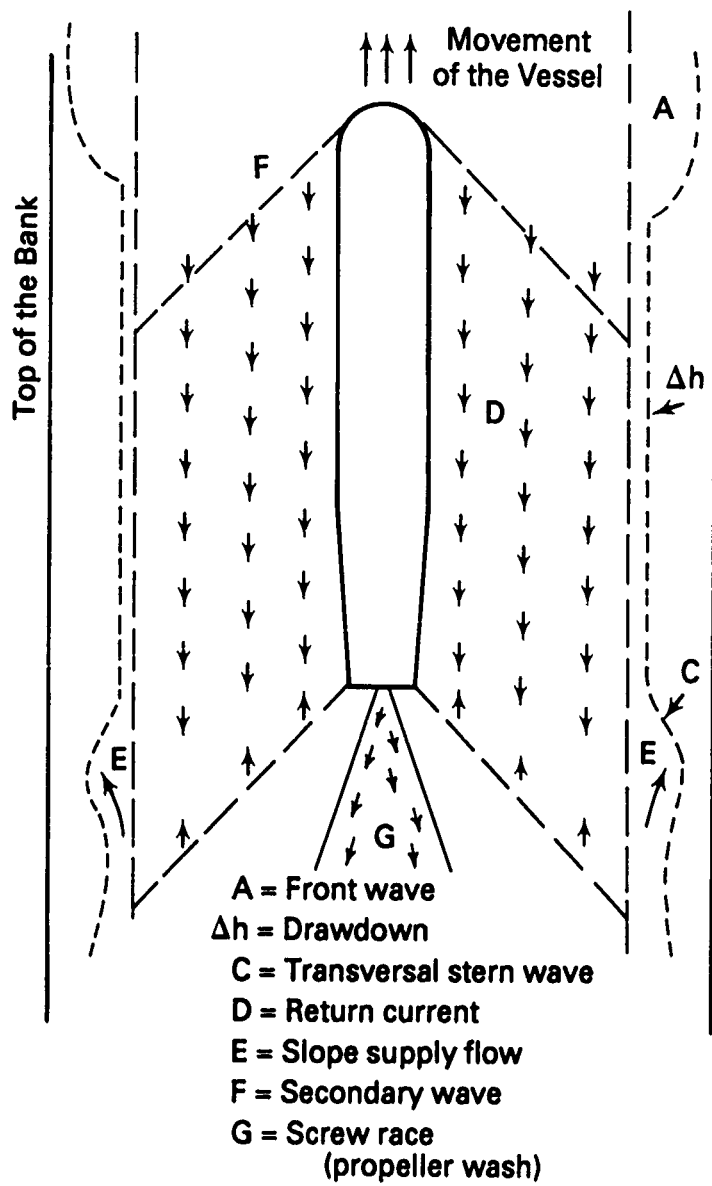


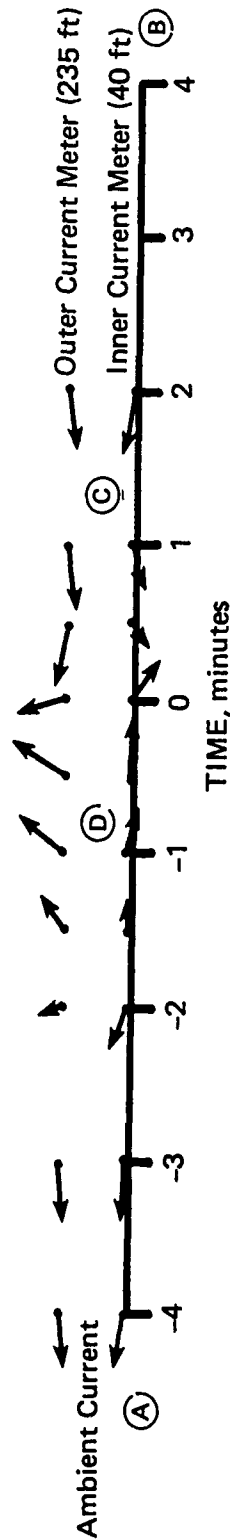
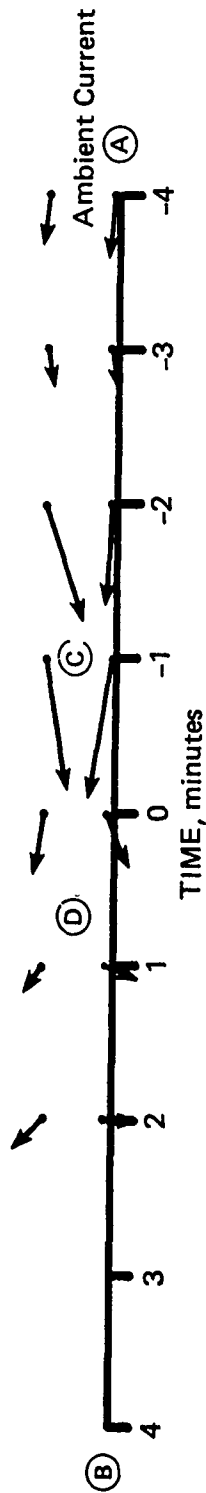
Figure 26. Schematic diagram showing water motion generated by a moving ship (after Blaauw et al. 1984)

0 FEET 500 (for tow speed of 8.3 ft/sec)

0 0.5 1.0  
SPEED (ft/sec)

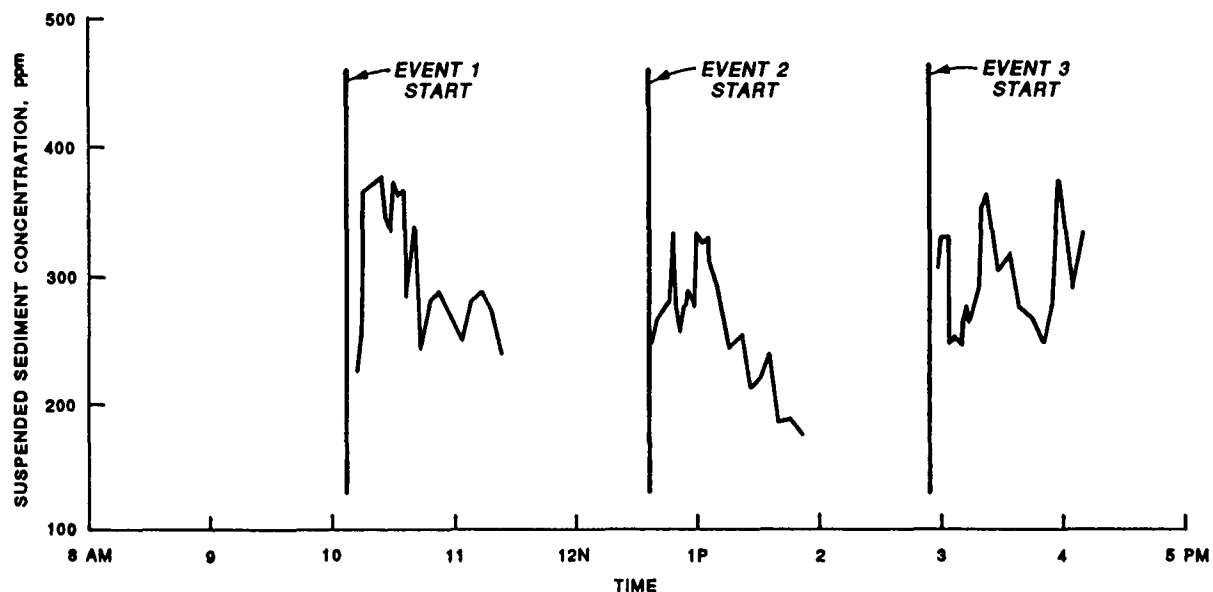
(C) Convergent Zone

(D) Divergent Zone



NOTE: The towboat crossed the instrument line at time 0.

Figure 27. Velocity vectors for Pool 26 during upstream (tow 26) and downstream (tow 23) passages (after Environmental Science and Engineering, Inc. 1981)



Note: Event 1 = four barges with a draft of 2.75 m moving upstream.

Event 2 = six barges with a draft of 2.75 m moving downstream at a speed of 9.0 km/hr.

Event 3 = four barges with a draft of 2.75 m moving upstream at a speed of 6.4 km/hr.

Figure 28. Suspended sediment concentrations versus time for tow passage at Hadley's Landing (RM 13.2 on the Illinois River, September 23, 1980)

## PART III: INITIAL CONSIDERATIONS

### Objectives

57. Selection of study sites to evaluate physical effects of navigation traffic should be based on a clear set of objectives. Obviously, there are many objectives that could direct a study of the physical effects of commercial traffic. Possible objectives of navigation effects studies may include:

- a. Determine the quantity of sediment resuspended.
- b. Quantify the lateral transport of sediment.
- c. Determine sedimentation rates at sensitive habitats.
- d. Evaluate scour and disruption of substrates.
- e. Determine altered velocity regimen, including increased turbulence intensity and reversal of flows.
- f. Determine shear force at or near the channel border using indirect methods.
- g. Measure wave heights, wave wash, and drawdown.
- h. Determine water quality parameters at or near sensitive areas.
- i. Determine pressure fluctuations at or near sensitive habitats.

### The Need for Site-Specific Studies

58. Two approaches are possible in designing studies to investigate the physical and biological effects of commercial navigation traffic. In one approach the investigator may wish to determine the general effects of a specified increase in commercial traffic throughout a river reach. There might be concern that an increase in tow traffic could affect the riverine ecosystem, which includes not only important wetland, shoreline, and slack-water habitats, but significant resources such as mussel beds, fish larvae, aquatic insects, worms, and submersed aquatic plants. Although system-wide concerns may be justified, these types of studies are time-consuming and expensive. Ecosystem processes and effects must be studied over a long period of time, usually 20 or more years (Bhowmik 1987b).

59. It is more realistic to identify sensitive resources in a river reach that possess value for wildlife and are likely to be affected by commercial or recreational traffic. Valuable areas (such as those indicated in

Figures 29 and 30) can be identified from maps, aerial photographs, ground-truthing, and background information. Such areas may include backwaters, wetlands, channel borders, island braided areas, confluences of the main river with its tributaries, or vegetated banks protecting bottomland forests. If many sensitive areas exist, then habitats can be categorized and ranked. Existing habitat evaluation methods (i.e., the Habitat Evaluation Procedures of the US Fish and Wildlife Service) can be used to place a value on aquatic or terrestrial habitats.

60. Once important sites have been identified, specific studies should be conducted to evaluate the distribution and condition of sensitive populations likely to be affected by passing tows. Biological factors such as mortality, density, species richness, relative abundance, and evidence of recent recruitment should be determined. These can be related to physical effects of traffic such as increases in suspended sediment concentration, resuspension and lateral movement of sediment, scour and deposition, changes in turbidity, alteration of velocity vectors (Figure 27), changes in turbulence intensity, drawdown exposure, and changes in water and sediment loads. Long-term monitoring could also be conducted at sites where traffic levels are predicted to change.

61. Important criteria in determining the value of a habitat include sinuosity, curvature, and deflection angles of the bends (Figure 1). These attributes can affect flow, secondary circulation, lateral distribution of velocity, suspended sediment characteristics, and water depth, which are all related to habitat value. In addition, cross-sectional shape of the river, historical sedimentation patterns, stability of banks, presence of submersed or emergent aquatic vegetation, standing timber, or logs, substrate heterogeneity and characteristics, presence of inflowing rivers or springs, and stability of adjacent terrestrial vegetation and soils are important habitat features. Large habitats with extensive littoral zones should be considered more valuable than small, isolated areas. Consideration should be given to the value of habitats as spawning, nursery, or feeding sites for migratory fish and waterfowl.

62. The results of research conducted at a specific site having representative physical and biological features of the entire system can, to some extent, be applied for a selected portion of the system. However, caution must be exercised in extrapolating site-specific findings to an entire river system.

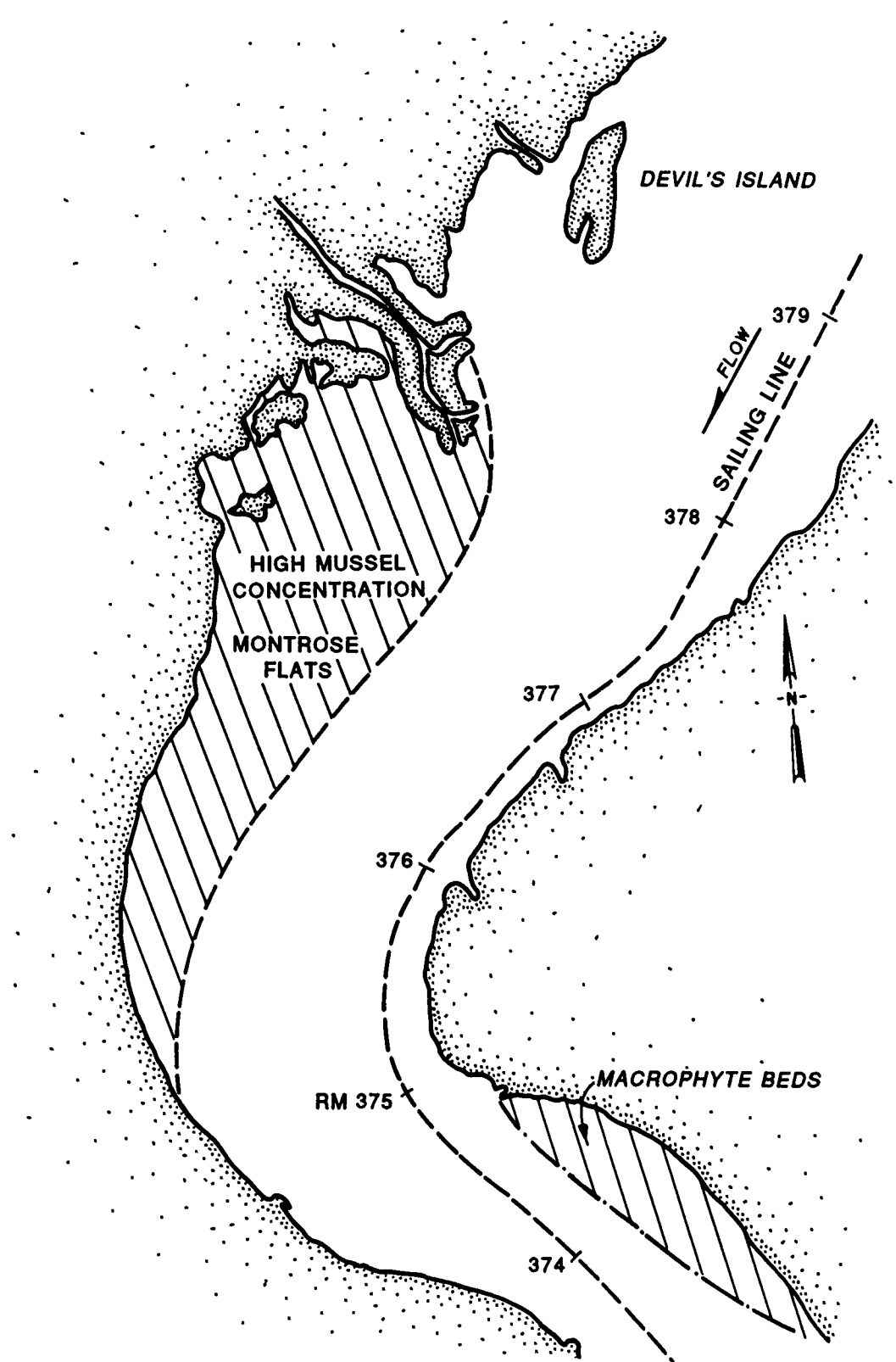
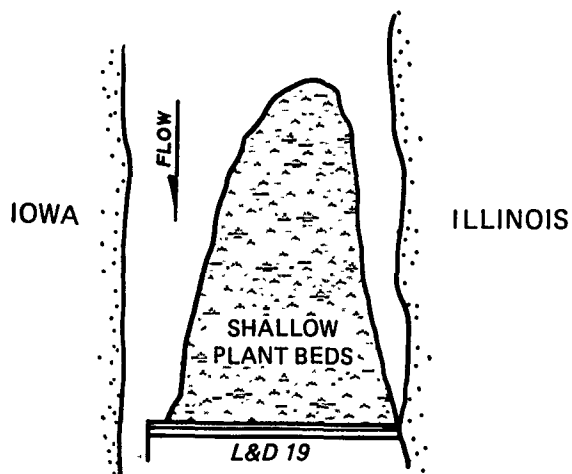
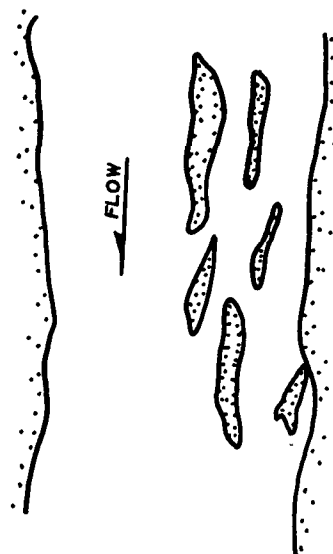


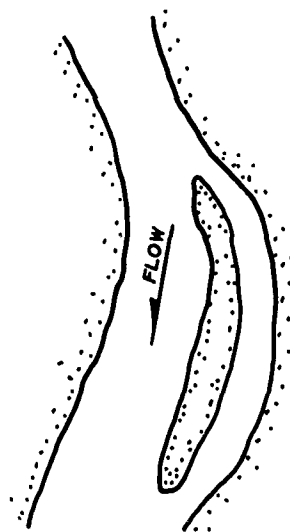
Figure 29. Major biological areas on the Mississippi River, RM 374-379



MISSISSIPPI RIVER



MISSISSIPPI RIVER  
BRAIDED ISLAND AND  
SIDE CHANNEL



ILLINOIS RIVER



ILLINOIS RIVER  
PEORIA LAKE

Figure 30. Plant beds and islands on the Mississippi and Illinois Rivers

63. Data collected from a river reach should be extrapolated to a similar reach with caution. Factors such as similar width-to-depth ratios, similar bed and energy slopes, curvatures, sinuosities and deflection angles, comparatively similar velocity distributions, and substrate composition and distribution are some of the important physical factors that must be considered before site-specific findings can be extrapolated to other sites.

64. Another technique that can be used in applying the results from one site to another is the development, calibration, and verification of physically based analytical models. After such model development has been completed, models can be applied to other sites to develop a conceptual analysis of the system. However, normally the application of the models is site-specific, and caution must be exercised before such analysis is carried too far.

### Site Selection

65. Once objectives have been established, the investigator needs to decide whether studies should be conducted at a single site or multiple sites. If the objectives are to obtain information on the physical effects of vessel passage, then the physical and morphometric characteristics of the entire river are important. However, when a single site must be evaluated, the physical, biological, and hydraulic characteristics of that site should be emphasized. An accurate assessment of these factors will enable extrapolation to other similar sites.

### Existing Physical and Hydrologic Characteristics

#### Physical characteristics

66. Once a site has been selected, the following steps should be performed (Figure 31):

- a. Measure river cross sections at a sufficient number of range-lines (Figure 31a) using standard sounding techniques.
- b. Develop cross-sectional profiles similar to sections A-A and B-B on Figures 31b, 31c.
- c. Compute cross-sectional area (A) and average depth (D) as follows (also see Figure 31b):



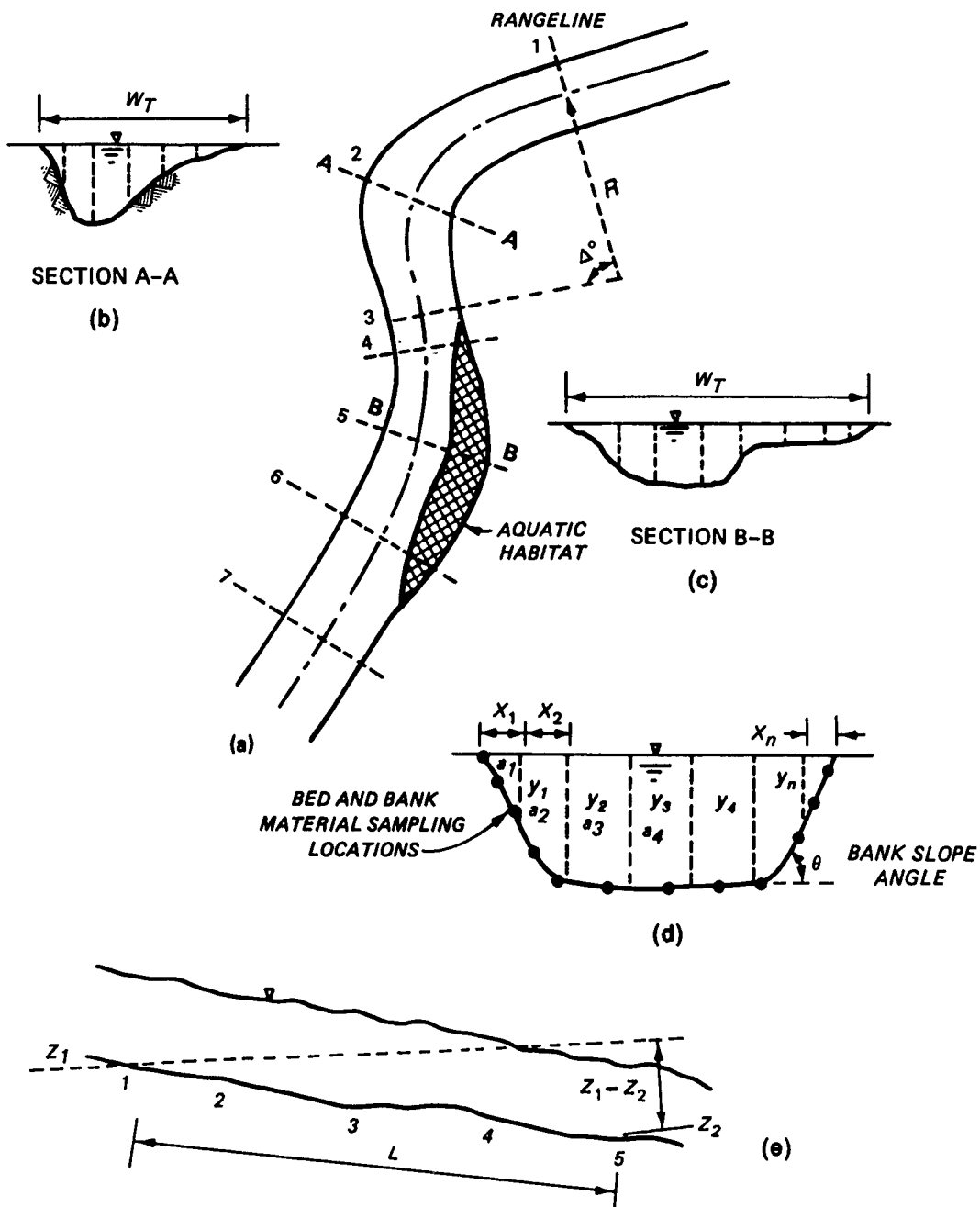


Figure 31. Typical river cross section

$$A = (1/2 x_1 y_1) + [y_1 + y_2 / 2] (x_2) + [(y_2 + y_3 / 2] (x_3) + \dots$$

$$\dots + 1/2 (x_n) (y_n)$$

$D = A/W_T$ , where  $W_T$  is the top width of the channel.

- d. Determine the width-to-depth ratio ( $W_T/D$ ).
- e. Determine from existing maps or field measurements the relative location of each rangeline (for example, rangelines 1 through 7, Figure 31a), the radius of curvature  $R$  (Figure 31a), and deflection angle ( $\Delta$  deg, if a curve is present within the study reach). Prepare a planform map of the reach (see Figure 31a).
- f. Determine the extent of the habitat (Figure 30 or Figure 31a) by planimetry of a map of the area.
- g. Determine the average depth of the aquatic habitat (Figure 31a) by dividing the volume of the habitat by the surface area.
- h. Collect bed and bank material samples at sufficient locations along and across the rangelines with sufficient resolution to characterize aquatic habitats (Figure 31d).
- i. Analyze the bed and bank material samples to determine physical characteristics such as particle size distribution (Figure 32). The formula for standard deviation is:  $\sigma = 1/2[(d_{84.1}/d_{50}) + (d_{50}/d_{15.9})]$ , where  $d_{84.1}$ ,  $d_{50}$ , and  $d_{15.9}$  are the sizes of the bed materials at which 84.1, 50, and 15.9 percent of the particles are finer than these respective sizes.
- j. Compute the uniformity coefficient with the following formula:
 
$$U = d_{60}/d_{10}$$
- k. Measure the bank slopes ( $\theta$ ) at selected rangelines (Figure 31d).
- l. Determine the thalweg profile and the average gradient of the river as follows (see also Figure 31e):  $S_o = (Z_1 - Z_2)/L$ , where  $S_o$  is the bed gradient of the river at the site and  $L$  is the thalweg distance between rangelines 1 and 5 or the selected interval.

#### Hydraulic characteristics

67. Hydraulic characteristics should be determined using the following steps:

- a. Measure point velocities at sufficient verticals (normally 20 to 25 verticals; see Figure 31d) to compute the average discharge at the cross section as follows:

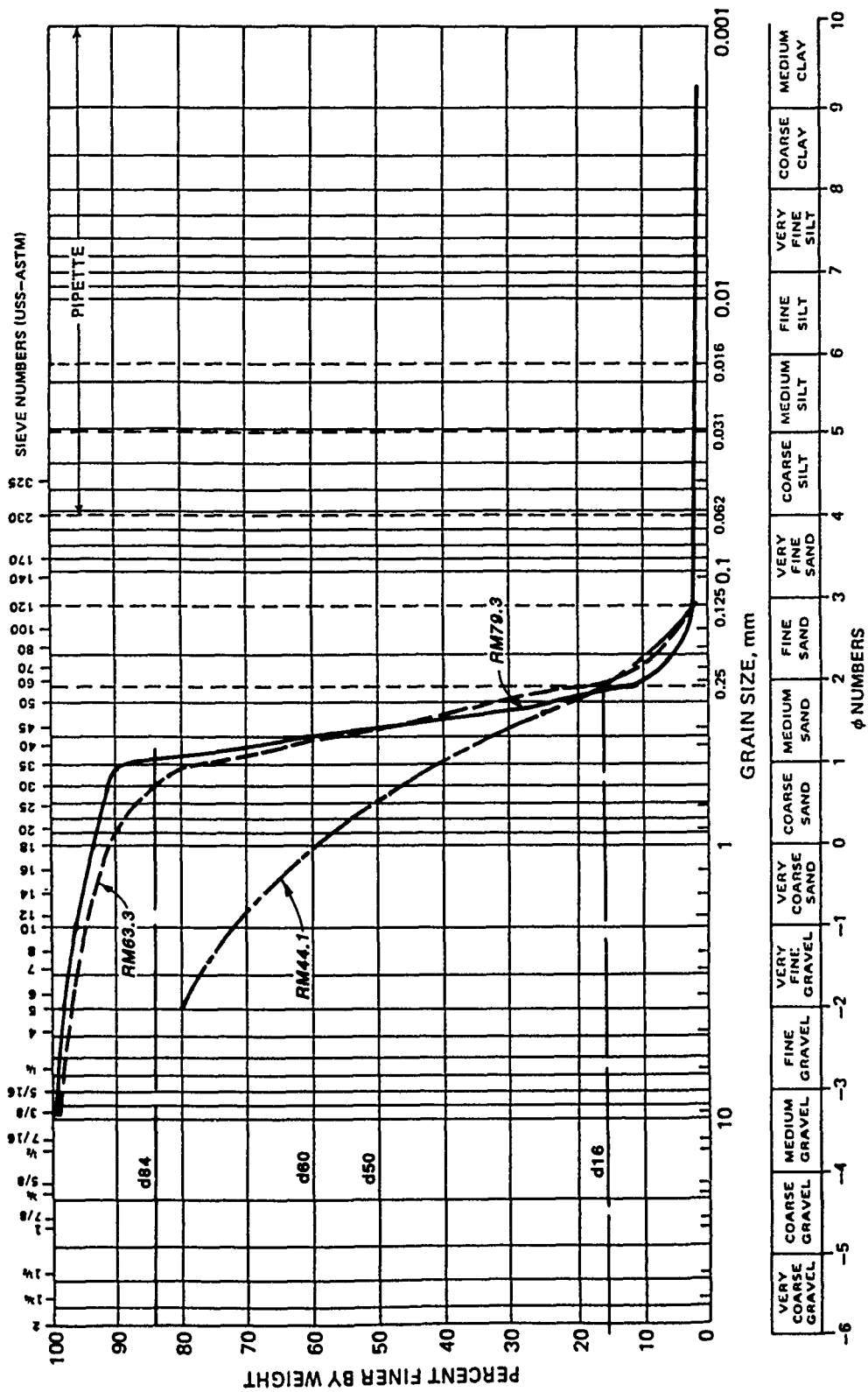


Figure 32. Typical sieve analysis of substrates in the center of the Illinois River for RM 44.1, 63.3, and 79.3

$$Q_w = 1/2(v_1 a_1) + 1/2(v_2 + v_3) a_2 + 1/2(v_3 + v_4) a_3 \dots \quad (6)$$

$$\dots + 1/2 v_n a_n$$

where

$v_1, v_2, \text{ etc.}$  = average velocity at respective verticals

$a_1, a_n, \text{ etc.}$  = cross-sectional areas between various verticals

$Q_w$  = total discharge at the cross section.

- b. Develop a flow-duration curve and a historical seasonal flow variation curve for the site (see Figures 10 and 12, respectively).
- c. Determine the flow duration of the frequency of the measured discharges by using the flow-duration curve. In addition, compare the magnitude of the flow at the time field data were collected to historical data.

#### Areas With Biological Importance

68. The borders of navigation channels, where water depth usually does not exceed 3 or 5 m, frequently support emergent vegetation and have extensive depositional zones suitable for freshwater mussels, burrowing mayflies, and other aquatic invertebrates. However, physical effects studies may have to be conducted at other reaches more suitable for physical effects studies. Usually the main channel is less valuable for aquatic organisms since it is subjected to high velocities and turbulence from commercial vessels. In contrast to the main channel, channel border areas, side channels, bottomland, ponds, and sloughs with reduced flow and substrate composed of fine-grained sediments, are valuable habitats. These habitats can provide (a) dissolved and particulate organic matter necessary for aquatic plants, microorganisms, and macroinvertebrates; (b) nursery areas for recreationally valuable fishes; (c) resting and feeding areas for waterfowl, wading birds, and aquatic mammals; and (d) winter refuges for riverine fishes that cannot tolerate low temperatures and high velocities in the main channel. The possible effects of commercial tow passage on backwater sedimentation have been studied by Johnson (1976), Simons et al. (1981), Bhowmik et al. (1981c).

69. Research conducted by scientists and engineers from the Illinois Scientific Surveys (Bhowmik et al. 1986, Bhowmik and Adams 1986), has indicated that the morphometric features of a river basin can serve as an

indicator of whether or not a site is sensitive for biota. Potentially sensitive areas include the outside shallow plateau around a bend: the convex area near a bend just downriver of the main bend; island and braided areas, especially downriver of existing locks and dams; the area immediately upriver of a lock and dam where high sediment deposition has decreased depth; constricted areas where sailing line is close to the bank; and areas just downriver of submerged dikes and the confluence between the main river and its tributary where deltaic deposits occur. Figures 29 and 30 show some of these areas that were found to be highly productive along the Mississippi and Illinois rivers. In all of these instances, the morphometric features play an important role in making these areas highly productive.

### Seasonal Variation

70. Seasonal variations in the hydraulic and biological characteristics of rivers are important when evaluating physical effects of navigation. Figures 10 through 12 depict variations in flow that occur within and between years. In addition, research conducted by Bhowmik et al. (1980, 1986) on the sediment transport in the Kankakee River and other Illinois rivers has shown that sediment movement changes between seasons. It has been determined that 60 to 90 percent of the annual sediment load in a river moves within a period of 60 to 90 days during storm events.

71. The disparate amounts of sediment transported by a river during a year make it imperative that data on natural variability be collected. Moreover, important biological activities (such as recruitment) are usually cyclic and not constant from year to year. Physical data must be collected and analyzed with regard to natural biological and physical variability.

### Consideration of Replicates

72. In a study of navigation traffic effects, true replicates (in the sense of most cause-and-effect studies) do not exist. Each vessel that passes a study reach may have a different configuration and horsepower. In addition, hydraulic and physical conditions can change during the course of a study, and as a result of vessel passage. Regardless, the investigator should collect physical data for more than one barge event. Tow passages could then be placed in categories which could be considered as treatments. Individual

passages (assuming they are similar) could be considered as replicates. Although some data may have to be eliminated (from atypical tows), this information will provide insight into variability associated with passage. Additional studies should be conducted at different times of the year to assess effects of variation in stage, water temperature, sediment concentration, and turbidity. Interpretation of these data will be easier if the investigator has an understanding of natural variability.

73. It may not be possible to replicate sites for a navigation effects study since physical and biological attributes are often variable. The major emphasis should be on conducting studies at sites representative of specified habitats. It is better to understand a few sites well, than many sites poorly or incorrectly.

## PART IV: MEASUREMENT OF PHYSICAL EFFECTS

74. Equipment and instruments needed to measure physical effects of commercial navigation traffic are described in this section.

### Suspended Sediment

75. Measurement of sediment discharge in flowing water requires knowledge of flow patterns and sediment movement. Instruments that are presently available will yield good results if used properly. Figure 33 displays a schematic of suspended sediment concentration in a natural channel and a typical suspended sediment sampler. The unmeasured zone in the figure is artificial and has been so designated because of sampling technique limitations. Most of the following information about sediment samplers was taken from Guy and Norman (1970).

76. The purpose of suspended-sediment samplers is to obtain material that is representative of the water-sediment mixture. When a suspended-sediment sampler is submerged with the nozzle pointed directly into the flow, water enters the container through the nozzle and air is exhausted. A suspended-sediment sampler should:

- a. Allow water to enter the sample bottle through the nozzle at the same velocity as ambient river velocity.
- b. Permit the sampler nozzle to reach a point as close to the riverbed as possible. This varies from 9 to 15 cm according to the sampler.
- c. Minimize disturbance to the flow pattern of the river, especially at the nozzle.
- d. Be able to support equipment already in use for flow measurement.
- e. Be simple and maintenance-free.
- f. Accommodate a standard 1-pint (473-ml) glass milk bottle.

### Depth-integrating samplers

77. A depth-integrating sampler is designed to collect a water-sediment sample from a river vertical at such a rate that the velocity in the nozzle at point of intake is equal to the ambient velocity while running the vertical at a uniform speed. A depth-integrating sampler collects and accumulates the sample as it is lowered to the bottom and raised to the surface. The sampler

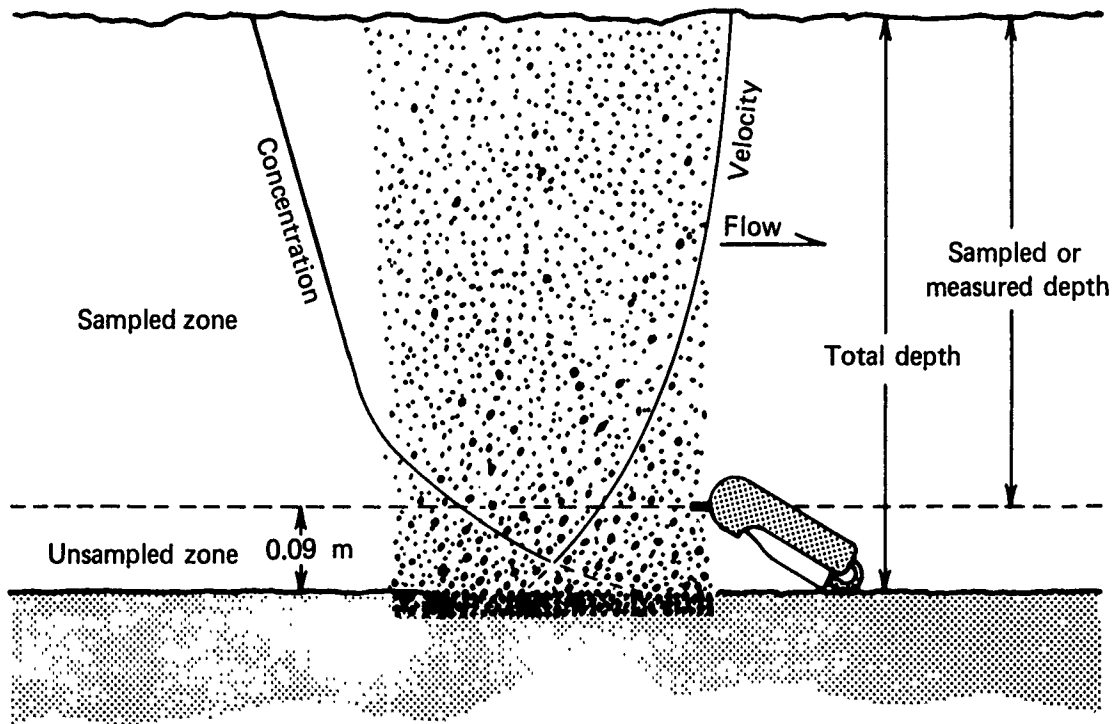


Figure 33. Measured and unmeasured sampling zones in a stream sampling vertical with respect to velocity of flow and sediment concentration (after Guy and Norman 1970)

must be moved at a uniform rate in a given direction but not necessarily at equal rates in both directions.

78. A point-integrating sampler can be operated to obtain a depth-integrating sample from deep or swift rivers by holding the valve open while integrating the river depth in parts. For rivers less than 9 m deep, the full depth can be sampled by integrating from the surface to the bottom only, or vice versa. If the river is deeper than about 9 m (the limiting distance through which the sampler can adequately integrate in one direction), then the vertical can be integrated in parts.

**Hand-held samplers**  
(US DH-48 and US DH-59)

79. One of two lightweight hand-held samplers can be used where rivers can be waded, or where a low bridge is accessible. The smaller of the two samplers is designated DH-48 (Figure 34). It consists of a streamlined aluminum casting 33 cm long, which partly encloses the container. The container, usually a round pint glass milk bottle, is sealed against a gasket in the head cavity of the sampler by a hand-operated spring-tensioned pull-rod assembly at



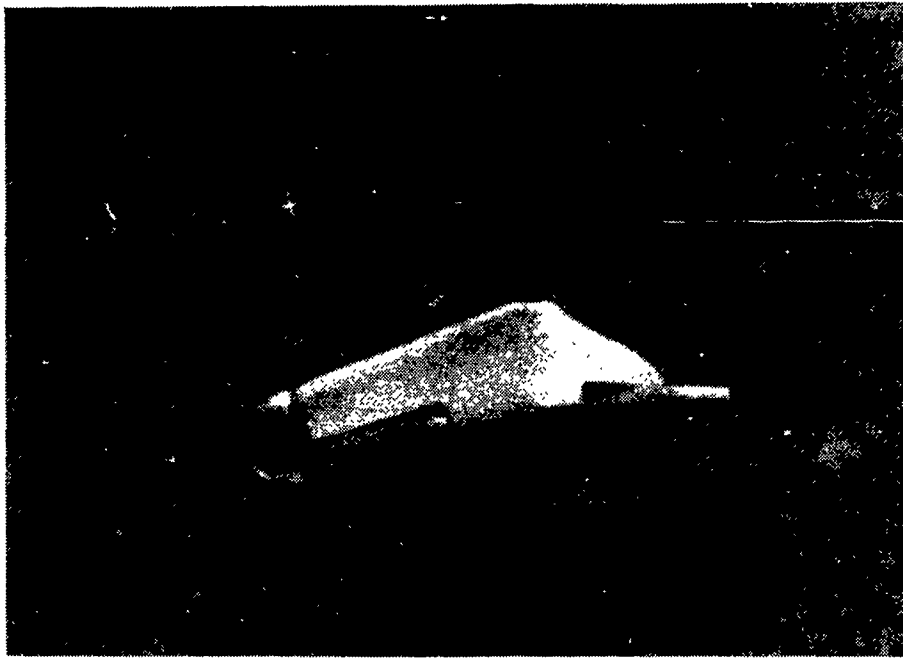


Figure 34. DH-48 sampler

the tail of the sampler. The sample is collected through the intake nozzle and is discharged into the bottle. The displaced air from the bottle is ejected downriver through the air exhaust alongside the head of the sampler. The sampler, including the container, weighs 2 kg. A standard river-gaging wading rod, or other suitable handle, is threaded into the top of the sampler body to suspend the sampler. The instrument can sample to within 9 cm of the riverbed. The sampler is calibrated with a nozzle that has an inside diameter of 6.3 mm, although a 4.8-mm nozzle can be used.

80. The other lightweight sampler, designated DH-59 (Figure 35), was designed to be suspended by a hand-held rope in rivers too deep to wade. It, too, only partly encloses the sample container. The 3.8-cm-long sampler body is made of bronze in the form of a streamlined casting, and weighs about 11 kg. Because of its light weight, it is limited to rivers with velocity less than 1.5 m/sec. The tail vane extends below the body of the sampler and the bottle (Figure 35). This extension forces the sampler nozzle to orient itself into the flow before submergence. The sampler will not get closer than about 10 cm to the riverbed. The instrument is calibrated and supplied with 6.3-mm, 4.8-mm, and 12.6-mm nozzles.

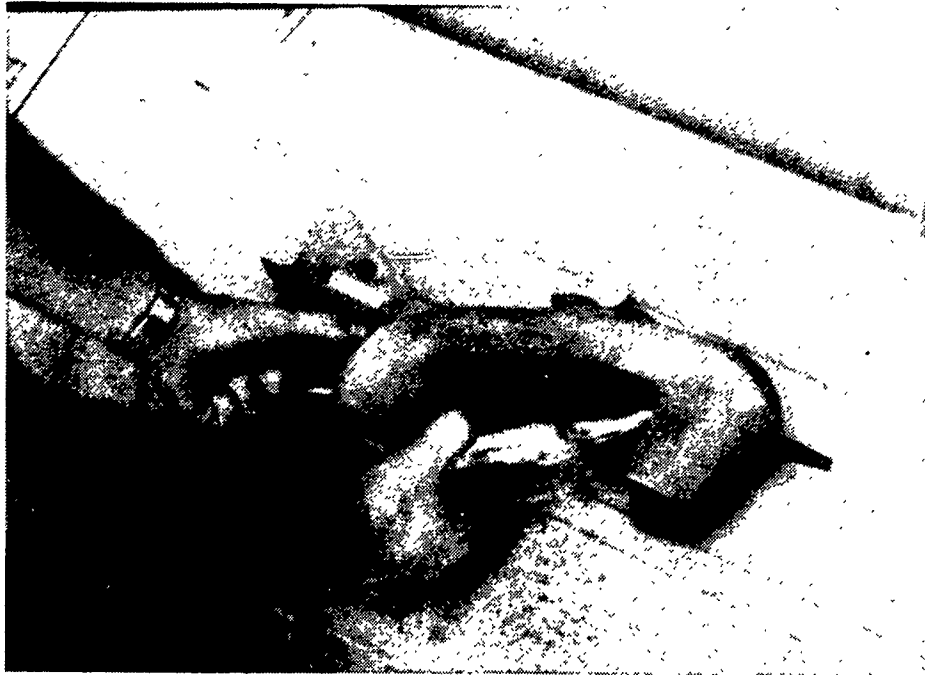


Figure 35. DH-59 sampler

81. These two lightweight hand samplers are most commonly used during normal flow in small and intermediate-sized rivers. Because they are small, light, durable, and adaptable, they are preferred on routine or reconnaissance trips. At most locations, a heavier sampler will be needed only for high flow. The small size of the hand samplers also enables the person taking a sample in cold weather to warm the sampler readily to eliminate ice in the nozzle or air exhaust.

#### Point-integrating samplers

82. Point-integrating samplers are more versatile than depth-integrating types. They can be used to obtain a sample that represents the mean sediment concentration at any point beneath the surface of a river except within a few centimetres of the bed, and also to sample continuously over a depth range. In depth integration, the sampling can start at any depth and continue in either an upward or downward direction for a maximum vertical distance of about 9 m.

83. A point-integrating sampler has a nozzle that points directly into the flow, and an air exhaust that permits air to leave as water enters. The intake and exhaust passages are controlled by a valve. When the valve is in the sampling position, the sampling action is the same as in a depth-integrating sampler. A pressure-equalizing chamber (diving-bell principle) is

enclosed in the sampler body to equalize air pressure inside with the external hydrostatic head at the intake nozzle at all depths. The inrush, which otherwise would occur when the intake and air exhaust are opened below the surface of the river, is thereby eliminated. There are many types of point-integrating samplers. One of the most commonly used is the P-72 sampler (Figure 36). It can be used for rivers up to 55 m deep. Other point-integrating samplers are described by Guy and Norman (1970).

#### Single-stage samplers

84. The single-stage sampler, US U-59, is used for small rapidly rising rivers where it is impractical to use a conventional depth-integrating sampler. This sampler is not usually used in large rivers.

#### Automated samplers

85. Automated samplers are used to collect sequential samples of a predetermined volume from a single point. Samples can be collected on a time-proportional basis by using the internal timing circuitry, or on a flow-proportional basis by using flow inputs from an external flowmeter. The sampler is usually self-starting and can be activated by an electronic water level sampler. One such sampler is ISCO model 1680. Samples are obtained with an internal pump that withdraws a specified amount of water at predetermined time intervals. This sampler is most useful for collecting samples during storms.

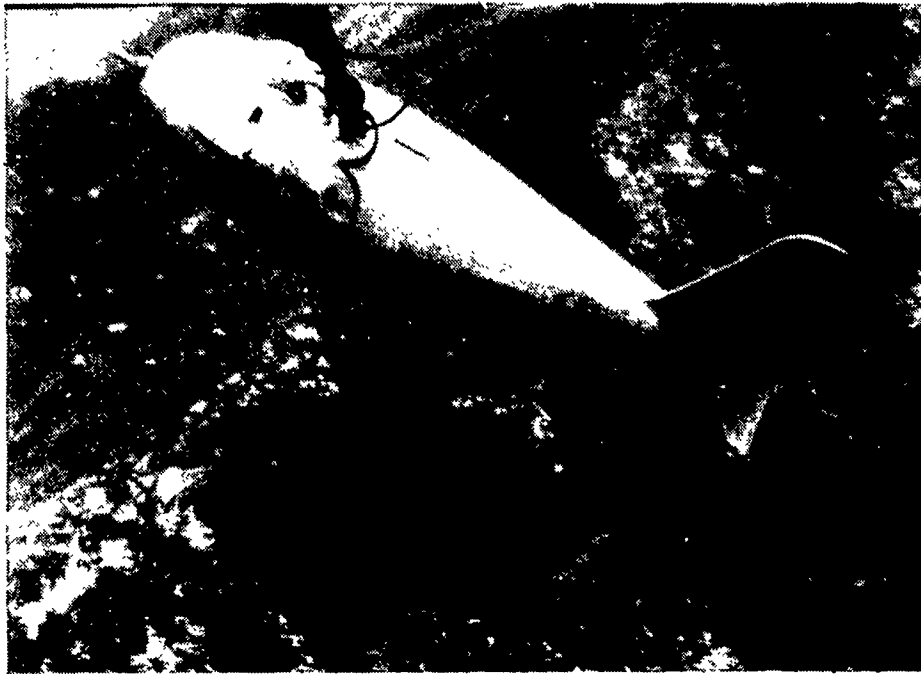


Figure 36. P-72 sampler

### Pump samplers

86. Another technique for collecting suspended sediment samples is to install a set of horizontal inlets at various locations on a vertical array. The inlets are connected with tubes that are passed through a peristaltic pump that will draw water continuously. Sampling can be performed from either a station on shore or a stable boat. This will enable the investigator to collect suspended sediment samples at any time interval (Figure 37). The bottom intake should be 70 to 150 mm above the bed and the top inlet should be below the water surface so as not to be exposed by waves or drawdown.

## Sediment Sampling

### Single vertical sampling

87. For a river reach with a stable cross section and a uniform lateral suspended-sediment distribution, sampling at a single vertical will usually be adequate. Pertinent information such as site, date, time, bottle number, gage height, temperature, sampler used, name of the river, and river conditions should always be obtained.

### Multi-vertical sampling

88. The distribution of sediments and bed roughness on a transect are affected by bed form which can vary from smooth to a very pronounced dune or antidune form. Thus, it is often unrealistic to relate sediment concentration for the entire cross section to concentration at a single vertical in a river. A realistic program for a wide river may require sampling at a number of verticals. On rivers where an accurate sediment discharge record is needed, it may be necessary to collect several sets of multi-vertical samples in a single day.

### Sediment discharge measurements

89. The best procedure for sampling for sediment as related to discharge is to collect the entire flow for a given period of time, evaporate the water, and weigh the sediment. Obviously, there are few instances where such a method could be employed. Instead, the sediment concentration of flow is determined by obtaining depth-integrated suspended-sediment samples either by the method of centroids-of-equal-discharge increments (EDI) across the river, or the method of equally spaced verticals across the river and an equal rate (ETR) at all verticals.

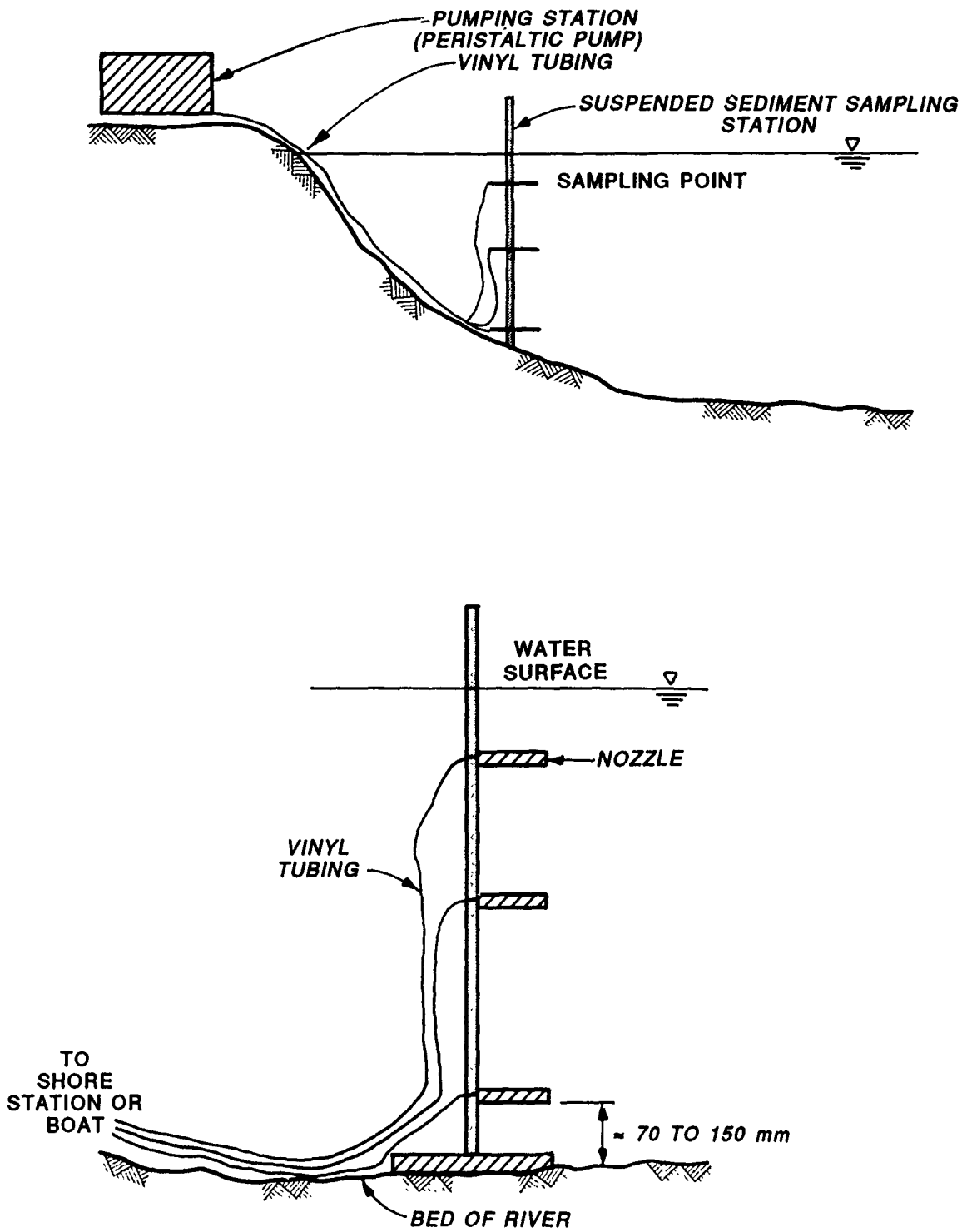


Figure 37. Typical pump sampling setup

90. In the EDI method, samples are obtained at the centroids of equal discharge increments and are usually limited to rivers with stable channels where there is little annual variation in discharge. This requires some knowledge of flow distribution in the cross section before sampling verticals can be selected. If such knowledge can be obtained, the EDI method can save time and labor over the ETR method, especially on larger rivers because fewer verticals are required.

91. In the ETR method, cross-sectional suspended-sediment samples are obtained by collecting a sample volume proportional to the amount of flow at each of several equally spaced verticals in the cross section. This equal spacing between verticals and an equal transit rate (ETR), both up and down in all verticals, yield a cross-sectional sample proportional to total flow. This is used most often in shallow rivers where the distribution of water discharge in the cross section is not stable.

92. The number of verticals required for an ETR sediment discharge measurement depends on the flow and sediment characteristics at the time of sampling and desired accuracy. The width of the segments to be sampled or the distance between verticals is determined by dividing width by the number of verticals.

93. Point samplers are used where depth exceeds the recommended 4.5 m for a round trip with depth-integrating samplers, and where the combination of depth and velocity causes the bottle to overflow at the maximum allowable transit rate. In addition, the velocity may be too high for the lighter samplers to be stable.

94. Either the ETR or EDI method is applicable for the point sampler when it is used for depth integration. Depths as much as 9 m can be sampled with point samplers by integrating the depth in only one direction at a time. The sampler is first lowered to the bed with the intake closed, and the depth is determined. It is then possible to estimate a transit rate to yield the desired sample quantity. The intake nozzle is opened, and upward integration from the bottom is maintained at a given transit rate.

95. Surface and dip sampling are sometimes used to collect sediments. Situations in which these are used include: (a) velocity is too high for the sampler to integrate, (b) large floating and/or moving submerged debris are present, (c) an appropriate sampler is unavailable, and (d) the water is very shallow.

96. A surface sample is taken on or near the surface, with or without a standard sampler. At some locations, velocities are so great that even the heaviest samplers penetrate the water for only a short distance before they are dragged downriver. Under these conditions it can be expected that all except the largest particles of sediment will be thoroughly mixed with the flow, and therefore a sample near the surface is appropriate.

#### Determination of Suspended Sediment Concentration

97. Suspended sediment concentration may be determined as the ratio of the weight of the sediment to (a) the weight of the water-sediment sample, (b) the weight of the water in the water-sediment sample, or (c) the weight of the pure water equal in volume to the volume of the sample. Discharge-weighted concentration is usually determined by the first method. For convenience, it is determined in milligrams per litre or parts per million. The discharge-weighted mean concentration in the vertical is obtained from depth-integrated samples collected with standard velocity weighting samplers. The mean concentration in the vertical also may be obtained from point samples.

98. The discharge-weighted mean concentration in the cross section may be computed from the mean concentrations of the several sampled verticals. If the sampled verticals represent centroids of equal discharge (EDI method), the mean concentration is the average of the several verticals or is the mean of the composited samples, provided all samples are of the same volume. If the sampled verticals are uniformly spaced and the same transit rate is used for all verticals (ETR method), the mean concentration is the ratio of the total weight of sediment to the total weight of the water-sediment mixture. Samples collected by the ETR method must be composited either in the laboratory or arithmetically, because the concentration of an individual sample is meaningless.

99. If sediment samples are obtained at a single vertical in a cross section, the relation of the concentration of the single-vertical sample to the mean concentration in the cross section must be determined prior to computation of sediment discharge. This relation, in the form of a coefficient, is determined by an analysis of cross-section concentration data. Daily mean concentration is the time-weighted mean value and is determined from a concentration graph (Porterfield 1972).

100. Sediment discharge is determined by multiplying the water discharge, in volume per second, by the concentration of suspended sediment, in milligrams per litre, and a coefficient:

$$Q_s = Q_w \times C_s \times k \quad (7)$$

where

$Q_s$  = sediment discharge, mass per day

$Q_w$  = water discharge, volume per second

$C_s$  = concentration of suspended sediment, milligrams per liter (mg/l)

$k$  = coefficient that is based on the unit of measurement of water discharge and that assumes a specific weight of 2.65 for sediment. With the appropriate conversion, the above in the English system becomes:

$$Q_s = Q_w \times C_s \times 0.0027$$

#### Bed Load

101. A review of available instrumentation for bed-load measurement indicated that one field instrument is available for measuring bed load (Hubbell 1964; Helley and Smith 1971). This is called the Helley-Smith bed-load sampler; its development and limitations are discussed in a report prepared by Helley and Smith for the US Geological Survey (1971). This sampler was designed for sampling coarse materials where the diameter of the bed materials varies from 2 to 10 mm and the flow velocity is no greater than 3 m/sec. The mesh opening of the collection bag is 0.25 mm; therefore when the median diameter of the bed materials is less than 0.25 mm, the mesh may get clogged or some of the bed load inside the bag can be lost.

102. Figures 38 through 40 show the Helley-Smith bed-load sampler in a laboratory, in the field setup, and just before being lowered into the Kankakee River (Bhowmik et al. 1980). The front of the Helley-Smith sampler has an opening about the same distance from the bed as shown in Figure 33 (about 8 cm) where it is assumed that bed-load movement will occur. The



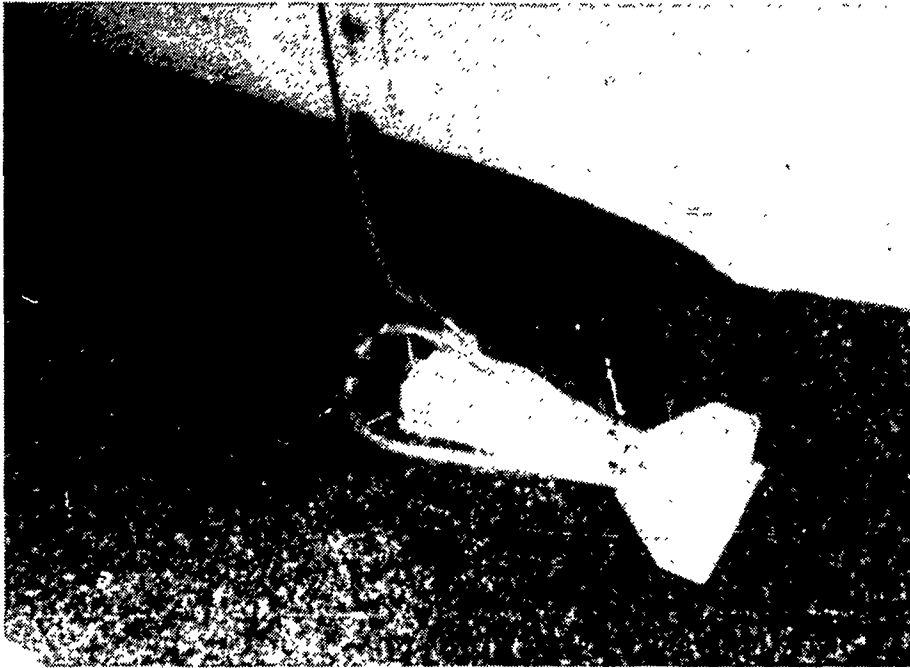


Figure 38. Laboratory setup for Helley-Smith bed-load sampler

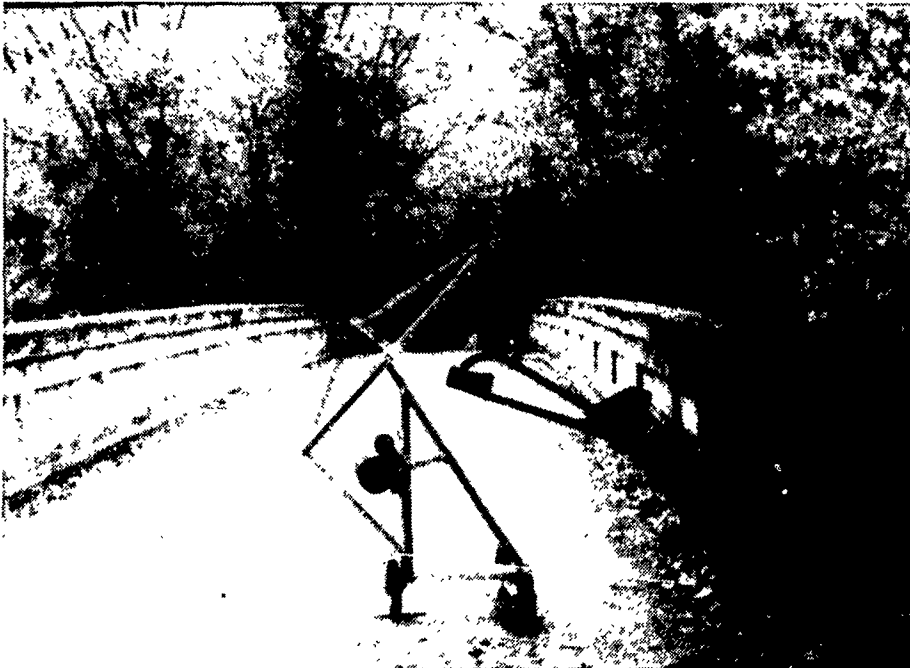


Figure 39. Helley-Smith bed-load sampler suspended from three-wheel base



Figure 40. Initiation of sampling with Helley-Smith bed-load sampler

sampler shown in Figure 38 is lowered to the riverbed, kept there for a certain period of time, and then taken out of the water. The sample collected within the nylon bag is then assumed to be the bed load that has moved for the time interval when the sampler was resting on the bed. When dried and weighed, this sample will yield bed-load movement for about an 8-cm-wide section of river bottom. With an assumption of uniform bed-load movement across the width of the river, the total bed-load movement for a certain period of time can be computed.

#### Sedimentation Rates

103. Many morphometric features force a natural river to deposit a portion of its suspended or bed load. Various techniques are available to measure short or long-term deposition rates. Some of these techniques are valid for large systems where the depth of water is 3 m or more, and others are useful for shallow areas such as the channel border areas shown in Figures 5, 7, 29, and 31. A few of these techniques are described below:

## Sediment traps

104. Sedimentation plates. At least two types of traps can be used in the field to measure sediment deposition rates. The first one is a flat plate that can range from 30 x 30 cm to 90 x 90 cm. The plate is placed at the bottom where the bed is flat (Figure 41a). The plate must be flush with the bed, and care must be exercised not to disturb surrounding areas. After sufficient elapsed time, the thickness of the sediment on top of the plate is measured. The sedimentation rate is determined by dividing the thickness of the deposited material by the time interval for which the plate was in place.

105. Sedimentation plates are not recommended for sites with high velocities and where depths are more than 1 m. These plates are useful in shallow, slow-moving water that permits accurate placement of the plate and measurement of deposited sediment. Such a trap will be useful on floodplains where water normally inundates areas only a few times in a year.

106. Tube traps. Another type of trap that can be used is called a tube trap (Figure 41b). A cylindrical tube is placed at the bottom of the river in areas where velocity is fairly low. The tube is closed at the bottom and open at the top. As sediment-laden water moves across the top of the tube, some material will be trapped in the tube. After a certain period of time the tube is retrieved, the thickness (or weight) of the sediment is measured, and the deposition rate is computed.

107. Traps such as this do not allow any exchange between flow and bed materials. This trap will thus show the sediment that drops because of gravity and not because of the net exchange of water and bed materials. Therefore, these traps will not provide a representative sedimentation rate where velocities are greater than 15 cm/sec.

108. Steel rod. The third type of sediment trap (actually not a trap in the true sense) is a steel rod that is driven into the riverbed. About 15 to 30 cm of the rod is exposed (Figure 41c). Once the rod is placed, the top elevation can be determined by surveying from a benchmark. Subsequently, the distance from the top of the rod to the bed can be measured at different time intervals to determine the sedimentation rate. The distance from the top of the rod to the bed should always be measured on the same side of the rod to avoid any inaccuracies caused by scouring. Again, this technique will be useful in shallow and clear-water habitats. At deeper sites, assistance from SCUBA divers will be needed to install and measure sedimentation rates using this technique.

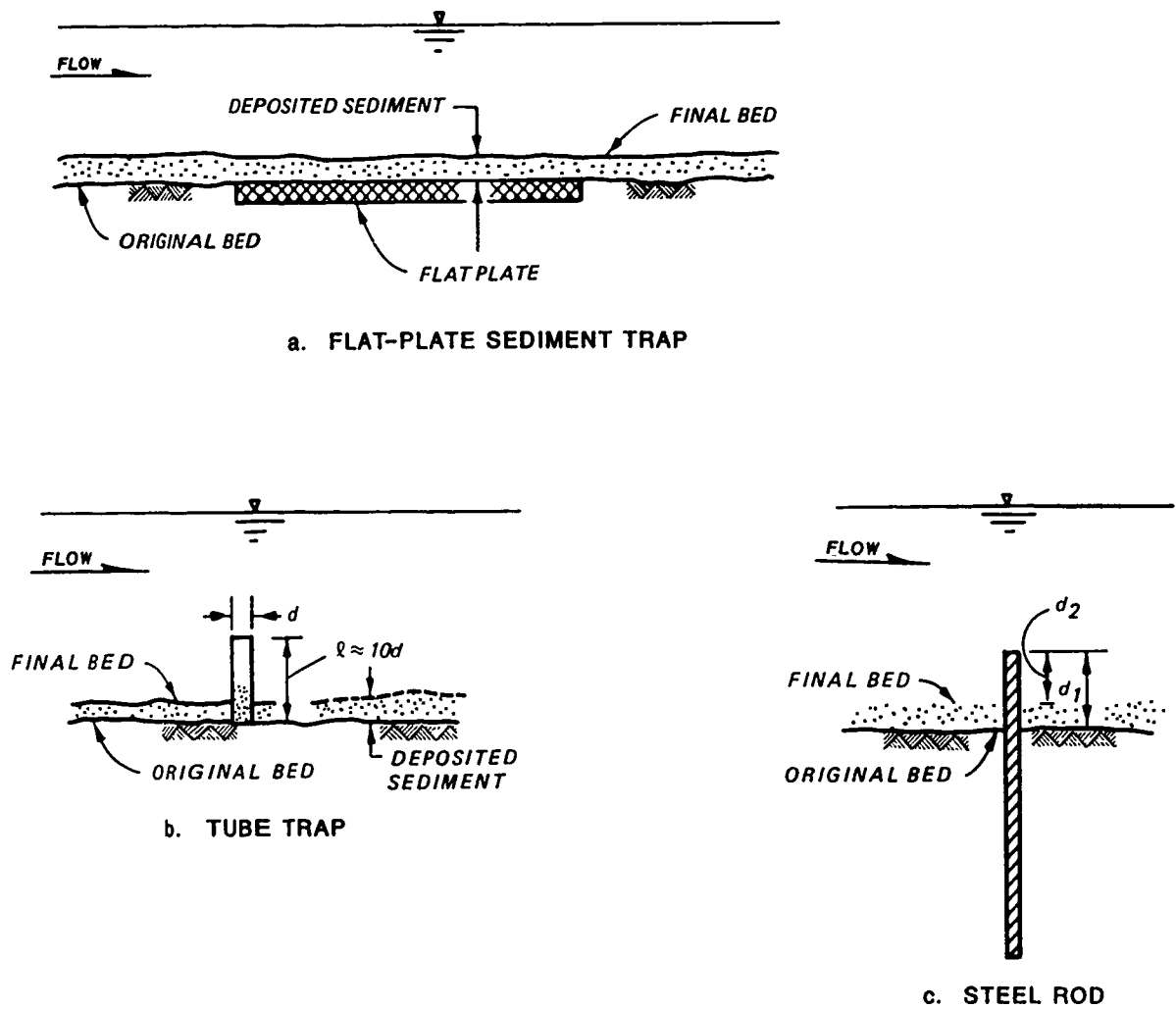
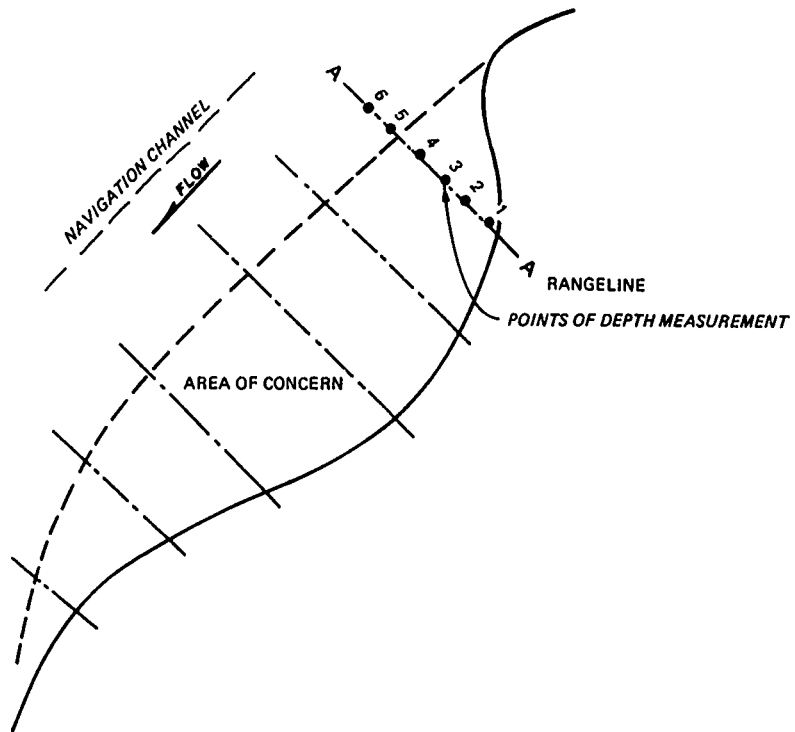


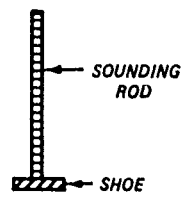
Figure 41. Types of sediment traps

Hydrographic mapping

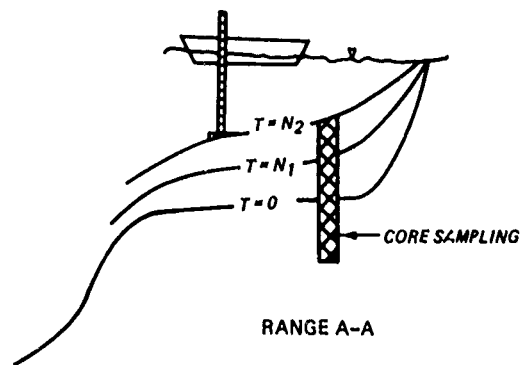
109. To determine sedimentation rates in large bodies of water, sounding data from specified time intervals are collected by using either standard sounding rods or electronic depth sounders. This technique must be associated with a fairly detailed ground survey to determine the relative locations of the rangelines. For the cross section shown in Figure 31d, depth determinations will involve depth measurements  $y_1$ ,  $y_2$ , etc., from a boat at the fixed rangeline (see Figure 42a for an illustration of this technique). The depths at points 1 through 6 on rangeline A-A can be measured from a boat by using a marked sounding rod similar to the one shown in Figure 42b. The sounding rod is usually 3 to 5 cm in diameter, is made from aluminum, and has a



a. Depth measurements from fixed rangelines



b. Marked sounding rod



c. Measuring sediment thickness from a boat

Figure 42. Typical hydrographic surveying

6.3-mm-thick shoe of about 15 x 15 cm that is attached at the lowest end of the rod. The flat shoe at the bottom prevents the rod from being pushed inside the sediment when the top of the sediment layer is to be measured from the boat (Figure 42c). Repeated measurements at different time periods will enable the researcher to develop plots such as the one shown in Figure 42c for time intervals such as  $T = 0$  to  $T = N_2$ , etc. These plots can then be used to determine sedimentation rates.

110. The bed profile shown in Figure 42c can also be developed using the depth sounder instead of the sounding rod. However, depth sounders must be used with caution. Depth sounders reflect sound waves from the bed to the sounder. If the bed is soft, the reflected sound wave will be distorted and the accuracy of the bed elevation will be affected. Depth sounders are normally accurate to about 40 cm. Therefore, in areas where sedimentation rates are low, the depth sounder is not suitable.

111. Sedimentation rates can also be determined by collecting an undisturbed core sample, slicing the sample at different depths, and then analyzing each for its depositional time by using  $Cs_{137}$  or  $Pb_{210}$ . However, both of these techniques have some limitations.  $Cs_{137}$  has limited affinity for fine-grained particles, and with  $Pb_{210}$  it is not always possible to discern sediment deposited within the last 3 to 5 years.

112. Once the bed elevation data at different rangelines are collected, these data can be used to develop a hydrographic map (Figure 43). Selection of a proper technique for the measurement of sedimentation rate depends on the objectives of the project and the desired levels of accuracy.

#### Bed Material Sampling

113. Bed materials are the sediments found in the bed of the river. Depending on the hydraulic characteristics, some sorting can occur over a period of time. Quantification of bed materials is needed to evaluate hydraulic and sediment transport characteristics of the river. Samplers described in this section are capable only of collecting bed material consisting of particles finer than 30-40 mm in diameter. In addition, very fine sediments (i.e., less than 0.062 mm) may not be collected efficiently with some of these samplers. Collection and analysis of particles larger than coarse gravel are difficult and costly because additional procedures are required to handle the heavy equipment needed for these samples.

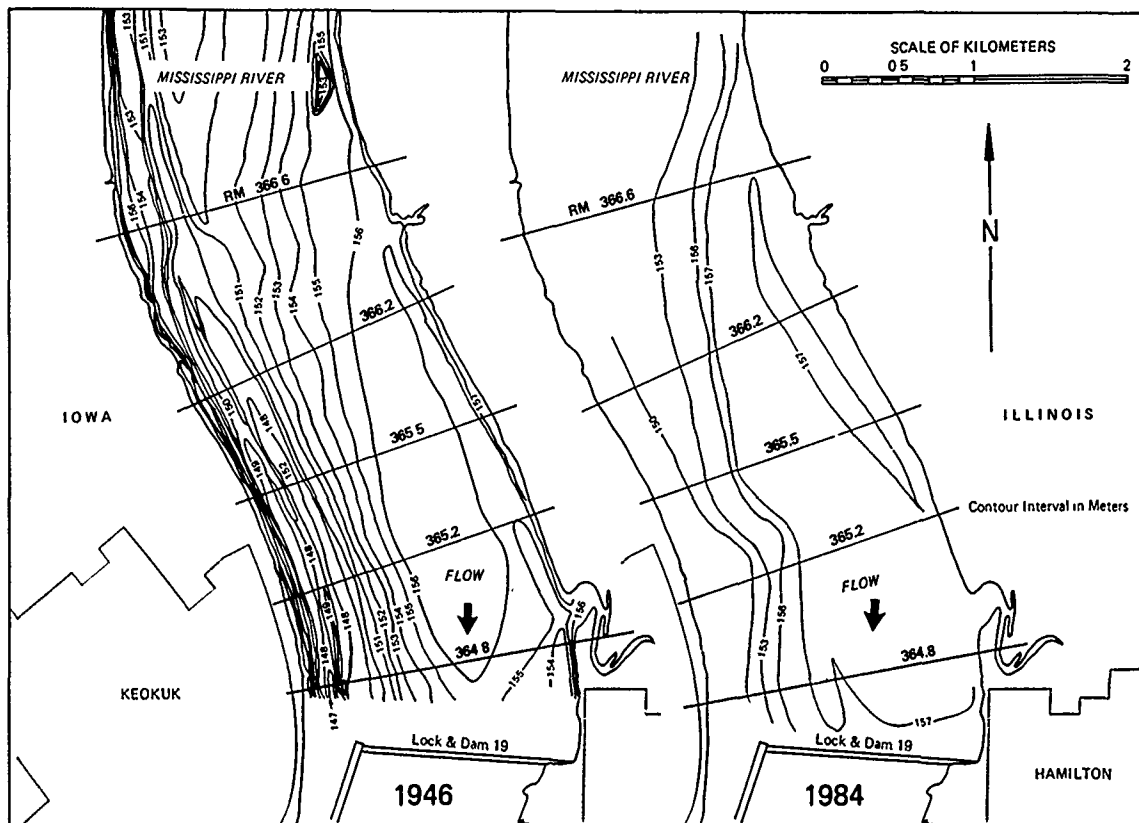


Figure 43. Hydrographic map of Pool 19 on the Mississippi River upstream of Lock and Dam 19

US BMH-53

114. The Federal Inter-Agency Sedimentation Committee has sponsored research projects (Guy and Norman 1970) in which three types of instruments were developed for sampling the bed material of rivers where most material is finer than medium gravel. The smallest instrument (US BMH-53) is designed to sample the beds of wadable rivers. The instrument is 1.17 m long and made of corrosion-resistant materials. The sample is collected with a stainless steel thin-walled cylinder 0.05 m in diameter and 0.2 m long, with a tight-fitting brass piston. The piston is held in position by a rod that passes through the handle to the opposite end. The piston creates a partial vacuum and compensates for some of the frictional resistance encountered when pushing the sampler into the bed. This partial vacuum also holds sediment in the cylinder while the sampler is being removed. The sample is extruded from the cylinder with the piston with a minimum of distortion so different strata can be subsampled.

## US BMH-60

115. Bed material of deep rivers or lakes can be sampled with the US BMH-60 sampler (Figure 44). This hand-held device is about 56 cm long and made of cast aluminum with tail vanes. It is available in weights of 13.6, 15.9, or 18.2 kg. Because of its light weight, its use should be restricted to shallow, low-velocity water where bed material is moderately firm and contains little gravel.

116. The US BMH-60 sampler consists of a scoop or bucket driven by a cross-curved constant-torque mortar-type spring that rotates the bucket from front to back. When activated by release of tension on the hanger rod, the scoop can penetrate into the bed about 4.3 cm and can hold approximately 175 cm<sup>3</sup> of material.

## Dredges

117. An Eckman dredge (Figure 45) can be used to collect bed materials in low-velocity rivers or lakes. However, in a river with high velocity, some of the fine particles may be washed out through the top screen. The Ponar dredge (Figure 46), which can be purchased in various weights, can be used in large rivers. These grab samplers are also used to collect sediments for macroinvertebrates. For larger rivers such as the Mississippi, Illinois, and Ohio, the Shipek dredge (Figure 47) is preferable to the previously described dredges (Bhowmik and Schicht 1980). This sampler is heavier, its mechanism is spring-loaded like that of the Eckman dredge, and it collects a fairly large undisturbed sample. These grab samplers will not obtain a stratified sample (mixing occurs) and they often do not close properly. To avoid dispersing fine-grained materials on the substrate surface they should be lowered slowly, not allowed to drop to the bottom. An undisturbed sample that will show the stratified nature of the deposited sediments can be collected by using a core sampler.

118. Sediment samples from riverbanks and beds can also be collected in shallow water with an ordinary shovel (Figure 48). Care should be taken to ensure that sediments are disturbed as little as possible.

119. A qualitative determination of the bed material sizes, especially the gravel-sized particles, can be made by placing a grid mesh over the substrate. This can be photographed for later analysis (Figure 49). This technique can provide semi-quantitative information rapidly with little expense.





Figure 44. US BMH-60 sampler

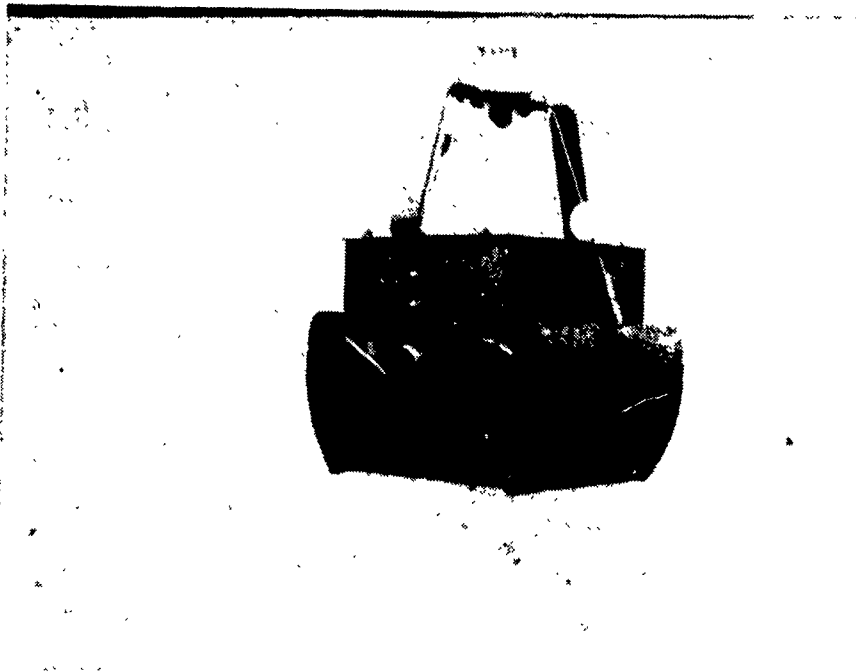


Figure 45. Eckman dredge



Figure 46. Ponar dredge

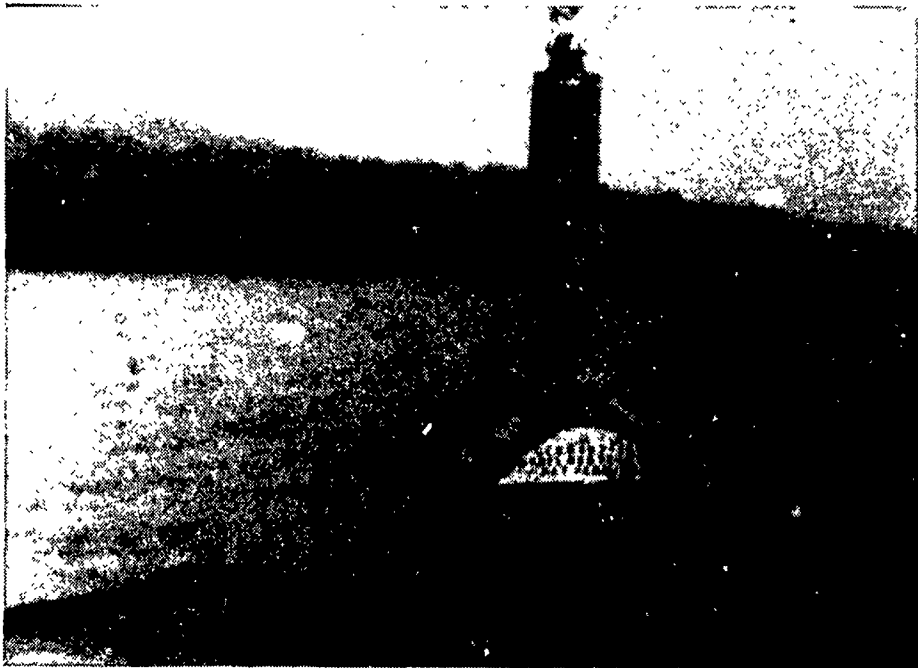


Figure 47. Shipek dredge



Figure 48. Sampling with a shovel

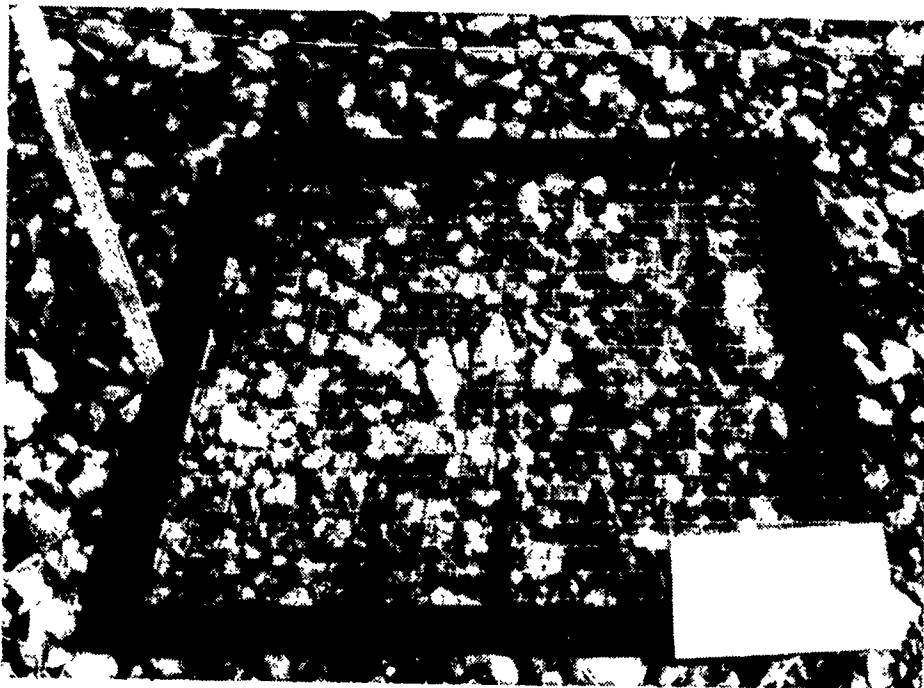


Figure 49. Grid sampling

120. Collected sediments should be brought to the laboratory for wet or dry sieve analyses to determine particle size distribution. For fine materials, a falling-velocity technique such as the use of a visual accumulation (VA) tube is appropriate.

#### Specialized sediment sampling

121. Often sediment samples have to be collected at sites where standard techniques may be unsuitable because the water body is either very small or very large. Sediment sampling in a large river usually requires a large, stable boat, and a heavy-duty winch (Figure 50). In addition, it is necessary to locate the survey boat from a land site.

### Velocity Measurements

#### Water discharge

122. Information on sediment transport must include a quantification of water discharge. Water depth and velocity must be measured at a series of sites along a transect, with discharge for the river computed from this information. Techniques for discharge measurement are given by Buchanan and Somers (1969).



Figure 50. Sampling for suspended sediments on the Mississippi River

123. A current meter, a timer, and a counter are used to measure discharge by means of conventional methods. The angular velocity of the meter rotor (i.e., the number of rotations per unit time) is proportional to the velocity of the water. A rating curve for each meter must be predetermined and checked frequently. The most common type of current meter now in use is the vertical-axis current meter, also called a Price meter, Type AA (Figure 51). This meter contains six cone-shaped cups mounted on a stainless steel shaft. For low-velocity measurement in shallow depths, a Pygmy meter, which is 0.4 the size of a standard meter, is generally used. Both types of meters can be hung from a cable with a sounding weight or attached to a wading rod for shallow-water measurements.

124. The cross section where discharge is to be measured is divided into 20-25 horizontal sections, and a single discharge for each section is measured. Figure 52 shows a river cross section divided into segments for velocity and depth measurements. Point velocities at either the 0.2, 0.6, or 0.8 depth are measured depending upon total depth. When depths are less than 60 cm, velocity is measured at the 0.6 depth and is assumed to be the average velocity for that vertical. For depths greater than 60 cm, velocities are measured at the 0.2 and 0.8 depths and are averaged. In all of these computations, it is assumed that the vertical velocity distribution follows a logarithmic distribution (Figure 16).

125. The discharge for each segment (such as ab, bc, cd, etc., in Figure 52) is computed by multiplying the average velocity by the width of the segment. For example, the average velocity for section bc is measured at vertical C, and the discharge equals the average velocity multiplied by width b to c and the average depth of the verticals at b and c. Summation of all discharges over the cross section will yield total river discharge. The discharge is generally expressed in cubic feet or cubic metres of water per second. Measurement and computation of discharges at a river cross section are essential to determine total suspended load.

#### Turbulent velocity fluctuation

126. Movement of commercial or recreational vessels can alter the velocity structure near the vessel and the shoreline. These fluctuations can last from a few seconds to a few minutes depending upon the size, speed, and direction of the vessel, its distance from the measuring point, characteristics of the waterway, and a host of other factors. Velocity changes can be measured at a coarse level by using the current meters described previously.

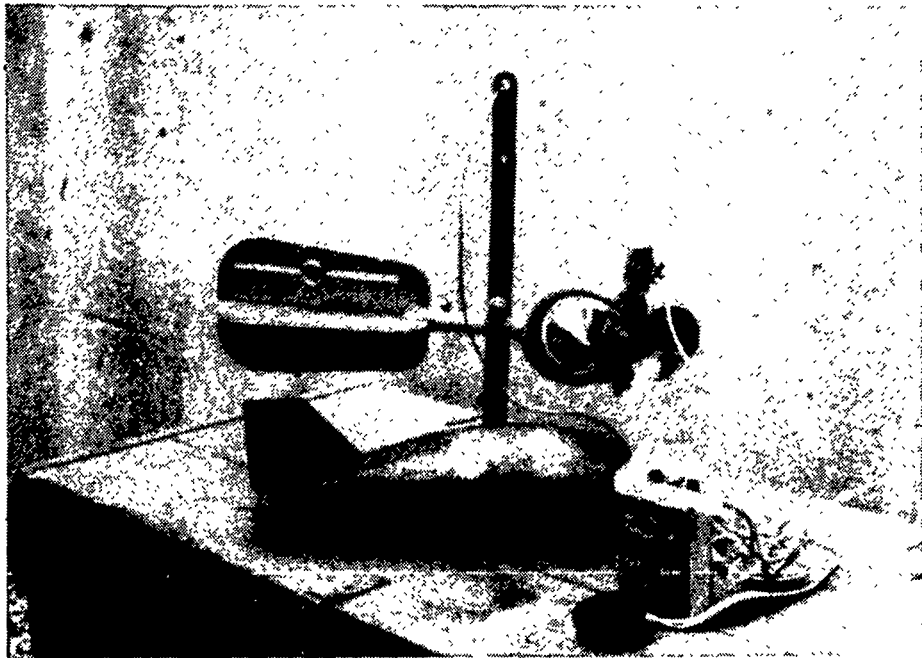


Figure 51. Vertical axis (Price-type) AA current meter with lead weight

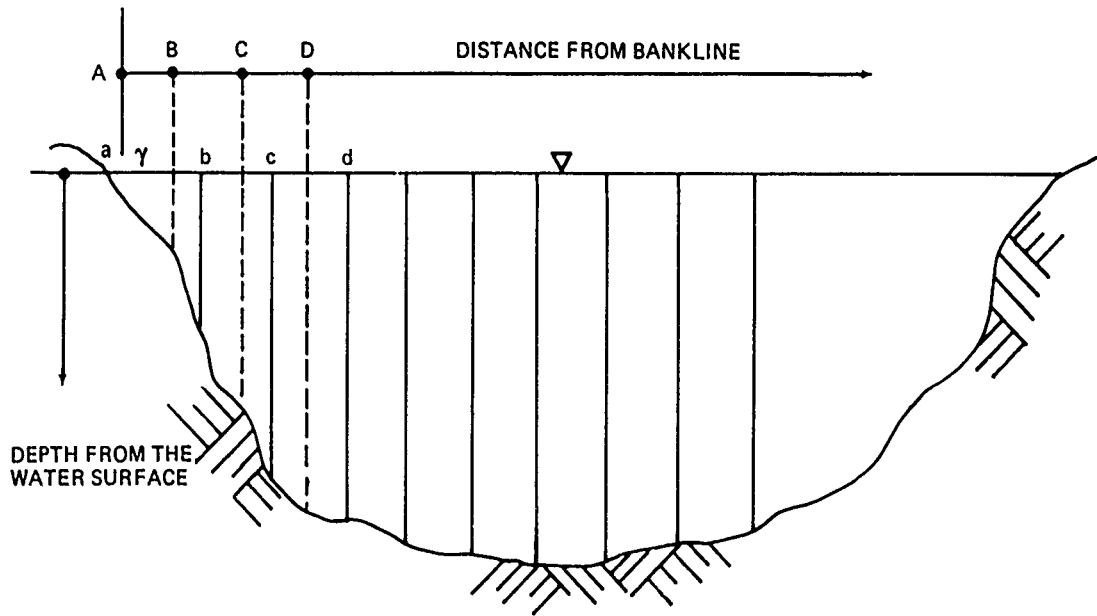


Figure 52. Discharge measurement in a stream cross section

At a finer level, velocity fluctuations are measured by the use of two-dimensional current meters that have much better resolutions. Current meters such as those manufactured by Marsh-McBirney, InterOceanic, etc., can be used. A brief description of the Marsh-McBirney meter is given below.

#### Electromagnetic current meter

127. The Marsh-McBirney 527 electromagnetic current meter consists of a transducer probe with a geomagnetic compass, a cable, and a signal processor. The probe consists of a 10.2-cm sphere on a 2.54-cm rod. The current meter measures velocity in a plane normal to and at right angles to the longitudinal axis of the probe. (The Marsh-McBirney Model 511 measures velocity in two directions although it lacks the compass.) These meters operate on the Faraday principle of electromagnetic induction, which states that a conductor moving in a magnetic field (generated from within the probe) produces a voltage that is proportional to its velocity. The electrodes placed on the wall of the probe detect the voltages caused by water flowing past the probe in a plane normal to the probe's axes. The flow-sensing volume around the probe is a sphere 30.6 cm in diameter (three probe diameters). Electromagnetic flowmeters require a short response time, usually several seconds, before recording instantaneous changes in velocities.

128. The two components of velocity together with the compass reading can be directly monitored on the three panel meters on the signal processor. The panel meter has three selectable full-scale ranges of 0.61, 1.53, and 6.1 m/sec. The outputs are within 2 percent of full scale over the velocity range of the instrument, and the compass accuracy is 10 deg at tilt angles up to 25 deg. The voltage output of the signal processor makes the velocity and the compass readings available to external computers and data logging equipment.

129. A battery-powered commercial data logger can be used to electronically record data obtained from a current meter. Certain models of data loggers contain an extensive internal memory that can be downloaded to a computer at a later time. When velocity data are to be collected continuously for a 3- to 5-day period and when data collection occurs at about 0.5-sec intervals, then facilities for downloading the data in the field will be needed. Typically this requires a lap-top computer and an external source of power such as can be obtained from a small generator.

130. An interface that transfers voltage outputs to the computer as digital signals was built at the Illinois State Water Survey and described by

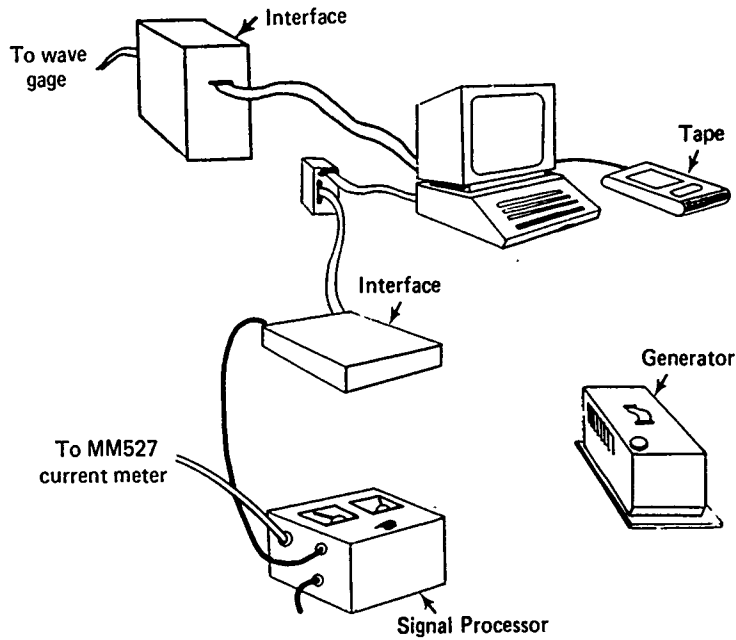
Demissie et al. (1986). Figure 53 shows the current meter and the electronics required for field data collection.

131. The support system for the current meter (Figure 53b) is an important consideration in the development of the data acquisition system. The sensor for the current meter has to be placed at a known depth in the river, and its orientation has to remain constant. A rigid support system that consists of a supporting platform, pole, and yoke can be constructed (Figure 53b). The yoke allows a 90-deg rotation of the meter probe so that secondary currents in transverse and vertical directions can be measured. The yoke is supported by a pole that can be raised or lowered at regular intervals to change depth. The pole is supported by the platform, which is attached to the ladder. Additional supports are needed to reduce vibration caused by river currents. Complete cross-sectional and vertical velocity distribution can be obtained by moving the entire support system along the river, lowering and raising the pole, and rotating the sensor as needed. However, this system will work only when water depth is 2 m or less.

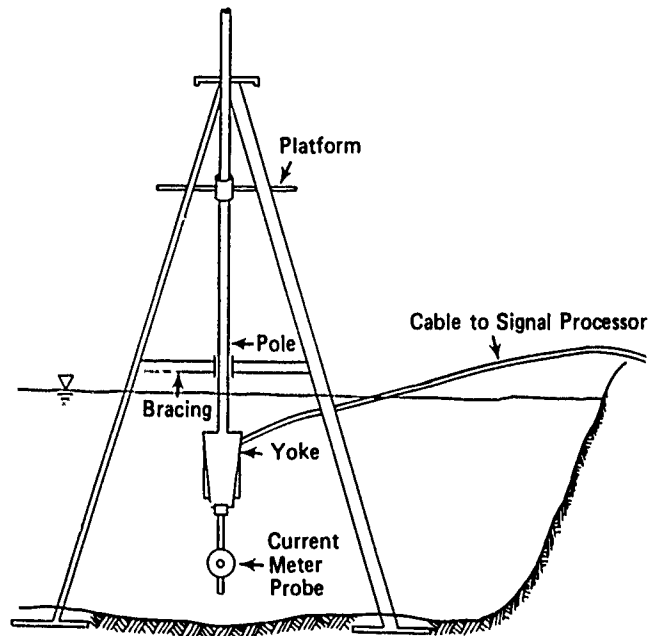
132. In shallow water, the support platform and pole can be firmly set at the collection site. The yoke and current meter should be securely attached to the pole on the platform. The cable from the current meter is then connected to the signal processor, which is located on the riverbank. The output from the signal processor is first transferred to the interface and then to the computer.

133. In some situations there may be concern that high river currents or turbulence from commercial traffic could upset the support platform. As an alternative, the current meter sensors can be secured to concrete or otherwise semipermanently anchored to the riverbed. Many other alternatives are available for anchoring the current meters. Aluminum posts anchored at three different locations with angular bases about 3 m long also have been used at the Illinois State Water Survey to anchor current meters in 3-4 m of water. A total of three meters were anchored with this system in the Illinois River in 1989 to collect physical data. In shallow water a single post with a hanging bar extending at least 10 diameters away from the post can also be used to anchor sensors. The meters depicted in Figure 54 were installed approximately 30 cm from the riverbed and were linked to an Esterline Angus model PD2064 Data Logger System installed on the shore. The technique was described by Environmental Science and Engineering (1981) as follows:



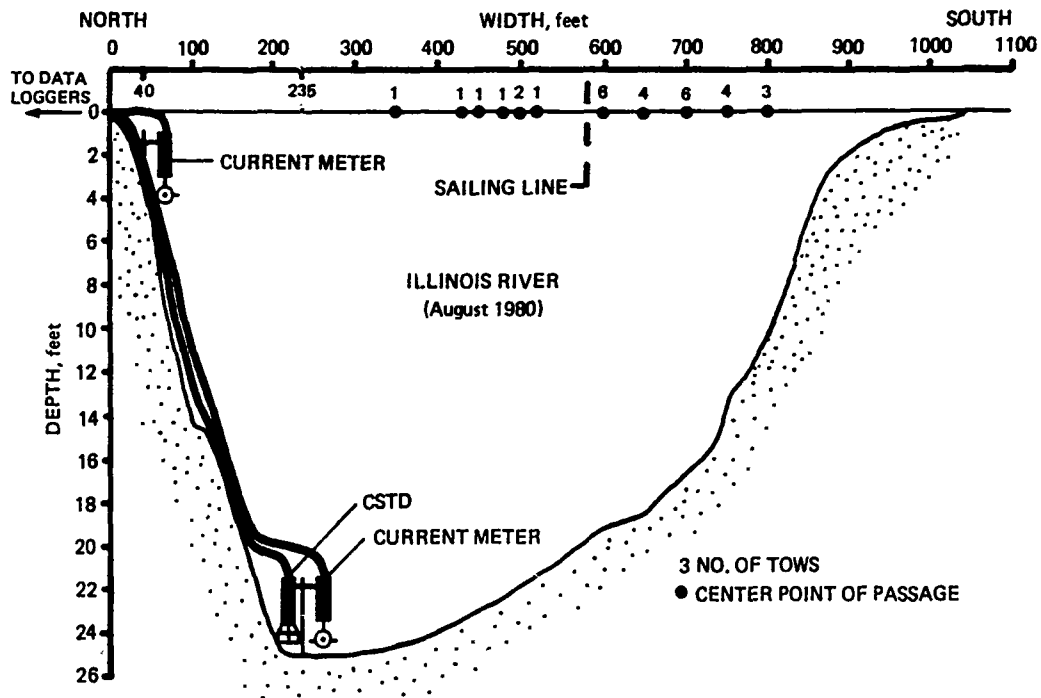


a. Components needed to measure and record water velocity

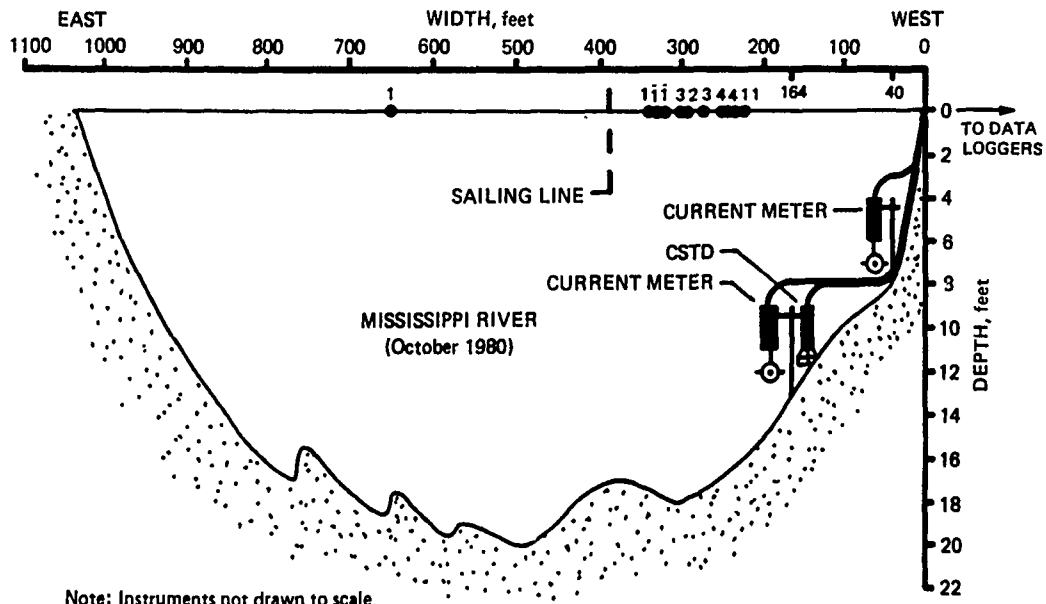


b. Placement of a velocity probe using a platform

Figure 53. Marsh-McBirney current meter setup (after Demissie et al. 1986)



a. Illinois River, August 1980



b. Mississippi River, October 1980

Figure 54. Cross sections of large rivers illustrating instrument placement and tow passage points (after Environmental Science and Engineering, Inc. 1981)

During each of the surveys, the data logger was programmed to record ambient river velocity every hour. As a tow approached the site, the recording interval was changed to 15 sec, and values were recorded from the time the tow was approximately 4 min from the instruments until it was approximately 3 min beyond the site. The water velocities were recorded on magnetic tape and on paper tape as a backup. The data and time of day to the nearest second were also recorded with each data set. In addition, 12 thumb-wheel settings were recorded with each velocity reading. The thumbwheels were used to code information such as tow identification number, distance from shore, direction (i.e., upstream or downstream, speed, number of barges, etc.

134. Data collected by the Marsh-McBirney current meter can be analyzed to determine the direction and magnitude of velocity, the range of velocity fluctuations (Figure 14), and the magnitudes of turbulence for a specified time interval (Figure 14). These current meters have a specific response time which is usually several seconds. In addition, on most meters it is possible to adjust the averaging time for an individual meter. Data obtained every second or less will show more fluctuations than data obtained and averaged for every 5 or 10 sec.

135. Water inflow and outflow from a specified region can be measured if enough current meters are available to obtain a detailed resolution of flow patterns. Since these meters are fairly expensive (usually between \$5,000 and \$10,000) a large number are not likely to be purchased for a study. Water velocities could be measured at two or more locations, one close to the vessel, the other some distance away. A single current meter will also show localized changes in velocity structure caused by vessel movement and whether or not the magnitude of these changes is likely to harm aquatic habitats. Continuous recording will show normal velocity fluctuations at the point where data are collected. All the meters should be installed at a depth where dewatering caused by waves or drawdown is not expected.

#### Pressure Fluctuations and Water Quality

136. Fluctuating pressures near the water-sediment interface can be measured with a pressure transducer. Simultaneous measurements of pressure fluctuations and selected water quality parameters can be accomplished with

available instrumentation. This was described by Environmental Science and Engineering (ESE) (1981) in the Illinois and Mississippi Rivers:

To measure the pressure and water quality parameters, an InterOcean model 513D CSTD was installed approximately 30 cm from the bottom near the outer current meter during each of the surveys (Figure 54). The instrument measured pressure, dissolved oxygen, pH, temperature, conductivity, and transmissivity at 1.5-sec intervals during each recording period. The instrument probes located in the river channel were linked to an InterOcean model 690M data logger located onshore. As a tow approached, the recorder was activated, and values for pressure and water quality parameters were recorded continuously on magnetic tape. Each of the probes on the instrument was either calibrated by the manufacturer or calibrated in the field against known standards. Upon return to the laboratory, the data were read from the magnetic tape and averaged into 10-sec values. The averaged values were then adjusted according to calibration curves developed from the field calibrations conducted during each survey. The 10-sec averages were then tabulated for presentation. Since observed fluctuations in the values were also important in assessing impacts, the maximum and minimum values that occurred during each tow passage were also tabulated...The pressure fluctuations can be measured with a pressure transducer such as the one used by ESE (1981) or the one that is available with InterOcean current meter S4, or others. Pressure transducers such as these measure the variations in hydrostatic pressures only. The pressure transducers do not measure the pressure fluctuations due to the rapid fluctuations of velocity. Fluctuating velocity data collected at different elevations with frequencies having finer resolutions can be utilized to compute indirectly the pressure fluctuations at a point. Analytical techniques can then be used to compute the velocity and pressure fluctuations at the sediment and water interface once sufficient data on a vertical have been measured in the field.

137. A tow could circulate water that is low in nutrients and dissolved oxygen from a deep pool to an area with different characteristics. Detailed analysis of water quality parameters should be undertaken only if it is a major objective of the study. Johnson (1976) found no change in dissolved oxygen following passage of commercial vessels. However, changes in turbidity due to a change in suspended sediment concentrations is possible in an alluvial river. Bogner, Soong, and Bhowmik (1988) used a Hydrolab to measure the variability of water quality parameters following passage of a barge on the Ohio River (Figures 55 and 56). The Hydrolab was used to measure temperature, pH, dissolved oxygen (DO), and specific conductance.

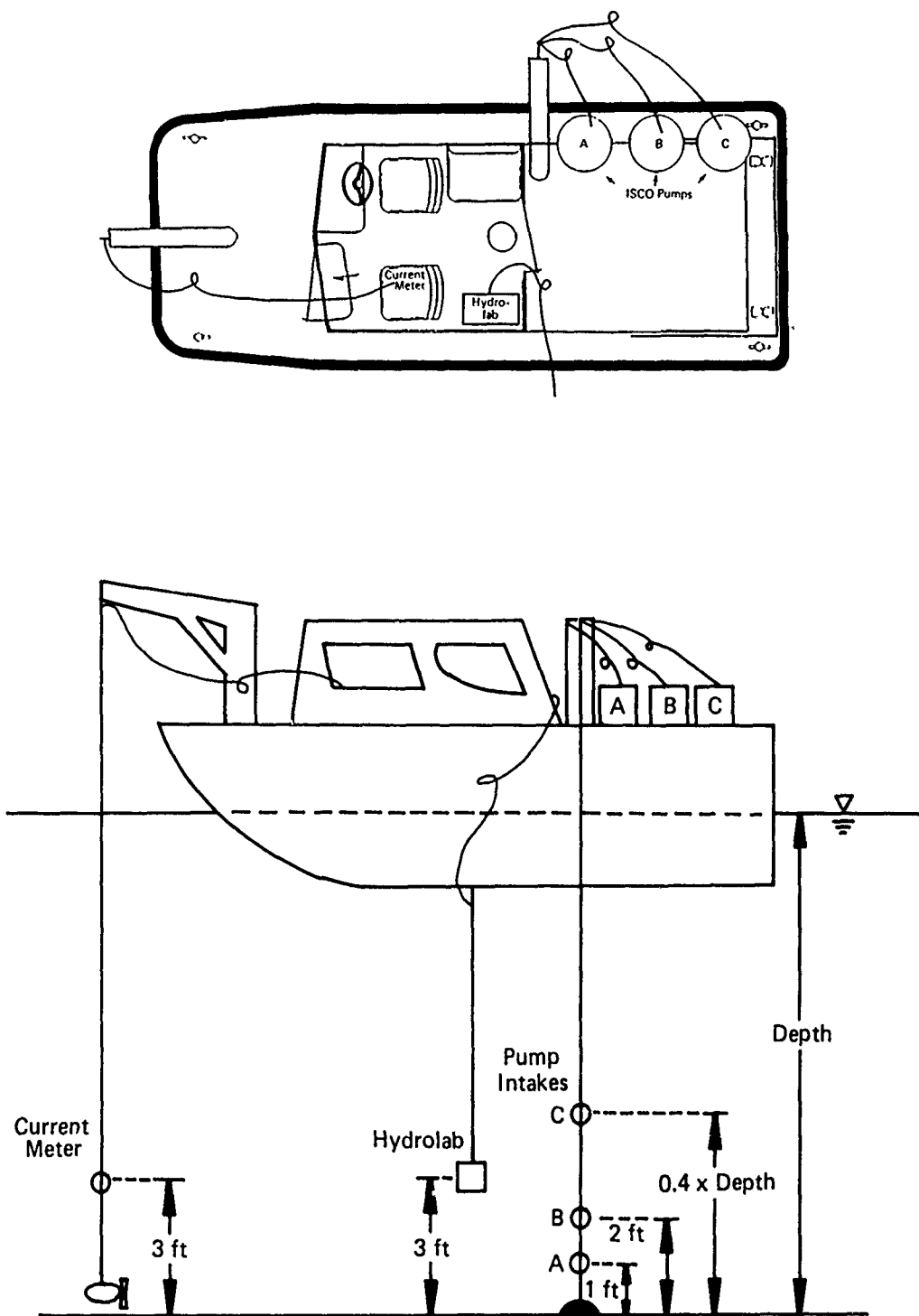


Figure 55. Two views of boat fitted with monitoring equipment



Figure 56. Water survey research boat with equipment set up for the Ohio River study

### Waves and Drawdown

#### Waves

138. As a vessel moves it generates a disturbance in the flow field. The flow around the hull is accelerated by changes in speed and direction of the vessel. The flow in front of the bow is decelerated until it reaches the stagnation point (where velocity is zero) because of flow blockage. These accelerations and decelerations result in corresponding changes in pressure and water level elevation. In areas where flow is accelerated the pressure and water level elevation drop, and vice versa. Waves are generated at the bow, stern, and any points where there are abrupt changes in hull geometry that disturb the flow field. As the vessel moves forward, the energy transferred to the water is carried away laterally by a system of waves similar to that shown in Figure 57 (Sorensen 1973; Comstock 1967). Figure 57 depicts deep water conditions where depth has no effect on flow field.

139. A vessel generally creates two sets of diverging and one set of transverse waves. Diverging waves move forward and out from the vessel, and transverse waves move in the direction of the vessel. The transverse waves meet the diverging waves on both sides of the vessel along two sets of lines called cusp lines, which form a  $19^{\circ} 21'$  angle with the sailing line for a point disturbance moving at a constant velocity in an initially still, deep, and frictionless fluid (Sorensen 1973). The theory to describe this wave

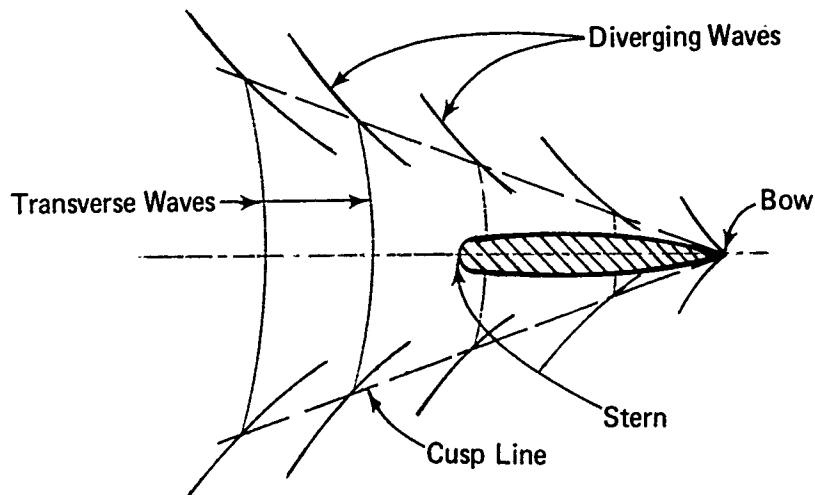


Figure 57. Wave pattern generated by a model ship in deep water

pattern was first developed by Lord Kelvin (1887). Sorensen has shown that the general wave pattern generated by a model hull in deep water agrees well with the wave pattern described by Lord Kelvin except for a small change in the cusp angle.

140. A typical wave system is shown in Figure 58, where  $C$  is the wave celerity (the speed the wave propagates forward),  $H$  is the wave height,  $X$  is the wave length (the distance between adjacent wave crests or troughs), and  $Y$  is the water depth. The wave period ( $T$ ), the time elapsed between two adjacent wave crests or troughs, is given by  $T = X/C$ . The ratio  $Y/X$  determines whether the wave system is in deep or shallow water. For deep water waves,  $Y/X > 0.5$ . In deep waters the wave celerity and wave length depend only on wave period, while in shallow water ( $Y/X < 0.5$ ) the wave celerity and wave length depend on depth as well as wave period (Ippen 1966; Sorensen 1973).

141. Since waves are generated at both the bow and the stern, they interact with each other at some distance from the vessel. If waves generated at the bow and stern are in phase, i.e., if the crest and trough of one set coincide with the other, they tend to reinforce each other and result in higher waves. If the waves are out of phase, they tend to cancel each other and result in smaller waves. Whether the waves will reinforce or cancel one another depends on the length Froude number:  $F_1 = V/(gL)^{0.5}$  (Comstock 1967; Sorensen 1973).  $V$  and  $L$  are the vessel velocity and length, respectively.

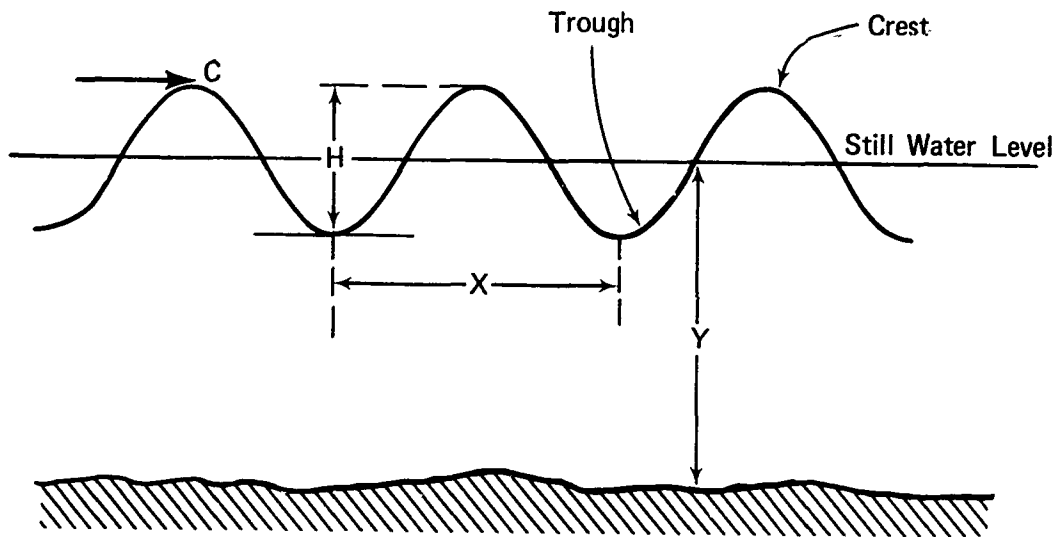


Figure 58. Descriptive sketch of a wave profile

142. In deep water, wave heights generally increase with respect to velocity, except when bow and stern waves tend to cancel each other. Wave heights then decay with distance from the vessel as the total energy per wave is distributed over a larger area (Sorensen 1973; Das 1968; Bhowmik 1976; Johnson 1968; Das and Johnson 1970).

143. Particle motion generated by waves in shallow water will reach the bottom, which will affect velocity patterns significantly. The important parameter in shallow-water waves is the depth Froude number ( $F_d = V/(gY)^{1/2}$ ), where  $V$  is the vessel velocity,  $Y$  is the water depth, and  $g$  is acceleration due to gravity. For  $F_d$  above approximately 0.4, waves will reach the bottom. As  $F_d$  increases (due to an increase in vessel velocity or a decrease in depth), diverging waves rotate forward and finally make a right angle with the sailing line for  $F_d = 1$ . Therefore at  $F_d = 1$ , both the diverging and transverse waves form a single wave that travels with the same speed as the vessel. The limiting vessel velocity, determined at critical  $F_d$ , is given by  $(gd)^{1/2}$  (Sorensen 1973).

144. In shallow water the depth restriction has been shown to play a significant role in modifying wave pattern. If a water body is narrow in the lateral dimension, a complex flow condition and wave pattern will result. When the channel is so narrow as to affect the flow pattern around a vessel, generated waves will be higher than those generated in unrestricted waters under similar conditions. This is because of a significant reduction in the flow area and the associated higher accelerations of flow around the vessel.



Higher acceleration results in lower pressures, which generate higher waves. A channel that is narrow and shallow will result in complex flow conditions and higher wave heights (Sorensen 1973).

#### Drawdown

145. As a vessel moves forward, it pushes water in front, sideways, and beneath it. At the same time, it leaves an open space behind, momentarily causing water to flow from all directions to fill the void. The propellers of the vessel also bring water from beneath the vessel. All these conditions cause acceleration of the water in the vicinity of the vessel. As the water accelerates, the pressure decreases. In other words the kinetic energy of the water increases as its potential energy decreases. The decreases in potential energy and pressure manifest themselves in decreased water levels. The associated drop in the vessel is known as "squat." The reduction in water elevation is referred to as drawdown.

146. In canal and harbor entrance design, the squat is of primary importance because of possible vessel groundings and loss of control. In riverbank erosion studies, water elevation fluctuation can be of great significance. The decrease in water elevation is greatest near the vessel and decreases moving away from the vessel. It is therefore reasonable to assume that drawdown at riverbanks is less than squat. However, squat and drawdown are assumed to be equal to simplify analysis (Schijf and Jansen 1953; Van de Kaa 1978).

147. Shallow and constricted channels greatly increase drawdown since flow in restricted channels is accelerated more than flow in unrestricted waterways. If a vessel travels close to one of the banks, drawdown will be higher in the region between the vessel and the riverbank than it would have been if the vessel had been traveling along the middle of the channel (Bouwmeester et al. 1977; Van de Kaa 1978).

148. Several attempts have been made to determine the squat of vessels in canals and harbor entrances because of the problem of groundings. The problem of squat has also become more serious in recent years as larger vessels transporting heavier cargo use channels and harbor entrances designed for smaller vessels.

149. As discussed earlier, squat and drawdown are generally treated as equal to simplify the physical phenomena as one-dimensional flow. Further assumptions made in analysis of drawdown or squat include constant vessel velocity in a straight channel, uniform squat over the length of the vessel,

and no losses due to friction. A schematic representation of the drawdown phenomenon is shown in Figure 59, where  $h$  is the drawdown,  $D$  is the draft, and  $Y$  is the hydraulic depth. Width, length, and submerged cross-sectional area are represented by  $b$ ,  $L$ , and  $A_m$ , respectively, and  $Z$  is the distance from the vessel to the water level monitoring device.

150. At least three systems can be used to measure wave height and drawdown. The first includes a staff gage and a video camera, the second includes an electronic wave gage connected to a minicomputer, and the third

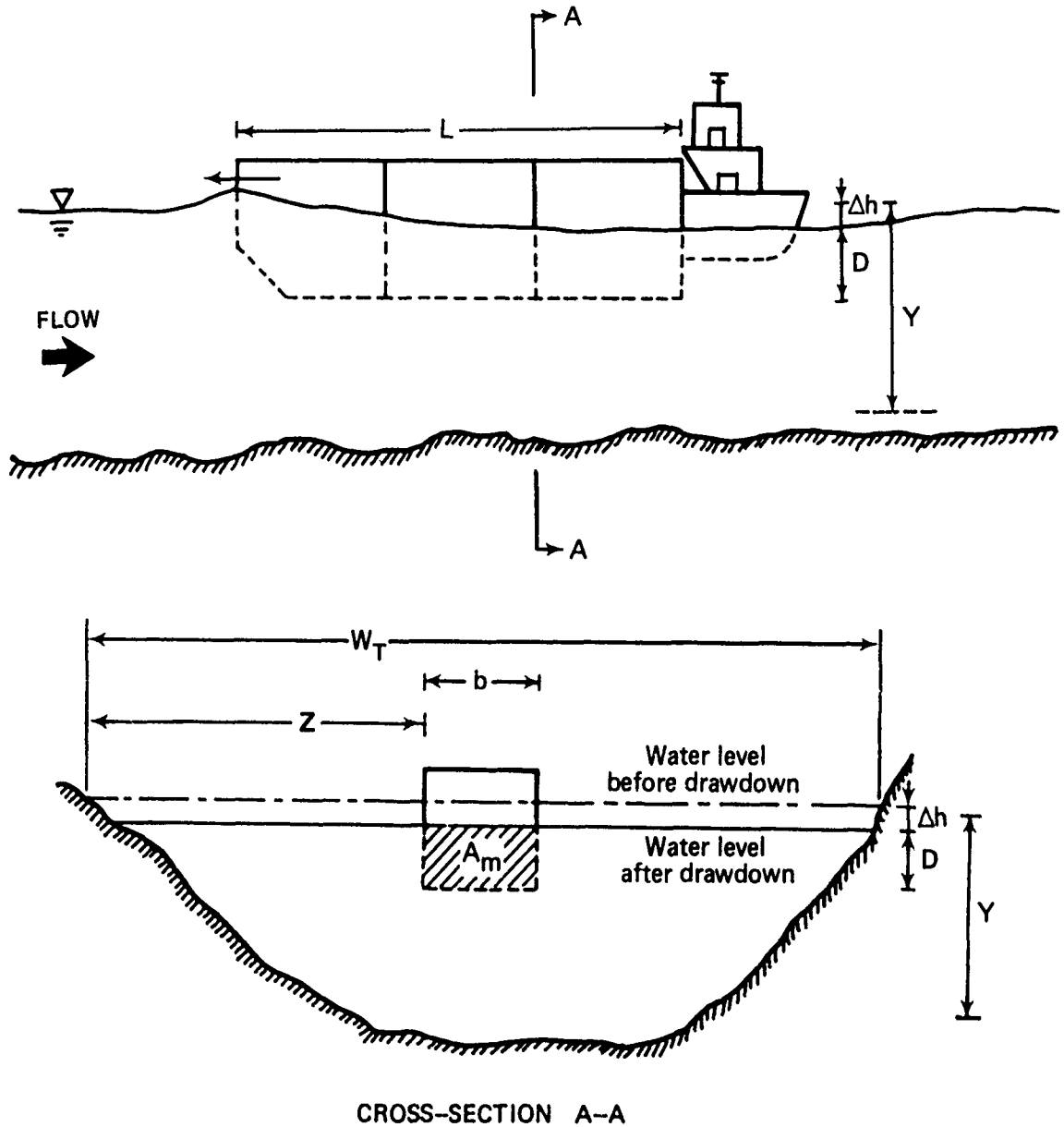


Figure 59. Schematic representation of drawdown

includes the use of submerged pressure transducers. Figure 60 shows a typical wave instrument setup that includes the electronic wave gage with the electrical cable, the staff gages (on the left), the camera, and a van with the computer system. Both systems involve the use of surveying instruments for measuring vessel speed, track of tow, and distance of tow from the shore. To install the first system, a fence post of sufficient length is first driven into the river bottom about 9 to 15 m from the shore or where wave data will be collected. The staff gage is bolted to the fence post so the water level is at the midpoint of the gage (Figure 61).

151. The camera is positioned on a tripod as close to the staff gage as possible. It should be positioned to reduce reflection from the water surface and to avoid having it on the dark side of the staff gage. The camera can be positioned on the riverbank or in shallow water, depending on site characteristics (Figure 62). Care should be taken to ensure that the camera and tripod are not knocked over by waves from commercial or pleasure boats or river currents. The movie camera is then focused on the staff gage, and its filter is adjusted to minimize reflection from the water surface. The camera is fitted with a remote control to start and stop taking pictures as needed. Once the installation is completed, wave data can be collected for any time interval. The film can be analyzed later to quantify wave height, period, etc. Although this can be laborious, it will generate a time-series plot of the wave trains as they pass the staff gage.

#### Electronic wave gage

152. An electronic system was built at the Illinois State Water Survey and tested in the field (Bhowmik, Demissie, and Guo 1982). The system includes electronic wave gages with exposed contact points 1.5 cm apart and a minicomputer to control data collection and to store information on cassette tapes (Figure 63). This figure also shows the Marsh-McBirney current meter probe that was used to collect velocity fluctuation data.

153. The wave gage consisted of a PVC pipe case, a 0.92-m sensor grid, and an electronics package (Figure 64). The case was divided into a section that protected the sensor grid and a section for electronic equipment. The sensor grid was protected by a 152-cm length of 5-cm PVC pipe with a 107-cm by 1.3-cm slot cut extending 30 cm from the top to 15 cm from the bottom. The sensor grid protruded through this slot to monitor the waves. A 5-cm PVC cap was connected to the bottom of the pipe. The electronics case, which consisted of a PVC fitting that expanded to a diameter of 10 cm, was cemented



Figure 60. Typical wave instrument setup during field data collection periods

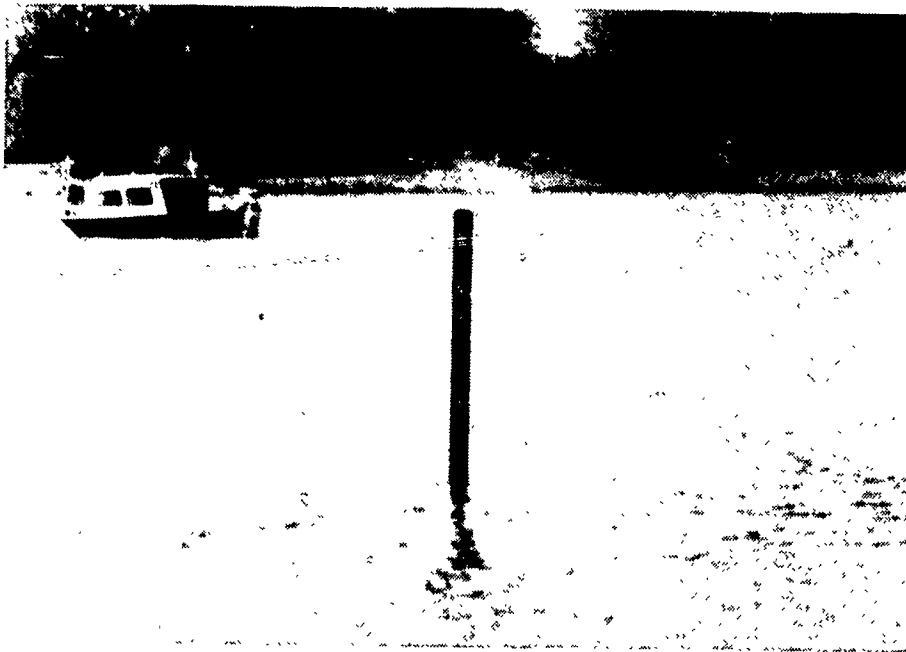


Figure 61. Staff gage in calm water



Figure 62. Wave gage with movie camera positioned on shore



Figure 63. Field setup of the wave gage and wave gage configuration

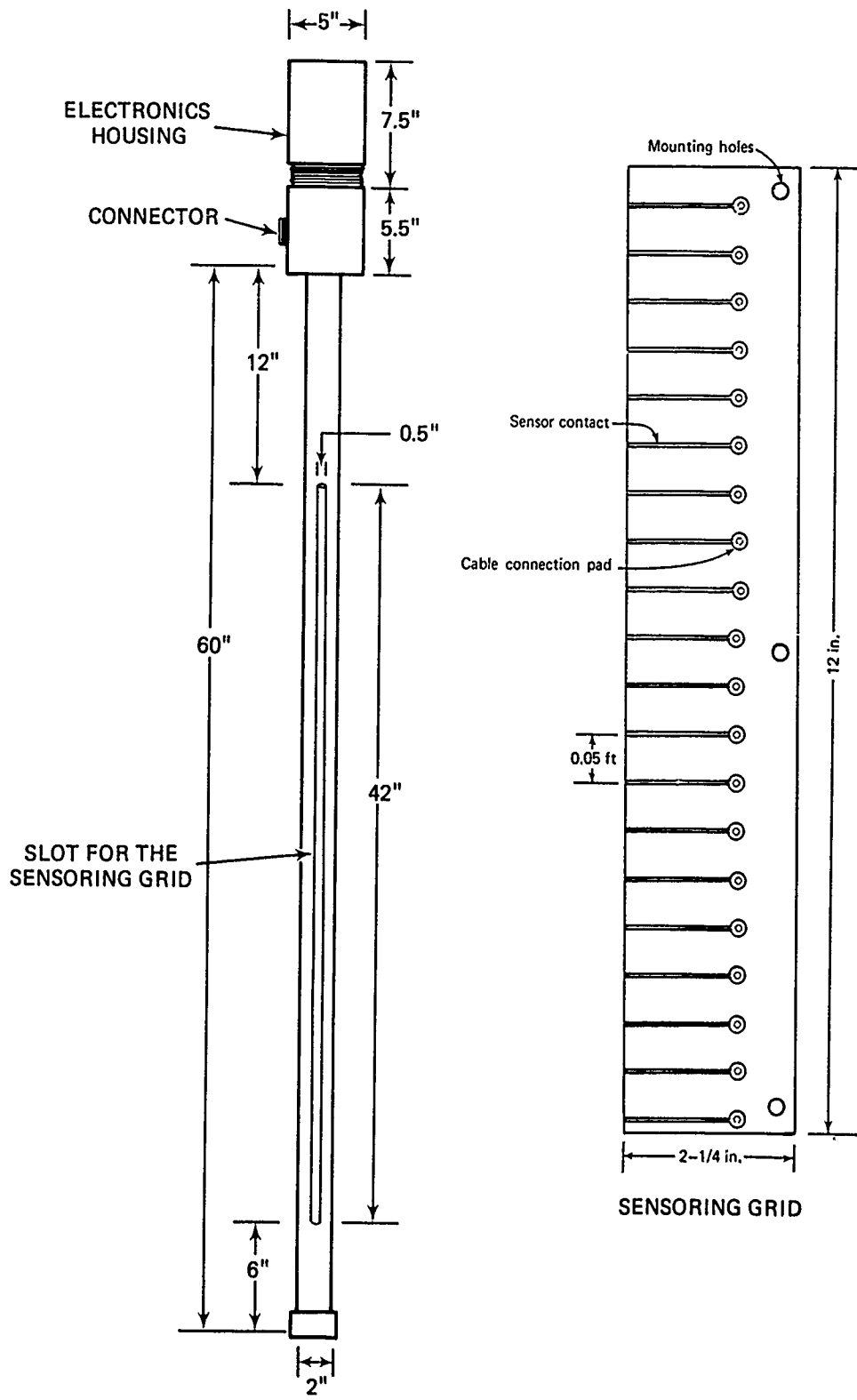


Figure 64. Electronic wave gage

to the top of the pipe. This section was 30 cm tall and was split approximately in half by a threaded section to permit access to the electronics. In the lower half section was a 35-pin connector that was used to connect the gage to the interface on shore. The wires from the sensor grid case to the electronics package compartment were sealed with silicone caulking compound to protect them from moisture.

154. The sensor grid consisted of three single-sided 0.16-cm copper-covered boards. These boards were etched to form a pattern of fingers spaced 0.13 cm apart (Figure 64). The fingers were gold-plated to maintain electrical contact with water. Twenty conductor ribbon cables were soldered to pads at the end of the fingers, and the contact sides of the boards were painted with spar varnish except for approximately 0.16 cm of contact end. This protected the solder joint and kept the contact area small to improve accuracy. The three boards were lined up to make a 0.91-m sensor grid. This grid was sandwiched between two aluminum strips (0.32 x 5.1 x 0.91 m and 0.16 x 1.27 x 0.91 m) and bolted into a 0.91-m piece of 0.99 x 1.3 x 0.16 cm aluminum channel. This channel was then bolted to the inside of the 5-cm PVC pipe so that the sensor extended through the 1.3-cm slot in the pipe. The aluminum strips and channel form a rigid support for the sensor grid and a secure method of mounting it to the PVC pipe. The 0.32-cm and 0.16-cm aluminum strips, as well as the copper-clad board, were notched every 15.2 cm to provide space for the 0.63-cm pop rivet thread inserts that were used to mount the sensor grid strip to the inside of a PVC pipe.

155. At the top of the sensor grid section of the PVC housing was the section that housed the electronics and cable connector. It was constructed from 10.2- to 7.6-cm and 7.6- to 5.1-cm reducers and a 10.2-cm threaded coupling. This allowed the pipe diameter to increase to 10.2 cm to house the electronics more easily. There were two circuit boards and a 10.2-cm aluminum disk separating the boards by 5.1 cm. The disk had a 5.7-cm hole in its center to pass cables from the sensor grid and the 35-pin connector to the electronics package. The lower circuit board had all the connectors for these cables, and the upper board had the electronic circuitry. This allowed for easy access to and removal of the electronics package if necessary. The housing was sealed with a 10.2-cm PVC cap. Vacuum grease was used to seal the threads from water. The electronics housing was also sealed from the sensor grid housing and connector with silicon caulking. The use of PVC pipe allowed

for an easily constructed instrument that was lightweight, waterproof, corrosion-proof, and strong.

156. The wave gage received power and a 1-KHz clocking signal from the wave gage interface via a 30.5-m, 15-pair twisted cable. The wave gage using these inputs sequenced the contacts one by one starting at the bottom. When the gage reached a contact that was out of the water, it stopped the sequence and loaded that number to the interface every 0.1 sec.

157. The wave gage interface generates 1-KHz timing, and power to run wave gages and pass data from the wave gage to the computer. The computer sequentially scanned the output of the wave gage and loaded the wave height information into memory. After the installation of the wave gage, the electrical cable from the wave gage was carefully laid on the river bottom and plugged to the computer interface.

158. The minicomputer contained cassette drives, a printer, a modem and an interface between the computer and the wave gages. The power supply to the computer and the wave gages came from either a small portable generator or from local power. The modem was used to interface the minicomputer with the computer for data transfer and analysis.

159. A schematic diagram of the wave and drawdown data collection system appears in Figure 65. Water level readings from the wave gages go to the interface, which transforms the data into readable form for the computer. The computer reads data that are stored in memory and then transferred to tape. The data can also be printed for inspection. The minicomputer can also send data to a mainframe computer via the modem and telephone lines. The electronic wave gage described above should be cleaned quite frequently so that organic material does not adhere to the contact surfaces.

160. Pressure transducers that can normally be installed near the bed of a river or at a depth that is not expected to be exposed to air can also be used to measure wave heights if the sampling frequency can be adjusted to a time interval of 0.1-0.2 sec. As the time interval increases, the resolutions for the wave height variation decrease, but still a good quantification of the maximum wave heights can be made with data collected at about 0.5 to 1-sec intervals with a pressure transducer.



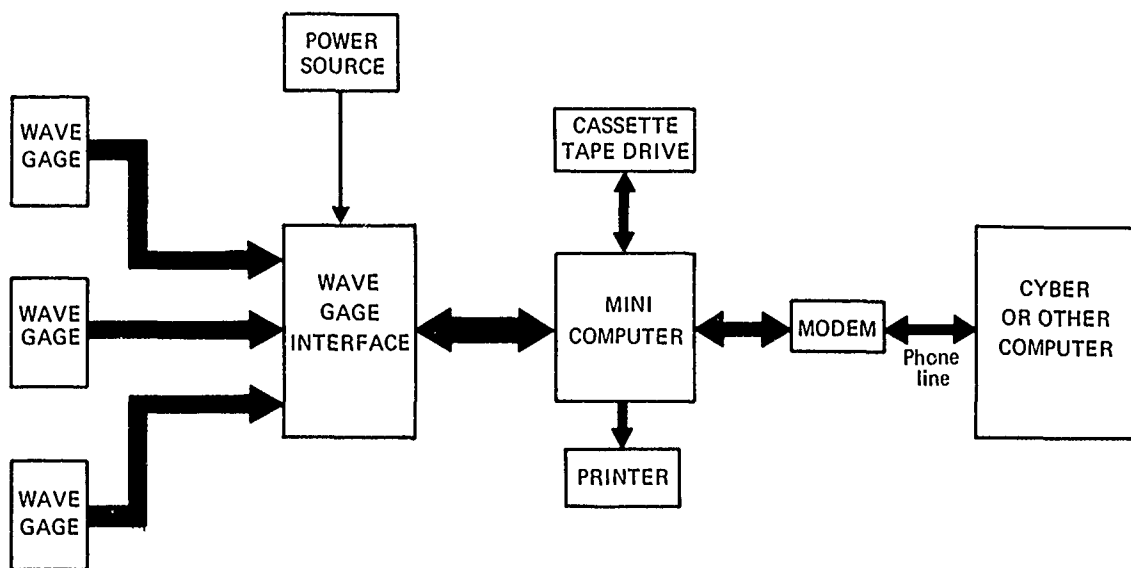


Figure 65. Schematic drawing of wave and drawdown measuring instruments

## PART V: FIELD DATA COLLECTION TECHNIQUES

161. Data collection procedures for analysis of the physical effects of commercial navigation traffic are discussed in this section. Techniques will not be universally applicable to all habitats in large rivers.

### Initial Considerations

162. After objectives of the study have been established, sites should be selected. Consideration should be given to the physical and biological factors outlined in Parts II and III. Maps, aerial photographs, and other available documents should be reviewed to ensure that sites can meet stated objectives and are representative. Once sites have been selected, they should be visited to determine access, availability of support systems, including emergency supports, and the suitability of the site for the specified objective(s).

163. The following factors are of prime consideration when choosing a site (considerations for a typical 2.75-m draft channel).

- a. Depth typical of the navigation channel.
- b. Representative width.
- c. Whether channel is natural or dredged.
- d. Representative channel geometry and configuration.
- e. Alignment.
  - (1) Straight.
  - (2) Representative bend(s).
  - (3) Crossings.
- f. Presence of obstructions.
  - (1) Wing dams.
  - (2) Bridges.
  - (3) Loading docks.
  - (4) Fleeting areas.
  - (5) Marinas/boat launches.
  - (6) Ferry crossing.
  - (7) Interferences from tributary mouths.
  - (8) Dredging or other operations.
- g. Site characteristics.
  - (1) Near a side channel if possible.

(2) Can also be used for intensive biological study.

(3) Not a barge fleeting area.

h. Others.

(1) Orientation of the sailing line with respect to river geometry.

(2) Constricted and nonconstricted reaches.

164. The following factors are of secondary consideration when choosing a site:

a. Access by land.

b. Access for vehicles.

c. Suitable for stations with adequate lines of sight.

d. Shore area availability.

e. Suitable area for installation of wave gages.

f. Safe boat landings.

g. A boat ramp and secure boat harbor (for river access).

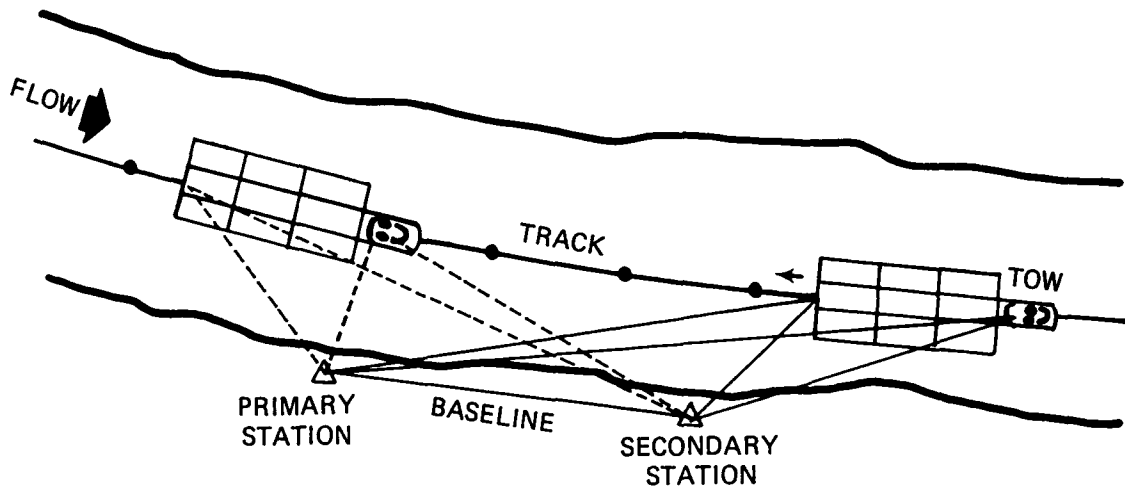
165. It is important to have an appropriate number of personnel. Three people are needed for each boat plus at least one individual on shore to operate current meters, to survey, and to obtain data on the tow.

#### Baseline Data

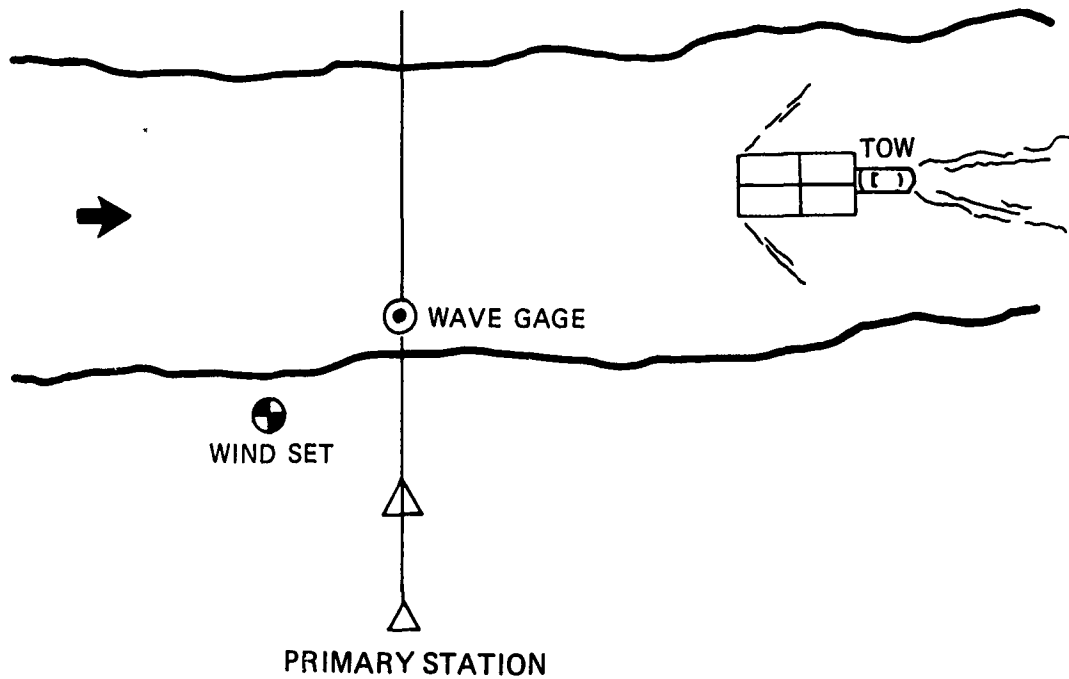
166. Figure 66 depicts a main channel and channel border area where information on physical impacts of navigation were collected by Bhowmik et. al. (1981a,b). The first item of work should be to establish a baseline of sufficient length (usually 250 m to 450 m) along one shore. This will be used for surveying and determining the track of moving tows. A semi-permanent marker should be set at each end of this line (Figure 67a). It is desirable to have the baseline situated so as to allow a clear line of sight along the entire line and an unobstructed view of the sampling area and channel approaches. In most cases, 2 to 4 km of the river can be viewed with little difficulty. This will ensure that tow tracks can be followed at least 600 m up- and downriver.

167. After the baseline is established, the site should be surveyed. This will define the shape and position of the shorelines adjacent to the sampling area and the locations of all data-gathering instruments. The precise distance between the survey stations (the length of the baseline) can be measured electronically, and routine land-survey procedures can be employed to





a. Semipermanent markers in place at each end of baseline



b. Placement of wave gage

Figure 67. Typical field setup for measuring physical effects of passage of a commercial vessel

produce a site configuration base map. This map can then be reproduced and used to plot the track data for individual tows, giving a visual representation of events as they actually occur.

168. Once the baseline has been established, background data should be collected. Figure 68 shows a schematic diagram indicating the overall background data collection system for a reach of a river. Background data that should be collected include hydraulic, geomorphic, geotechnical, sediment transport, and bed material characteristics. The following data should be obtained:

#### River width

169. At a minimum, measure width at three sections such as A-A, B-B, and C-C (Figure 68).

#### Depth and velocity

170. Measure depth and velocity at 20-30 verticals at sections A-A, B-B, and C-C (Figure 68). The velocity data should be collected from all stations with either standard or two-dimensional current meters. If a standard current meter is used, it will require velocity measurements from the 0.2 and 0.6 depths (if depth is more than 0.61 m) or from the 0.6 depth (if depth is less than 0.61 m). Data from five points (0.1, 0.2, 0.4, 0.6, and 0.8 depths) should also be collected to determine variations in vertical velocity.

#### Bed and bank materials

171. Bed and bank material samples should be collected at the locations depicted in Figure 68. Quantification of the distribution of bed materials in channel border areas may require extensive sampling.

#### Core samples

172. Core samples should be collected from sections A-A, B-B, and C-C (Figure 68) to determine particle size distribution.

#### Stages and water surface profile

173. Stage and water surface elevations should be obtained from at least three stations (Figure 68).

#### Suspended sediment

174. Suspended sediment samples should be collected from three ranges (Figure 68). These data should be obtained from 20-30 verticals in each section. Enough samples should be obtained to determine the particle size distribution of suspended sediments.

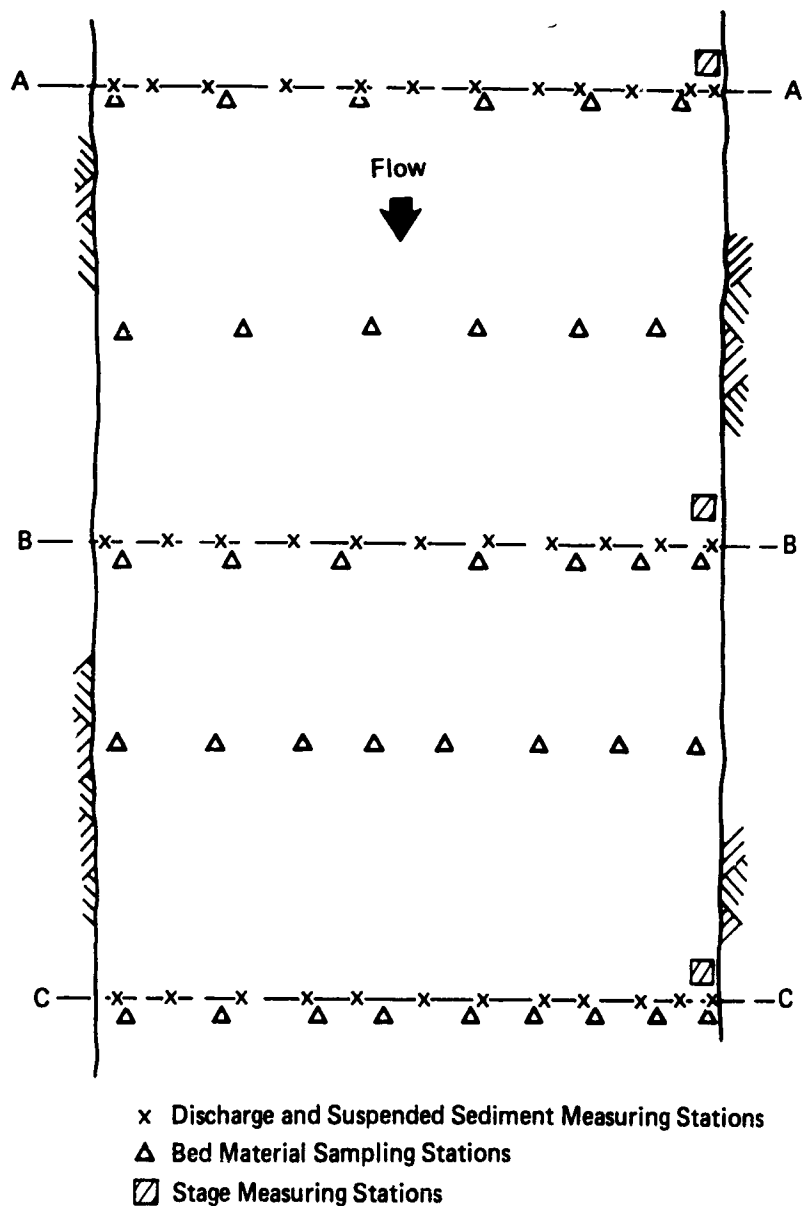


Figure 68. Schematic drawing showing the background data collection setup

Water quality

175. Basic water quality data such as turbidity, pH, specific conductance, and dissolved oxygen should be collected from the three ranges (Figure 68).

Geomorphic data

176. The following geomorphic data should be collected: a quantification of the planform of the study reach; presence of curved and straight reaches upstream and downstream of the study reach; location of the sailing line; orientation of the reach with respect to prevailing wind direction and

sailing line; and, presence or absence of side channels, backwaters, or tributaries.

### Field Studies

177. During tow passage, data should be collected continuously. Schematic arrangements for field data collection are shown in Figures 68, 69, and 70. The following should be collected as a tow passes:

#### Velocity

178. Velocity data should be obtained from 12-16 points on both sides of the river from about 6 verticals (Figure 69) using multi-dimensional velocity meters. Turbulence intensity and shear stress can be computed from the velocity data.

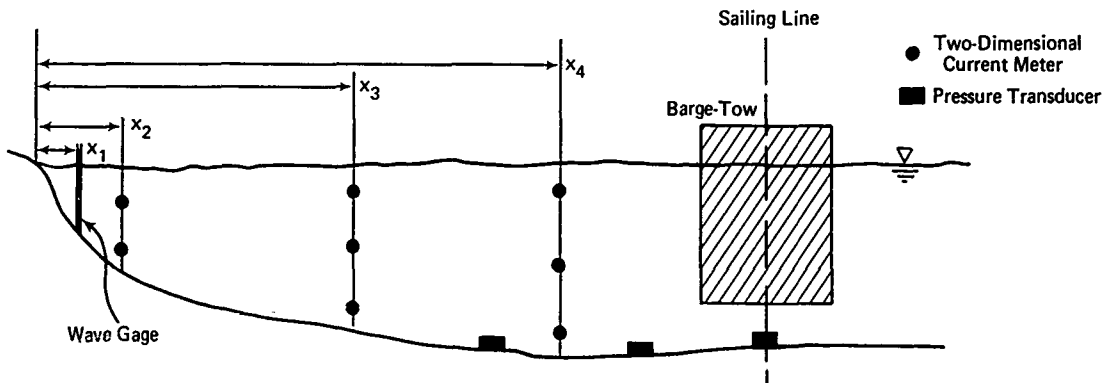


Figure 69. Typical field setup for velocity, pressure, waves, and drawdown data collection

#### Pressure

179. Data on pressure fluctuations should be collected from three to five locations during an event (Figure 69). Pressure transducers should be installed at or near biologically sensitive areas.

#### Waves

180. Wave data should be collected from two stations, one on each side of the river (Figure 69). Wave data can be collected at 1-sec intervals before vessel passes. However, during an event, wave data should be collected at 0.1- to 0.2-sec intervals.

#### Drawdown

181. Drawdown data should be obtained at two locations. Wave gages can also be used to measure drawdown. The wave and drawdown data can also be



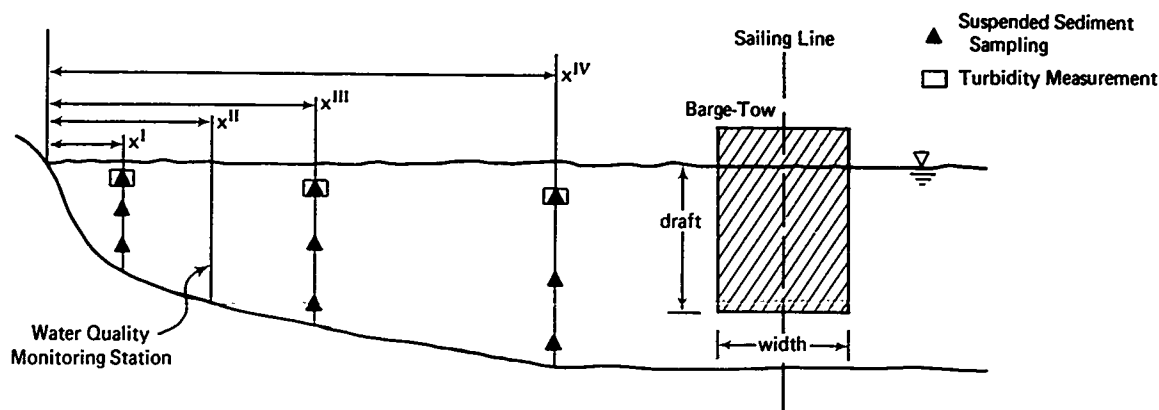


Figure 70. Typical field setup for suspended sediments, turbidity, and water quality measurements

collected with a video camera and staff gages if electronic wave gages or pressure transducers are unavailable. If a camera is used, it should be installed so that it will be unaffected by waves, drawdown, or currents. When pressure transducers are used, they should be programmed to collect data at 0.1-sec intervals.

#### Suspended sediment sampling

182. Suspended sediment samples should be collected at 20- to 30-min. intervals to determine ambient concentration. The following procedure was followed by Bhowmik et al. (1981a) for two events. When the bow of an approaching barge crossed the transect line, visible and audible signals were given by boat A (Figure 71). Stopwatches were then started in all three boats. This time was called "barge elapse time" to denote the time in minutes after the barge passed. Boat A, which was out of the main channel for safety reasons, was usually in its position on the transect when the tow passed. Boat A began sampling immediately, while boats B and C remained a safe distance from the tow until it had passed, when they maneuvered into position.

183. During the first 30 min after the tow passed, a depth-integrated suspended sediment sample was taken every 2 min. For the next 30 min, samples were taken at 5-min intervals. During the last 30 min, a sample was collected every 10 min. A total of 24 samples were collected per boat for the full 90-min sampling period. If another tow arrived before 90 min had passed, the sampling routine was restarted.

184. Pump samplers can be used to collect suspended sediment samples (Figures 70 and 72). When they are installed, the frequency of data

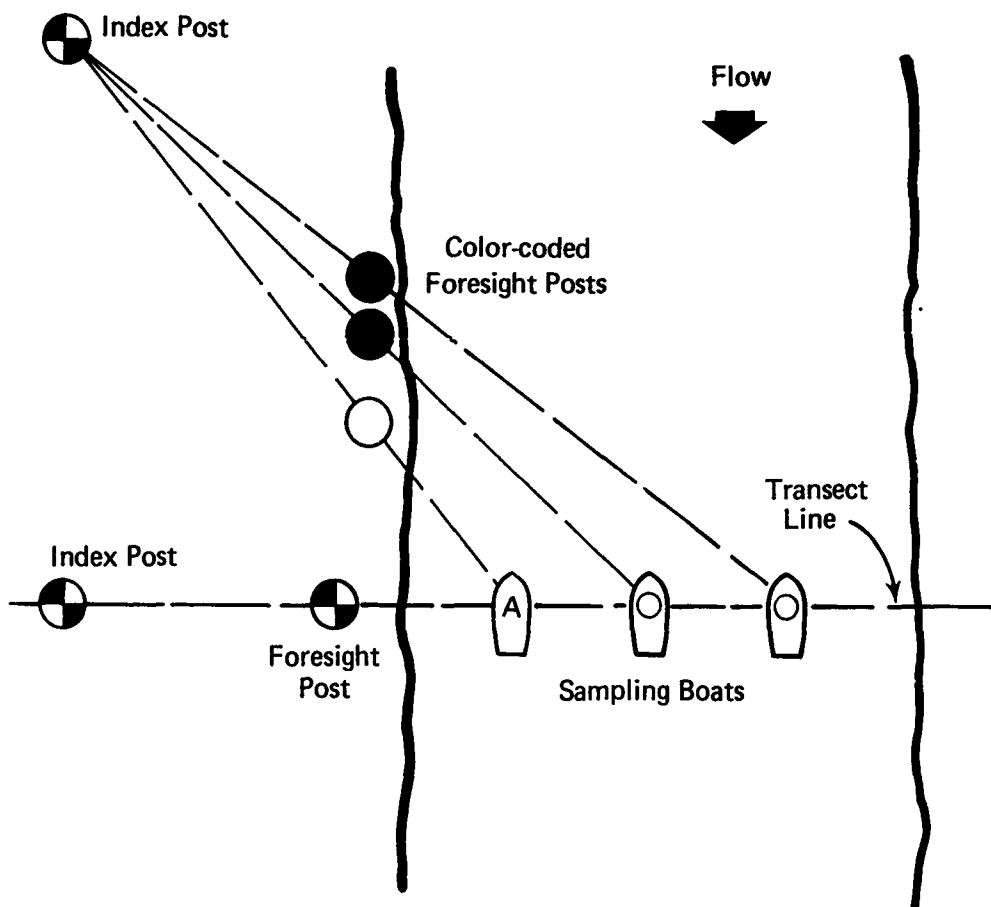


Figure 71. Delta post system for repositioning sampling boat across a large river

collection can be increased to about 1-min intervals. If the biologically sensitive area extends over the whole width of the river, then suspended sediment samples should be collected on both sides (Figure 70). Suspended sediment sampling should be continued for about 90 min for each event. Sufficient samples should also be collected to determine particle size distribution for ambient conditions as well as during an event.

#### Sedimentation rates

185. A plate or tube sediment trap can be used to analyze short-term sediment deposition rate. These instruments have already been described in Part IV (Figure 41).

#### Water level recording

186. Water levels can be recorded continuously at the site. These and other geometric data are used to determine hydraulic parameters such as WT, D, wetted perimeter, and average velocity.

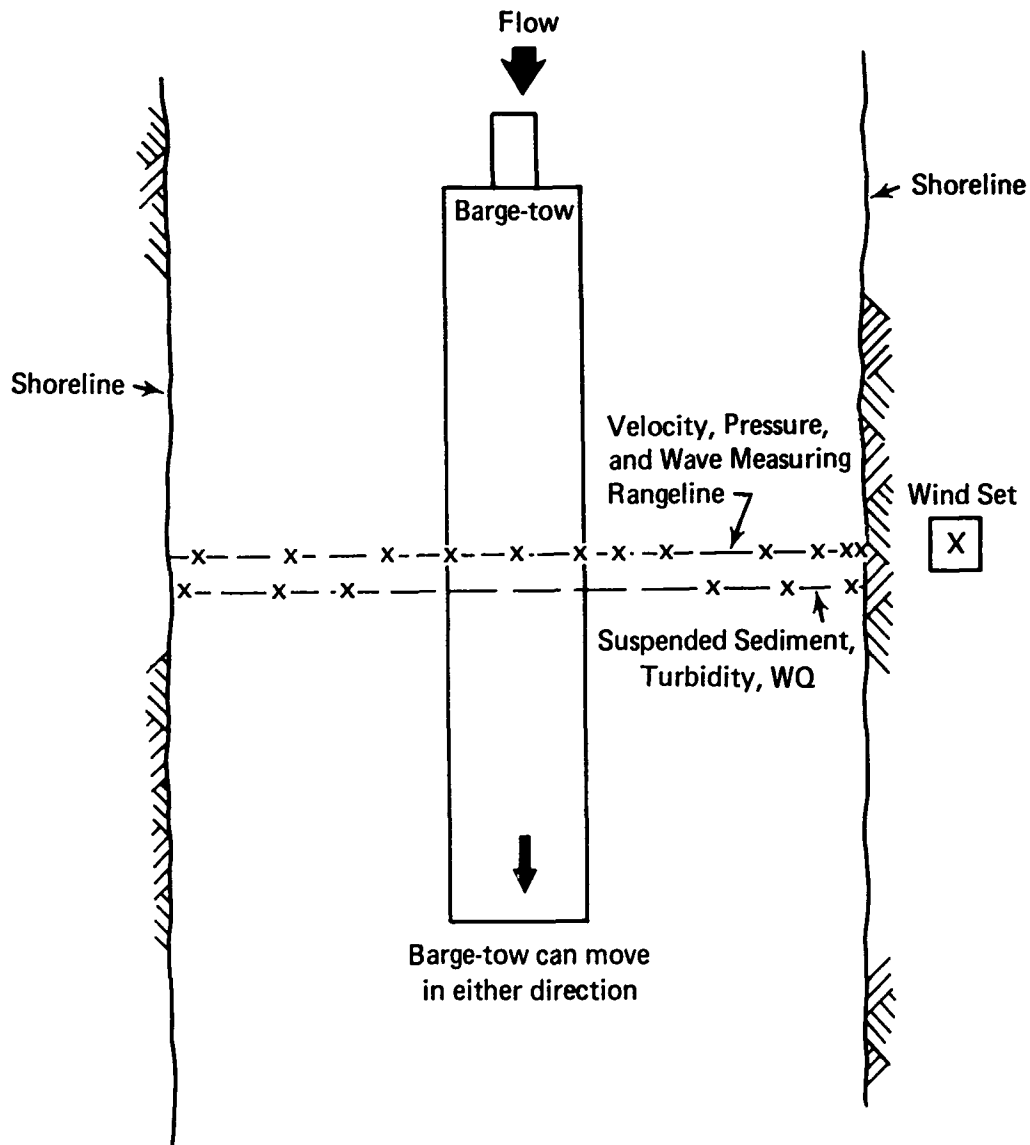


Figure 72. Plan view of a typical field setup

Water quality

187. Water quality data should be collected at two verticals, one on either side of the river, to determine DO, pH, temperature, turbidity, and specific conductance. These should be collected from near the main channel border areas (MCBA) (Figure 70).

188. Biologists frequently require information on turbidity as well as suspended solids. A field turbidimeter measures the amount of light reflected at a 90-deg angle by sediment particles. Turbidity measurements should be taken if there is concern about light penetration for sight-feeders or to support growth of aquatic plants. In some cases, water samples collected for suspended sediments can also be used to determine turbidity.

## Traffic Characteristics

189. Detailed descriptions of some aspects of traffic-related data collection follow.

### Vessel parameters

190. In addition to the determination of the track of the vessel and its distance from the shoreline and the sampling boat, other data that should be recorded include vessel type, draft, size, number of barges, direction of movement, and the names of the tows. The tow name can be used to obtain data on size, engine power, and propeller type from the Inland River Record (Owen 1981). Under some conditions, propeller diameter, pitch, and turning speed may be required and can often be obtained from the captain.

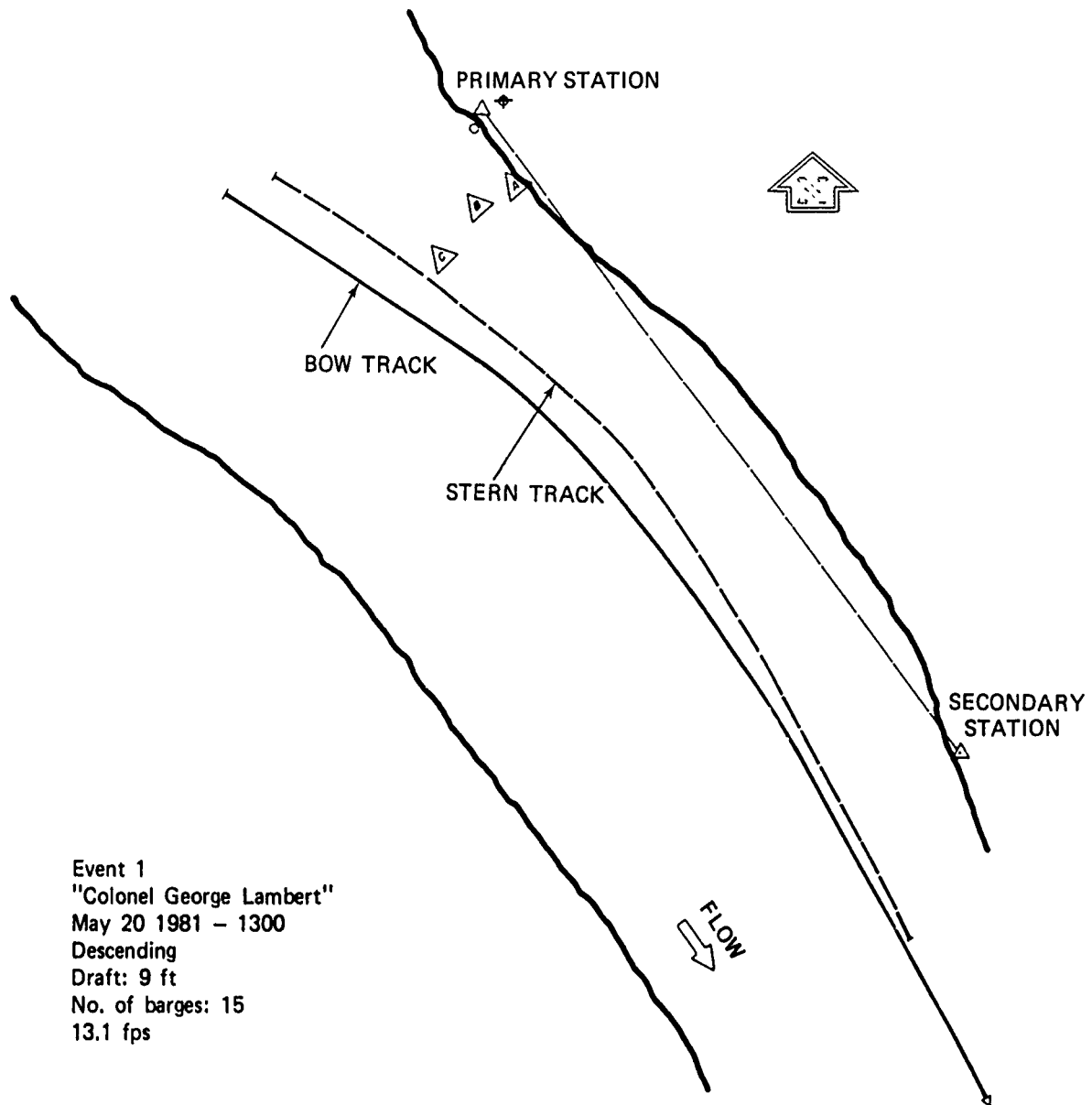
### Vessel track

191. Two theodolites should be installed (Figure 73) to follow the track of the vessel. As soon as the vessel is visible from both stations, horizontal angles should be measured simultaneously to a previously agreed upon point on the tow (usually the center-line foresight mast which is present on the bow of the leading barge of most tows). These angles are measured to the nearest 1' of arc and recorded. The procedure should be repeated for the stern of the tow, where the sighting point is usually the radar mast or the jack-staff.

192. These angular measurements should follow each other as rapidly as possible and are to be taken in pairs. An angle to the bow from each station must be measured and an angle to the stern from each station must be measured simultaneously, forming a set of angles consisting of two pairs. A battery-powered tape recorder may be easier and faster than taking notes.

193. Data collection should continue at regular intervals until the tow passes. This procedure may appear cumbersome, but each pair of angles can be measured and recorded in approximately 30 sec. Usually an interval of about 1 min can be left between sets of angles. This method has proved effective even during multiple tow passages (Bhowmik et al. 1981a, 1981b). Coordination between stations can be maintained by continuous radio communication, with all actions initiated and directed from the primary station.

194. A graphic depiction of each track can be developed by plotting the point of intersection for each pair of angles on the base maps and connecting the resulting points. Having measured angles to both bow and stern, it is



Event 1  
 "Colonel George Lambert"  
 May 20 1981 - 1300  
 Descending  
 Draft: 9 ft  
 No. of barges: 15  
 13.1 fps

Figure 73. Tow tracking at Mosier Landing

possible to show differences in tracks of each end of the tow. Such a track is shown in Figure 73 (from Bhowmik et al. 1981a). The technique described above is one that can be used in tracking tows in a navigation channel. Alternatively a radar tracking system could be set up to continuously monitor the barge.

195. Researchers from the Illinois State Water Survey used a microwave system where two transponders were kept at the primary and secondary sites located either on the same side or on the opposite side of the river. The third transponder was installed on a boat which followed the tow at a predetermined location and distance. Based on information from the three transponders, tow tracks were developed. However, this system will only determine a single track for a single reference point on the tow.

#### Tow velocity determination

196. The speed of tows can be determined by timing the tracks. When the first angle (bow or stern as convenient) is measured, a stopwatch should be started. The watch can then be stopped at the last angle measurement. The resulting elapsed time is then used to determine the average speed of the tow. These velocities are relative to the shore, and it may be necessary to adjust them for effects of current. The velocity of the tows is actually a by-product of the bearing intersection procedure used to track the tows.

#### Sampling boat reposition

197. If suspended sediment samples are obtained from boats at predetermined points on the river, then the technique developed by the Illinois State Water Survey (Bhowmik et al. 1981a) should be used. This system (the delta system) consisted of a series of shore-based, color-coded visual guides. When aligned by the boat operator, these indicated the correct position fairly closely (Figure 71). The primary survey station was established near a line that constituted a channel transect to which sampling locations were referenced. Two 2.4-m brightly painted posts were erected on the shore 30.5 m apart on the transect line. The post farthest from shore was termed the index post, and the other was called the foresight post. When the two posts appeared to be aligned (one behind the other), the boats were positioned on the transect line.

198. The boats were arranged and anchored along this line. Figure 74 shows three work boats (A, B, and C) in position. Boat C was located in the main channel directly in the tow track, boat A was out of the main channel closest to shore, and boat B was located halfway between boats A and C and on the transect line. At some convenient distance upstream, usually 122 or 152 m, another index post was erected in a clear area on shore (Figure 71). Between this post and the water, color-coded foresight posts were set in positions that were aligned with each of the sampling boats. This part of the system had a delta shape, which prompted its name. Each boat now had two sets



Figure 74. Sampling boats in position for data collection

of visual references for its correct position: one alignment defined the transect line, and the color-coded alignment intersected the transect line at the boat's correct position.

199. The system functioned as follows: The sampling boats moved out and into the channel as a tow passed. The boats moved upstream to reach their position, since steering into the current allowed more precise handling. The boats were carefully maneuvered to the point where the transect line and the color-coded alignment intersected, which defined the appropriate sampling position. The boats were immediately moved directly upriver taking into account the effects of wind and current, and the anchors were set. Each boat was then allowed to drift back downstream and the anchor line was secured when the boat was positioned correctly. This required good radio communication among all sites. Depending on the primary objective of a study, the number of boats required at a site can vary from one to five or six.

200. Figure 72 shows a schematic diagram of a typical straight reach where data for navigation impact studies were collected. It may be necessary to collect wind data to separate the effects of barge traffic from wind.

## Backwater Lakes and Side Channels

201. This section describes techniques that can be used to measure physical effects of commercial traffic at the entrance to a backwater lake or at the inlet and outlet of a side channel. This procedure could also be used for main channels and channel borders. These habitats are usually some distance from the main shipping lane, and thus data collection can continue without being affected by navigation traffic. Procedures described previously for preliminary planning and site selection would also be similar for backwater lakes and side channels.

202. Figure 75 shows a side channel where the physical effects of commercial traffic were measured by Bhowmik et al. (1981b). For this study it was necessary to calculate a water and sediment input budget for the side channel in addition to determining the physical effects of waves, drawdown, and alteration of velocity structure.

203. The following data should be collected from the main channel (MC) and MCBA:

### River width

204. Widths should be measured at 5 to 10 cross sections between range-lines A-A and B-B (Figure 76) and from the backwater areas (Figure 77).

### Depths

205. Depths should be measured at about the same number of cross sections where widths are to be measured and at 20-35 verticals at each cross section.

### Water surface and bed profiles

206. The water surface and bed profiles should be measured between sections A-A and B-B (Figure 76) and within the backwater area (Figure 77). Water surface elevations between various points within a backwater area such as the one shown in Figure 77 may not vary much, but usually the bed elevations will.

### Velocity and discharge

207. Velocities should be measured at 20-30 verticals at sections A-A and B-B (Figure 76) and section A-A (Figure 77) to determine flows.

### Suspended sediment

208. Suspended sediment concentrations should be measured at sections A-A and B-B (Figure 76), and at section A-A (Figure 77) to determine sediment



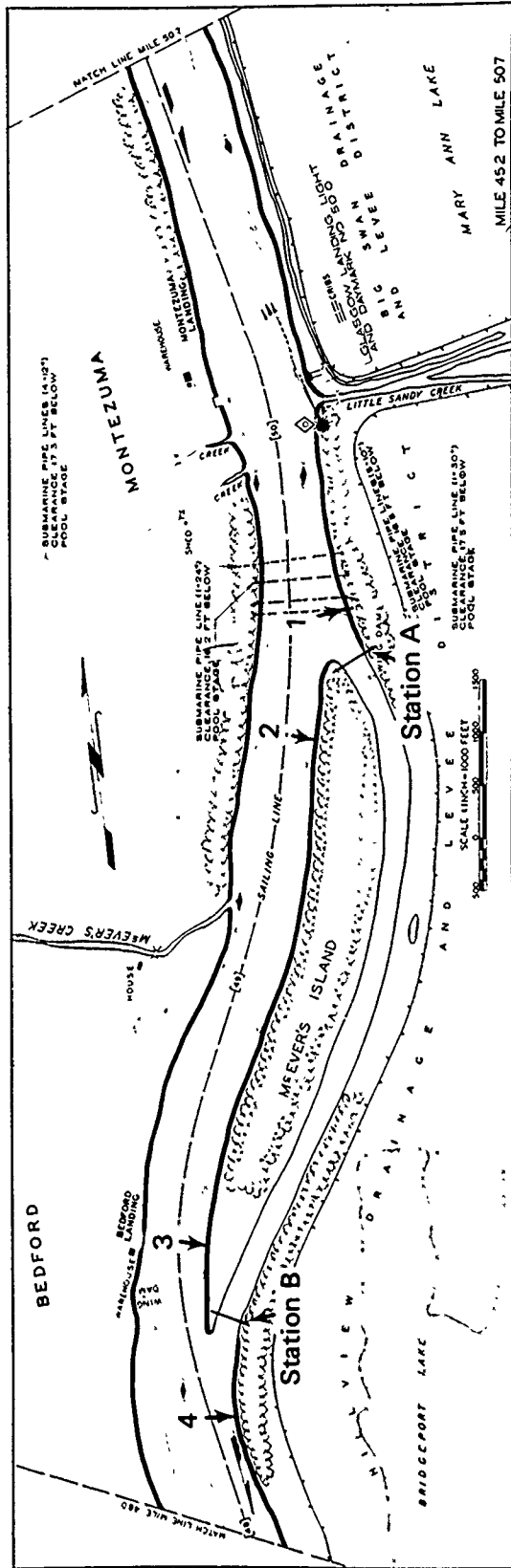


Figure 75. McEvers Island study site for side channel

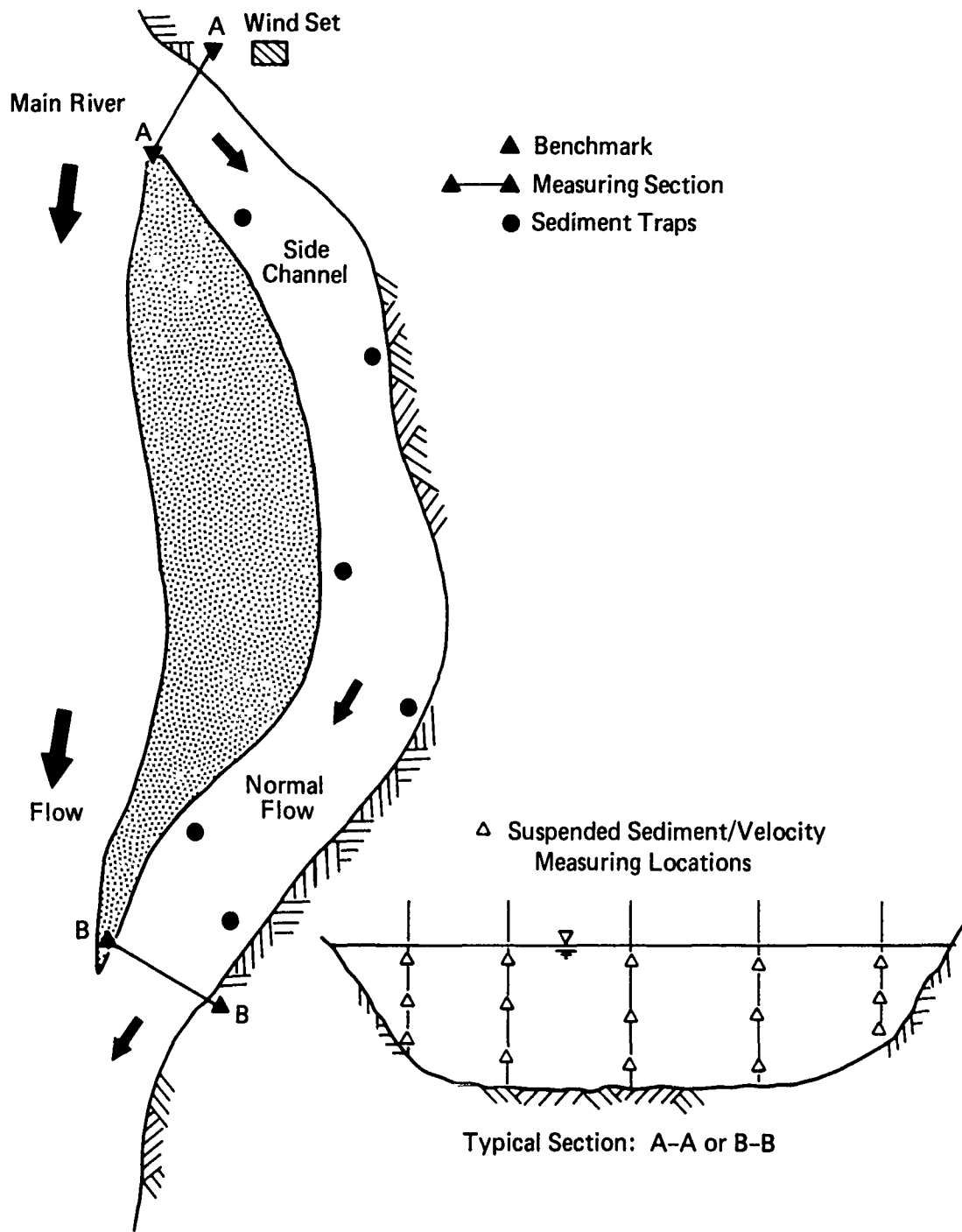


Figure 76. Schematic diagram showing the typical arrangement for instrumentation for a side channel

loads. Sufficient samples should be collected to determine particle size distribution.

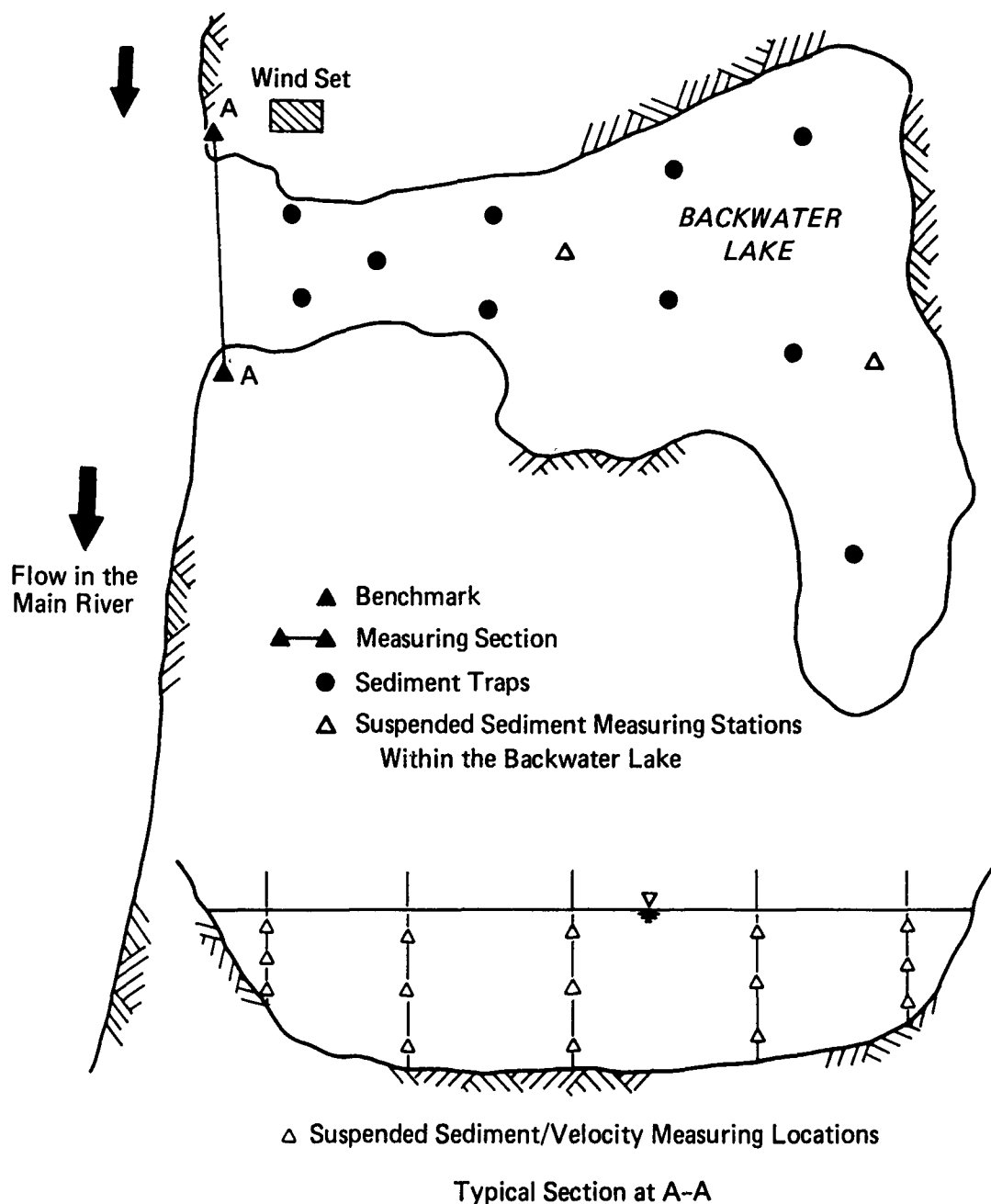


Figure 77. Schematic diagram showing the typical data collection arrangement for a backwater lake

#### Sedimentation patterns

209. Historical sedimentation patterns should be obtained and compared with current data. Techniques such as  $Cs_{137}$  or  $Pb_{210}$  may be needed to determine the sedimentation rates. These data will allow a comparative analysis of the impacts of navigation traffic on sedimentation rates and patterns. Bed material samples should be collected from sufficient points (15-20) to determine particle size distribution.

### Sediment quality

210. Bed material and core samples from 15 to 20 locations should be collected to determine quality of deposited sediment.

### Data Collection at Backwater Lakes and Side Channels

211. Data collection for barge tow events at the mouth and exit section of the side channel, and at the mouth and inside of the backwater lake, must proceed in a systematic manner. After all of the necessary equipment has been purchased and suitable sites have been selected, the necessary measuring equipment should be installed as shown schematically in Figures 76 and 77 for side channel and backwater areas, respectively. The following data should be collected:

#### Velocity and discharge

212. Detailed water velocity data should be collected at sections A-A and B-B (Figure 76) and section A-A (Figure 77) continuously just before, during, and after an event. Velocity data should be obtained from 5 to 6 verticals or more, depending upon the availability of meters. The data can be used to compute discharges before, during, and after an event. The velocity data can also be used to determine turbulent fluctuations of velocity and shear stress. In addition, inflow, outflow, and the water budget can be computed from these data.

#### Pressure

213. Pressure transducers can be installed at the above-mentioned sections and in side channels and backwaters to determine fluctuations caused by traffic.

#### Suspended sediment

214. Suspended sediment samples should be collected from three points at each of five verticals from sections A-A and B-B (Figure 76) and from section A-A (Figure 77) while velocity data are being collected. These data should be used to determine inflow, outflow, and sediment budget of the side channel and backwater. The sediment budget will establish whether or not barge-tow events generate pulse inputs of sediment to the side channel and backwater. Sufficient samples should be obtained to determine particle size distribution.

### Sedimentation rates

215. The short- and long-term sedimentation rates within the side channel and backwater should be determined by installing sediment traps (Figures 76 and 77). Also hydrographic maps should be prepared to determine present and altered bed elevations.

### Stage fluctuations

216. Stage recorders should be installed at sections A-A and B-B (Figure 76) and section A-A (Figure 77) to determine stage fluctuations.

### Traffic characteristics

217. Data on the number and configuration of barges (width, draft, direction, distance, towboat horsepower, and propeller rpm) should also be obtained.

### Wind characteristics

218. Wind data should be collected near sections A-A or B-B (Figure 76) and section A-A (Figure 77).

### Main channel data collection

219. Data from the main channel must be collected to determine variabilities and how they relate to those observed at the mouth and exit section of the side channel or at the mouth of the backwater.

## Impact of Recreational Traffic

220. Vessels of all sizes, from canoes to 15-barge tows, all use large rivers, and every vessel interacts with the river by its displacement, propulsion, and maneuvering. Barge tows cause moderate wave action, but cause drawdown, large return velocities, waves, and high turbulence from their propulsion system. Small power boats tend to generate substantial wave trains, but small propeller jets. Larger cabin cruisers and towboats without barge convoys generate the largest wave trains on the river and have propulsion wakes in proportion to their power.

221. There have been few studies of waves generated by recreational boats. Controlled experiments were conducted by Bhowmik (1976) to develop criteria for shore protection. Sorenson (1973) studied waves generated by boats and ships in harbors and connecting channels. Das (1969) used model tests to develop wave characteristics for vessels in restricted waterways. Most of these studies concerned large vessels. Bhowmik, Demissie, and Guo

(1982) measured waves on the Illinois and Mississippi rivers, but worked mainly on barge tows, not recreational vessels.

222. A few studies such as those by Bhowmik and Schicht (1980), Karaki and van Hoften (1974), and Hurst and Brebner (1969) investigated the role of wind and boat-generated waves on bank erosion along waterways. Camfield, Ray, and Eckert (1979) concluded that there is a general lack of information on waves and boat wakes and their contribution to bank erosion. Lubinski et al. (1980) indicated that information on wave height, period, and energy spectra for both wind and boat-generated waves was needed.

### Conducting Studies of Recreational Traffic

#### Controlled experiments

223. Since few data on recreational traffic are available, controlled experiments should be used to determine basic physical characteristics of waves generated by these craft. The following data should be obtained:

#### Wave characteristics

224. Recording electronic wave gages should be installed at a distance of 3 to 7 and 20 to 25 m, respectively, from the shore (Figure 78).

#### Boat tracks

225. Guide buoys should be set at 3 to 5 specified distances from the shore where recreational craft will traverse at specified speeds.

#### Data Collection

226. Recreational crafts of various sizes, shapes, etc., should move at a constant speed along fixed tracks. The boat type and speed could be varied along each track. Wave data should be collected continuously for each event from both wave gages. Three suspended sediment sampling stations should be installed with two point intake ports (Figure 78). Suspended sediment samples should be obtained from all six points during each event. Sampling should be initiated before the start of an event and should continue for 30 to 60 min after an event. Background data should be obtained to determine the ambient suspended sediment concentrations. Wind gages should be installed to assess the effects of wind on wave generation.

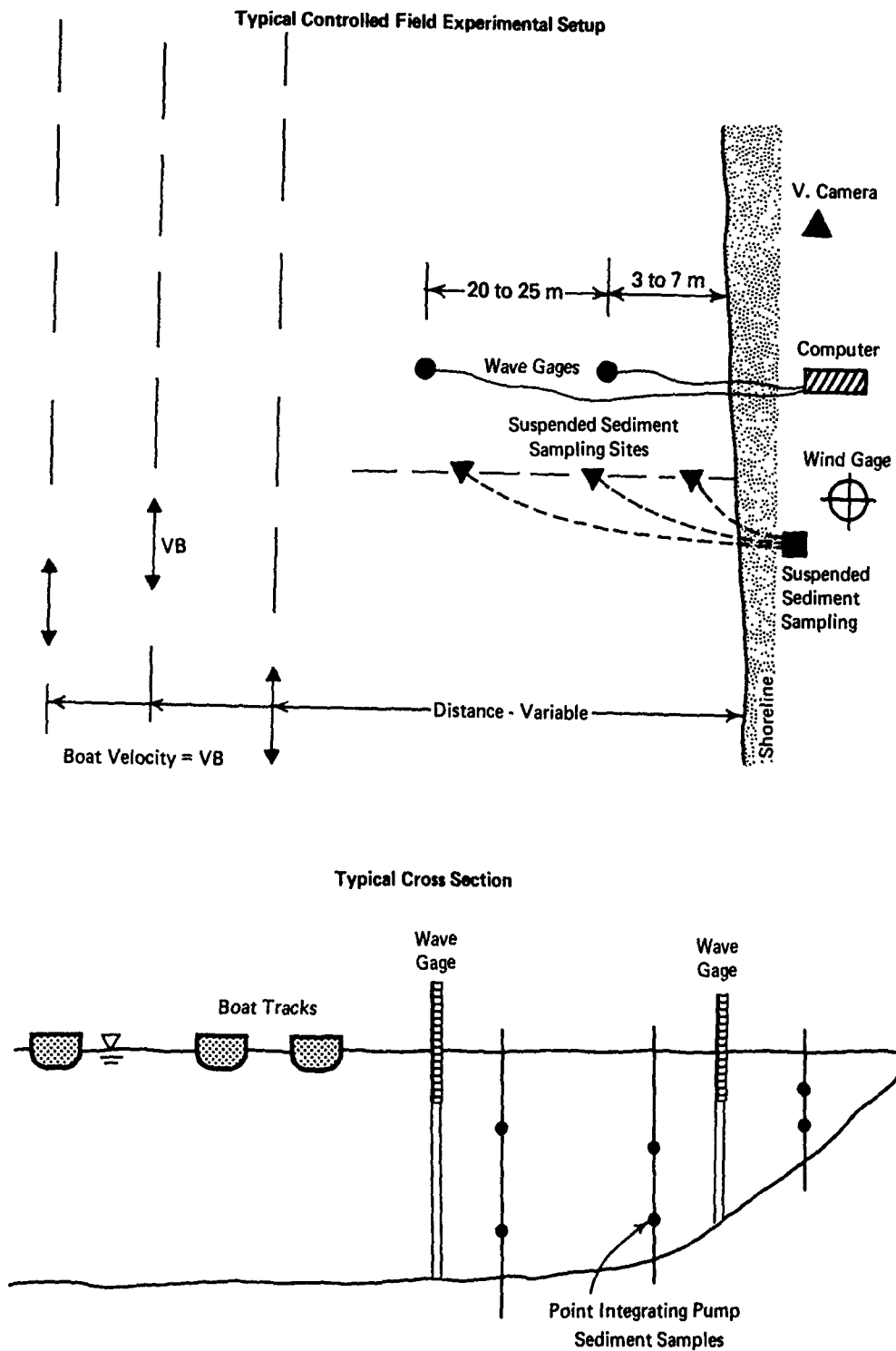


Figure 78. Typical arrangement for controlled field experiments for waves generated by recreational traffic

## Bank Erosion

### Field data collection

227. Field data should be collected from the sensitive backwater areas where other hydraulic and biological data are to be collected. Data collection techniques should be similar to those outlined from the controlled experiments except that the speeds, distances, tracks, etc. of the recreational craft will not be controlled. Only naturally occurring and event basis data should be collected. However, an attempt should be made to gather as much background data as possible so that analysis of the waves generated by the uncontrolled movement of the recreational craft can be compared with the results from the controlled experiments. For the uncontrolled or naturally occurring events, data on suspended sediments at various locations within the sensitive backwater must also be collected. Suspended sediment samples should also be collected to determine the particle size distribution of the resuspended sediments.

228. Separation of bank erosion into that caused naturally and that caused by navigation is difficult because of the interdependence of causative factors. However, a quantification of erosion rates can be made and then followed by an evaluation of the relative effects of navigation. Figure 79 shows instruments that can be used to determine erosion rates. The following outline is recommended for these studies.

- a. Establish a surveying benchmark.
- b. Measure bank profiles at three to five cross sections (lines A, B, and C, Figure 79).
- c. Install shallow piezometers to measure the hydraulic gradient before, during, and after tow passages.
- d. Collect 5 to 10 sediment samples to determine particle size distribution.
- e. Conduct periodic surveys to determine erosion rates.
- f. Record bank profile before and after a tow passes to determine if that event initiated erosion.
- g. Analyze all data to determine the impacts of tows on bank erosion.



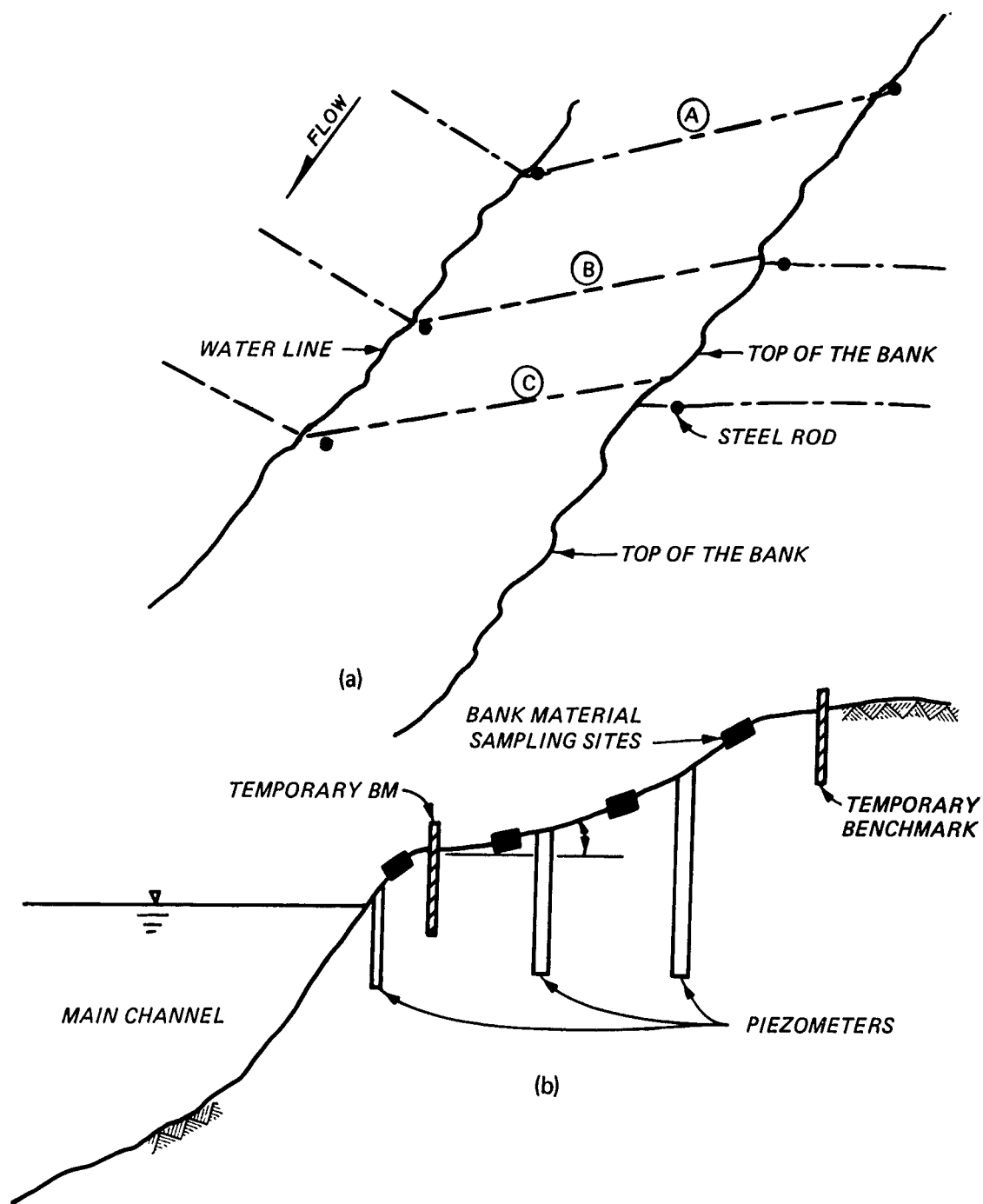


Figure 79. Techniques for collecting data on bank erosion

## PART VI: DATA ANALYSIS

229. Part IV and the first two sections of Part V described equipment and methods for collecting data to determine the physical effects of navigation traffic. Since the objective is usually to determine site-specific impacts at a biologically sensitive area, data collection and analysis must be tailored to that particular site with consideration of its hydraulic, geomorphic, and biological characteristics.

### Site Characteristics

230. From preliminary data, establish the following:

- a. Determine whether the reach is straight or curved. If the reach is straight, determine its length, upstream and downstream curvature, and features such as wing dams (dikes that protrude partway into the channel), tributary inflow, etc. If the reach is curved, determine the radius of curvature, deflection angle, ratio of width to radius of curvature, approximate length of the straight reaches (if any) both before and after the curved reach, other features, and sinuosity.
- b. Determine width, depth, wetted perimeter, hydraulic radius, width-depth ratio, cross-sectional shape, and planform of the study reach.
- c. Determine bank and bed material characteristics including particle size distribution, standard deviation, and uniformity coefficient.
- d. Determine the main channel area, left and right channel border areas, zones of high biological activity (sensitive habitats), including the areal distribution and general orientation of the habitat with respect to the general flow pattern of the river.
- e. Determine the prevailing wind direction; maximum, minimum, and effective fetches; and other variables that may impact the wind-generated wave characteristics of the test site.
- f. If available, historical information on the erosive nature of the river reach under study should be obtained.

### Flow Characteristics

231. The following analyses should be completed based on the hydraulic data collected prior to initiating physical effects studies:

- a. Develop a flow-duration curve to determine the frequency of flow.

- b. Develop seasonal flow variation curves similar to Figure 12.
- c. Determine or compute the discharge for various stages.
- d. Determine average velocity, characteristics of the lateral and vertical velocity distributions, the presence or absence of secondary circulation, natural variations in point velocities in both the lateral and vertical directions, and magnitudes of the ambient turbulence intensity at the locations where physical data are to be collected. If the site is located at a bend, determine the variations in lateral and longitudinal velocity distributions around the bend, especially near the test site.

### Sediment Transport Characteristics

232. Suspended sediment data that should be collected to determine ambient characteristics of the site have been discussed in Part II. In addition, the following activities should take place.

- a. If point samples were collected, determine the lateral and vertical sediment concentration profiles.
- b. Determine the particle size distribution of the suspended sediments.
- c. Quantify bed load movement.
- d. Compare and contrast the water temperatures at the time of the data collection with the water temperatures that are normally present at the site for that time of the year. This determination must be made on the basis of historical data for the site or for a nearby site such as a gaging station.

233. Hydraulic, hydrologic, and sediment data to be collected during passage of tows, barges, or recreational traffic should be analyzed with procedures similar to procedures given in the last section. However, some additional analyses will be needed to determine the relative magnitudes of increases in velocity, turbulence, suspended sediment concentrations, sedimentation rates, etc., and are discussed below.

#### Suspended sediment

234. Suspended sediment data should be collected during an event. Data should be collected at various time intervals to evaluate changes through time. In addition, the following should be performed:

- a. Plot ambient suspended sediment concentrations before, during, and after the event. These will enable a determination of the average ambient sediment concentration at the sampling station and the magnitude and duration of any elevated sediment concentration during an event (see Figure 28).

- b. On the basis of the time series plots, determine how the elevated sediment concentrations and durations correlate with the physical and hydrological characteristics of the river (geometry of the river; blockage factor; and, bed material characteristics) and the tow (length, width, draft and submerged area of the barges; distance, speed and direction of movement of the tow).
- c. Determine (using statistical methods) whether elevated suspended sediment concentration (resulting from traffic) is significantly different from ambient conditions. For each event determine statistical parameters such as standard deviation, variance, coefficient of variation, and skewness.
- d. On the basis of the previous analyses, determine if statements can be made on the significance of the elevated sediment concentrations and how they relate to traffic.

#### Bed load

235. Collection of bed-load data may not be feasible on sand channels when bed-load samplers are not available. However, if Helley-Smith bed-load samplers are used, relative changes in bed-load transport due to the movement of commercial traffic can be determined.

#### Sedimentation rates and hydrographic mapping

236. If sediment traps or plates are used to determine sedimentation rates (Figure 41), then total vertical deposition can be determined for the duration of the field experiment. Ideally, sediment deposition rates should be determined for each event and these values should be compared with ambient and long-term sedimentation rates. Sedimentation caused by traffic can be compared to ambient rates to determine traffic effects. In addition, precise hydrographic maps, that can be used to determine the areal distribution of deposition and the relative magnitudes of sedimentation at various sites, can be developed before and after field experiments. These analyses can demonstrate the directional aspects of sedimentation patterns.

#### Bed materials

237. In Part IV, procedures for the collection of bed material samples were discussed. However, variations in bed material characteristics before and after field experiments may not be discernible. If a sufficient number of sediment plates or traps are available, analyses will show the composition and particle size distribution of resuspended sediments.

Velocities, velocity  
fluctuations, and turbulence

238. Sufficient point velocity data must be collected to determine the magnitude and duration of altered velocity regimen due to the river traffic. If these data are collected for use in numerical models, the investigator may wish to obtain information on propeller diameter, pitch, and rotation speed. The following analyses should be performed:

- a. Determine the magnitude and change in direction of velocity vectors during tow passage (Figure 27). If sufficient data are available from an array of two-dimensional velocity meters at several verticals, then the curvilinear distributions (rotational characteristics) of the velocity vectors can be determined. Turbulent fluctuations of the velocities should also be determined. The impact of velocity fluctuations on aquatic habitats can then be determined.
- b. Time series analyses of the velocities (both the lateral and longitudinal components) should be performed to determine various statistical parameters. Determine how the resultant velocity vector changes as a result of commercial vessel passage.
- c. Once the means and standard deviations for ambient conditions and as a result of vessel passage have been determined, turbulence intensities for various time periods and time intervals can be computed. Variations in turbulence intensities before, during, and after vessel passage will help determine if turbulence from commercial traffic could be detrimental to biologically sensitive areas.
- d. Correlate velocity fluctuations, and their directional changes, with traffic and river characteristics. The following should be considered in this analysis: length, width, direction, speed, distance, area of submerged portion of the barges, and configuration of the tows; as well as width, depth, wetted perimeter, hydraulic radius, ambient velocity, stage orientation, and roughness characteristics of the test reach.

Pressure fluctuations

239. Pressure fluctuation data are usually collected with pressure transducers at selected points. These data may be collected in conjunction with the velocity data. The following information is needed:

- a. Determine the magnitude of maximum and minimum pressures generated by vessel movement. Sufficient low pressures generated during an event may increase the lift force at the bed, which can dislodge bed materials and disrupt fish larvae or macroinvertebrates.
- b. Perform standard time series statistical analyses to determine various parameters (similar to velocity fluctuation analyses).

### Water quality

240. Probably the most important water quality parameters in a navigation impact study are turbidity, dissolved oxygen content (DO), and sediment oxygen demand (SOD). Other parameters, including trace metals and organic compounds in the water column and resuspended sediment, can also be measured. Turbidity will probably increase, especially near the channel border, as a result of the altered velocity regimen and waves generated by traffic. The SOD may change as a result of the resuspension of organically rich sediments.

### Waves and drawdown

241. Probably the most significant factors that should be considered in the analyses of wave and drawdown data are their maximum values and durations. Maximum values will indicate if waves will be detrimental to channel border habitats and shores. Maximum drawdown, durations, and frequencies may indicate if these changes will affect the areal distribution of sensitive shoreline habitats. If possible, maximum wave height and drawdown should be correlated with vessel parameters (distance, speed, direction, draft, and total submerged area), as well as hydraulic geometry of the river. Analyses that have been used by previous researchers are discussed in Parts I and IV.

### Recreational Traffic

242. In studies of recreational traffic, data from controlled experiments and natural events should be analyzed. The basic data will be the sequence of wave height with time for each event. The type of boat, its speed and distance from the instruments, and environmental conditions (especially wind speed and direction) will be part of the data set. For the controlled experiments these data should be analyzed for energy and wave height spectra. Records of wind waves should be analyzed as part of the background data.

243. Regression analysis should be used with dimensional analysis to correlate wave height, frequency, and energy to boat type and speed. The reduction in wave height with distance is expected to be similar to that proposed by Das (1968) and used by Bhowmik (1976). Correlations should be developed between the traffic characteristics and the concentration of the resuspended sediments.

244. The data for uncontrolled traffic conditions should be subjected to similar analyses, except that only unusually large, fast, or close events will be distinguishable from the concurrent and criss-crossing waves of

several boats. If the shoreline is riprapped, or there are vertical bulkheads, wave reflection will also confuse the observed patterns. However, duration of waves of different height or energy can be determined. An attempt should be made to identify waves from large recreational boats and any barge tows that pass at or near the site.

#### Bank Erosion

245. In analyses of bank erosion, consideration must be given to hydraulic and geotechnical forces acting on the riverbank and to the importance of these forces. Factors that should be considered include:

(a) changes in velocity and turbulent fluctuations of velocity, (b) direction and magnitude of the primary velocity component or the resultant velocity, (c) composition of the river bank, (d) presence of piping and seepage forces, (e) overbank drainage patterns, magnitudes, and direction, (f) duration of the impinging waves, and, (g) relative magnitudes of wind-generated waves compared to traffic-generated waves.

246. The above discussion focused primarily on impact data that are collected from the main channel and channel border. However, similar analyses can also be performed with hydraulic data collected in a side channel or a backwater lake. A sediment budget and the effects of attenuation or reduction of wave heights at the inlets of the channel or the backwater lake could also be determined. Otherwise, analyses could be based on the above-described techniques.

## PART VII: CONCLUDING REMARKS

247. The primary objective of this report is to outline procedures that can be used for the measurement and analyses of physical data to measure changes that are generated with the movement of navigation traffic in large rivers.

248. Part I contains a brief description of the purpose and scope of the report, summaries of recent investigations of navigation studies, and basic considerations in the extrapolation of the data for system-wide application. Part II provides a description of the various hydraulic, sediment transport, and vessel-induced parameters that need to be considered in navigation studies. Generalized evaluation, analyses, and variation of these parameters in a natural river system are also discussed. Some theoretical backgrounds are given for velocity fluctuations, turbulence intensity, velocity distributions, and sediment transport characteristics of rivers.

249. Part III considers the basic evaluation that must be done before collection of field data. Included is information on clarifying study objectives, methods for selecting sites, needs for specific physical and hydrologic data, and information on the importance of replicate samples. Part IV describes instruments that are necessary to collect physical, hydraulic, and sediment transport data for a river. This includes instrumentation for suspended and bed-load sampling, determination of sedimentation rates, development of hydrographic maps, collection of bed and bank material samples, measurement of velocities and velocity fluctuations, quantification of pressure variations, and collection of wave and drawdown data.

250. Part V, which is based on materials presented in Parts I through III, discusses development of plans for data collection and analysis. Methods for studying pre-and post-navigation periods are presented. Data collection and analyses pertain to physical impacts to the main channel and channel border, as well as to side channels or inlets to backwater lakes. A brief outline of information needed to evaluate hydraulic and sediment transport characteristics of a river is also included. This fundamental knowledge is important for planning and executing a navigation impact study.

251. Part VI outlines the procedure that can be followed for the analysis of the data. This includes an evaluation of the field sites, variability of flows, including velocities, movement and deposition of sediments, effects of recreational boating, and changes in bank erosion rates. This



report can serve as a guide for the development and implementation of field measuring techniques for the determination of the physical changes associated with the movement of navigation traffic in an inland waterway.

## REFERENCES

- Alavain, V., and Furry, J. C. 1988. "Measurement and Analysis of Traffic-Induced Transient Motion in Navigation Channels," Hydraulic Engineering, S. R. Abt and J. Gessler, eds., pp 991-996.
- American Society of Civil Engineers (ASCE). 1975. "Sedimentation Engineering," Manuals and Reports on Engineering Practice, No. 54, New York.
- Bhowmik, N. G. 1976. "Development of Criteria for Shore Protection Against Wind-Generated Waves for Lakes and Ponds in Illinois," Illinois State Water Survey Contract Report 170, Champaign, IL.
- \_\_\_\_\_. 1979. "Hydraulics of Flow in the Kaskaskia River in Illinois," Illinois State Water Survey Report of Investigation 91.
- \_\_\_\_\_. 1984. "Hydraulic Geometry of Floodplains," Journal of Hydrology, Vol 68, pp 369-401.
- \_\_\_\_\_. 1987a. "Hydrologic Research at LTER Sites," EOS, Transactions of the American Geophysical Union, Vol 68, No. 37.
- \_\_\_\_\_. 1987b (Jun). "Some Natural and Human Influences on Streams and Rivers," Water International, Vol 12, No. 2, pp 55-59.
- Bhowmik, N. G., and Adams, J. R. 1986. "The Hydrologic Environment of Pool 19 of the Mississippi River," M. M. Sonart, K. S. Lubinski, and R. A. Sehmik, eds., Hydrobiologia, Vol 136, pp 21-30.
- Bhowmik, N. G., Adams, J. R., Bonini, A. P., Guo, C. Y., Kisser, D. J., and Sexton, M. A. 1981a. "Resuspension and Lateral Movement of Sediment by Tow Traffic on the Upper Mississippi and Illinois Rivers," Illinois State Water Survey Contract Report 269, Champaign, IL.
- Bhowmik, N. G., Adams, R. A., Bonini, A. P., Klock, A. M., and Demissie, M. 1986. "Sediment Loads of Illinois Streams and Rivers," Illinois State Water Survey Report of Investigation 106, Champaign, IL.
- Bhowmik, N. G., Adams, J. R., and Sparks, R. P. 1986. "Fate of Navigation Pool on the Mississippi River," ASCE Journal of Hydraulic Engineering, Vol 112, pp 967-970.
- Bhowmik, N. G., Bonini, A. P., Bogner, W. C., and Byrne, R. P. 1980. "Hydraulics of Flow and Sediment Transport in the Kankakee River in Illinois," Illinois State Water Survey Report of Investigation 98.
- Bhowmik, N. G., Demissie, M., and Adams, J. R. 1988. "Long-Term Ecological Research of Large Rivers: Importance of Hydrology and Hydraulics," Proceedings of the VIth World Congress on Water Resources, International Water Resources Association IWRA, Ottawa, Canada, May 29-June 3.
- Bhowmik, N. G., Demissie, M., and Guo, C. Y. 1982. "Waves Generated by River Traffic and Wind on the Illinois and Mississippi Rivers," University of Illinois Water Resources Center Research Report No. 167, Champaign, IL.
- Bhowmik, N. G., Demissie, M., and Osakada, S. 1981. "Waves and Drawdown Generated by River Traffic on the Illinois and Mississippi Rivers," Illinois State Water Survey Contract Report 271, Champaign, IL.

- Bhowmik, N. G., Lee, M. T., Bogner, W. C., and Fitzpatrick, W. P. 1981b. "The Effects of Illinois River Traffic on Water and Sediment Input to a Side Channel," Illinois State Water Survey Contract Report 270, Champaign, IL.
- Bhowmik, N. G., and Schicht, R. J. 1980. "Bank Erosion of the Illinois River," Illinois State Water Survey Report of Investigation 92, Champaign, IL.
- Bhowmik, N. G., and Simons, D. B. 1969. "Stabilization of Alluvial Channels," presented at National Water Resources Conference of the American Society of Civil Engineers, New Orleans, LA.
- Bhowmik, N. G., and Stall, J. B. 1979. "Hydraulic Geometry and Carrying Capacity of Floodplains," University of Illinois Water Resources Center Report 145, Urbana, IL, also Illinois State Water Survey Contract Report 225, Champaign, IL.
- Blaauw, F. C. M., van der Knapp, F. M. C., de Groot, M. T., and Pilaneyzk, K. W. 1984. "Design of Bank Protection of Inland Navigation Fairways," Publication No. 320, Delft Hydraulics Laboratory, Delft, The Netherlands.
- Bogner, W. C., Soong, T. W., and Bhowmik, N. G. 1988. "Physical Impacts of Navigation: Ohio River Field Data Collection," Illinois State Water Survey Contract Report 443, Champaign, IL.
- Bouwmeester, J., van de Kaa, E. J., Nuhoff, H. A., and van Orden, R. G. J. 1977. "Various Aspects of Navigation in Restricted Waterways," Twenty-fourth International Navigation Congress, Section I, Communication 3, Leningrad, Russia.
- Buchanan, T. J., and Somers, W. P. 1969. "Discharge Measurements at Gaging Stations," Book 3, Chapter A8, Techniques of Water-Resources Investigations of the United States Geological Survey, US Government Printing Office, Washington, DC.
- Camfield, F. E., Ray, R. E. L., and Eckert, J. W. 1979. "The Possible Impact of Vessel Wakes on Bank Erosion," US Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, MD.
- Chow, V. T. 1959. Open Channel Hydraulics, McGraw-Hill Co., New York.
- Chow, V. T. 1964. Handbook of Applied Hydrology, McGraw-Hill Co., New York.
- Comstock, J. P. 1967. Principles of Naval Architecture, Society of Naval Architects and Marine Engineers, New York.
- Das, M. M. 1968. "Relative Effect of Waves Generated by Large Ships and Small Boats in Restricted Waterways," Report No. HEL-12-9, University of California, Berkeley, CA.
- Das, M. M., and Johnson, J. W. 1970. "Waves Generated by Large Ships and Small Boats," Proceedings of the 12th Conference on Coastal Engineering, Chapter 138, Washington, DC.
- Demissie, M., and Bhowmik, N. G. 1985. "Peoria Lake Sediment Investigation," Illinois State Water Survey Contract Report 371, Champaign, IL.
- Demissie, M., and Bhowmik, N. G. 1987. "Long-Term Impacts of River Basin Development on Lake Sedimentation: The Case of Peoria Lake," Water International, Vol 12, pp 23-82.

- Demissie, M., Bhowmik, N. G., and Adams, J. R. 1983. "Hydrology, Hydraulics, and Sediment Transport, Kankakee and Illinois Rivers," Illinois State Water Survey Report of Investigation 103, Champaign, IL.
- Demissie, M., Soong, T. W., Bhowmik, N. G., Fitzpatrick, W. P., and Maxwell, W. H. 1986. "Secondary Circulation in Natural Streams," University of Illinois Water Resources Center Research Report 200, Champaign, IL.
- Einstein, H. A. 1950. "The Bed-Load Function for Sediment Transportation in Open Channel Flows," Technical Bulletin 1026, US Department of Agriculture, Soil Conservation Service, Washington, DC.
- Environmental Science and Engineering, Inc. 1981. "Navigation Impact Study, Illinois River, Pool 26, August 1980; Mississippi River, Pool 9, October 1980; Phase III, Task 9," Illinois Natural History Survey, Grafton, IL.
- Graf, W. H. 1971. Handbook of Sediment Transport. McGraw-Hill Co., New York.
- Guy, H. P., and Norman, V. W. 1970. "Field Methods for Measurement of Fluvial Sediment," Book 3, Chapter C2, Techniques of Water-Resources Investigations of the United States Geological Survey, Washington, DC.
- Helley, E. J., and Smith, W. 1971. "Development and Calibration of a Pressure-Difference Bed Load Sampler," Open file report, US Geological Survey, Water Resources Division, Menlo Park, CA.
- Hubbell, D. W. 1964. "Apparatus and Techniques for Measuring Bedload," US Geological Survey, Water Supply Paper 1748, US Government Printing Office, Washington, DC.
- Hurst, C. K., and Brebner, A. 1969. "Shore Erosion and Protection: St. Lawrence River, Canada," XXIInd International Navigation Congress, Section 1, Subject 6.
- Ippen, A. T. 1966. Estuary and Coastline Hydrodynamics, McGraw-Hill, New York.
- Johnson, J. H. 1976. "Effects of Tow Traffic on the Resuspension of Sediments and on Dissolved Oxygen Concentration in the Illinois and Upper Mississippi Rivers under Normal Pool Conditions," Technical Report Y-76-1, US Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Johnson, J. W. 1968. "Ship Waves in Shoaling Waters," Proceedings of the Eleventh Conference on Coastal Engineering, Chapter 96.
- Karaki, S., and van Hoften, J. 1974. "Resuspension of Bed Materials and Wave Effects on the Illinois and Upper Mississippi Rivers Caused by Boat Traffic," CER 74-75 SKJV9, Colorado State University, Fort Collins, CO.
- Kincaid, G. 1987. "The Gallipollis Locks and Dam Replacement, Ohio River," Proceedings of the Workshop on the Environmental Effects of Navigation Traffic, D. A. Nelson and A. C. Miller, eds., pp 62-71.
- Kothandaraman, V. and Evans, R. L. 1973. "Use of Air-Water Relationships for Predicting Water Temperature," Illinois State Water Survey Report of Investigation 69, Champaign, IL.
- Lord Kelvin (Sir William Thomas). 1887. "On Ship Waves," Proceedings of the Institute of Mechanical Engineers, London, England.

Lubinski, K. S., Bhowmik, N. G., Evans, R. L., Adams, J. R., and Demissie, M. 1980. "Identification and Prioritization of Study Needs Related to the Physical, Chemical, and Biological Impacts of Navigation on the Upper Mississippi River System," Illinois State Water Survey Contract Report Number 259, Champaign, IL.

Makowski, P. B., Lee, M. T., and Grinter, M. 1986. "Hydrologic Investigation of the Highland Silver Lake Watershed: 1985 Progress Report," Illinois State Water Survey Contract Report 380, Champaign, IL.

Owen, D. 1990. "Inland River Record 1990," The Waterways Journal, p 494.

Porterfield, G. 1972. "Computation of Fluvial-Sediment Discharge," Techniques of Water-Resources Investigations of the Geological Survey, Chapter C3, Book 3, US Government Printing Office, Washington, DC.

Schijf, J. B., and Jansen, P. O. 1953. Eighteenth International Navigation Congress, Section I, Communication I, Rome, Italy.

Schnepper, D., Hill, T., Hullinger, D., and Evans, R. 1981. "Physical Characteristics of Bottom Sediments in the Alton Pool, Illinois Waterway," Illinois State Water Survey Contract Report 263, Champaign, IL.

Simons, D. B., Ghaboosi, M., and Chang, Y. H. 1987. "The Effect of Tow Boat Traffic on Resuspension of Sediment in the Upper Mississippi River System," prepared by Simons and Associates, for the St. Louis District of the US Army Corps of Engineers, Fort Collins, CO.

Simons, D. B., Li, R. M., Chen, R. H., Ellis, S. S., and Chang, T. P. 1981. "Investigation of Effects of Navigation Activities on Hydrologic, Hydraulic, and Geomorphic Characteristics," Working Paper 2 for Task D, Simons and Li Associates, Fort Collins, CO.

Simons, D. B., and Senturk, F. 1977. "Sediment Transport Technology," Water Resources Publications, Fort Collins, CO.

Sorensen, R. M. 1973. "Ship Generated Waves," Advances in Hydrosience, Vol 9, V. T. Chow, ed., Academic Press, New York and London.

Sparks, R. E., Thomas, R. C., and Schaeffer, D. J. 1980. "The Effects of Barge Traffic on Suspended Sediment and Turbidity in the Illinois River," completion report to the US Fish and Wildlife Service, Rock Island, IL.

van de kaa, E. J. 1978. "Aspects of Navigability, Power, and Speed of Push-Tows in Canals," Proceedings of the Symposium on Aspects of Navigability of Constraint Waterways Including Harbor Entrances, Vol 3, Delft Hydraulics Laboratory, Delft, The Netherlands.