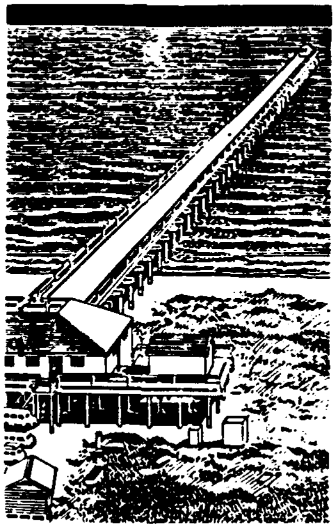
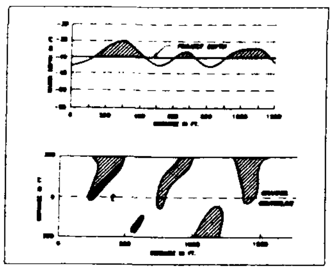
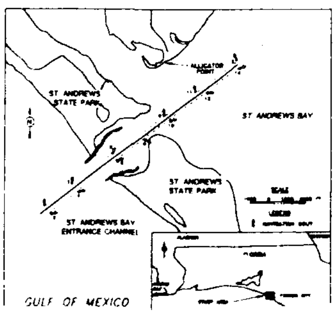
(2)

US Army Corps of Engineers







IMPROVEMENT OF OPERATIONS AND MAINTENANCE TECHNIQUES RESEARCH PROGRAM

TECHNICAL REPORT HL-90-17

SAND WAVES

Report 1
SAND WAVE SHOALING IN NAVIGATION CHANNELS

by

Douglas R. Levin, W. Jeff Lillycrop

Coastal Engineering Research Center

and

Michael P. Alexander

Hydraulics Laboratory

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

September 1992
Report 1 of a Series

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

Under Work Unit 32386

HYDRAULICS LABORATORY

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1992

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

4. TITLE AND SUBTITLE
Sand Waves; Report 1, Sand Wave Shoaling in Navigation Channels

5. FUNDING NUMBERS
WU 32386

6. AUTHOR(S)
Douglas R. Levin, W. Jeff Lillycrop,
Michael P. Alexander

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
USAE Waterways Experiment Station, Coastal Engineering Research Center and Hydraulics Laboratory
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report
HL-90-17

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

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

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

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report evaluates shoaling problems attributed to sand waves in navigation channels. The mechanics of bed form development are reviewed, and the physical characteristics, occurrence, and distribution of sand waves are described. Methodology to determine the magnitude of the shoaling problem and dredging techniques that have been used in channels shoaled by sand waves are also discussed.

14. SUBJECT TERMS

Bed forms	Sediment transport
Dredging	Shoaling
Sand waves	Wave action

15. NUMBER OF PAGES
56

16. PRICE CODE

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

PREFACE

This study is part of ongoing research being conducted by the US Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC). It is sponsored by Headquarters, US Army Corps of Engineers (HQUSACE), under the Improvement of Operations and Maintenance Techniques Program (IOMT) Work Unit 32386, "Mitigating Sand Waves in Navigation Channels." The IOMT Program Manager is Mr. Robert F. Athow, Jr. Mr. Jim Gottesman is the HQUSACE Technical Monitor.

Direction for this study was provided by Dr. James R. Houston, Director, CERC; Mr. Charles C. Calhoun, Jr., Assistant Director, CERC; Mr. Thomas W. Richardson, Chief, Engineering Development Division (EDD), CERC; Ms. Joan Pope, Chief, Coastal Structures and Evaluation Branch, EDD; and by Messrs. Frank A. Herrmann, Jr., Director, Hydraulics Laboratory (HL); Richard A. Sager, Assistant Director, HL; William H. McAnally, Jr., Chief, Estuaries Division (ED), HL; and William D. Martin, Chief, Estuarine Engineering Branch, ED. Ms. Dawn M. Logue, EDD, CERC, assisted in the research. Drafting of figures was performed by Ms. Lynn Bassonet and Messrs. Leslie R. Wallace, Perry L. Reed, and Darryl Bishop, EDD, CERC. The report was prepared by Messrs. Douglas R. Levin and W. Jeff Lillycrop, EDD, CERC, and Michael P. Alexander, ED, HL. Technical review was provided by Drs. Clifford L. Truitt and Todd L. Walton, Jr., CERC, and Messrs. William D. Martin and Mitch A. Granat, HL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

CONTENTS

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

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

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
degrees (angle)	0.01745329	radians
feet	0.3048	metres
feet per second	0.5921	knots
miles (US statute)	1.609347	kilometers

SAND WAVES

SAND WAVE SHOALING IN NAVIGATION CHANNELS

PART I: INTRODUCTION

1. This report is the first in a series designed to evaluate shoaling problems attributed to sand waves in navigation channels. The primary objectives of this investigation are threefold: (a) to develop an understanding of the mechanisms that contribute to the formation of sand wave shoaling, (b) to review the conditions of its occurrence under natural settings, and (c) to determine the various alternatives that may be used to remove these shoalings from impacted navigation channels. These mitigative alternatives are being studied under the auspices of the "Improvement of Operations and Maintenance Techniques" (IOMT) Research Program, sponsored by Headquarters, US Army Corps of Engineers (HQUSACE). The research is being carried out at the US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center (CERC). The specific IOMT work unit is entitled "Mitigating Sand Waves in Navigation Channels."

2. Sand waves are a class of bed form. Part II of this report reviews the mechanics of bed form development in controlled laboratory experiments. Part III presents a literature review of the physical characteristics, occurrence, and distribution of sand waves in riverine, coastal, and nearshore settings. Next, the problem of sand waves occurring within navigable waterways are in discussed in Part IV. Methodology that may be used to determine the magnitude of a shoaling problem caused by sand waves is presented in Part V. A summary of dredging techniques that have been used in channels shoaled by sand waves is included in Part VI in addition to design modifications that may reduce shoaling occurrence in navigation channels. Future reports will present a more complete package a more complete package of analytic and empirical design tools that may be implemented to minimize sand waves in navigation channels.

Problem Statement

3. A bed form is a wavelike accumulation of transported sediments, the predominant component of which is consolidated, noncohesive sands. Sediment

transport may be effected by wind or flowing water. Sand dunes, the product of eolian transport, are the most familiar bed form in a nonaqueous environment. In riverine or tidal settings, bed forms most commonly noted are ripples. In essence, sand waves are giant ripples that form where water is deep enough, sand supply is plentiful, and flow velocities are unidirectional or contain flood or ebb-dominant tidal flow and are relatively strong.

4. Many of the navigation channels designed, constructed, and maintained by the US Army Corps of Engineers are subject to shoaling by large sand waves (Alexander, in preparation) which form when certain dynamic criteria are met. The conditions of formation may occur periodically (i.e. seasonally); hence, sand waves may form in a previously navigable channel with little forewarning. Where the crests of these features rise above the required channel depth, they pose a hazard to navigation (Figure 1).

5. Individual sand waves are not significantly different in size from small localized shoals. However, they are wave forms that recur at semiperiodic intervals along significant distances of a channel reach. Selective removal of the crest of each sand wave using conventional dredging technology is an uneconomic method of mitigating this shoaling problem.

6. Dredging offers a short-term solution to the sand wave problem because they reform rapidly following removal. Costly stop-gap measures being used to combat this problem include frequent dredging, overdepth dredging, or both.

Study Objectives

7. The overall IOMT program goals include the development of techniques that will reduce operating costs by decreasing energy consumption, improving the safety and efficiency of operations, and enhancing the utility of Operations and Maintenance such as locks, dams, and vessels. The specific objective of the sand wave research is to formulate means for lowering channel maintenance costs by either reducing sand wave formation and through improved dredging practices. The first phase of this study evaluates the conditions under which sand waves form. This information will be used to establish design criteria that may be used to minimize the occurrence of sand waves in newly constructed channels, or mitigate the problem in existing ones. In the second phase of the study, dredging technologies and alternative

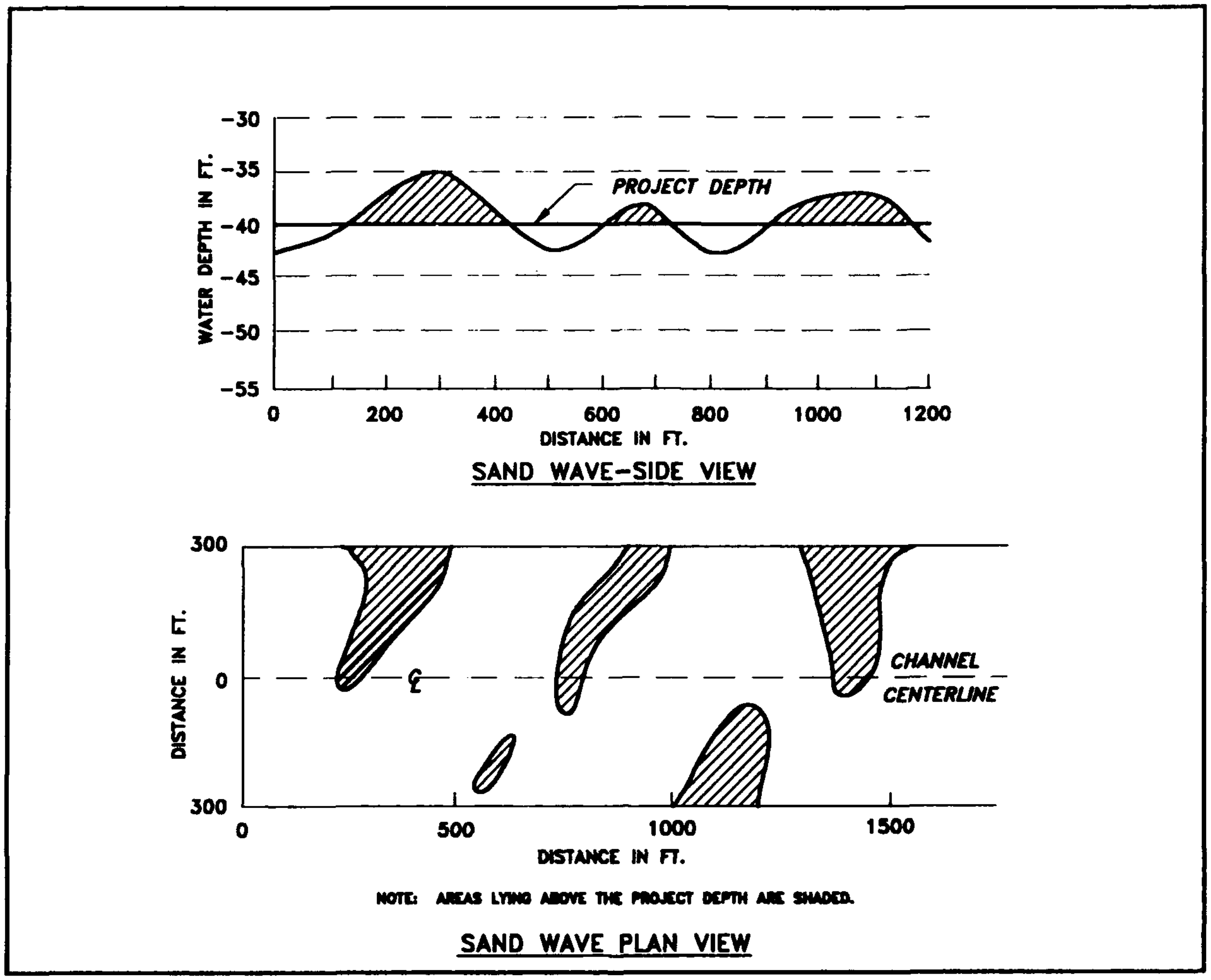


Figure 1. Sand wave crests impinging on navigation channel in the Columbia River, Oregon

cost-effective techniques for maintaining sand wave-prone channels will be detailed.

Report Objectives

8. Man-made streams built within the confines of indoor laboratories provide controlled environments used to develop an understanding of sediment transport dynamics. These artificial streams, or "flumes," have been used to study the interaction of sediments with flowing water since the early 1900s (Gilbert 1914). By using flumes, investigators can hold certain parameters constant while changing others. For example, by using a uniform sediment size beneath a water column of fixed depth, the flow velocity of water can be changed to study its effect on sediment movement. Although flume-generated

bed forms are much smaller than those under consideration in this report, the information can be scaled to dimensions advantageous to the understanding of sand wave behavior. Part II of this report serves as a basic introduction to bed forms. Published data gathered from flume experiments will be used to demonstrate the dynamics of bed form generation. Standardized nomenclature adopted for this report will also be introduced.

9. Literature is replete with reference to the occurrence of sand waves under natural conditions. Part III of this report reviews this information with respect to the formation of sand waves in riverine, estuarine, coastal inlets, and nearshore regions. These field investigations detail the intrinsic characteristics of sand waves and report the conditions under which these bed form types are observed. They also describe the dynamics of bed form migration.

10. Two specific sites that experience chronic navigation and maintenance difficulties due to sand waves are presented in detail in Part IV of this report. The first location is the Columbia River, Oregon, where large sand waves form during the spring freshet. When the seasonal increase of discharge subsides, the river stage lowers while crests of sand waves formed during the flood season remain largely at their previous level. The sand wave crests then impact the channel depths during average to low-flow periods. They do not pose a problem during the high river stages when they form.

11. Because of the extended reach of the Columbia River impacted by sand waves, structural alterations of the channel are not economically feasible. The Portland District is experimenting with a sand wave skimmer designed to remove sand wave crests, thus increasing the time interval between mobilization of larger dredges. The second problem location discussed in this report is at St. Andrew Bay near Panama City, Florida. A relatively short section of the jettied inlet channel requires frequent dredging because of a chronic sand waves problem. In this case, the sand waves are not that large, but they compound a channel that is already shoaled. It may be feasible to alter the jetty configuration to reduce both the shoal and sand wave formation, thereby reducing the frequency of maintenance dredging.

PART II: FLUME-GENERATED BED FORMS

12. A subaqueous occurring bed form is a wavelike accumulation of sediments (Figure 2) whose size is fundamentally proportional to the water depth, flow velocity, and sediment grain size. Morphologically, the horizontal distance between successive wave crests or troughs is the wavelength. The vertical distance between the lowest point of the wave trough and the crest is the wave height. In bed form geometry the wavelength is up to a hundred times greater than the wave amplitude. The ratio of wavelength to wave height is normally not less than 10:1 and averages closer to 30:1 (Zarillo 1982).

13. Where the bed form shape is asymmetric, the gentler sloping ramp between the trough and the bed form crest is termed its stoss side while the steeper side is its lee. The slope of the stoss side of a sand wave is, on average, about 4 deg.* The lee side of the bed form always points in the direction of water flow. It has an average steepness of 12 deg or less (Taylor and Dyer 1977, Perillo and Ludwick 1984, Terwindt 1971), but may reach the angle of repose in some cases. The angle of repose is the steepest angle that a sloping bed can attain without slumping. For all sand-sized sediments, this slope is 33 deg. When velocities are high enough, sediment transport is initiated, and sediment grains are pushed up the stoss side of the ripple toward the bed form crest. From there, singular grains fall down the steep lee side of the bed form into the trough of the next ripple. The process of the grain tumbling down the lee side of the ripple has contributed to more conventional nomenclature that refers to this portion of the bed form as a "slip face."

14. For a understanding of the formation and migration of bed forms in nature, it has been helpful to look at simplified, first-order relationships under laboratory-controlled conditions. For this purpose, flumes are used (Figure 3). A generic flume is a glass-sided, open top, rectangular box that looks essentially like an elongated aquarium. The dimensions of a flume used by Harms (1969) was 61 m long, 2.44 m wide, and 1.22 m deep. The glass sides offer an unimpeded view of the flume bed. The flume showcase is fitted with a water pump and faucet on one end and a standard bathtub-like drain on the

---

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

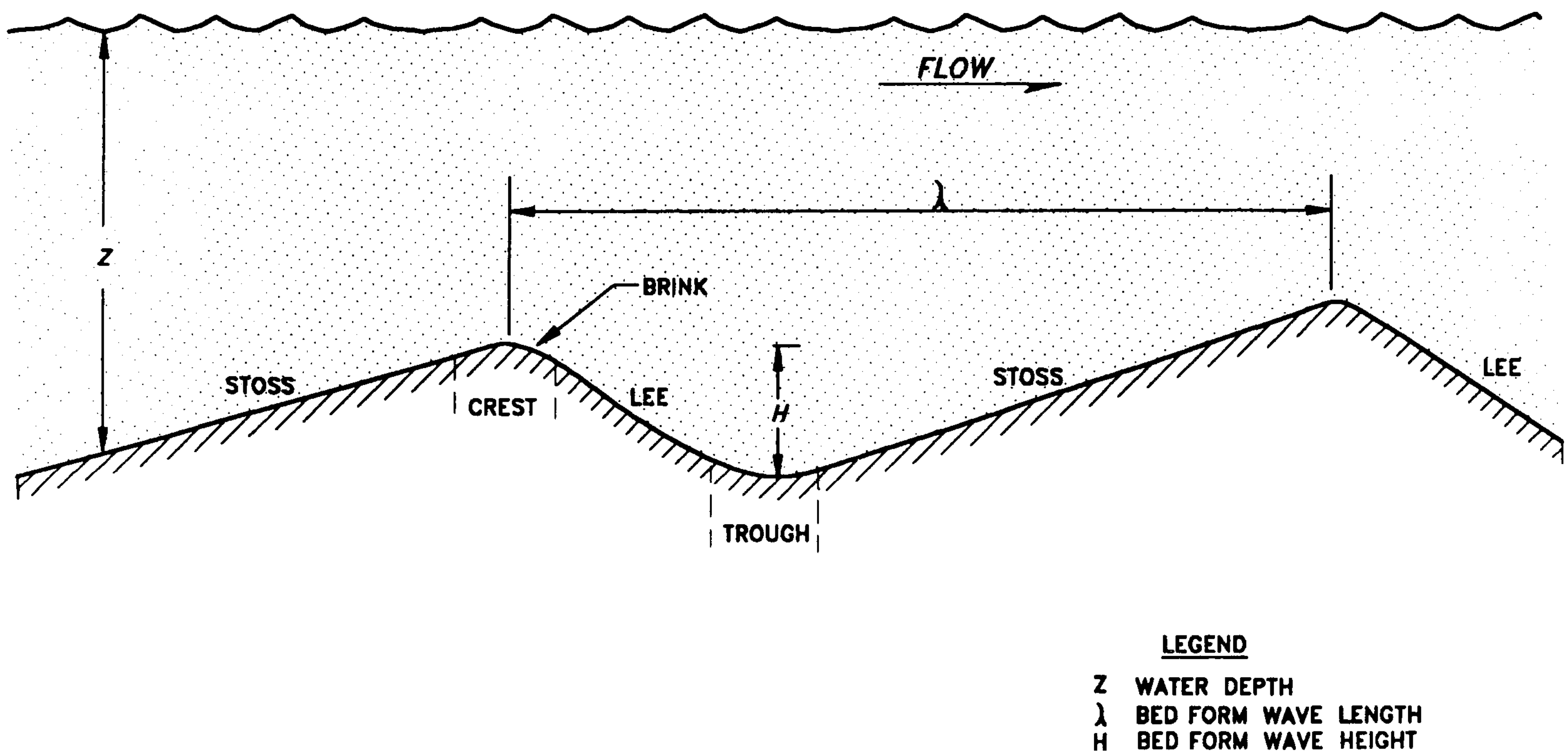


Figure 2. Bed form shape and associated components

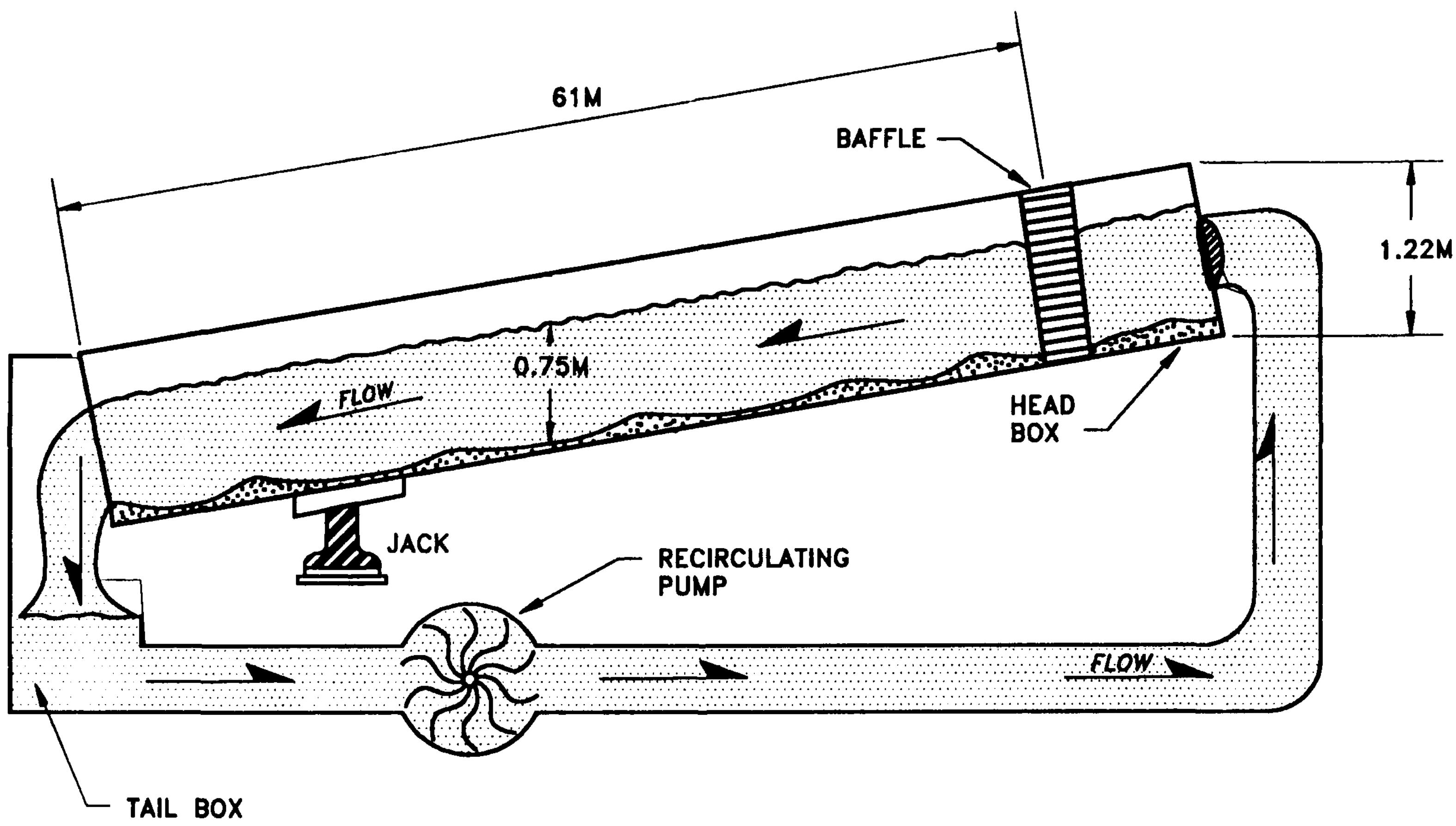


Figure 3. Flume diagram (modified from Harms 1969)

other end. Normally a section of baffles is installed between the pump box and the showcase to simulate flow from an upstream source rather than from a faucet.

15. With the water pump turned on, a finite supply of water in the system recirculated through the flume at a calibrated flow rate. This rate can be changed in two ways: The system pump can be accelerated to increase flow, or the flume can be physically tilted using a series of jacks to increase simple gravitational forces. Flow depth can be changed by adding or reducing the volume of water in the system. Flow depth changes can be simulated by varying the density/viscosity of the flume fluid. This simulation is accomplished by warming or cooling the water or by using a substitute liquid type.

16. The horizontal movement of water creates shear against the flume boundaries. The difference between shear and pressure are distinct. Pressure is a force applied vertically to an object's plane. For example, in a flume, the weight of the water applies pressure on the bottom. When the flume water is flowing, a tangential force is applied against the bottom. This force is shear (Figure 4).

17. Reynolds (1965) performed experiments in flumes to examine the dynamics of water under a variety of conditions. He injected a stream of dye into a flume to trace the path of the water molecules. Initially, these experiments were conducted without sediment so that the bottom was smooth. Under low flow conditions, the streamline was linear, and the water flow was defined as laminar or nonturbulent. When the flow velocities were increased, turbulence disrupted the streamline. Turbulent flow helps to initiate sediment transport.

18. When sand is added to the flume, the dynamics of an erodible bed can be studied under controlled conditions. The interaction of three basic conditions can be investigated. The changing variables are flow depth, flow velocity, and sediment size. Altering one of these variables while holding the others constant provides determinative data that can be analyzed for salient relationships. Flume experiments are constrained by size and can be used only to study small-and medium-size bed forms such as ripples and megaripples. Sand waves are depth-limited bed forms that do not normally form in waters less than 5 m deep (Boothroyd 1985).

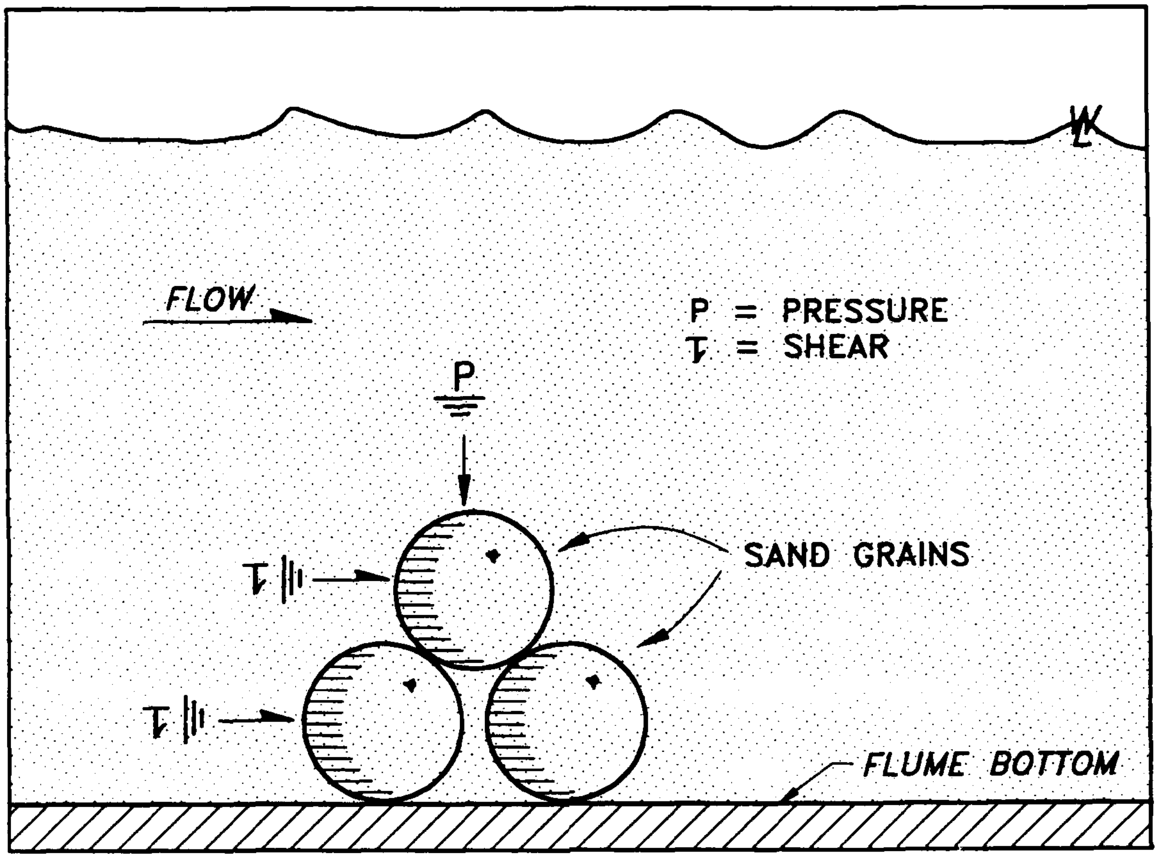


Figure 4. Forces imparted on grains by flowing water. A vertical component, pressure, pushes down on the top of the grains. When the water is flowing, a force called shear is directed tangentially across the stream bed

19. Sediments cannot be moved until certain conditions are met. Flow must exceed a critical level of shear before sediment can be moved. This moment, termed threshold of movement, is proportional to the size of the sediment. A priorie, it might appear reasonable to assume that the smaller the sediment, the easier it is to transport. This assumption is generally true once the sediment has been placed in suspension. However, it is not true when considering the forces necessary to erode the material from the bed. Clay and silt sediments are more difficult to erode than sands (Hjulstrom 1939). The electrostatic charge shared by the smaller particles impart a cohesiveness to the sediments that make them less susceptible to transport. Sands, on the other hand, are noncohesive and are mobilized more easily (Figure 5).

20. Sediment transport is initiated when the transporting medium reaches a critical velocity. At this moment, the shear imparted on the substrate is greater than the frictional component produced by the weight of the

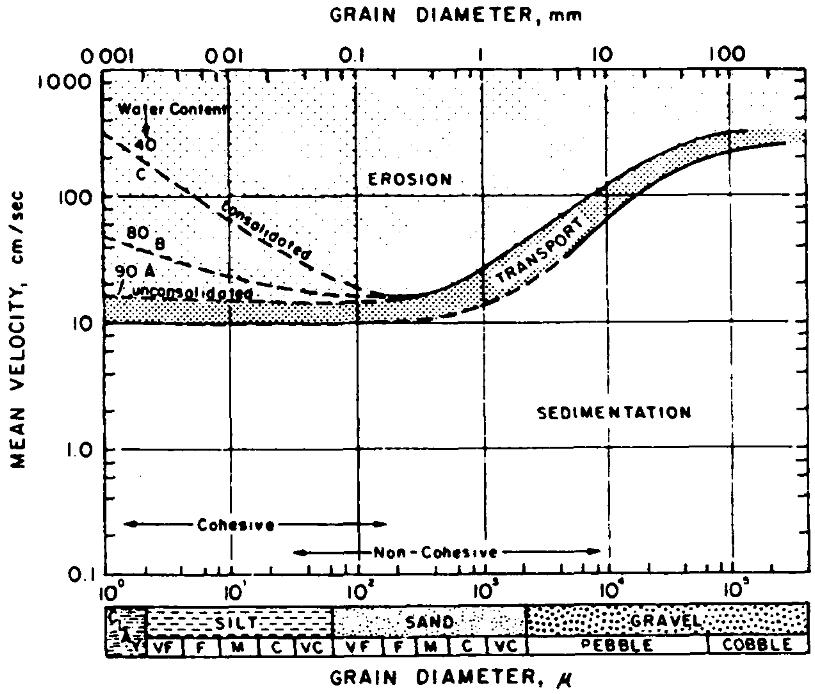


Figure 5. Diagram depicting thresholds of movement for sediments of different size. Cohesive unconsolidated sediments are more difficult to move than sands. Sediments are eroded when current velocities exceed the threshold of erosion depicted by the stippled area. Once eroded, a lesser current is required to transport sediments across the stream bed. When currents decelerate to velocities less than required to move sediment material of certain sizes, it is deposited onto the stream bed. (Modified from Hjulstrom 1939)

sand, and sediment begins to move. Once the grain of sand is lifted, the shear forces spin it and propel it in the direction of stream flow. The velocity required to initiate sediment movement is greater than that necessary to transport it. In the course of everyday life, one might notice that the initial effort required to push a stalled car is greater than that needed to maintain its forward progress.

21. Shortly after flow in a flume reaches 20 cm/sec, fine sands will be mobilized. Almost immediately after sediment movement is initiated, ripples will form. Ripples, the smallest common bed form, have wavelengths between 10 and 60 cm and heights between 0.5 and 5 cm. When bed shear stress is augmented by increases in velocity, the dynamics of the simple bed form begin to change. Increased flow causes currents to separate from the stream bed at the brink of the bed form crest and then reattach somewhere along the downstream

ripple trough (Figure 6). Larger sediments avalanche down the bed slip face while smaller material may be momentarily suspended. Where the currents become reattached to the bed, scour may occur, altering the uniformity of the bed. Increasing flow strength causes a proportional change in sedimentation characteristics that translate into a systematic change in bed form shape (Kennedy 1963, Middleton and Southard 1977). Linear-crested ripples evolve to undulatory and the cuspate and then finally rhomboid (Figure 7) (Hayes and Kana 1976).

22. Bed form migration rates vary with flow conditions. In general, they move orders of magnitude slower than the flow velocity. Bed form migration rates are easily comprehended if the path of a single grain of sand can be traced through one wavelength of movement (Figure 8). Starting with the trough, a grain of sand is pushed up the stoss side of the ripple over the crest and down the lee side. At the toe of the slip face, the sand is trapped within the body of the bed form until the crest migrates by. When the sand grain is reexposed in the trough of the crest, it again becomes available for transport.

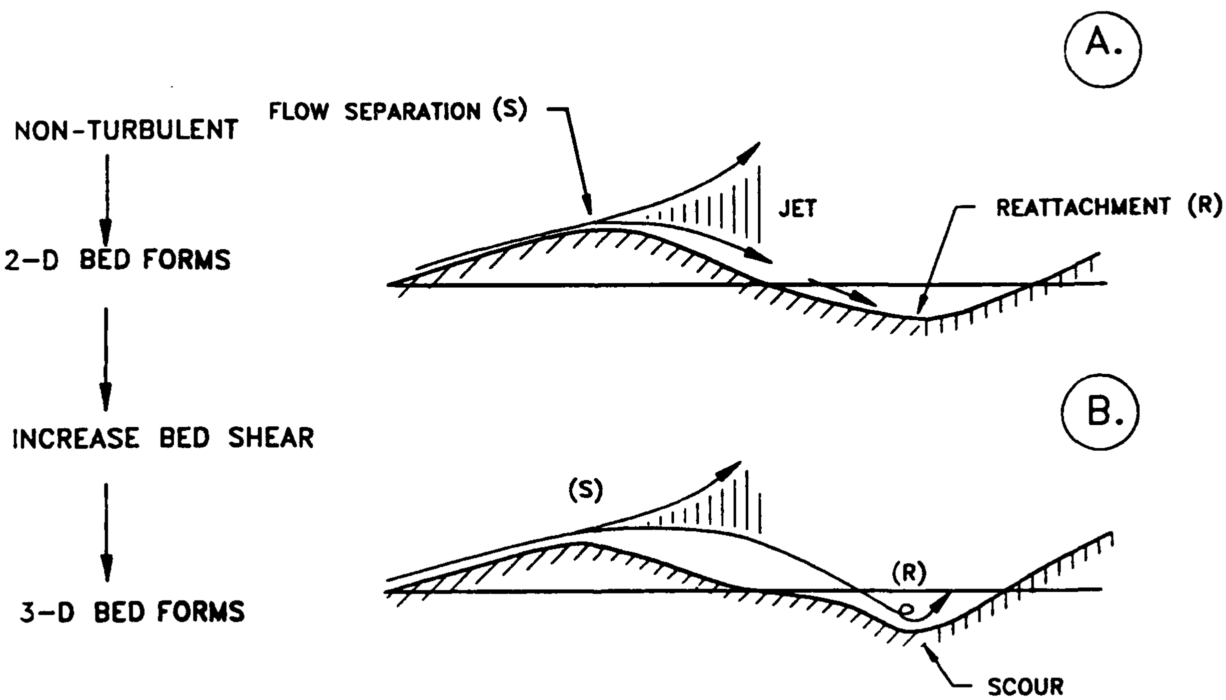
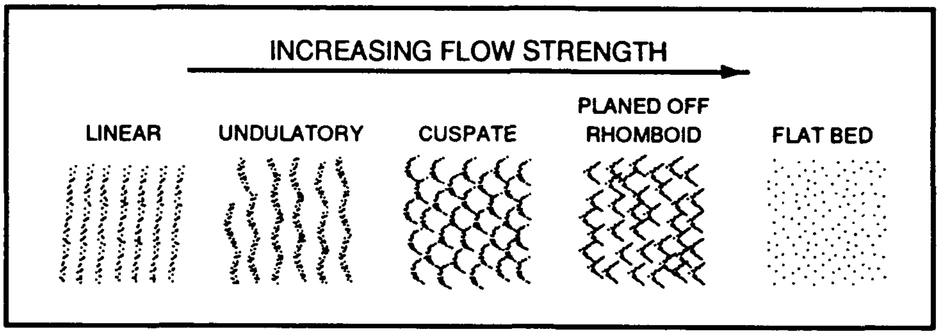
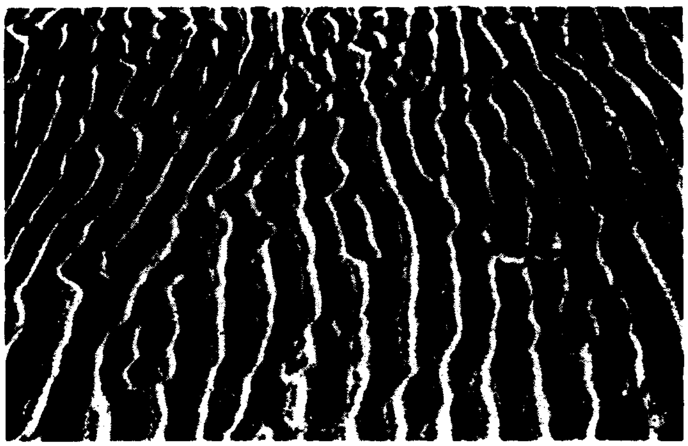


Figure 6. Jet current behavior over the brink of a ripple. In A, at low velocity, the current streamlines hug the bed form near the crest. In B, the flow jet separates at the brink of the brink of the bed form and reattaches at a point of scour in the downstream trough.



a. Change in shape from 2-D to 3-D bed forms with increasing flow strength (modified from Hayes and Kana 1976



2-D

b. Undulatory

3-D

c. Cuspate (Photographs by Jon Boothroyd)

Figure 7. Diagram showing staged change of ripples from two-dimensional (2-D) to three-dimensional (3-D) (b and c from Boothroyd and Hubbard 1974)

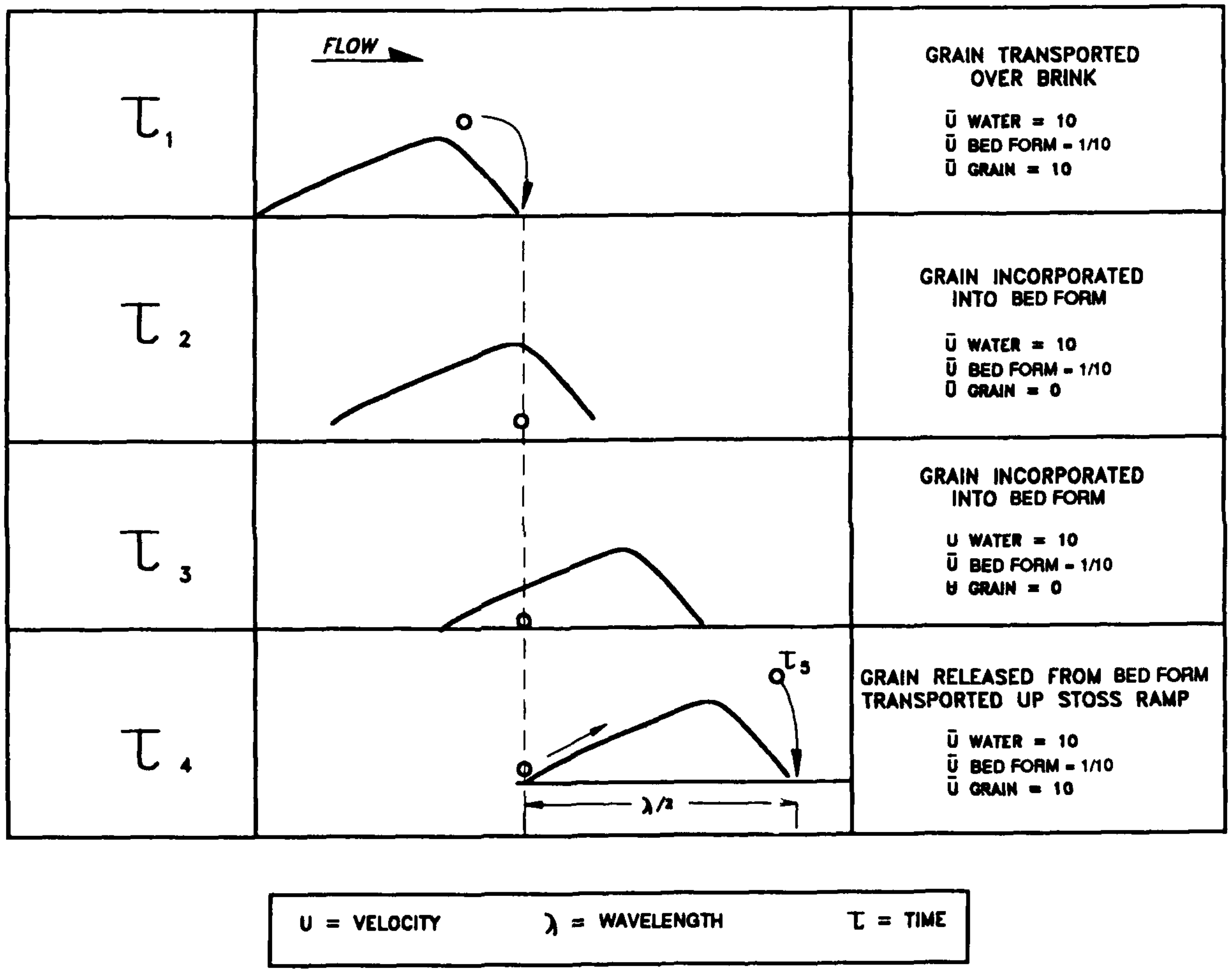


Figure 8. The path of a single grain transported within a moving bed

23. Continued increases in flow energy cause the ripple bed forms to build upon one another until the next class of bed form is formed. Megripples are described by Boothroyd (1985) as the amalgamation of ripples under intensified flow conditions. Megaripples have wavelengths up to 5 m and amplitudes between 5 cm and 1 m. Megaripples are formed when flow velocities exceed 50 cm/sec and the average sediment grain size in 0.6 mm. At this point, the sequence of intertidal bed forms diverges. In depth-limited waters, increases in flow velocity cause higher order bed forms to emerge. Cuspate megaripples eventually become plane beds (Simons, Richardson, and Nordin 1965). In deeper water, megaripples may be accompanied by the formation of sand waves. Where sand waves are present, increasing flow velocity may cause megaripples to build over the sand waves. Megaripples migrate over the backs of sand waves 50 times faster than the rate of movement of the larger bed form (Boothroyd and Hubbard 1974).

24. In the mid-1960s, the American Society of Civil Engineers (1966) defined bed forms of wavelengths between 0.6 and 6 m as "dunes." The majority of journal articles classified these larger ripples as "small sand waves" (Allen 1977; Jones, Kain, and Stride 1965). In a review of over 30 technical articles dating from 1970 (Klein 1970) to 1987 (Aliotta and Perillo 1987), "megaripple" was used predominantly to describe these bed forms. In accordance with rationale presented by Boothroyd (1985), the use of the term "megaripple" to describe subtidal or intertidal bed forms with wavelengths between 0.6 and 6 m was proposed to avoid confusion with sand dunes commonly described in eolian environments. More recently, a group of scientists whose research involved the study of bed forms met to rectify this problem in terminology. Ashley et al. (1990) suggested that bed forms occurring underwater be identified as subaqueous dunes. According to this new classification, sand waves would be classified as large to very large subaqueous dunes. The term "sand wave" will be used in this report to denote this bed form type (Table 1).

25. It is important to note that once ripples or megaripples are formed, they will remain intact when flow conditions decrease. Bed forms will not be eradicated until flow conditions are strong enough to alter the state of the bed. However, a current weaker than required to initiated bed form formation will remobilize the bed forms that are already in place (Allen 1977).

Table 1

Bed Form Classification*

Type	L**	H
	Common Terms	
2-D mergaripple	1-25 m	--
3-D mergaripple	1-15 m	--
Sand wave	10-100 m	--
Transverse bars	100-300 m	--
	Recommended Terms	
Subaqueous Dune - small	0.6-5 m	0.075-0.4 m
Subaqueous Dune - medium	5-10 m	0.4-0.75 m
Subaqueous Dune - large	10-100 m	0.75-5 m
Subaqueous Dune - very large	>100 m	>5 m

* Adapted from Ashley et al. (1990).
** L = bed form wavelength; H = bed form height.

26. Flumes are efficient tools that provide basic understanding of sediment transport in flowing water. However, they are limiting by virtue of their physical size. Ripples and megaripples can form in water depths as shallow as 0.75 m. This depth and commensurate multidirectional currents can be artificially provided to move sediments within the confines of a laboratory. Greater depths can be modeled in larger flumes and by altering fluid dynamics to simulate deeper water. Other restrictions inherent in flume experiments involve the narrow, long shape of the glass-sided flume that offers unrealistic boundary conditions. The main limitation of flumes in regards to sand waves lies in depth restrictions. Sand wave formation is limited to waters more than 5 m deep. It is not feasible to perform full-scale laboratory simulations of sand waves. Instead, dimensional analysis is applied to flume investigations of ripple and megaripple formation to give engineers and geologists a first-order approximation of the conditions necessary to move sediments in bed forms. In actuality, this formation contributes significantly to the understanding of sand wave formation under natural conditions.

PART III: SAND WAVE OCCURRENCE IN NATURAL SETTINGS

27. The study of bed form formation and migration in natural settings has been aided greatly by flume experiments. The same fundamental forces affect the formation of bed forms in riverine, estuarine, coastal, and Continental Shelf environments (Zarillo 1982). According to Zarillo (1982), sediment movement in a natural setting is correlated to near-bottom current velocities, water depth, and mean grain size. These statistically significant relationships between sediment and water movement had been concluded previously in laboratory settings (Harms 1969, Franco 1968, Middleton and Southard 1977, and others).

28. Flume investigations provide less variation than is found in natural settings. The uniformity of the flume design was the primary key to early understanding of sediment transport mechanisms. In natural settings, there are infinite variations in flow depths and boundary conditions that contribute to the morphology and distribution of bed forms. Bed form type, dimension, and orientation can vary greatly over relatively short distances. However, their occurrence can be explained by the fundamental relationships derived through laboratory experimentation: water velocity, sediment grain size, and in some cases water depth. Measurement of these parameters in the field environment will explain the morphodynamics of sediment transport at any site.

29. The determination of the dynamic conditions conducive to the development of sand waves is of paramount concern to those responsible for maintaining navigable waterways. In many coastal areas, sand wave formation is the primary cause of channel shoaling (Whetten and Fullen 1986, Langhorne 1973, Lillycrop et al. 1986). The following paragraphs describe the physical environment of sand waves in various settings.

30. In bed form classification, there is not standardized cutoff between megaripple and sand wave dimensions. The reference most cited when establishing this criterion on is Boothroyd and Hubbard (1974). In their work on the Parker River Estuary, sand waves were defined as bed forms with wavelengths greater than 6 m. Wave heights of megaripples and sand waves were mixed and could not be used to segregate the two bed form classes.

Sand Wave Height

31. In literature, bed forms classified as sand waves have a height range between 0.6 m in St. Andrew Bay, Florida (Salsman et al. 1966) and 30 m. Sand waves 30 m high have been surveyed off the Portuguese coast of East Africa (Cloet 1954) and on Cultivator Shoal of Georges Bank (Jordan 1962). In estuarine environments where water depths are limited, sand wave heights range from 0.8 m in the Minas Basin, Bay of Fundy (Dalrymple 1984) to 6.0 m in the Bahia Blanca Estuary, Argentina (Aliotta and Perillo 1987). Whetton and Fullen (1986) measured sand waves 5.5 m high in the Columbia River, Oregon. The average height of sand waves surveyed in waters greater than 20 m, along continental margins, straits, and submarine canyons, is greater than 5 m (Boggs 1974; Karl, Cacchione, and Carlson 1986; McCave 1971). In St. Georges Channel in the Irish Sea, Harvey (1966) measured sand waves with average heights of 15 m in 150 m of water. Sand wave height appears to be limited in some cases by meteorological events. In the North Sea, sand wave heights are periodically decreased when storm waves are produced by gale force winds. During interstorm periods, the sand waves build their crests to previous heights (Terwindt 1971). In the Gulf of St. Lawrence, Canada, sand waves appear best formed and attain their greatest heights beneath ice where water/surface interaction is minimized (Reinson 1979). In their study of sand waves in the Westerschelde Estuary in The Netherlands, Terwindt and Brouwer (1986) found that the increase in bed form height was caused by scour within the troughs. The actual distance between the bed form crest and the water surface remained unchanged. Table 2 lists the heights of sand waves from various geographical locations.

Sand Wave Wavelength

32. The wavelength of sand waves in nature is as varied as the height. Using the Boothroyd and Hubbard (1974) classification scheme, 6 m is the minimum wavelength that can be used to classify a bed form as a sand wave. The range of sand wave length is between 6 and 1,000 m. The upper end of the range is defined by sand waves measured on Cultivator Shoal of the Georges Bank (Jordan 1962). The range of wavelengths measured in nearshore environments such as estuaries or rivers is (excluding Boothroyd and Hubbard 1974) 6 to 330 m. The 6-m cutoff was used by Terwindt and Brouwer (1986) in the

Westerschelde Estuary, The Netherlands. The large extreme end member was measured by Itakura et al. (1986) in the Ishikari River, Japan. Table 2 lists wavelengths of sand waves measured at other locations.

Water Depth

33. The depth of water in which sand waves are found is also varied (Table 2). Smaller sand waves with wavelengths of 6 m and heights of less than 0.5 m have been mapped in tidal estuaries with depth minimums of less than 3 m (Terwindt and Brouwer 1986, Boothroyd and Hubbard 1974). Sand waves also occur in the Bering Sea down to nearly 500-m depth (Karl, Cacchione, and Carlson 1986). In general, however, the formation of larger scale sand waves in the nearshore is limited to water depths exceeding 5 m (Zarillo 1982). It is the larger scale sand waves that impact navigation channels. It is of paramount importance to note that the depth of water in which sand waves are apt to form is independent of the depth that they may occur. The conditions necessary to form or activate sediment movement in sand waves may occur only periodically. Short term, this may be determined by tidal phases (Dalrymple 1984, Boothroyd and Hubbard 1974). In the Columbia River, high discharge resulting from spring runoff contributes to sand wave growth and migration. The sand waves are inactive for the reminder of the year (Whetten and Fullen 1986).

Sediment Size

34. Sediment size and supply also play an important role in sand wave formation. There appears to be a distinct criterion requiring ample supplies of noncohesive sands of a particular size range (Table 2). In the Thames River Estuary, sand waves were not found in areas dominated by a clay bottom (Langhorne 1973). This factor might appear obvious, in that, the term "sand wave" implies that sand is an integral ingredient for their formation. In St. Andrew Bay, Florida, sand waves were surveyed in an area that had been floored previously by silty clay (Waller 1961). This sudden change in substrate characteristics was the result of constructing the jettied channel between the seaward barrier. This breach disrupted the longshore sediment transport and allowed sand to be transported into a region that had been floored by mud (Salsman, Tolbert, and Villars 1966).

Table 2

Variability of Sandwaves, Worldwide

Location	Z*	H	L	Sand	Vel
Columbia River, Oregon	10	5.5	200	--	0.6
Thames Estuary, G.B.	20	8	--	0.14	--
Sapelo Island, Ga.	6	0.8-1.3	15-45	0.3	1.0
Parker River Est, Ma.	6	0.5	>6	--	0.6-0.8
Westerschelde, Netherlands	<3	0.2	>6	--	0.5-0.6
St. Andrew Bay, Florida	11	0.6	13-20	--	1.2
Long Island Sound	10	to 4	10-100	--	0.35-0.4
Weser River, Germany	4	to 3	--	0.5	1.0
Ishikari River, Japan	8	2.0	330	0.26	--
Bay of Fundy, Canada	17	0.15-3.4	13-40	0.13-1.6	0.5-2.0
Minas Bay, Canada	6.4	0.8	38	0.27-1.27	1.0
Gulf of St. Lawrence	3-5	2.0	60	--	--
Bahia Blanca, Argentina	10	6	80-200	0.2	--
Isle of Man, Irish Sea	11	6	125	--	0.3
Irish Sea	80-100	15	200	0.6-0.9	1.0
Navarinsky Canyon, Bering Sea	>175	5	650	--	--
SE African Continental Margin	50	0.8-8	7-200	--	0.6
North Sea	20	3-15	144-1,200	<0.5	0.5-0.8

* Z = depth in meters, depth may vary tidally
H = bed form height, meters
L = bed form wavelength, meters
Sand = mean grain size, or range of sand size, mm
Vel = mean velocity, or range of velocity in sandwave field m/sec
-- = no data

35. Terwindt (1971) found that sand waves were absent where mud comprised more than 15 percent of the bottom sediment. In addition, sand waves were not found where the median grain size was greater than 0.5 mm (coarse sand). Similar findings were reported in studies of sand waves in Long Island Sound. Sand waves were not found where the bottom sediments either contained 10-percent muds or more than 12-percent coarse sand (Bokuniewicz, Gordon, and

Kastens 1977). Gravel bottoms were found to limit the formation of sand waves in the North Sea, off the coast of Holland (McCave 1971). McCave also noted that sand wave height diminished with decreased mean grain size. Zarillo (1982) showed a statistically significant relationship between increasing sediment size and increasing sand wave dimensions. The range of sand size found to be most prevalent in sand waves is 0.25 to 0.5 mm (Dalrymple, Knight, and Lambias 1978). This range is confirmed by an investigation of sand wave dynamics conducted by Zarillo (1982). Table 2 lists the grain sizes reported in sand waves from various investigations.

Velocity Asymmetry

36. Sand waves occur where currents are unidirectional or velocity asymmetry is present. The lee side of the sand wave points in the direction of dominant currents. In riverine flow, the sand waves may face downstream. In estuaries, current reversals due to upstream movement of the saltwater wedge may produce sand waves pointing upriver. Current velocities required to initiate sand wave migration have been determined by several authors. Sand wave migration in the Parker River Estuary was initiated at speeds of 60 cm/sec (Boothroyd and Hubbard 1974). Terwindt and Brouwer (1986), Whetten and Fullen (1986), and McCave (1971) reported initial sand wave movement at current speeds between 0.5 and 0.6 m/sec. Although it appears that similar current velocities have been reported for initiation of sand wave migration, Zarillo (1982) has found statistical evidence that the velocity term is only one component of the equation that accurately relate flow dynamics to bed form migration.

Flow Power and Bed Shear

37. In his investigation of bed form stability in Duplin River, Georgia, Zarillo (1982) found that flow power, flow depth, mean grain size, and shear velocity are all significantly correlated to bed form size. Flow power considers both current speed and surface water slope in its calculation. Shear stress considers bed roughness as an added factor in the equation.

38. In the Duplin River, water retention in the tidal creek/marsh system caused a large surface water slope during the first half of the ebb tide. This contributes to large values of flow power and shear stress during the

outgoing tide. As a result, bed forms in this river are primarily ebb-dominated. Flow and shear velocities occurring during incoming tides are not of sufficient strength to alter these bed forms. Though Zarillo (1982) concedes that maximum flow velocity may be used to explain the occurrence and stability of bed form fields, relationships of shear velocity and flow power with bed form dimensions will do so more precisely. This concept can be more aptly explained by looking at flow power as a function of time-velocity asymmetry.

39. In the Minas Basin, Nova Scotia, sand wave orientation was highly correlated with bottom current velocity asymmetries (Klein 1970). Ebb-oriented sand waves were present in channels where the maximum velocity (V_{max}) exceeded 90 cm/sec. Flood currents through this same channel never exceeded V_{max} 65 cm/sec. The opposite was true in channels occupied by flood-oriented sand waves. Tidal current velocities peaked at 90 and 65 cm/sec for flood and ebb tides, respectively. Sand wave migration was limited to the tidal phase that produced larger flow velocities. Note that in the Minas Basin, the mean grain size of the sand waves is coarse and has a threshold velocity greater than 65 cm/sec. Even though the lesser current affects the bed forms for longer periods of time during the tidal cycle, it is not of sufficient strength to move the sediments. The ebb tide affected this particular channel for a shorter period of time; yet the flow power produced during that time greatly exceeded that of the flood tide.

Distribution of Naturally Occurring Sand Waves

40. In rivers, sand waves form and migrate under conditions where flow is typically downstream. Classic examples of sand waves in riverbeds have been reported in the Mississippi River (Wright and Coleman 1974) and Columbia River, Oregon (Whetten and Fullen 1986). Sand waves found in deep marine environments appear also to be affected by confined currents. In the Navarinsky Canyon head, Bering Sea, active sand waves are found in nearly 500 m of water. The responsible current is caused by internal waves directed in a down canyon direction (Karl, Cacchione, and Carlson 1986). Currents produced by density stratification are responsible for sand waves with average heights of 15 m occurring in St. Georges Channel of the Irish Sea in 150 m of water (Harvey 1966).

41. Sand waves are also commonly observed in tidal inlets and estuaries. For flood- or ebb-oriented bed forms to form, a prevalent current direction must be present. Boothroyd and Hubbard (1974) concluded that megaripples are a product of maximum current velocity and less dependent on time-velocity asymmetry. Megaripples will form rapidly when sufficient currents occur. Sand waves, however, form at lower current velocities, yet require substantial time-velocity asymmetry. Currents capable of initiating sand wave migration must be more powerful than or of significantly longer duration than the flood currents. Sand waves on the flood-tidal delta of the Parker River Estuary began landward migration with current velocities of 0.6 m/sec. Where V_{max} exceeded 0.8 m/sec, megaripples became superimposed on the sand waves. Bed form migration was accelerated during spring tides due to greater flow velocities. The effect that the increased tidal exchange had on bed form height during spring tides was not reported in this investigation. The flood-tidal delta on which the sand waves were located shields these bed forms from maximum ebb-tidal currents and contributes to the segregation of flood- and ebb-oriented bed forms.

42. Terwindt and Brouwer (1986) observed sand wave dynamics in the Westerschelde Estuary in The Netherlands. These are relatively small intertidal sand waves with wavelengths of 6 m and heights averaging less than 0.5 m. The threshold movement for sand waves was between 0.5 and 0.6 m/sec. Where current reversals occurred, bed form orientation from the previous tide was completely erased at current speeds exceeding 0.85 m/sec.

43. The concept of segregating flood and ebb channels in a tidal inlet was first introduced by Hayes (1975). In a tide-dominated inlet, the main ebb channel is dominated by seaward flowing currents. During the latter stages of the ebb tide and the beginning of the flood tide, the inertial flow of the current in the main ebb channel continues its seaward movement. Initially, flood-tidal waters enter the inlet through marginal flood channels (Figure 9). The channels are affected by time-velocity asymmetry of the tidal currents. Postma (1967) described this phenomenon as one where either the ebb or flood portion of the tidal cycle dominates a channel. As a result of this flow segregation, bed forms of different orientation may be found laterally across a channel cross section.

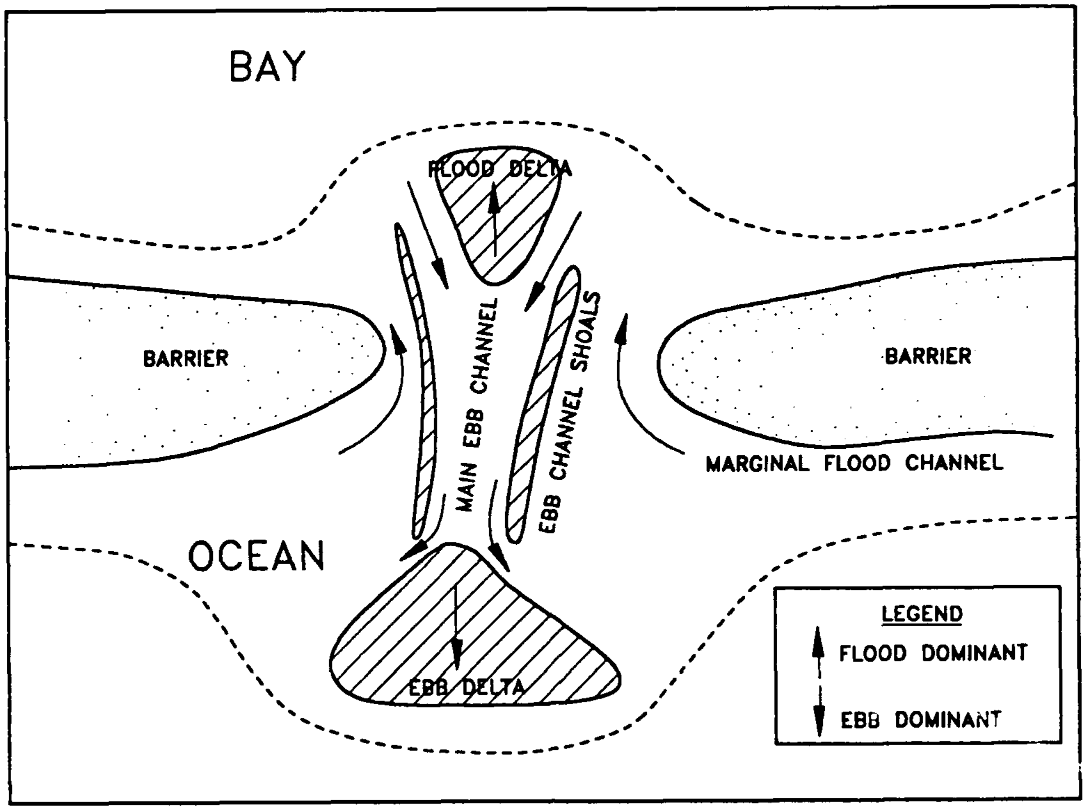


Figure 9. Plan view of a tidal inlet showing segregated flood and ebb channels (modified from Hayes 1975)

Predictability of Sand Wave Dimensions

44. Sand wave morphodynamics have been studied and discussed in literature for over 20 years (Kennedy 1963, Jopling 1965, Gill 1971, Reynolds 1976, Davies and Wilkinson 1978, Richards 1980, Haque and Mahmood 1985; and others). Equations have been derived to predict sand wave height versus wave length (Dalrymple 1984), maximum wavelength versus water depth (Yalin and Karahan 1978), sand wave steepness versus water depth (Haque and Mahmood 1985), and height versus shear stress (Gill 1971). The ultimate objective of these researchers is to be able to mathematically model the type and size of bed forms that will form under specific flow conditions.

45. Dalrymple (1984) presents an empirical relation developed from 58 sand wave samples in the Bay of Fundy:

$$H = 0.0637 * L\text{^^}0.733 \qquad (1)$$

H = sand wave Height

L = sand wave Length

^^ = subscript "to the n^{th} power," where n = 0.733

This relationship was tested using field data taken at several locations. It generally underpredicts sand wave dimensions (Table 3).

46. An equation presented by Yalin and Karahan (1978 relates the maximum theoretical sand wave length to the maximum size of the leeward eddy. The relationship is described as follows:

Table 3

Predicted Versus Actual Sand Wave Dimensions

Reference No.	Height m	Wavelength m	Predicted Height
14	5-8	100-500	1.9-6.1
53	5.8	125	2.19
82	0.3-2.0	10-60	0.3-1.3
109	0.9-1.3	15-45	0.5-1.0

$$L_{max} = 2piD \qquad (2)$$

$L\ max$ = maximum bed form wavelength

Pi = 3.1427 (constant)

D = water depth

Where both variables are known for a particular site, Yalin's equation consistently predicted the wavelength to be almost half of the measured maximum (Table 4). Accordingly, perhaps if the multiplier were increased from 2 to 4, it would be a more accurate equation.

47. Haque and Mahmood (1985) present a relationship for sand wave steepness that is derived for finite depth based on rotational, inviscid flow.

$$\frac{a}{L} = 0.4\ (m)\hat{}\hat{} - 1.178\ \left[1 - \exp\left\{\frac{-2.5D}{L}\right\}\right] \qquad (3)$$

Table 4

Predicted Versus Actual Sand Wave Wavelength

Location*	Depth ft	Wavelength, ft Max	Avg	Predicted
Columbia River	40	500	303	251**
Delaware Bay	90	890	675	565
Georges Shoal	90	3,300	2,700	565
Cultivator Shoal	85	2,100	1,200	534
Mississippi River	30	--	300	188
	50	--	265	314
	60	--	240	377
	80	--	400	502

* Data from Jordan (1962).
** Predicted by Yalin and Karahan (1972).

a = sand wave height

L = wavelength

m = nondimensional value describing flow in a plane

D = water depth

In Table 5 a comparison is made between measured and predicted parameters by using this equation. The predicted measures of a/L were accurate to ±50 percent. This equation predicted sand wave height to a better degree, with accuracies ranging from 70 to 90 percent of the actual value.

Table 5

Actual Versus Predicted Sand Wave Dimensions

Measured D	L	a	D/L	a/L	m	Predicted a/L	a
40	303	7	0.13	0.02	3.5	0.03	7.8
90	675	17	0.13	0.03	2.5	0.04	26.0
85	1,200	20	0.07	0.02	3.5	0.01	17.8
30	300	4.4	0.10	0.01	6	0.01	3.2
60	240	8	0.25	0.03	6	0.02	5.1

* Modified from Haque and Mahmood (1985).

48. A relationship of shear stress and bed form shape is presented by Gill (1971):

$$\frac{H}{d} = \frac{1}{6}\left[1 - \left(\frac{T}{t}\right)\right] \tag{4}$$

H = maximum height H

d = mean flow depth

T = critical bed shear stress

t = measured bed stress

Although Zarillo (1982) stresses that bed shear stress can be used to describe specific bed form dynamics more accurately, the measurement of all parameters necessary to calculate that value has not often been accomplished. As a result, the accuracy of the equation published by Gill (1971) cannot be determined.

49. An equation that enables engineers to predict what bed forms will form in natural channels does not exist. Before such an equation can be formulated, the specific dynamic factors contributing to their formation must be identified. In his work on the Duplin River, Doboy Sound, Georgia, Zarillo (1982) provides strong evidence that such an equation should consider flow power, shear velocity, flow depth, and sediment grain size. A primary objective of the Sand Wave Program is to advance the knowledge of sand wave development in hopes of determining an equation that will predict bed form morphodynamics under specified condition. The literature review of sand wave research worldwide has revealed some consistencies regarding their presence or absence.

PART IV: SITE-SPECIFIC SAND WAVE SHOALING PROBLEMS

50. Two navigation channels that are shoaled by sand waves are presently being studied. The Columbia River, Oregon, channel is hampered by sand waves formed during seasonally high discharge. At the jettied entrance to St. Andrews Bay, Panama City, Florida, the marked channel is also affected by sand waves. Though the sand wave dimensions are of different scales, both channels are compromised by their presence.

51. Both locations require frequent and costly dredging to maintain their design depths. In an effort to reduce maintenance costs, they are both being studied. To structurally alter the extended reach of the Columbia River affected by sand waves, the use of conventional engineering would be cost prohibitive. In this case, alternative dredging techniques are being tested. In Panama City, the area of the channel affected by shoaling is relatively limited. Design modifications to the jettied channel are being studied to increase time periods between maintenance dredging.

Columbia River Navigation Channel

52. The Columbia River is located along the Oregon and Washington border (Figure 10). The navigation channel maintained by the Corps of Engineers has a reach of 100 km and an authorized depth of -12.2 m, Columbia River Datum (CRD). River flow varies seasonally with low flow discharge rates of approximately 2,800 cu m/sec occurring in summer months. During the spring runoff following snowmelt, the Columbia River discharge rate reaches a maximum exceeding 11,000 cu m/sec. The median size of sediments found in the river near Portland is 0.35 mm.

53. Sand waves are found along much of the river extending from its mouth to beyond Portland at River Mile (RM) 100 (Figure 11). They have heights often exceeding 15 ft with wavelengths over 1,000 ft. The sediment sampled from the Columbia River near Portland is presumed to be representative of that comprising the sand waves. The lee side of these bed forms faces downstream even in reaches where tidal influences cause flow reversals.

54. Sand waves are a problem during summer months when the river discharge is at a minimum and the river stage is low. During these times, the crests of sand waves formed on the river bottom shoal the channel. The river dynamics at this time do not favor active growth of the sand waves.

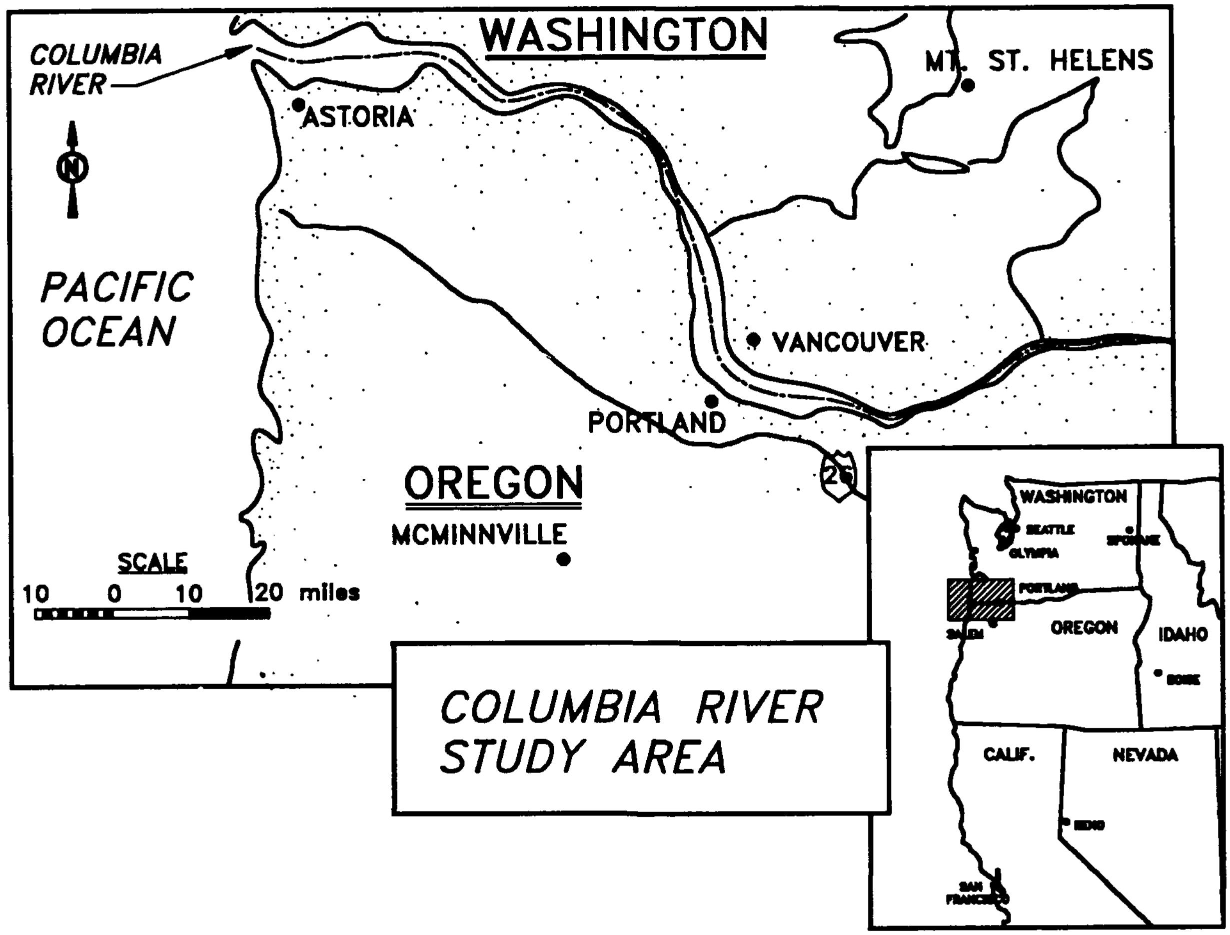


Figure 10. Location map of Columbia River, Oregon

Surface/water interactions have been shown to limit the height that sand waves can attain (Reinson 1979, Terwindt 1971). In one study, increased current velocities were shown to increase sand wave height by scouring the bed form trough, not by actual building of the crest (Terwindt and Brouwer 1986). The sand waves impacting the Columbia River have probably not increased in height; rather, the river surface has lowered closer to them. In some reaches of the Columbia River, tops of sand waves are periodically exposed during lowered river stages (Whetten and Fullen 1986). Accordingly, the navigation problems in the Columbia River are not significantly higher during high river stages when the sand waves are presumably active.

55. The environmental conditions present during the formation of sand waves in the Columbia River are not known. Bathymetric surveys run during different times of the year do not reveal a predictable pattern. A survey of

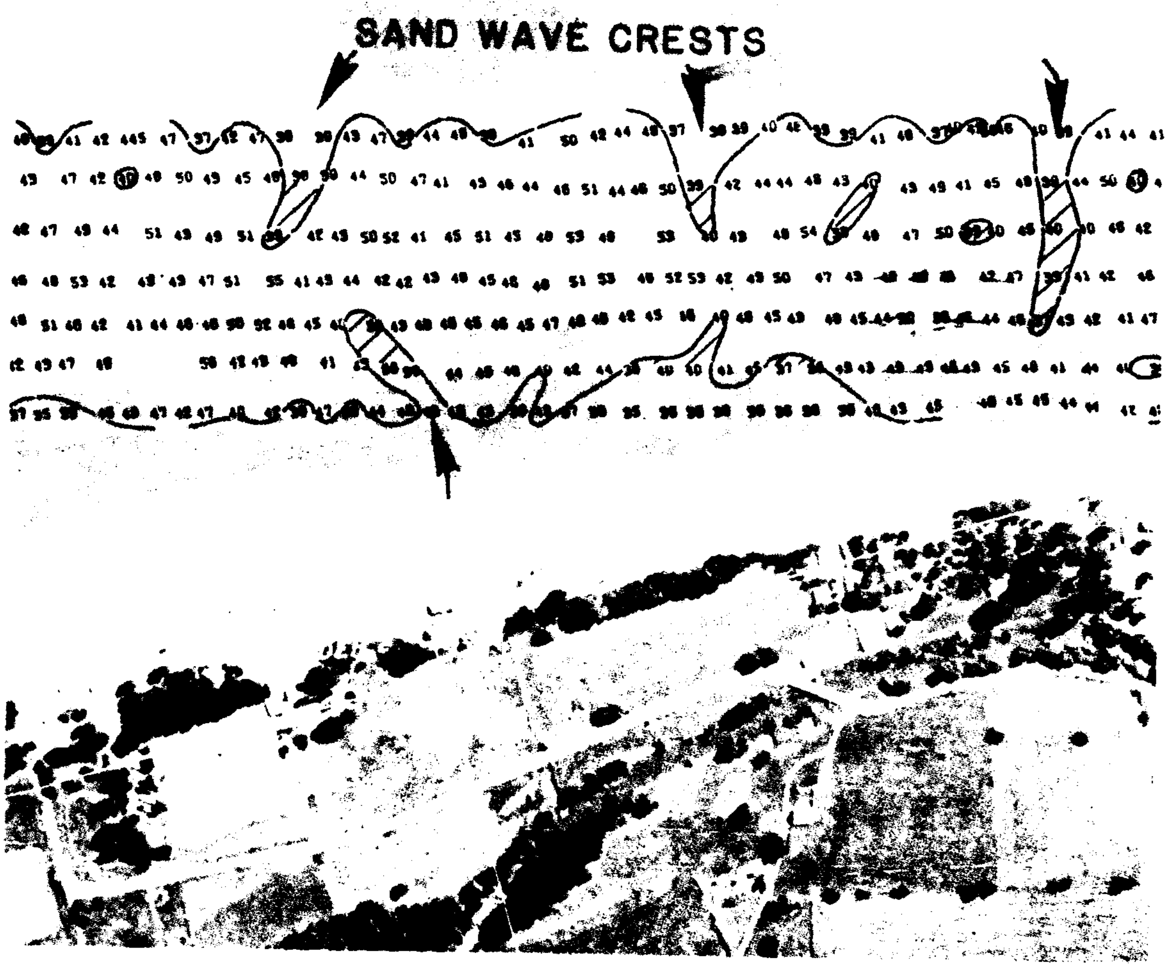


Figure 11. Example of sand waves occurring in the Columbia River

Willows Bar at RM 96 and 97 revealed that the conditions of the river bottom varied (Table 6)

Table 6

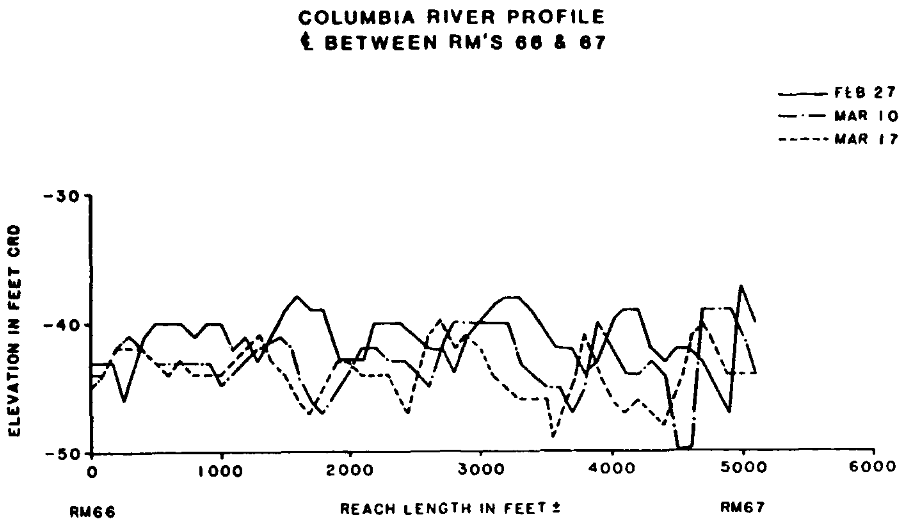
Bottom Survey at Willows Bar, RM 96 to 97

Survey Date	Bottom Observed
Feb 1984	Flat bed
Aug 1984	Sand waves
Jul 1985	Small sand waves
Jan 1986	Sand waves

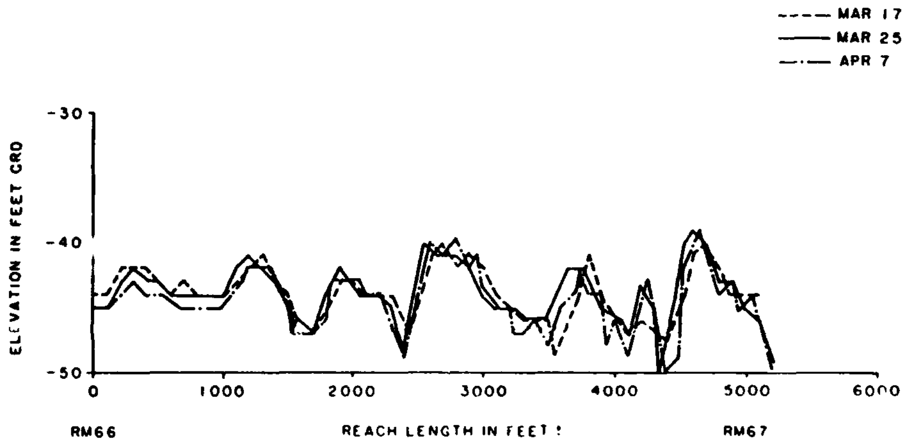
56. To fully investigate the ramifications of this survey, more data are necessary. There should be a high level of confidence that each survey covers the exact same area. This condition can be verified by reviewing the techniques used during the survey. They should have used identical methodology and equipment. If in fact the river bottom does change periodically, it does so because it is reaching to changes in flow conditions. Discharge records kept for large rivers like the Columbia could be reviewed to discern whether there had been a marked change between February and August of 1984. If, for example, this stretch of river had extraordinary discharge for January of 1984 and a drop to steady-state discharge for the following several months, it can be deduced that the January flow caused planar bed conditions to occur. An increase in discharge volume coupled with higher river stages could result in the sand wave height increase that occurred between July 1985 and January 1986.

57. The Portland District surveyed one stretch of river seven times in a 4-month period between February and June 1986. Without precise horizontal control, it is difficult to quantify the actual movement of the sand waves. Confident quantitative determinations of bed form migration require that the vessel survey the exact same track as it did in previous surveys (Langhorne 1973), an extremely difficult task without the use of advanced microwave positioning systems. Assuming that the repetitive survey did, in fact, retrace previous tracklines, sand waves up to 3 m high with wavelengths of 300 m moved several 100 ft downstream between February and March (Figure 12). Sand waves up to 10 ft in height with wavelengths of nearly 1,000 ft were present. The bed form apparently did not migrate between March and April. Reactivation of the sand wave movement appears to have taken place in late spring and early summer between April and June. As in the Willows Bar case, it would be informative to correlate the apparent variation in bed form migration to river discharge.

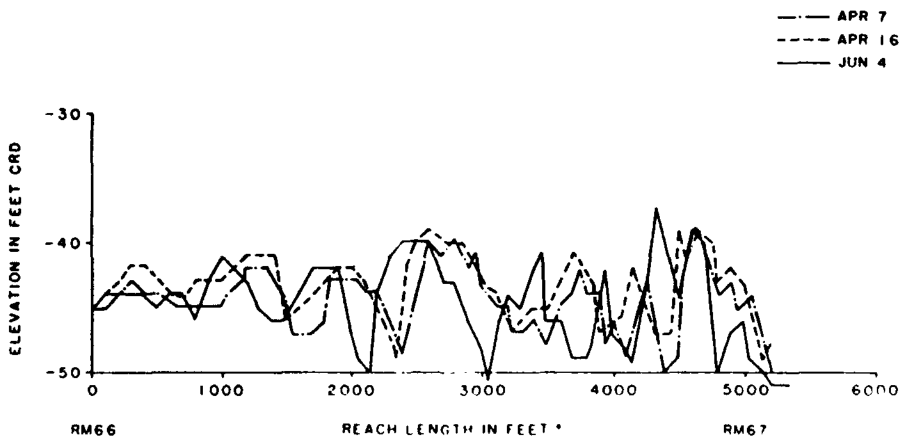
58. The extent of the sand wave problem in the Columbia River is such that structural modification to the river banks would be cost prohibitive. The only alternative is dredging. To date, channel maintenance has not been decreased by improvisation of conventional dredging techniques. Presently, the Portland District uses hopper dredges, which are costly to operate and require crews of over 20 persons. Hopper dredges operate by lowering a drag head to a selected depth as it moves along the channel. When a shoal is encountered, dredging resumes. Where only the upper portion of sand waves are



a. February - March



b. March - April



c. April - June

Figure 12. Repeated profiles documenting sand wave migration in the Columbia River

causing the shoaling problem, the cutter head is only intermittently in contact with the bottom. This is an inefficient and costly dredging technique to use when the cutter head is not in constant contact with the bottom. Dredged materials are sidecast adjacent to the navigation channel. This disposal technique is probably self-defeating. Nothing guards the sediments reentering the dredged channel.

59. During the summer of 1987, the Portland District experimented with a sand wave "skimmer" developed and operated by Western Pacific Dredging Co., a division of Riedel International, Inc. The skimmer technique is designed explicitly to remove shoals in the channel caused by sand waves. At the time that conventional dredge techniques would be required to deepen a continuous reach of channel, the hopper dredge would be used. The skimmer equipment consisted of a tug and barge equipped with pumps and a horizontal boom. The boom was fitted with nozzles through which pressurized water was pumped. A horizontal shield fitted to the boom above the nozzles aided the direction of the water jets against the bottom sediments (Figure 13). This technique was designed to accomplish one of two objectives. The sediments were either sheared off the bottom by the force of the water or they were fluidized, or both. In concept, pumping water into the sediments increases the pore water pressure and makes them easier to transport. Operationally, the skimmer was lowered to a sand wave crest, the pumps started, and the water jets directed against the sediments. The bottom sediments were suspended into the water column and transported into the downstream sand wave trough.

60. The skimmer has been tested on a reach of the Columbia River containing sand waves between 2 and 5 m high having wavelengths up to 200 m. The crests of these bed forms reach up into the authorized channel decreasing its usable depth by 0.3 to 1.4 m. The bottom sediments range from medium sand to coarse gravel. Cursory examination of the results of the field suggests that the skimmer does remove sand wave crests. Calculation of a benefit/cost ratio to determine whether this technique is more economic than conventional hopper dredging is not yet complete.

Panama City, Florida, Navigation Channel

61. Sand waves are compromising the entrance channel to St. Andrews Bay in Panama City, Florida (Figure 14). The channel was constructed in the

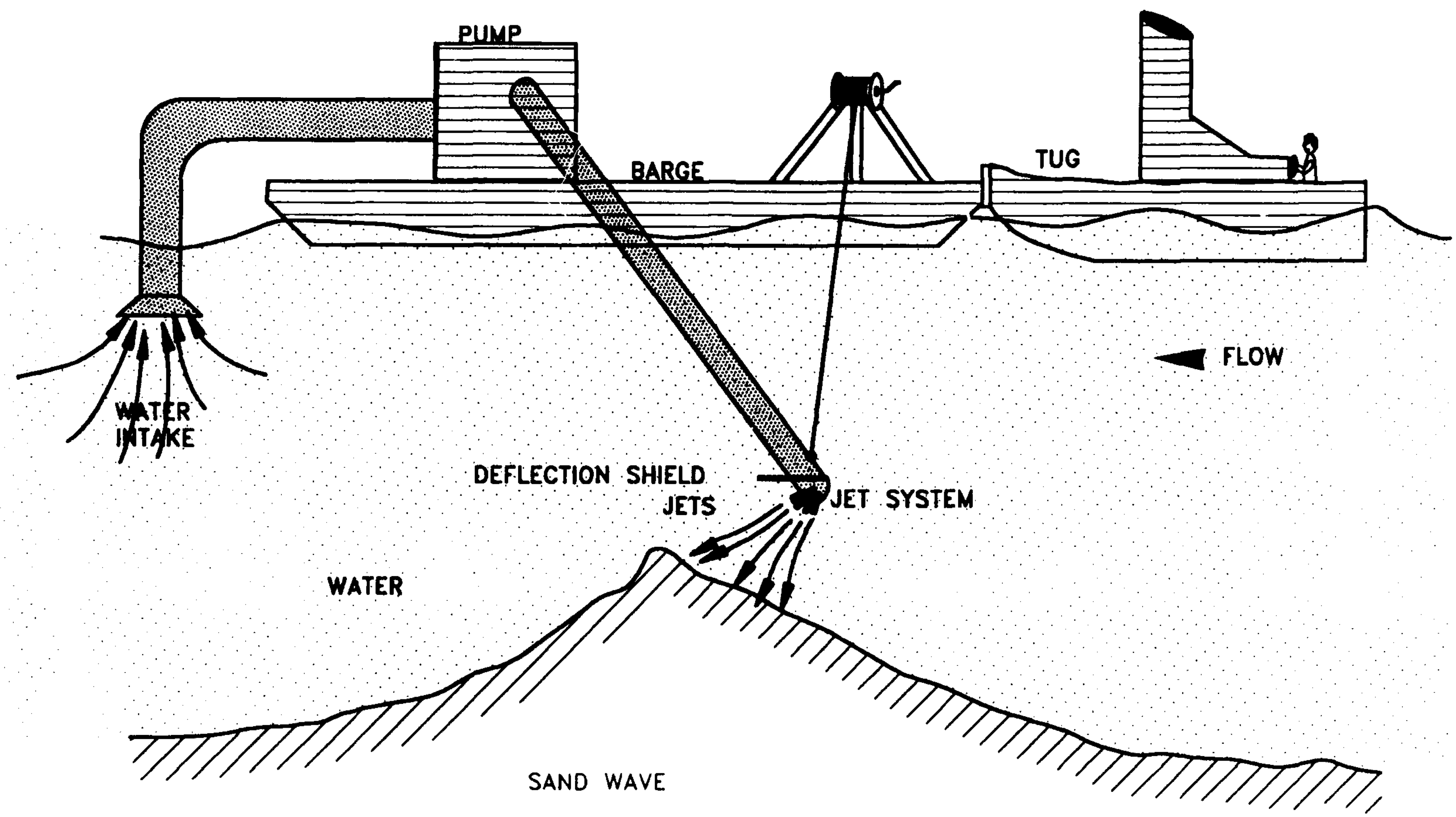


Figure 13. Diagram of a skimmer dredge

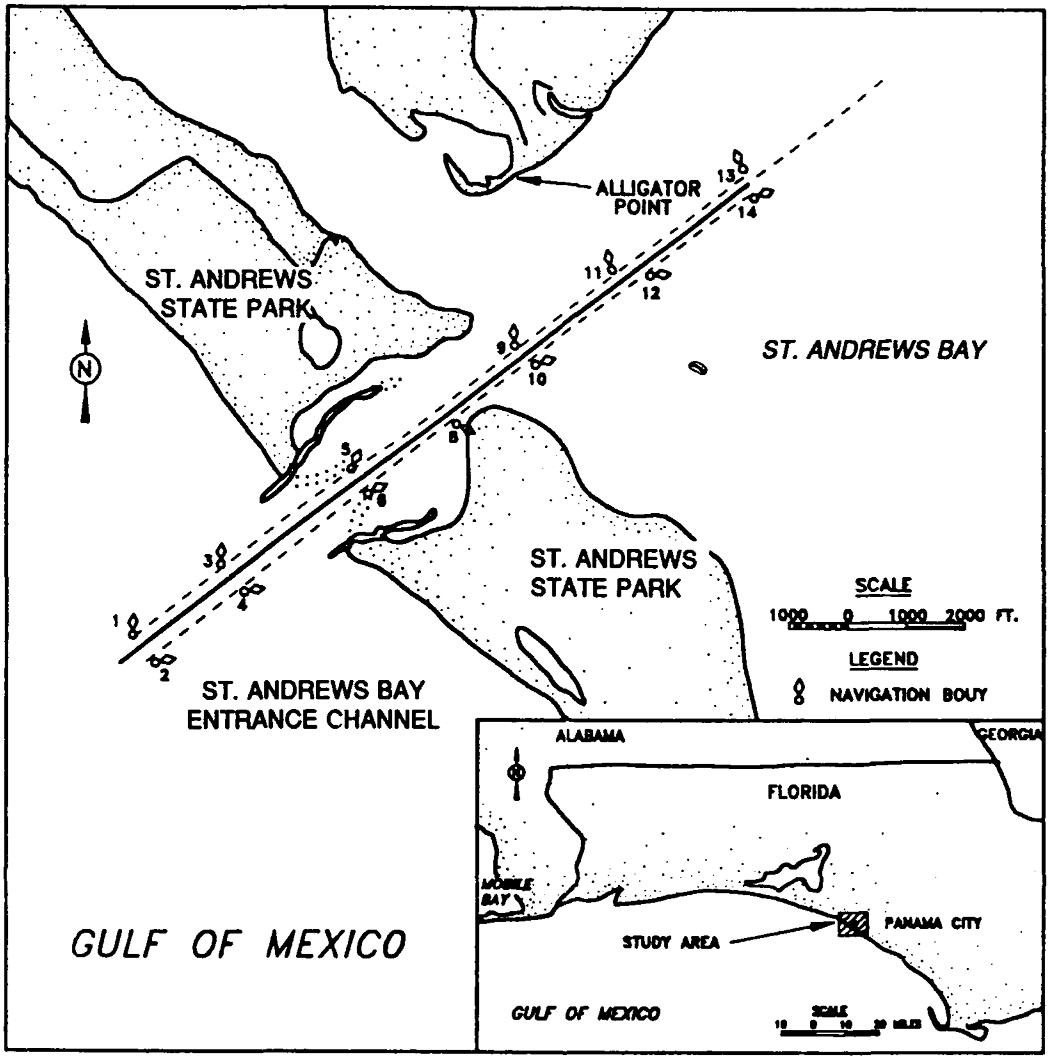


Figure 14. Location map of the entrance to St. Andrews Bay

1930's through Lands End Peninsula as an alternate to the easterly located natural entrance into St. Andrews Bay. The natural channel was longer and considered hazardous to navigation. The new channel shortened and stabilized the route between St. Andrews Bay and the Gulf of Mexico. The jetted inlet has a general north-south configuration with a navigation depth of -32 ft mean low water (mlw). The distance between the two jetties is 1,500 ft. This channel is maintained by the Mobile District, Mobile, Alabama.

62. The problematic sand waves in the St. Andrews Bay entrance channel are located between jetties. More specifically, they are located in the mid to eastern side of the channel. The channel thalweg hugs the western jetty. Scour rather than shoaling is the problem in that area. The sand wave heights

appear to range between 1 and 4.5 m. The larger sand waves located near the jetty extremes actually "piggyback" on top of a larger channel margin shoal (Figure 15). Actually termed a "channel-margin linear bar" (Hayes 1975), this shoal commonly forms beside main ebb channels in response to interacting waves and tidal currents. The buoyed navigation channel is centered over this bar. The ebb-oriented sand waves support the hypothesis that this shoal is subject to time-velocity asymmetry. By drawing a line through the troughs of the sand waves, the actual bed form heights can be measured more accurately. The sand wave heights average approximately 1 to 1.5 m. Sand waves found in the bay are smaller and do not have any direct impact on the channel shoaling problem.

63. Maintaining this channel is made more difficult because it is centered over a natural shoal area. Dredge operations must be repeated every 12 to 24 months to maintain required channel depths. The dredge interval has been increased slightly by dredging the channel 2.4 m deeper than required. The new channel depth is equivalent to the average height of the sand waves that form in the channel. By overdredging, the crests of sand waves that form shortly after dredging remain below the design navigation depth. Within 4 months of dredging, the channel margin shoal reforms. The combined

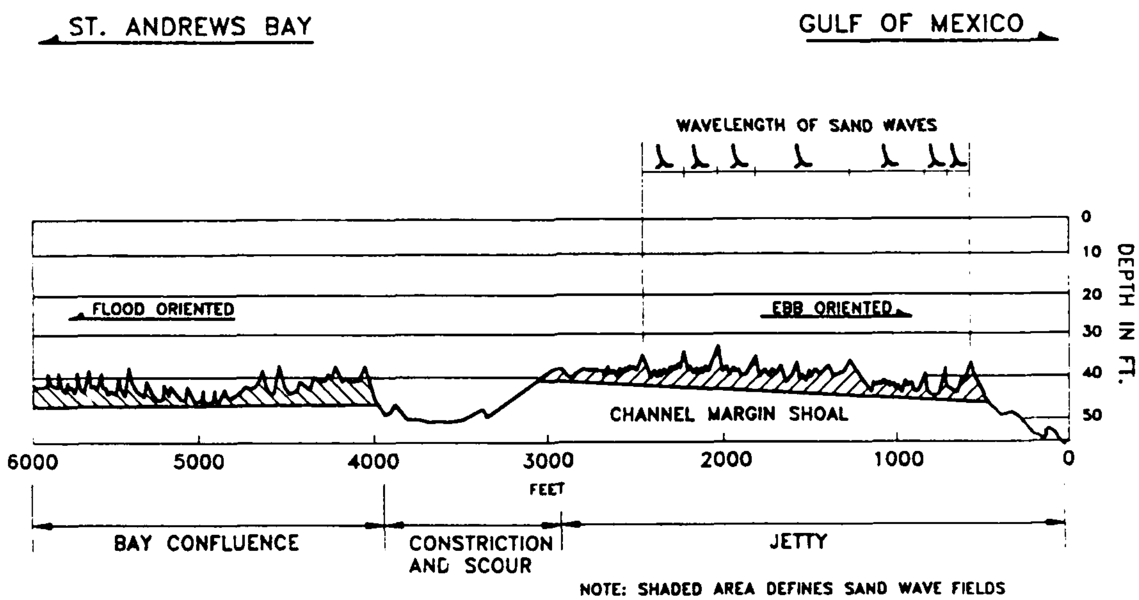


Figure 15. Bathymetric profile along shoaled channel. Note that the sand wave field sits on top of a channel margin shoal. Sand waves in the jettied channel are not ebb oriented. In the bay they are flood oriented

thickness of the shoal and overriding sand waves result in a 2-m-thick deposit.

64. To date, the exact conditions under which the sand waves in this area form have not been determined. Further, sand wave migration within the jettied channel has not been confirmed, although it is assumed. From what has been ascertained through a literature review of the natural occurrence of sand waves, the basic requirements necessary for their formation are present in this area; the sand size ranges between 0.2 and 0.35 mm, there is an inexhaustible sediment supply transported to the channel by longshore sediment transport, and the area of sand wave occurrence is affected by ebb-dominant time-velocity asymmetries (Lillycrop et al. 1989).

65. A study conducted in 1987 (Lillycrop et al. 1989) evaluated methods to reduce the shoaling problem in the bay entrance channel. To reduce the problem of sand waves, three schemes were considered: (a) modifying the inlet in an effort to produce hydraulic conditions unfavorable to sand wave formation, (b) reducing the sediment supply entering the channel, and (c) identifying a more efficient method to physically dredge the entrance channel.

66. Two options were evaluated to modify the channel velocities by using a one-dimensional inlet flow model, INLET (Seelig, Harris, and Herchenroder 1977). The first option was to increase velocities through the inlet such that conditions would produce a flat bed flow regime. Exercising this alternative may, however, produce hazardous boating conditions during portions of the tidal cycle. The second option considered would decrease velocities that would favor the formation of smaller bed forms.

67. Model results showed that decreasing the distance between the jetties approximately 400 ft would increase maximum ebb velocities to about 91 cm/sec and maximum flood velocities to about 88 cm/sec. Existing conditions have maximum ebb and flood velocities of approximately 75 and 70 cm/sec, respectively. Combined with dredging, this channel configuration may favor the reformation of bed forms in the channel, albeit smaller megaripples that would not be large enough to interfere with navigation.

68. To lower velocities to requisite conditions favorable to smaller bed form formation, a much wider inlet would be required. Channel configurations included jetty spacing over 3,000 ft apart (over twice the existing dimensions) and deepening the existing channel to -70 ft mlw. None of these alternatives were able to reduce velocities sufficiently to limit bed form growth. Preliminary conclusions of this investigation suggested that

constricting the inlet to increase flow velocities was possible but probably not economically justifiable.

69. The third elective identified method(s) to reduce the amount of sediments entering the navigation channel. Not long after the inlet was constructed, shoaling became a problem. A study by the Beach Erosion Board in 1946 recommended lengthening the jetties. This finding agreed with those presented by an area engineer who, in 1936, recommended extending the jetties at least 1,500 ft. The 1987 study also concluded that extending the jetties gulfward would reduce the amount of longshore transport material entering the inlet. However, such an extension would cause erosion to the downdrift beach area. The 1987 study further recommended reveting the inlet channel banks through the inlet to prevent continued channel bank erosion and thus reduce the amount of material feeding the sand waves.

70. A fourth relatively simple alternative may serve to reduce shoaling in the St. Andrews Bay entrance. The navigation channel is presently positioned over a natural ebb channel shoal. The main ebb channel located against the west jetty is as much as 5 m deeper than the marked channel. The deeper channel is maintained by the ebb jet that is naturally pushed against the jetty structure. If this channelized flow were structurally deflected to the east, the main ebb channel could be "trained" to follow the more centralized buoyed route. A test model would verify the feasibility of this option.

71. A sand wave dredge very similar to the one tested on the Columbia River was also considered. Tidal velocities are sufficient to flush agitated material gulfward once they are flushed into the water column. The Mobile District has experimented unsuccessfully with modified dredges in this channel. Their modified "Farm Harrower" could not move the large quantities of sand contained in the sand wave.

72. These two site examples are presented to demonstrate the variability of sand wave shoaling problems experienced by the Corps of Engineers. The solutions to the respective problems appear different. The Columbia River will probably favor dredging options because the affected stretch of river is too long to armor. In Panama City, the short reach of jettied channel affected by sand wash shoaling may be more economically feasible to solve by altering the jetty configuration.

PART V: GUIDELINES FOR STUDYING SHOALED CHANNELS

73. The "state of the art" for managing sand wave shoals in navigation channels is not far advanced. Definitive predictive equations to allow engineers to design bed form free harbor entrances do not exist, nor have the economic benefits of specialized dredges been fully evaluated. One of the objectives of this work unit is to develop guidelines that will help the engineer determine if a problem exists and to introduce design measures that may help to alleviate present or future problems. Ultimately, these studies will forward the knowledge base of sand wave formation and contribute to more definitive design criteria for future projects.

74. When it becomes important to study sand waves that are interfering with a navigation project, several data sets should be collected so that an accurate assessment of the problem can be made. Once this portion of the investigation is complete, engineering solutions to the problem can be determined. Once it has been determined that there is a problem, a thorough historic investigation for that particular area should be conducted. This research should include information such as the natural tendencies of the channel prior to stabilization, modifications to the back bay, and when the channel was first constructed. Additional data that may be helpful include information regarding historic bathymetric change, shoreline change, structural modification of the immediate channel boundaries and bay system, or noticeable changes in sedimentation types or rates. Physical characteristics of the region including tidal range, wave heights, freshwater discharge, and the recurrence interval of storms will also contribute to the full understanding of the problem.

75. Specific survey methodology may be employed to determine whether sand waves are compromising channel depths in navigable waterways. A reconnaissance level bathymetric survey will usually determine the presence or absence of bed forms. Both cross-sectional and axial surveys must be run to ensure capture of the bed form shape in the Fathometer records. The bed form crests will be nearly perpendicular to the channel boundaries. It is important that several survey lines be run perpendicular to the bed form crest. Surveys made only in a cross channel direction may not detect bed forms in a navigation channel. Channels impacted by sand waves and surveyed by the use of channel cross sections alone will not be accurate. Average channel depths

could be biased deep or shallow depending on where along a sand wave the data have been gathered.

76. A survey grade bathymetric survey employing precise horizontal positioning techniques will allow accurate determination of sand wave shape, crest height, and wavelength. Correct bathymetric survey techniques must be employed during this portion of the program. High-quality cross-channel bathymetric surveys collected at 50- to 100-ft intervals combined with select survey lines run down the channel axis are necessary data to collect when dredged material volumes in channels shoaled by sand waves are to be calculated.

77. Side-scan sonar is an additional tool that may be used to determine the extent of bed form distribution in a channel (Figure 16), Side-scan sonar will also determine whether bed form fields with varied orientation are present. A 100-Khz system will map a wider swath of seafloor than a 500-Khz system. A 500-Khz system has a more limited field of vision but will capture more bottom detail. A Fathometer should be collecting bathymetric data at the same time as the side scan to enable accurate determination of the water depth of the seafloor features. The Fathometer frequency is approximately 40-Khz and will not interfere with the side scan records. The same methodologies used to determine horizontal position in a bathymetric survey may be used for a side-scan tow.

78. Although the side scan has a wide field of vision, this survey should also be run perpendicular to the bed form crest. Since the bed form crests are perpendicular to the channel axis, a side-scan survey of an affected channel area should not require more than one pass. Actually, side-scan sonar tows should be run into the prevailing current, if one is encountered. This technique will minimize yaw of the side scan and ultimately provide better data.

79. If the bed form field cannot be covered in one pass, a second one should be run parallel to the initial run. The line spacing should approximate 70 percent of the side-scan field, allowing for 30-percent data overlap. For example, if the range of the side scan is set at 100 m, then the line spacing should be 70 m.

80. If side-scan sonar is employed, an analog unit without slant range may be used. This less expensive unit will provide usable data to discern the length and breadth of the sand wave field. It is necessary to employ an

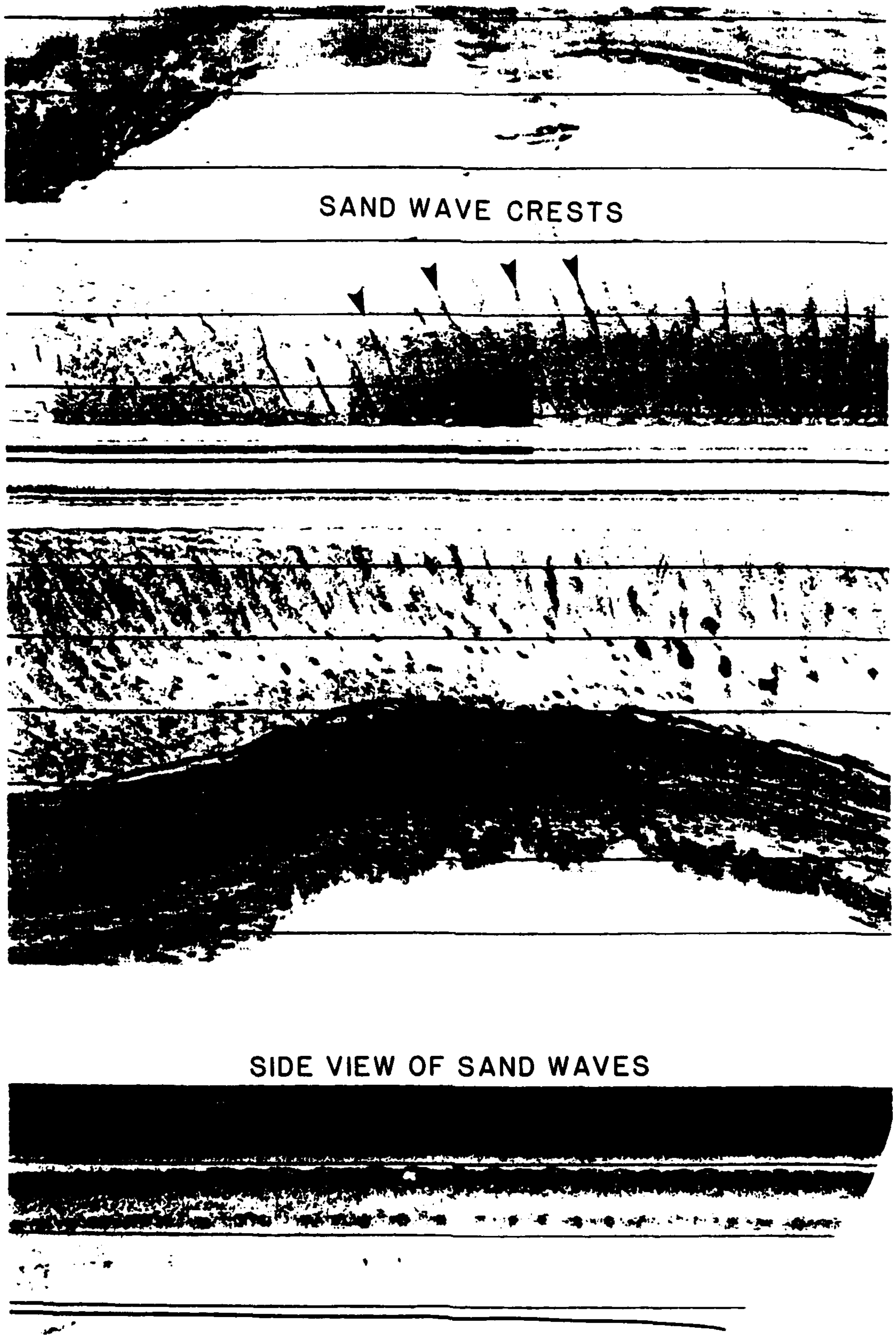


Figure 16. Sample of side scan survey data showing bed form field

experienced operator to ensure acquisition of usable record. Boat speed, cable length, and depth of the towed fish need to be recorded to produce a complete data package.

81. Data analysis should also be performed by an experienced individual. The derivation of quantitative information from side-scan records collected with analog units lacking slant range correction requires previous training. Newer digitized side-scan sonar systems account for slant range correction prior to producing the data product. These systems also take boat speed into account when printing records. Though more expensive to use in the field, the data, unlike that gathered by the analog equipment, are as usable as a map or chart. The reduced costs realized in data production and interpretation will compensate for the expense of the field operation. Once a horizontal scale has been determined, measurements can be taken simply. In addition, because the data are collected digitally, new data sets can be reproduced in the office at various scales to facilitate more specific analysis.

82. The sedimentology of the sand waves should also be determined. Samples should be gathered from known positions within and around the bed form field. This information will be used to determine whether there is a sedimentological cutoff between presence or absence of the sand waves. Samples may be collected remotely using a variety of grab samplers, i.e. ponars, shipecks, etc. Divers may also be employed for sample retrieval. The sample should be analyzed using standard sedimentological methods. Important parameters to determine are mean grain size and percentage of muds.

83. Current and water-level data should also be collected to determine the hydrodynamics of the affected system. A well-designed data collection program is essential to understanding site-specific bed form dynamics. These data will later be used to suggest channel design modifications that may mitigate shoaling problems. Current measurements can be made using in situ recording current meters (Lillycrop et al. 1989, Terwindt and Brouwer 1986) or can be recorded manually by lowering a profiling current meter over the side of a stationary boat (Boothroyd and Hubbard 1974).

84. Flow velocity needs to be measured at different levels in the water column. The flow velocity neat the sediment/water interface is probably more important than surface measurements. In a tidally affected area, these measurements should, ideally, be taken throughout the tidal cycle during spring, mean, and neap tide conditions. In areas affected by riverine discharge,

seasonal variations in flow should be measured. These data will enable the determination of time-velocity asymmetries.

85. According to Zarillo (1982), in addition to flow velocity measurements, a precise measurement of the slope of water surface is required. This term combines all of the natural parameters that contribute to sediment transport.

86. In some cases, divers have been stationed at the seafloor to observe the interaction of the bed form with flow (Boothroyd and Hubbard 1974). The visual confirmation of the initiation of bed form movement at a critical velocity provides important information. For example, if sand waves in a particular channel form only when currents exceed 60 cm/sec, then engineering designs that will lower the V_{max} to below this velocity should alleviate the shoaling problem. Diving in tidal currents is extremely difficult and can be dangerous. If this methodology is to be employed, considerations should be made to decrease energy expenditure by the divers in addition to implementing ample safety precautions (Boothroyd and Hubbard 1974).

87. Before design modifications to a sand wave prone channel can be identified, a knowledge of the site-specific processes contributing to sand wave formation is essential. The data set collected using these guidelines will assist in the efficient resolution of the shoaling problem.

PART VI: DREDGING ALTERNATIVES FOR CHANNELS SHOALED BY SAND WAVES

88. Where structural design cannot be used to solve shoaling problems, dredging may be the only alternative. As in the case of the Columbis River, various dredge types may be engaged before the most economic means are discovered. Further research will help in the design of dredges used specifically for the removal of sand wave shoals. These dredges must be designed for riverine, tidal/estuarine, and nearshore channel maintenance.

89. Dredging sand wave prone reaches of a river channel is typically performed by hopper dredges or cutter head pipeline dredges. However, neither are designed for efficient sand wave dredging. The hopper dredge drag head may lose contact with bottom sediments as it passes over a sand wave trough. A similar situation exists for the pipeline dredge. The cutter head swings an arc at a fixed depth and may also lose contact with bottom material. The distance between sand wave crests becomes more of a problem for the cutter head dredge as it moves much slower during operations than the hopper dredge. The dustpan dredge is more efficient for removing sand waves, but its use is limited to rivers because it lacks the ability to operate in coastal areas subjected to higher wave climates.

90. Along with the inefficiencies associated with dredging sand waves, conventional dredged material disposal practices associated with all of the dredges mentioned above may cause additional considerations. In rivers, dredged material disposal is along channel banks, in upland disposal areas, or in open water outside the navigation channel. Because river sediments that feed bed forms enter the channel primarily from bank erosion, runoff, and (to a lesser extent) by wind-blown forces, these conventional practices can compound the sand wave problem. The end result is a less efficient operation resulting in a greater dredging cost per cubic yard.

91. Various devices have been constructed, and many more thought of, to dredge sand waves. They range in principle from agitating or suspending bottom sediments to allow natural currents to carry the material away, to construction of large scoops or rakes that excavate wave crests. Some of the methods discussed in the following paragraphs originate from existing techniques used to remove linear or small shoals from navigation channels. They are based on the need to quickly mobilize and excavate small shoals or sand waves that encroach on channels posing navigation problems. Of primary importance is to do these tasks economically.

92. The dredge "Sandwick" is effecitve in removing small shoals from shallow coastal entrances by agitating material and allowing ebb-tidal currents to carry sediments from the navigation channel (Bechly 1975). The dredge is a modified Navy landing craft. A shield constructed on the stern of the craft can be lowered hydraulically to deflect propeller wash downward, thus causing scour of the shoal. The same approach could be used for removal of sand waves from where proper conditions exist. Depths would need to be shallow enough for the dredge to operate, or a larger version of the "Sandwick" would be required.

93. Another method for agitation is to pull a large, horizontal I-beam along the bottom with the use of tugs. A device such as this was used in Savannah Harbor with good results (Stuber 1976). The tugs were also to suspend and consequently move between approximately 240 to 3,380 cu yd of sediment and silt per hour. The material was removed from around ship docks and carried out of the immediate area by ebb-tidal flow.

94. Other methods of agitation dredging exist and can be classified in one of the five following categories (Richardson 1984):

a. Drags. This type consists of a rake, large beam, or other instrument that is dragged behind a support boat for the purpose of agitating the bottom material. An example of this method is the Savannah Harbor project.

b. Propeller wash. This consists of direct displacement of material caused by a vessel's propeller agitation. An example is the "Sandwick".

c. Water jets. This method uses water forced through tiny jets to directly suspend the bottom sediments. An example of this method is the device the Port of Portland has constructe.

d. Vertical mixers. These are designed to operate in fixed locations and run off compressed air. They are designed to suspend the sediments allowing currents to carry the material out of the problem area.

e. Conventional dredges. These include hopper, side-cast, and dustpan dredges. They are designed to remove bottom sediments and dispose of the material relatively close by and near the surface, allowing currents to carry it farther away.

95. The Mobile District modified a large farm plow for dragging sand wave crests off into the sand wave trough. This method is unlike the others discussed because rather than agitating material, the device plowed sand from the sand wave crest and moved it into the trough. The objective was to fill the trough with crest material, thus decreasing the elevation below the

desired navigation limit. The device did not work well because of the large quantity of sand that had to be removed from the crests.

PART VII: CONCLUSIONS

96. This report summarizes the current state of knowledge regarding sand waves and conditions that favor their formation. It also reviews technologies that are presently being used to remove chronic sand wave shoals from navigation channels. This review provides a starting point for additional efforts under the "Mitigating Sand Waves in Navigation Channels" IOMT work unit.

97. Two fundamental directions can be investigated to mitigate sand wave shoaling problems. One uses dredging equipment designed specifically to remove or displace sand waves. The other approach involves implementation of engineering solutions to prevent hydrodynamic conditions favorable to sand wave formation. The final solution may use one or both of the alternatives. As seen in the Oregon and Florida examples, this selection can be site specific.

98. Under the IOMT work unit, data collection, evaluation, and theoretical development will be carried out to establish methods for predicting sand wave formation and geometry. These efforts will be aimed at providing the engineer or scientist with design guidance so that new channels can be planned that restrict sand wave formation. Also, design guidance and methodologies could be implemented to assist in the evaluation process to determine if modifications could be achieved to reduce sand wave problems.

99. Ultimately, it will be a combination of design criteria and more effective dredging technologies or practices that help to reduce sand wave problems in navigation channels. Future study efforts will include field data collection because development of design criteria requires further theoretical development and field data are necessary for testing and evaluating any new ideas. Dredging alternatives and technologies will be studied to optimize existing practices and identify new directions.

REFERENCES

Alexander, M. P. "Sand Waves; Report 2, Engineering Considerations and Dredging Techniques," Technical Report in preparation, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Aliotta, S., and Perillo, G. M. E. 1987. "A Sand Wave Field in the Entrance to Bahia Blanca Estuary," Marine Geology, No. 76, pp 1-14.

Allen, J. R. L. 1962 (Apr). "Asymmetrical Ripple Marks and the Orgin of Cross-Stratification," Nature, Vol 194, pp 167-169.

__________. 1977. Physical Processes of Sedimentation, Allen and Unwin, London.

American Society of Civil Engineers. 1966. "Nomenclature for Bedforms in Alluvial Channels," Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, Vol 92, No. 3, pp 51-64.

Ashley, G. M., et al. 1990. "Classification of Large-Scale Subaqueous Bedforms: A New Look at an Old Problem," Journal of Sedimentary Petrology, Vol 60, No. 1, pp 160-172.

Bechly, J. 1975. "Sandwick Gives Nature a Boost for Shoal Removal," World Dredging and Marine Construction, Vol 11, pp 37-41.

Boggs, S., Jr. 1974. "Sand Wave Fields in Taiwan Strait," Geology, Vol 5, pp 251-253.

Bokuniewicz, H. J., Gordon, R. B., and Kastens, K. A. 1977. "Form and Migration of Sand Waves in a Large Estuary, Long Island Sound," Marine Geology, Vol 24, pp 185-199.

Boothroyd, J. C. 1985. "Tidal Inlets and Tidal Deltas," in R. A. Davis, ed., Coastal Sedimentary Environments, Second Revised Expanded Edition, Springer-Verlag, New York, pp 445-532.

Boothroyd, J. C., and Hubbard, D. K. 1974. "Bed Form Development and Distribution Pattern, Parker and Essex Estuaries, Massachusetts," Miscellaneous Paper 1-74, US Army Corps of Engineers, Coastal Engineering Research Center, Vicksburg, MS.

Cloet, R. L, 1954. "Hydrographic Analysis of the Goodwin Sands and the Brake Bank," Geographic Journal, Vol 120, pp 203-215.

Dalrymple, R. W. 1984. "Morphology and Internal Structure of Sand Waves in the Bay of Fundy," Sedimentology, Vol 31, pp 365-382.

Dalrymple, R. W., Knight, R. J., and Lambias, J. J. 1978. "Bedforms and Their Hydraulic Stability Relationships in a Tidal Environment, Bay of Fundy, Canada," Nature, Vol 275, pp 100-104.

Davies, A. G., and Wilkinson, R. H. 1978. "Sediment Motion Caused by Surface Water Waves," Proceedings of 16th Coastal Engineering Conference, Hamburg, Vol 94, pp 1577-1595.

Franco, J. J. 1968. "Effects of Water Temperature on Bed-Load Movement," Journal of Waterways an Harbors Division, American Society of Civil Engineers, Vol 94, pp 343-352.

Gilbert, G. K. 1914. "The Transportation of Debris by Running Water," Geological Survey Water-Supply Paper, No. 86, US Government Printing Office, Washington, DC.

Gill, M. A. 1971. "Height of Sand Dunes in Open Channel Flows," Journal of Hydraulics Division, American Society of Civil Engineers, Vol 97, No. 12, pp 2067-2074.

Haque, M. I., and Mahmood, K. 1985. "Geometry of Ripples and Dunes," Journal of Hydraulic Engineering, American Society of Civil Engineers, Vol 111, No. 1, pp 48-63.

Harms, J. C. 1969. "Hydraulic Significance of Some Sand Ripples," Geological Society of America Bulletin, Vol 80, No. 1, pp 363-396.

Harvey, J. G. 1966. "Large Sand Waves in the Irish Sea," Marine Geology, Vol 4, pp 49-55.

Hayes, M. O., and Kana, T. W., 1976. "Terrigenous Clastic Depositional Environments," Technical Report No. 11-CRD, Coastal Research Division, Department of Geology, University of South Carolina, Charleston, SC.

Hayes, M. O. 1975. "Morphology of Sand Accumulations in Estuaries," in L. E. Cornin, ed., Estuarine Research, Vol 2, "Geology and Engineering," Academic Press, New York, pp 3-22.

Hjulstrom, F. 1939. "Transportation of Detritus by Moving Water," in D. D. Trask, ed., Recent Marine Sediments, Society of Economic Paleontologists. Mineralogists Special Publication 4, pp 5-31.

Itakura, T., et al. 1986. "Observations of Bed Topography During the 1981-Flood in the Ishikari River," Journal of Hydroscience and Hydraulic Engineering, Vol 4, No. 2, pp 11-19.

Jones, N. S., Kain, J. M., and Stride, A. H. 1965. "The Movement of Sand Waves on Warts Bank, Isle of Man," Marine Geology, Vol 3, pp 329-336.

Jopling, A. V. 1965. "Geometrical Properties of Sand Waves" Journal of the Hydraulic Division, American Society of Civil Engineers, Vol 91, No. 3, pp 348-360.

Jordan, G. F. 1962. "Large Submarine Sand Waves," Science, Vol 136, pp 879-848.

Karl, H. A., Cacchione, D. A., and Carlson, P. R. 1986. "Internal-Wave Currents as a Mechanism to Account for Large Sand Waves in Navarinsky Canyon Head, Bering Sea," Journal of Sedimentary Petrology, Vol 56, No. 5, pp 706-714.

Kennedy, J. F. 1963. "The Mechanics of Dunes and Antidunes in Erodible-Bed Channels," Journal of Fluid Mechanics, Vol 16, No. 4, pp 521-546.

Klein, G. D. 1970. "Depositional and Dispersal Dynamics of Intertidal Sand Bars," Journal of Sedimentary Petrology, Vol 40, No. 1, pp 1095-1127.

Langhorne, D. N. 1973. "A Sandwave Field in the Outer Thames Estuary, Great Britain," Marine Geology, Vol 14, pp 129-143.

Lillycrop, W. J., Rosati, J. D., and McGehee, D. D. 1989. "A Study of Sand Waves in the Panama City Entrance Channel," Technical Report CERC-89-7, US Army Corps of Engineers, Coastal Engineering Research Center, Waterways Experiment Station, Vicksburg, MS.

McCave, I. N. 1971. "Sand Waves in the North Sea off the Coast of Holland," Marine Geology, Vol 10, pp 199-225.

Middleton, G. V., and Southard, J. B. 1977. "Mechanics of Sediment Movement," Lecture Notes for Short Course No. 3, Society of Economic Paleontologists and Mineralogists.

Perillo, G. M. E., and Ludwick, J. C. 1984. "Geomorphology of a Sand Wave in Lower Chesapeake Bay, Virginia, U.S.A," Geo-Mar. Lett., Vol 4, pp 105-112.

Postma, H. 1967. "Sediment Transport and Sedimentation in the Estuaries Environment," in G. H. Lauff, ed., Estuaries, American Association Advanced Science Publication, Vol 83, Washington DC, pp 158-179.

Reinson, G. E. 1979. "Longitudinal and Transverse Bedforms on a Large Tidal Delta, Gulf of St. Lawerence, Canada," Marine Geology, Vol 31, pp 279-296.

Reynolds, A. J. 1965. "Waves on the Erodible Bed of an Open Channel," Journal of Fluid Mechanics, Vol 22, pp 113-133.

________. 1976. "A Decade's Investigation of the Stability of Erodible Stream Beds," Nordic Hydrology, Vol 7, pp 161-180.

Richards, Kelvin J. 1980. "The Formation of Ripples and Dunes on an Erodible Bed," Journal of Fluid Mechanics, Vol 99, pp 597-618.

Richardson, T. W. 1984. "Agitation Dredging: Lessons and Guidelines from Past Projects," Technical Report HL-84-6, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Salsman, G. G., Tolbert, W. H., and Villars, R. G. 1966. "Sand-Ridge Migration in St. Andrews Bay, Florida," Marine Geology, pp 11-19.

Seelig, W. D., Harris, D. L., and Herchenroder, B. E. 1977. "A Spatially Integrated Numerical Model of Inlet Hydraulics," GITI Report No. 14, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Simons, D. B., Richardson, E. V., and Nordin, C. F., Jr. 1965. "Sedimentary Structures Generated by Flow in Alluvial Channels," in G. V. Middleton, ed., Primary Sedimentary Structures and Their Hydrodynamic Interpretation, Society of Economic Paleontologists and Mineralogists, Special Publication 12, Tulsa, OK, pp 34-52.

Stuber, L. M. 1976. "Agitation Dredging - Savannah Harbor," Proceedings, World Dredging Conference, WODCON VII, pp 337-390.

Taylor, P. A., and Dyer, K. R. 1977. "Theoretical Models of Flow near the Bed and Their Implications for Sediment Transport," in E. Goldberg, I. N. McCave, J. J. O'Brien, and J. Steele, eds., The Sea, Vol 6, Wiley-Interscience, New York, pp 579-601.

Terwindt, J. H. J. 1971. "Sand Waves in the Southern Bight of the North Sea," Marine Geology, Vol 10, pp 51-67.

Terwindt, J. H. J., and Brouwer, M. J. N. 1986. "The Behaviour of Intertidal Sandwaves During Neap-Spring Tide Cycles and the Relevance for Paleaeoflow Reconstructions," Sedimentology, Vol 33, pp 1-31.

Waller, R. A. 1961. "Ostracods of the St. Andrews Bay System," M. S. Thesis, Department of Biological Science, Florida State University, Tallahasee, FL.

Whetten, J. T., and Fullen, T. J. 1986. "Columbia River Bed Forms," International Association for Hydraulic Research.

Wright, L. D., and Coleman, J. M. 1974. "Mississippi River Mouth Processes: Effluent Dynamics and Development," Journal of Geology, Vol 82, pp 751-778.

Yalin, M. S., and Karahan, E. 1978. "Steepness of Sedimentary Dunes," Journal of the Hydraulics Division, American Society of Civil Engineers, Vol 4, pp 381-392.

Zarillo, G. A. 1982. "Stability of Bedforms in a Tidal Environment," Marine Geology, Vol 48, pp 337-351.

Waterways Experiment Station Cataloging-in-Publication Data

Levin, Douglas R.
Sand waves. Report 1, Sand shoaling in navigation channels / by Douglas R. Levin, W. Jeff Lillycrop, Coastal Engineering Research Center and Michael P. Alexander ; prepared for Department of the Army, U.S. Army Corps of Engineers ; monitored by Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station.
56 p. : ill. ; 28 cm. -- (Technical report ; HL-90-17)
Includes bibliographic references.
1. Sand waves. 2. Sediment transport. 3. Channels (Hydraulic engineering) 4. Sand bars. I. Lillycrop, W. Jeff. II. Alexander, Michael P. III. United States. Army. Corps of Engineers. IV. Coastal Engineering Research Center (U.S.) V. U.S. Army Engineer Waterways Experiment Station. VI. Improvement of Operations and Maintenance Techniques Research Program. VII. Title. VIII. Title: Sand wave shoaling in navigation channels. IX. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; HL-90-17.
TA7 W34 no.HL-90-17