HYDROLOGY OF COASTAL WATERS

Prepared by

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Coastal and Ocean Engineering Division
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ABSTRACT

This report is a brief review and summary of selected literature pertaining to estuarine hydrology. It consists of seven chapters.

1. Introduction
2. Definition of an Estuary
3. Hydrologic Data Collection in Tidal Estuaries
4. Salinity Intrusion in Tidal Estuaries
5. Siltation in Estuaries
6. Hydrologic Implications of Deepwater Channels in Tidal Estuaries
7. Suggestions for Research

PREFACE

A research study of selected literature was made as part of the Coastal and Ocean Engineering program at Texas A&M University.

The report was written in partial fulfillment of the requirement for the master of engineering degree under the supervision of Dr. John B. Herbich, Head of the Coastal and Ocean Engineering Division of the Civil Engineering Department at Texas A&M University.

Cooperation of Mr. A. B. Davis, assistant Chief of the Engineering Division of the Corps of Engineers, U.S. Army, Galveston District, and member of the Corps of Engineers Committee on Tidal Hydraulics, is gratefully acknowledged.

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COASTAL WATERS

I. INTRODUCTION

Estuaries are important to human welfare through their role in transportation, production of food, waste disposal, and various recreational activities. Many of the world's largest metropolitan areas have developed near estuaries which have been adversely affected by human activities.

The development of coastal areas has been very rapid in recent years, but knowledge of estuarine environments has not kept pace with the resolution of problems arising from their intensive use. Need for a more comprehensive understanding of estuaries and their surroundings and the lack of an adequate means to exchange information concerning estuarine research has led to the organization of various conferences and symposia across the country. One such symposium was held at Raleigh, North Carolina on May 12, 1967. The purpose of the symposium was to review and discuss current research and investigations that deal with two aspects, namely ground water and estuarine hydrology, of the coastal waters of North Carolina. It is the second aspect - estuarine hydrology (or hydrology of coastal waters), that is the subject of this paper.

It is the purpose of this paper to discuss some of the general causes and effects of upland discharges and salinity intrusions in tidal estuaries. A brief review and summary of portions of the proceedings of the previously referenced symposium and other selected literature pertaining to the present state of knowledge of factors affecting estuarine hydrology and related phenomena are also included in various chapters of this report.

II. DEFINITION OF AN ESTUARY

The problem of defining an estuary and delineating the area of estuarine oceanography has concerned many investigators for several years. The problem exists because it is difficult to develop a definition that will include all the bodies of water that the investigator wishes to talk about and exclude all the others.

Historically, the term "estuary" has been applied to the lower tidal reaches of a river. However, Pritchard[(32)] believes that, from a physical standpoint, the definition of an estuary should recognize certain basic similarities in the distribution of salinity and density, as well as the circulation pattern and the mixing processes. He also believes that the definition of an estuary should indicate the importance of the boundaries which control the distribution of properties and the movement and mixing of waters.

With these features in mind, Pritchard[(32)] has defined an estuary as follows: "An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage".[1]

The first requirement of the definition, that an estuary be "a semi-enclosed coastal body of water", is important because the circulation pattern in an estuary is influenced to a considerable degree by its lateral boundaries.

Further, the definition indicates that because the estuary is a coastal feature, the size of the bodies of water under consideration is limited. In other words, the estuary does not form the coast but is a part of the coast. The physical significance of this restriction is that the lateral boundaries of relatively large bodies of water are less important to the kinematics and

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[1]Pritchard, D. W., WHAT IS AN ESTUARY: PHYSICAL VIEWPOINT, Estuaries, American Association for the Advancement of Science, Publication No. 83, 1967, p. 3

dynamics of water movement than they are in a real estuary.

The next requirement of the definition, "a free connection with the open sea" is included by Pritchard(32) to indicate that communication between the ocean and the estuary must be sufficient to transmit tidal energy and sea salts. The connection is considered adequate if the inlet allows free passage of the ebb and flood flows at all stages of the tide.

The last requirement of Pritchard's definition is that, within the estuary, sea water be "measurably diluted with fresh water derived from land drainage". It is this dilution of sea water that provides the density gradients which drive the characteristic estuarine circulation patterns.

Caspers(5) points out that a precise definition of the word "estuary" becomes even more difficult after a thorough study of estuarine animals and an attempt to characterize the brackish-water fauna. According to Caspers(5) brackish water is typical of many, but not all, estuaries and that the terms "estuary" and "estuarine" often are confused in biological studies. For example, Pritchard's(32) definition of an estuary, according to Caspers(5) could also apply to most of the marine lagoons.

Caspers(5) believes that, in order to have a clear definition that would establish the common characteristics of all estuaries, it is necessary to distinguish between lagoons and estuaries. Caspers(5) believes that it is possible to distinguish between lagoons and estuaries by comparing their hydrological features such as the instability of salinity. According to Caspers(5), when the inflow of fresh water in a separated basin develops a stable body of brackish water, it may be considered a lagoon; and if the mixing of fresh and sea waters is not stable but shows periodic changes, the basin may be considered an estuary.

Caspers(5) points out that the unstable conditions of estuaries determine their principal biological features. For example, the environmental conditions in brackish water lagoons, expressed by the salinity, are relatively stable. However, as pointed out by Hann[13] the unstable conditions of estuaries, which can effect aquatic life communities, are brought about by the vertical stratification which is induced by density difference. This density difference which is generally the result of dissolved or suspended materials or difference in temperature, is discussed further in Chapters IV and V. As Hann[13] points out, the stratification is important because the different strata are drastically different environments with different aquatic life communities. Moreover the eventual mixing of the entire system can have catastrophic effects on certain biota and can temporarily degrade the quality of the water so that it is less desirable for domestic and industrial use.

Caspers[5] concludes his analysis of definitions and biological considerations of estuaries with the following listing of some of the main features of estuaries in general:

1. Estuaries are limited to river mouths in tidal waters.
2. Estuaries frequently indicate saline areas, but the extent of these areas differs, depending on the amount of freshwater inflow.
3. In extended estuaries, tide-induced currents reach upstream into freshwater zones. In these cases, the upper limit of the estuary corresponds to the upper limit of tidal influence.
4. Estuaries, in contrast to lagoons, are characterized by the instability of environmental factors.

Bowden[3] defines an estuary as a partially enclosed body of water which receives an inflow of fresh water from land drainage and which has a free connection with the open sea. This definition follows closely with that of Pritchard[32]. It includes coastal plain estuaries and fjords, as well as certain gulfs, sounds, and inlets. According to Bowden[3], it also includes embayments formed behind offshore bars, provided they have a salinity significantly lower than the open sea.

Therefore, according to Pritchard[32] and Bowden[3], the main physical problems to be investigated in an estuary are the water movements, the mixing processes, and the distribution of salinity which results from their combined action. The distribution of temperature, as pointed out by Bowden[3], is usually of secondary importance in an estuary because, although it undergoes considerable variation, it has a less important effect on the density of the water.

Some of the methods of observation of estuaries, and the general causes and effects of salinity intrusions on tidal estuaries are discussed in Chapters III, IV, and V.

III. HYDROLOGIC DATA COLLECTION IN TIDAL ESTUARIES

A knowledge of physical and chemical conditions is necessary to understand tidal estuaries and to plan, construct, operate, and maintain a wide variety of physical works for water resources development and pollution abatement in these estuaries. Unfortunately, the required physical and chemical data are usually difficult to obtain, expensive to process, and cumbersome to interpret. Accordingly, there is a critical need for the development of rational means for determining optimum amounts of time series and space field data such as stage, current velocity, and salinity measurements, which are needed for engineering purposes.

Of all the characteristics which typify estuaries, as pointed out by Mangelsdorf,[28] perhaps the most distinctive is salinity variation. The complete range of salinities from fresh water to sea water is always found, and only found, where freshwater runoff meets the sea.

Many investigators believe that because salinity values are so local and transient in estuaries, there is rarely much to be gained in determining them with maximum precision. In most cases salinity measurements in estuaries call for greater convenience of measurement, not greater precision. It is not more decimal places which are needed, but simply more frequent measurements in more places.

Purposes of Salinity Measurements

Mangelsdorf[28] lists four main purposes for the use of salinity measurements in estuaries, each of which requires a different level of precision.

a. There are studies of transport, flushing, and mixing such as the Chesapeake Bay studies. Quantitative work of this nature, based on detailed salinity profiles, requires salinity data accurate to ± 0.1‰, or even to ± 0.01‰.

b. Salinity can be used in a more qualitative manner as a tracer to label different water masses in an estuary according to the amounts of sea water they contain. Following isohalines, one can trace out the boundaries due to eddies, stratified flow, and to "streakiness" of flow. Such a qualitative study of the dynamics of an estuary and of the changes in behavior during a tidal cycle should always precede any detailed quantitative measurements.

c. Salinity, or the lack of it, is an ecological factor to the biologists. Salinity limits the distribution of various species. In general, salinities measured to a relative precision of 5 percent should be adequate for ecological purposes. This would come to ± 1‰ when the total salinity is about 20‰, and ± 0.1‰ when the salinity is only 2‰, etc.

d. Salinity concerns water users on the streams flowing into an estuary. Occasional salinity intrusions are a major factor in the quality of the water supply available to these people. A method which can detect small amounts of sea water in otherwise fresh water is particularly desirable.

Conductivity Measurements

Despite this variety of purposes of salinity measurements and the markedly different levels of sensitivity required, Mangelsdorf[28] points out that almost all of these measurements can be well performed -- in many cases best performed -- by determinations of the electrical conductivity of the water. Sea salt is an electrolyte mixture which is completely dissociated in water into its component ions. Each ion carries on electric charge and is free to move. Every ion contributes to the electrical conductance of a seawater solution. The more sea salt, the greater the conductivity, almost (though not quite) in direct proportion.

There is, according to Mangelsdorf[28], only one minor drawback to conductivity as a measure of salinity: The conductivity of salt water also depends on the temperature, and salinity and temperature frequently change together. The conductivity of water increases with temperature because the ions move faster as the water warms up, about 2 1/2 percent faster per degree centigrade. Rough temperature corrections can easily be made or, in cases requiring greater accuracy, standard tables are available. Therefore, Mangelsdorf[28] asserts that the corrected conductivity value is a direct measure of the total electrolyte content of the water.

Gunnerson[10,11] reported on the results of analyses of data on dissolved oxygen and specific conductance in two Atlantic coast estuaries, the Potomac River and Raritan Bay. It was shown that the essential data were obtained with a 2-hour sampling interval. It was also shown that, for slugs of pollution, continuous monitoring is meaningful only at the point of discharge. Later, Gunnerson[12] reported that a 2-hour sampling interval was found to be the optimum for collection of diurnal cycle data such as tides and photosynthesis in San Francisco Bay. Estimates of phase relationships of stage, velocity, and salinity provided Gunnerson with a basis for evaluating hydrologic data collection and utilization near the mouth of the Sacramento River. Based on analyses of these data Gunnerson also concluded that the presence or absence of a diurnal inequality in the tide does not appear to be a significant factor in planning hydrologic observations in tidal estuaries.

San Francisco Bay and the Sacramento-San Joaquin Delta have been investigated for about 40 years, resulting in a number of reports on combinations of hydrography, salinity incursion, water supply, waste disposal, transportation, fisheries, recreation, and model studies. Bonderson et al.[2], have compiled the most recent bibliography on this study area.

Various types of tracer studies including radioactive tracers, natural tracers, and fluorescent tracers have been conducted to measure sediment and water movements in coastal waters. Pritchard and Carpenter[33] have shown that the Rhodamine B dye tracer is one of the most sensitive and least expensive labels for measuring water movements. Rhodamine B is a fluorescent pigment, relatively resistant to photochemical decay. It fluoresces maximally at 580 millimicrons and has a maximum absorbance at 550 millimicrons. Chlorophyll and its derivatives are probably the main component of the fluorescence background in tracer studies.

As in the case of salinity measurements, temperature variations are the main sources of error in quantitative work. For every degree centigrade rise in temperature the fluorescence decreases 2.3 percent. Therefore, temperature should be monitored continuously while sampling to correct for this decreasing sensitivity.

Hydrologic Studies of the Coastal Waters of North Carolina

Rhodamine B was used by Horton[19] in a dye tracer study of water currents in the Pamlico River Estuary, North Carolina, during the summer of 1966. A brief review of the hydrography of that estuary and the results of the dye tracer study are contained in a paper which was presented at a symposium on hydrology of the coastal waters of North Carolina on May 12, 1967. The purpose of the symposium was "... to review and discuss current research and investigation dealing with ground water and estuarine hydrology in the Coastal Region of North Carolina as a basis for intensified work to provide the information and techniques necessary for sound planning, development, and management of the coastal water resources."[1]

Two papers presented at the symposium that deal with hydrologic data collection in the Pamlico River Estuary, including the one mentioned above,

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[1] Proceedings, Symposium on Hydrology of the Coastal Waters of North Carolina, May 1967, p.v.

are summarized in this chapter for the purpose of determining what factors should be considered for tidal estuaries in general.

Horton, D. B.

WATER CURRENT STUDIES IN PAMLICO RIVER ESTUARY, Proceedings, Symposium on Hydrology of the Coastal Waters of North Carolina, pp. 95-103, May 1967.

The Pamlico River estuary (Figure 1) runs in a northwest-southeast direction from Washington, North Carolina, to Pamlico Point where it enters Pamlico Sound. Because of the damping effect of Pamlico Sound, the estuary has a tidal range of only seven to nine inches. The estuary is shallow, averaging 7.5 feet in the upper portion to 13 feet in the lower reaches.

One hundred and fifty pounds of Rhodamine B dye was deposited in the river at station 5 (Figure 1) over a three day period from August 3 to August 5, 1965. Reliable estimates of the size and location of the dye patch were possible for four days after insertion.

The boundaries of the dye patch are shown in Figure 2. The average net movement of the patch was about 915 meters per day downstream.

The author used a tidal prism model of the Pamlico River estuary to estimate exchange rates and predict half-life of contaminants introduced into the model to compare these with salinity data and Rhodamine B dye concentrations. The model developed by Ketchum[25] was used.

In Ketchum's model, the estuary is divided into several volume segments, each defined by an effective mixing length equal to the average distance which is covered by the flooding tide. It is assumed that complete vertical mixing takes place in the model, that steady state conditions exist during the time period that the model is used, and that there are no large lateral differences in salinity. Incomplete vertical mixing in the model can be accounted for by a correction term derived from salinity stratification.

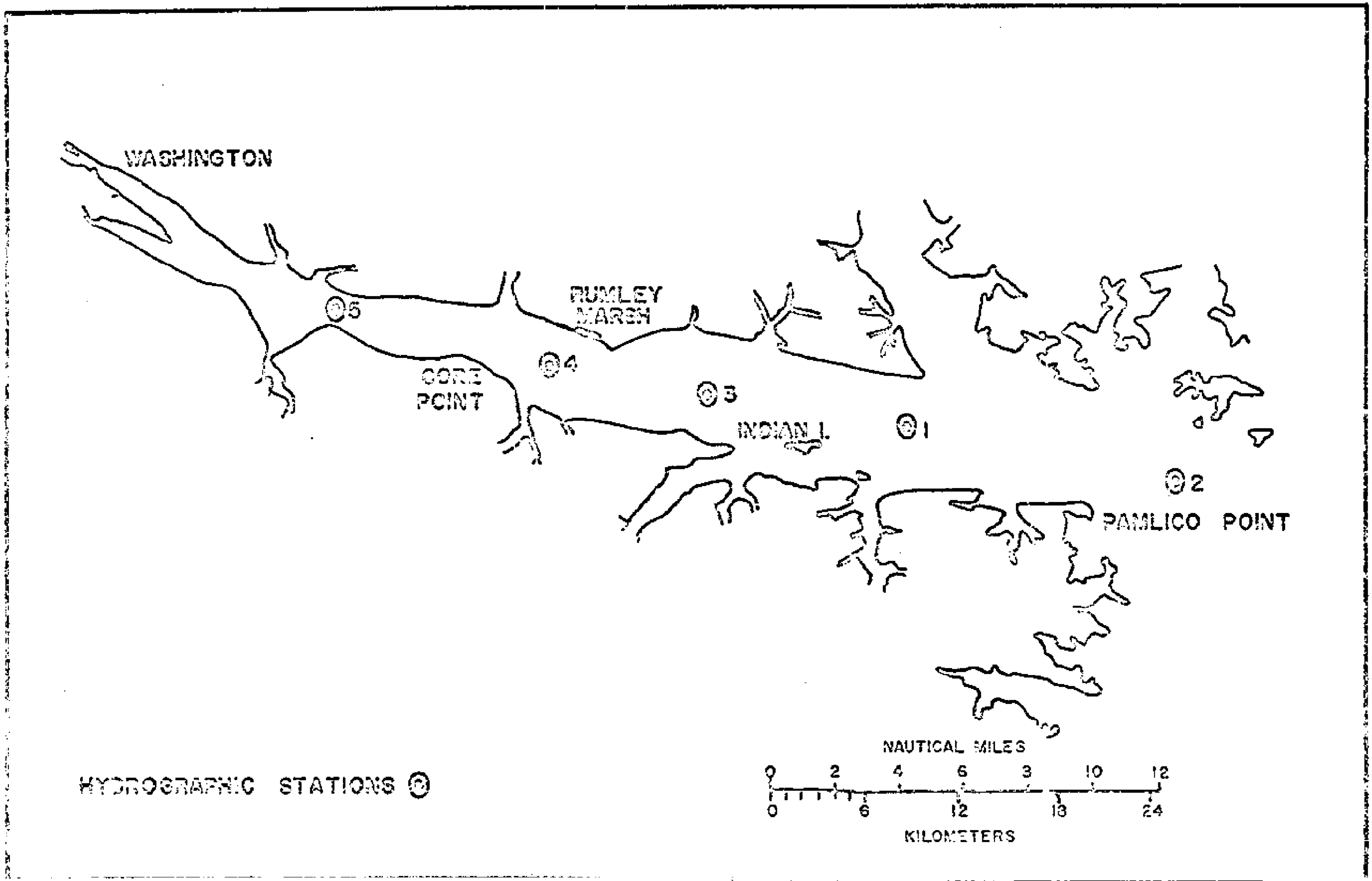

FIGURE 1[2] Pamlico River estuary between Washington, North Carolina and Pamlico Light Station (locations are shown and referred to in the text).

[2] Modified after "Water Current Studies in Pamlico River Estuary", [illegible], *Symposium on Hydrology of the Coastal Waters of North Carolina*, May 19[illegible], p. [illegible].

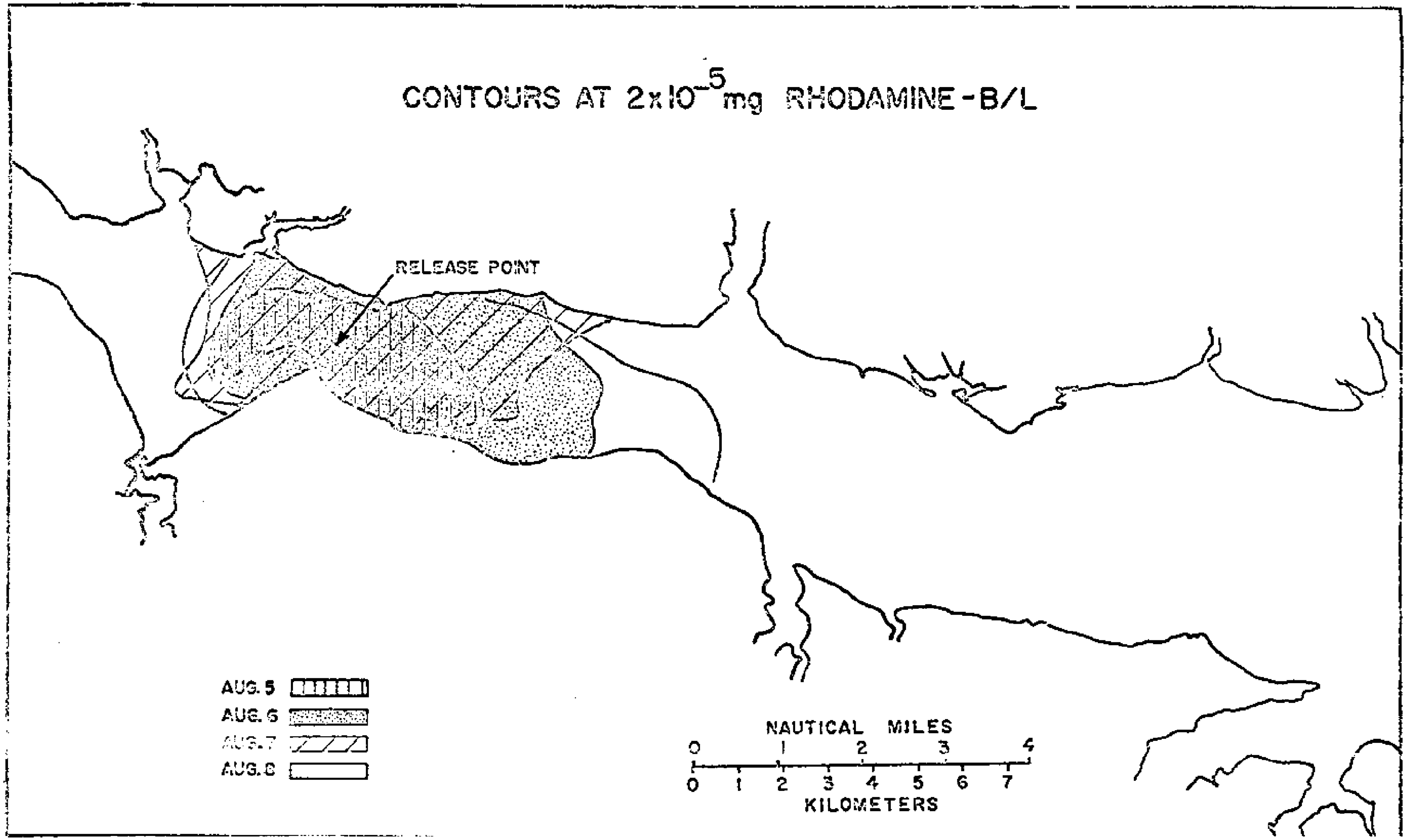

FIGURE 2[3] Rhodamine B dye location in the Pamlico River estuary on the first four days after insertion, 1966.

[3]Modified after "Water Current Studies in Pamlico River Estuary", [illegible], Symposium on Hydrology of the Coastal Waters of North Carolina, [illegible]

When stratification exists, it is assumed that mixing in the model is limited only to the upper layers and the volumes are computed only to the mixed depth.

Schultz and Simmons[35] noted that when the flow ratio of a coastal plain estuary, which is the ratio of volume of freshwater inflow during a tidal cycle to the tidal prism, is less than 0.1, the estuary is of the well-mixed type which may make vertical salinity differences undetectable. This phenomena is discussed further in Chapter V. Based on an analysis of the freshwater inflow during the month preceding the dye insertion in Pamlico River estuary, Horton assumed that vertical mixing was complete.

Comparison of the salinity values that were predicted by the model to the observed salinities in the Pamlico River revealed that the calculated salinities averaged between 12 and 26 percent higher than observed for most of the estuary which, according to Horton[19], is reasonably good correspondence. A considerable part of the salinity discrepancy between the observed and calculated results was expected due to fresh water which accumulated during periods of high freshwater inflow.

The predicted flushing time, which is the average length of time for the river water to move through all of the segments of the estuary, is 587 days under low freshwater flow conditions. Average exchange ratios and half-life values for freshwater were estimated for various regions of the estuary. The exchange ratio is the proportion of the river water within a volume segment, that is lost to the adjacent seaward segment on the ebbing tide. The half-life is the amount of time for half of the river water introduced to a volume segment to be removed during a tidal cycle.

The predicted flushing time for the section of the estuary in which the dye was released corresponds to an average transport which was much less than the actual net dye movement. Therefore, the actual flushing time during the period of time may have been considerably less than the predicted value. The author points out that this apparently large discrepancy is probably due to the fact that the freshwater inflow may have been underestimated (only an average value for the month preceding the dye insertion was used in the calculation), and vertical mixing was assumed to be complete. Also, most of the net seaward movement may have been at the surface in spite of the small amount of stratification observed. Hansen and Rattray(14) pointed out that the advective (gravitational) component of salt flux is not necessarily proportional to salinity stratification.

Two important transport mechanisms not taken into account by Horton were wind and diffusion. Horton observed that wind brought about considerable change in water level in the estuary, and therefore it must be important in salt transport and flushing mechanisms. However, he did not have the independent criteria necessary to assess the relative importance of wind stress.

In conclusion, the author found that the volume segment model of tidal flushing does not accurately fit the hydrographic characteristics of the Pamlico River estuary. Better correspondence was found for model estimates and observed data during higher freshwater inflow conditions. Horton(19) believes that estimates of exchange ratios, flushing times, and half-life values for the estuary are representative for average freshwater inflow conditions. Also, the attempt to fit the model to the known parameters of freshwater inflow, basin topography, and tidal amplitude gave insight into the relative importance of other pertinent parameters.

Woods, W. J.

HYDROGRAPHIC STUDIES IN PAMLICO SOUND, Proceedings, Symposium on Hydrology of the Coastal Waters of North Carolina, pp. 104-114, May 1967.

The second of the two papers dealing with the collection of hydrologic data in tidal estuaries presented at the previously referenced symposium at

North Carolina is a report on a study of plankton ecology. In 1962 William J. Woods[40], the author of that report, learned of the phosphate mining operation proposed for the Pamlico River area. This presented the author with the opportunity to study plankton ecology in a natural situation in which there was a possibility of radical change of phosphorous concentration, which is an important environmental parameter. In order to establish that a change had occurred, it was necessary to determine the physical, chemical, and biological conditions that existed before the mining operations began. When Woods submitted his findings at the symposium, phosphate mining had not yet been put into operation. Therefore, before and after comparisons of data concentrations were not possible. However, the data that Woods collected should provide sufficient information to critically evaluate the impact of such a mining operation.

Several sampling stations which were established in Pamlico Sound and other major estuaries and inlets are shown in Figure 3. Vertical salinity and temperature measurements were made at meter intervals and surface and bottom samples were analyzed for dissolved oxygen, plant pigment concentrations, nitrate, nitrite, ammonia and total nitrogen, and phosphate and total phosphorous. Some of these parameters are discussed below.

Temperature Conditions in Pamlico Sound. The author observed that it is extremely unusual for surface temperatures over the entire sound and estuary complex to vary more than three or four degrees centigrade in any one month. Therefore, the author inferred that temperature of water in the major rivers and in the open sound closely follow that of air temperatures. On the average, the greatest temperature variations occur in November when the gradient decreases from the inlets to the rivers, and in June when the reverse is true. In general, particularly in the open sound, there is very little vertical temperature variation. Temperatures as high as

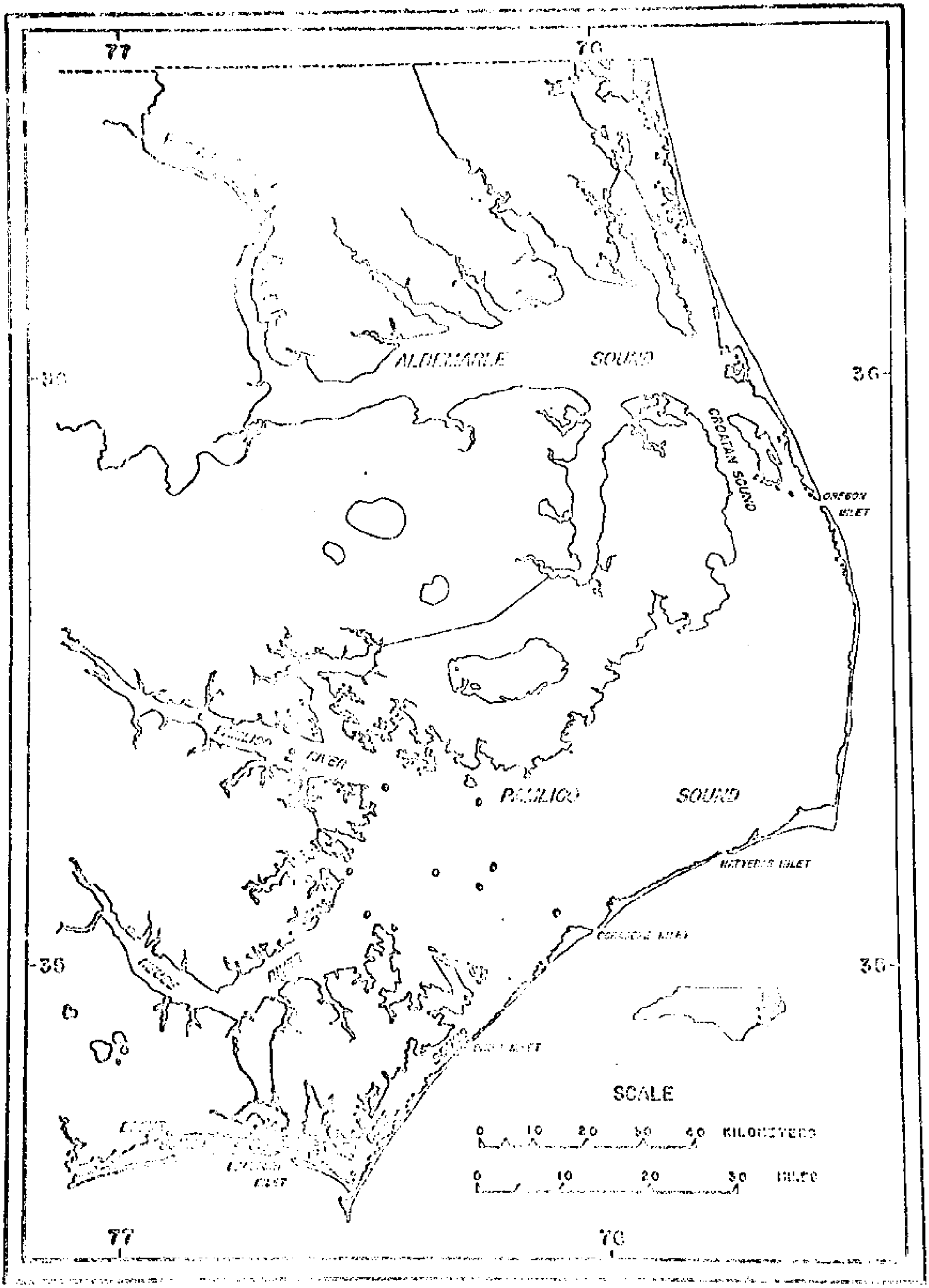

FIGURE 5[4] Map of coastal North Carolina showing location of major estuaries, inlets and sampling stations (○).

[4]Modified after "Hydrographic Studies in Pamlico Sound". Proceedings, Symposium on Hydrology of the Coastal Waters of North Carolina, May 1967, p. 196.

28°C and as low as 2.5°C were measured.

Salinity Conditions in Pamlico Sound

Vertical Salinity Distribution. The author observed that, in the open sound there is frequently a slight difference (0.5 to 1.0%) between salinity concentrations at the surface and at the bottom. The higher salinities, of course, usually occur at the bottom and most of the increase in salinity appears to occur in the meter of water above the bottom. In 1964 and 1966 there were periods when unusually large differences in salinity of surface and bottom water occurred in the open sounds. In 1964, these differences occurred during the spring, summer, and fall, with differences up to about 6% being noted. The author believes it is reasonable to assume that the vertical differences recorded in 1964 are due to a widespread occurrence of freshwater outflow from tributary rivers. Examination of monthly river-flow data reveals no correlation between river flow and the occurrence of salinity stratification. However, examination of riverflow data on a daily basis reveals that increased flows in two major rivers occurred about four to seven weeks prior to occurrence of salinity stratification in the open sound. Based on this, the author reasoned that a flushing time of one to two months can be estimated for Pamlico Sound, at least during periods of high flow. During 1966 salinity values did not differ much from average. However, a distinct layering was observed during July and August. This difference was due not to low surface readings but rather high salinity concentrations at the bottom. Since this situation existed only in areas removed from tributary rivers, it indicates that the occurrence was due to something other than freshwater runoff. Examination of wind records revealed that the wind was blowing from the north at speeds up to 23 miles per hour for two days prior to the time samples were collected in August. For five days prior to that, the wind was flowing from a southerly direction at velocities up to 25 miles per hour. Roelofs and Bumpus[34] have discussed the movement of high-salinity water from Core Sound into Pamlico Sound by strong southwest winds and that winds from the north produced reverse effects. This points up the complexity of salinity distribution in the Pamlico Sound system.

Horizontal Salinity Distribution. As the author expected, a much wider range of concentrations was found for horizontal distribution of salinity. Salinities increase, of course, from the mouths of the rivers to the inlets. It has been reported that there is no daily variation in salinity concentrations in Pamlico Sound. The greatest variation occurs at the mouths of Neuse and Pamlico Rivers, the smallest at locations closest to the inlets. Generally, lowest concentrations occur during the spring and highest concentrations occur during winter.

Various hydrologic investigators seem to agree that wind and freshwater runoff are the factors controlling horizontal salinity distribution in Pamlico Sound. Woods' examination of surface salinity distribution for February and July of 1967 seem to verify this conclusion. During the month of February, the prevailing wind was from the north with velocities in the 15 to 30 mile per hour range about 30 percent of the time. Typical discharges for this month from the Roanoke, Pamlico, and Neuse Rivers, in thousands of cubic feet per second, were 249, 122, and 144 respectively. The combination of reduced flow from the Roanoke River and the southwest winds moved higher salinity water up into the northern part of Pamlico Sound. Reduced flow from Neuse River and the prevailing wind permitted high salinity water to move across the lower part of Pamlico Sound and also changed the salinity in Core Sound.

Although, according to the author, the temperature and salinity distribution in the Pamlico Sound complex is generally well understood, a good estimate of flushing time under all conditions still cannot be given and the circulation pattern within the sound is not fully understood. However, temperature-salinity data for Pamlico Sound are now in a form that makes analysis possible. Several projects recently completed or planned for the near future, including additional dye tracer studies similar to the one previously discussed, should provide a fuller understanding of the Pamlico Sound complex.

Other water quality parameters included in Woods' hydrologic studies of the Pamlico Sound Complex were dissolved oxygen, phosphorous, and nitrogen. This summary of Woods' report, which was presented at the previously referenced symposium, is concluded with a discussion of the author's findings on these remaining parameters.

Dissolved Oxygen. During the course of his investigation, Woods measured dissolved oxygen concentrations ranging from about four milligrams per liter to eleven milligrams per liter. The highest concentrations occurred during periods of cold water and the lower concentrations occurred when the water was warmer. Dissolved oxygen seldom went below 50 to 60 percent saturation and, particularly during winter months, was normally close to 100 percent. Usually there was not much variation in surface dissolved oxygen concentration throughout the sound. However, dissolved oxygen at the bottom was found to be slightly different. Although vertical differences in the open sound were slight, there was frequently a vertical difference in concentrations in rivers entering the sound. In the Pamlico River, low oxygen concentrations at the bottom were the rule at the upstream stations during periods of warm water. The author also noted occasional oxygen depletion.

Phosphorous. The analytic method which was used to determine phosphate-phosphorous was sensitivity to 0.016 μgAt P/L. During the course of the author's investigation, concentrations ranged from below the limit of sensitivity to 1.0 μgAt P/L at the surface and up to 1.5 μgAt P/L at the bottom.

The typical range of total phosphorous levels was 1.0 to 2.5 μgAt P/L, but consistently high values as high as 25 to 30 μgAt P/L were recorded during 1964. Previously noted abnormal salinity distributions occurred over the sound during 1964, which the author attributed to river inflow.

Nitrogen. Nitrate-nitrogen concentrations ranged from below the sensitivity of the analytic method (0.10 μgAt N/L) to a "normal" high value of about 1.0 μgAt N/L. However, high levels of nitrate-nitrogen concentrations were noted during the same period of high phosphorous concentrations.

According to Wilder(39), the estuaries of coastal North Carolina represent one of the more valuable natural resources in the state. They comprise more than 500 miles of navigable water, into which are discharged an average of about 13 billion gallons of freshwater of good quality each year. Their potential value for industry, recreation, and sensible waste disposal is unlimited. Yet, considering their potential, these estuaries have not been adequately studied. To fill the need for additional information concerning them, the U.S. Geological Survey, in cooperation with the State of North Carolina, initiated a program in the early 1950's to investigate the chemical quality of estuarine waters, which has continued to the present.

Recent development of sophisticated water quality data collection systems has proved to be very helpful in studying the chemical and physical hydrology of streams in coastal North Carolina. Such special instrumentation make it possible to obtain a more representative picture of the water quality variations in fast changing systems such as estuaries.

To date, probably the most comprehensive study dealing with hydrologic data collection in the coastal waters of the state of Texas was conducted by Collier and Hedgpeth(6). Their basic data dates back to the late 1930's and its published form is now some 20 years old.

Their paper is a presentation of the hydrography of the system of bays and tidal lagoons which join the Gulf of Mexico through Aransas Pass, with particular reference to temperature and salinity conditions, tides, and climatic factors.

It includes a descriptive explanation of the geomorphology, salinity exchange, tidal cycle and temperature conditions which characterizes the waters concerned, primarily as an aid to understanding the biological cycles which are governed by these physical conditions.

More studies like the one authored by Collier and Hedgpeth are needed for the entire Texas coast. New improved techniques, such as those employed by investigators of the Atlantic and Pacific Coasts, should be considered in an effort to obtain large amounts of definitive data more efficiently. Combined with newer methods for measuring water movement and other environmental factors which control estuaries, special instrumentation provide us, for the first time, with the necessary techniques to gain some real understanding of estuarine hydrology. Continual monitoring of pertinent hydrologic and chemical parameters is required to assess the effects of man on the physical, chemical, and biological properties of our state's tidal estuaries. The hydrologic implications of deepwater channels in tidal estuaries is considered in Chapter VI as one example of the effect that man has on these important water quality properties.

IV. SALINITY INTRUSION IN TIDAL ESTUARIES

The ecology of estuaries has recently become the object of prime consideration by marine scientists and coastal engineers. Intensive research activities have been stimulated by the fact that most of our large population centers are located along the coasts which has placed increased demands on the resource potentials of our estuaries. Channels are deepened and widened for navigation, freshwater inflows are modified by control structures, and estuary waters are polluted by waste disposal from nearby industry and communities. Many conflicting interests have arisen as such exploitation has proceeded often without regard to consequences to the estuarine environment.

The effective use of our tidal estuaries require increased interference by engineering measures. The consequences of man's interference are interrelated and means of predicting them must be found if the economics of improvements are to be evaluated properly. A number of systematic attempts have therefore been made to correlate the intrusion of saline waters with tidal characteristics based on actual observations of salinity conditions in real estuaries. The inadequate state of knowledge in this area was brought to the attention of the profession in 1950 by a comprehensive report of the Tidal Hydraulics Committee of the U.S. Corps of Engineers[7], and by the proceedings of the Colloquium on Tidal Flushing of the Office of Naval Research[29]. A completely revised edition of the Tidal Hydraulics Committee Report, dated May 1965[8], was used extensively for the preparation of this paper.

The first attempts to analyze salinity intrusions in estuaries were based on the freshwater-tidal prism ratio, and were concisely presented by Ketchum[25]. Ketchum's model was discussed in Chapter III. Since Ketchum assumed that complete mixing existed in each section at high tide, his formulation was limited to the highly mixed conditions of saline intrusion and to large ratios of tidal prism to freshwater discharge in a tidal cycle. Arons and Stommel[1] studied the time-average salinity distribution in a rectangular estuary by a concept of mixing length. The results of their studies are represented in the form of distribution curves in terms of the total length of the intrusion. Pritchard[30,31] reviewed various estuarine circulation patterns and proposed a method of classifying them on the basis of the degree of mixing that took place. Hansen[15] studied the relationship between the mean salinity distribution and the circulation in partially mixed estuaries to define conditions under which different types of estuarine regime are likely to occur. His results concur in many respects with Pritchard's[30] discussion of the relation between the nature of the salinity distribution and the external parameters, namely: river discharge, tidal mixing, width, and depth.

Considerable progress has been made in recent years in defining the details of diffusion characteristics in terms of the flow processes which occur within the intrusion length by systematic studies in laboratory channels[22], [17], [26], [18], [3], while observations on scale models continue to furnish proof of the important connection between tidal flow, salinity, and freshwater flow.

The Corps of Engineers Committee on Tidal Hydraulics initiated an investigation of salinity intrusions and related phenomena in 1954. The objectives of the investigation were to determine the effects of the physical and hydraulic features of estuaries (such as tidal prism, tidal range, freshwater discharge, channel depth, channel width, etc.) on:

a. the extent of salinity intrusion,

b. the nature of salinity intrusion,

c. the magnitudes and durations of current velocities, and

d. other factors considered essential to the proper solution of estuarine problems that are encountered by the Corps of Engineers.

The general investigation was designed to cover the following four phases:

a. the extent of salinity intrusion and the mean salinity distribution.

b. the vertical mixing of fresh and salt water and the resulting vertical salinity distribution.

c. the vertical distribution of current velocities as affected by salinity distribution.

d. the movement and deposition of sediments as affected by density-current phenomena.

Two reports on the first three phases, written by Harleman and Ippen[18,22], probably represent the most significantly controlled experiments in estuarine behavior. The experimental portions of the investigations were conducted at the U. S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi using a 327-foot long flume. A detailed consideration of Harleman and Ippen's work are beyond the scope of this paper. However, summaries of the results and conclusions included in their reports[21] are given below:

Ippen, A. T. and Harleman, D. R. F.

> ONE-DIMENSIONAL ANALYSIS OF SALINITY INTRUSION IN ESTUARIES, <u>Technical Bulletin No. 5</u>, Committee on Tidal Hydraulics, U. S. Army, Corps of Engineers, June 1961.

Ippen and Harleman's one-dimensional approach proceeded from the conservation of salt equation:

$$\frac{\delta s}{\delta t} + (u_{(x,t)} - U)\,\frac{\delta s}{\delta x} = \frac{\delta}{\delta x}\,(D_x'\,\frac{\delta s}{\delta x}) \qquad (1)$$

wherein s = local, instantaneous salinity concentration as average for the vertical section

$u(x,t)$ = average tidal velocity for any section at X and at any time t

U = temporal mean fresh water velocity for the section

D_x' = local dispersion coefficient including mass transfer by internal currents caused by density gradients

If tidal action and freshwater flow are assumed to remain relatively constant for a period of several days or weeks a quasi-steady state of salinity distribution should be reached and Equation (1) may be separated into two parts. The first part deals with the periodic translation of the salinity concentrations by tidal action to and fro:

$$\frac{\delta s}{\delta t} + u_{(x,t)} \frac{\delta s}{\delta x} = 0 \qquad (2)$$

and the remaining terms state that any seaward transport of salt, if averaged over a tidal cycle, is compensated by upstream dispersion, hence:

$$U \frac{\delta s}{\delta x} + \frac{\delta s}{\delta x} (D_x' \frac{\delta s}{\delta x}) = 0 \qquad (3)$$

Equation (2) can be integrated if the tidal velocity u is given as a function of x and t by tidal analysis, assuming no effects from density variations. Equation (3) can then be reduced to the form:

$$\frac{U}{D_x'} \delta_x = \frac{\delta s}{s} = \ln s + C_1 \qquad (4)$$

and may be integrated further only by making certain assumptions about the variation of the mean value of D_x' with distance x at a given tidal time such as low water slack. A particular solution in agreement with extensive experimental evidence in a rectangular tidal channel has been given in references (20) and (22). This one-dimensional approach has contributed greatly to the correlation of the dispersion characteristics of experimental and natural estuaries with the pertinent tidal conditions and the freshwater flow regime. An "apparent" dispersion coefficient D_0' can be derived for the seaward end of an estuary by observations of salinity and tidal conditions and by predicting changes in its value for changes in tidal amplitude a, in tidal prism P_t, freshwater discharge Q_f, and depth of channel h. This correlation is based on the observation from harmonic tidal analysis that the magnitude of tidal energy dissipation G in relation to the gain of potential energy g by the fresh water passing to the ocean by mixing is responsible for the relative degree of dispersion in the estuary. Dividing the dispersion coefficient for a shear flow in open channels: $D_o = 4.5\ u_o\ h \sqrt{f}$ as adapted from the development by G. T. Taylor, it has been shown (21) that

$$\frac{G}{J} = f\left(\frac{D_o'}{D_o}\right) = M_o\ \left(\frac{P_t}{Q_f T}\right) \frac{a}{h} \cdot \frac{1}{\Delta\rho/\rho} \qquad (5)$$

wherein M_o = characteristic number of estuary geometry roughness and tidal period

P_t = tidal prism, computed as inflow during flood tide

$\frac{a}{h}$ = tidal amplitude to depth ratio

$\frac{\Delta\rho}{\rho}$ = relative density difference between fresh and ocean water

U_o = maximum tidal velocity at ocean end

f = Weisbach-Darcy resistance coefficient

It can be seen (21) that the ratio D_o'/D_o may be amplified tenfold with low values of the parameter given in Equation (5) when the freshwater flow is increased on the tidal prism and tidal amplitude are decreased. Therefore, increased stratification is indicated. For large values of the parameter, the ratio of the dispersion parameter approaches unity for near homogeneous fluids, smaller freshwater flows, and for large tidal amplitudes as the estuary approaches a well-mixed condition.

Harleman, D. R. F., and Ippen, A. T.

TWO-DIMENSIONAL ASPECTS OF SALINITY INTRUSION IN ESTUARIES: ANALYSIS OF SALINITY AND VELOCITY DISTRIBUTIONS, Technical Bulletin No. 13, Committee on Tidal Hydraulics, U. S. Army, Corps of Engineers, June 1967.

For a fuller understanding of the mixing processes in the salinity intrusion zones of estuaries, the two-dimensional aspects also are discussed briefly.

Figure 4 of Reference[18] gives a typical evaluation of the distribution over relative depth y/h of the time-average horizontal velocity components $\bar{u}$ in terms of mean freshwater velocities U_f. The different profiles represent successive stations from the ocean near Station 5 to the end of the salinity intrusion near Station 200 in the Vicksburg flume. The velocities $\bar{u}$ are calculated by integrating the instantaneous velocities u over a complete tidal cycle. This results in a residual value $\bar{u}$ to be attributed to the effects of the density or salinity gradients. Maximum values of $\bar{u}$ are reached near Stations 40 and 80 where the ratio of $\bar{u}/U_f$ approaches 3.5 near the bottom in the upstream direction, while values near the surface are nearly twice as large in the downstream direction. The author points out that the average saltwater transport in the lower half of the channel sections is upstream and of higher concentration until a stagnation zone is reached near Station 160, where the intrusion ends. Sediment settling into the lower half of the sections will be gradually transported upstream as long as it is entrained by the turbulent shear flow due to tidal action. The mechanism for the increase in the dispersion coefficient D_o' also may be derived from the flow pattern of Figure 4[18]. The velocities are temporal averages of the current. Therefore, from continuity, the net increase in upstream flow between Stations 5 and 40 must result from a net vertical convection downward from the upper portions to the lower portion of depth. Conversely, the opposite trend must exist in the upstream section of the channel between Stations 80, 120, and 160. The author thus points out that a net circulation of saline water exists within the estuary which contributes to the mixing of fresh and salt water. This circulation continues with increasing intensity as stratification and hence vertical and horizontal salinity gradients increase which results in larger values

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*Symbols are defined in the Glossary at the end of this chapter.

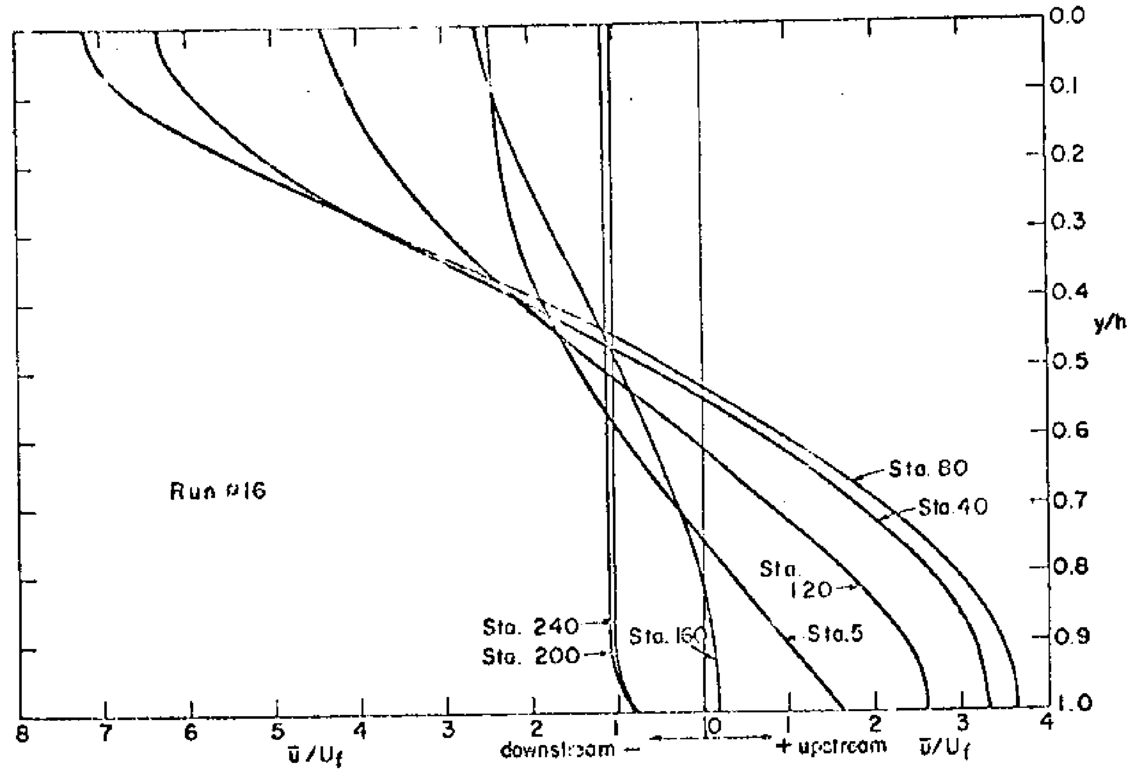


FIGURE 4. Time-Average Horizontal Velocity Distribution in Experimental Tidal Channel with Salt Water - Fresh Water Mixing.

of the dispersion coefficient D_0'. However, the values of the mean vertical velocities are much lower than the mean horizontal velocities. Their approximate order may be given as $\bar{v} \approx \frac{\bar{u}h}{L_i}$, since the respective flow cross-sections are proportional to the depth h and the intrusion length L_i.

According to the author, the conditions in actual estuaries in different locations generally have been found to demonstrate the same trends as found in the Vicksburg flume experiments. Thus, sediments approaching the mouth of an estuary are often carried by the entering saline currents into the estuary and deposited as shoals.

Ippen[20] and other investigators agree that the many research studies in the area of "Estuary Hydrodynamics" has led to a qualitative understanding of the basic pattern of the interaction of tides, salinity, and fresh water for estuaries in general. However, they indicate that quantitative results are not yet available for estuaries of other than simple geometric cross section and plan.

The remainder of this chapter will be concerned with a general discussion of the internal flow processes and the basic elements of salinity intrusion which create various salinity distributions.

Analyses of salinity intrusion in estuaries is a very complex subject involving the basic mechanism of mass transfer by turbulent diffusion and mass transfer by convective currents which are associated with tidal motion and the presence of liquids of varying densities. Local salinities are the result of (a) the complex interaction of horizontal and vertical convective of salinity by the transient and turbulent tidal shear flows, (b) the convective currents generated by the density gradients, and (c) the seaward convective velocities that result from the freshwater flow into the estuary. As indicated by Ippen and Keulegan[23], depending on the relative strength of these currents, the characteristics of the salinity intrusions usually are identified in terms of the observed salinity distribution as follows:

a. The unmixed or fully stratified case which has a fairly well-defined interface or discontinuity in salinity distribution.

b. The partially-mixed case in which the local salinity varies a large amount vertically in terms of the local mean salinity.

c. The well-mixed case in which the salinity variations over a vertical section varies only slightly from the local mean salinity.

Case a represents a well-defined problem with distinct characteristics of its own. This type has been studied extensively by Keulegan[26,23], who has defined its shape as a function of the pertinent flow parameters. Harleman[16] has given the analytical solution, which, according to Ippen[20], agrees well with the shape determined from experiments.

Sediment transport and deposition in estuaries provide one of the primary motives for the analysis of salinity intrusion in estuaries. Experimental and field studies have shown conclusively that the density currents generated by the saline waters in estuaries and their interaction with tidal flows are primarily responsible for shoaling. However, the prediction of sediment movement from tidal and salinity intrusion studies remain purely qualitative. The topic is dealt with on this basis in Chapter V.

Basic Elements of Salinity Intrusion

The basic conditions producing the temporal mean current patterns of salinity intrusions in estuaries are illustrated in Figure 5[8,20]. Fully stratified and well-mixed estuaries are represented schematically. The temporal mean velocities are obtained by averaging the instantaneous velocities due to tide, freshwater flow, and density variations over a tidal cycle. Therefore, the convective velocities responsible for the salinity intrusion may be considered in the steady state. The velocity patterns shown in Figure 5[8,20] therefore represent these mean velocities which are generated by the salinity gradients and the freshwater flow. Fresh water is assumed to enter the channel at $x = L_i$ and to leave at $x = 0$ at the saltwater

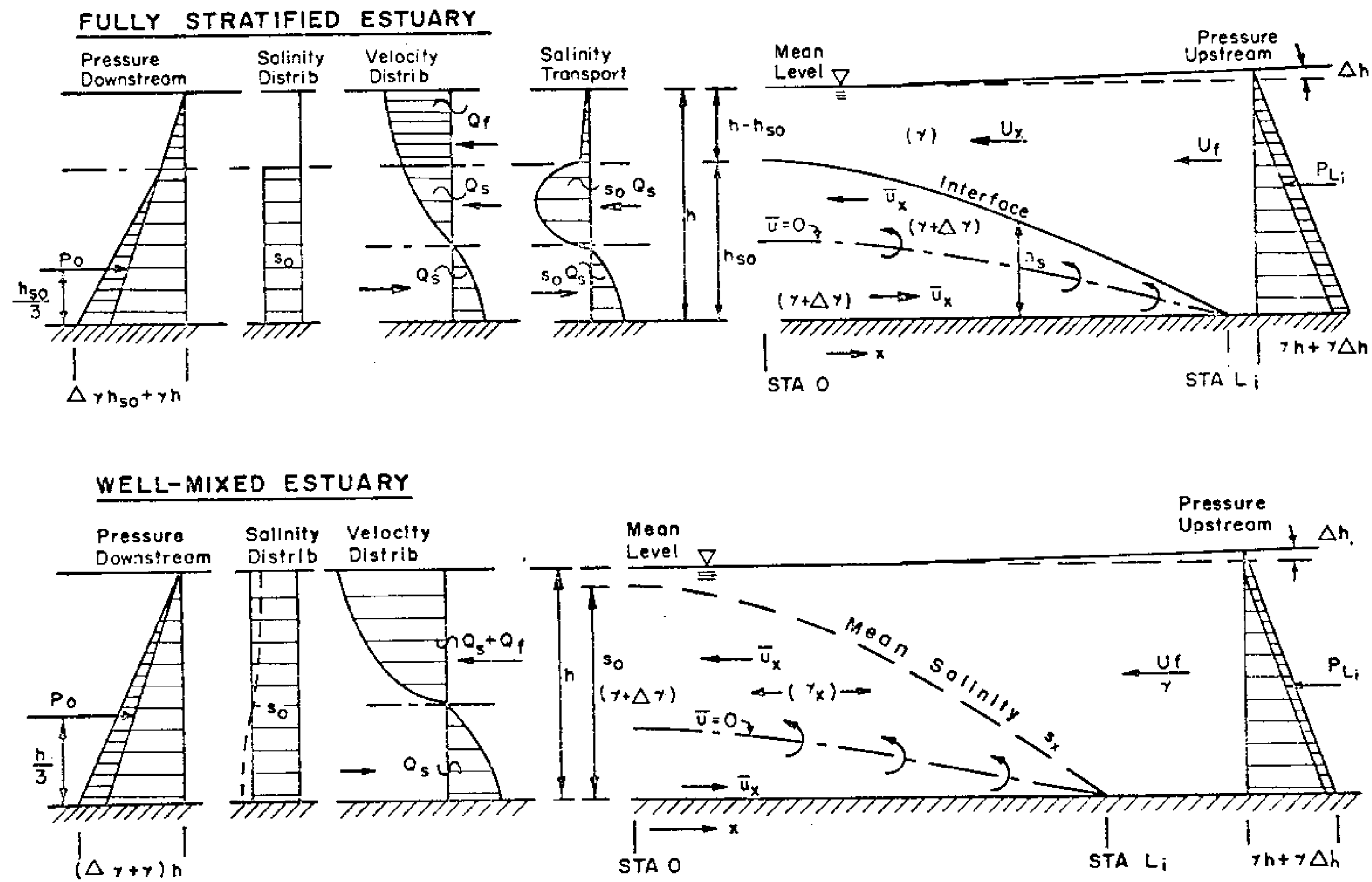


FIGURE 5[2]. Schematic Representation of Salinity Intrusion in Estuaries.

[2]Modified after References (8) and (20).

basin. A saline water flow in the upstream direction underflows the seaward flow, which is essentially fresh water in the stratified case and a mixture of fresh and salt water in the mixed-flow condition. Therefore, a line of zero longitudinal mean velocity separates the upstream and downstream currents through which, however, vertical convection of saline water takes place into the upper layers flowing downstream.

The salinity wedge essentially has three layers of flow. Near the bottom a saltwater flow exists in the upstream direction which is confined between the bottom and a line of zero horizontal velocity. Above this line, the saltwater flow is reversed into the downstream direction. Finally, the freshwater flow above the interface is seaward. The flows in the two saltwater layers decrease in magnitude toward the toe of the salinity wedge and must satisfy the continuity condition such that the vertical transfer of salt water through the line of zero horizontal velocity equals the rate of change of flow in each saltwater layer. For stratification to exist, the continuity condition must apply to both transport and fluid flow below the interface.

The driving forces for the individual layers can be understood by considering the pressure diagrams in Figure 5[8,20]. At station 0, the salinity produces an additional hydrostatic pressure which increases linearly in magnitude below the interface to a maximum intensity of $\Delta \gamma h_{so}$. At station L_1, the hydrostatic pressure force is increased by a uniform amount of $\gamma \Delta h$. The summation of these forces results in downstream gradients in the two upper layers and in upstream gradients in the lowest layer of flow. The local gradients in each layer of flow are compensated by the rate of change of momentum of the local fluid masses and by the internal shear stresses. However, the equilibrium, or steady state, condition is subject to a moment which affects the circulation experienced by the salt water. Therefore, the resulting motion pattern is distinct from the normal channel flow.

The stable salinity wedge exists when the density difference alone results in currents below the interface which are too weak in turbulence generation to produce mixing. Interfacial waves also have negligible effects because of the stabilizing gravitational properties. Thus the salinity wedge in some estuaries, such as the mouth of the Mississippi River, may even be moved upstream and downstream by weak tides without breaking up. The stable salinity wedge can only be broken up by introducing a relatively large turbulence-producing mechanism that is independent of the current produced by the density difference themselves.

The partially and well-mixed states of salinity intrusion can be considered by referring to the schematic representation of the well-mixed estuary in Figure 5[8,20]. The conditions of the mixed-flow estuary has essential differences from the stratified estuary. The intrusion is no longer clearly defined by an interface, but now is definable only by plotting mean values of salinities throughout the intrusion length. A finite salinity is measured locally as a time average at the free surface which, depending on the state of mixing, will increase by a smaller or larger percentage toward the bottom. If this increase is less than 50% of the surface salinity, the degree of diffusion is termed "well-mixed." For variations higher than 50%, the term "partially-mixed" is used. Because the state of mixing for either of these conditions is usually the result of tidal action, the density flows which still are generated by the longitudinal and vertical gradients of salinity are now coupled to this external mixing process and cannot be defined separately.

For the purpose of simplification, it is assumed in the lower sketch of Figure 5[8,20] that essentially uniform mixing exists at the seaward end so that the hydrostatic pressures can be given there as linearly increasing as the result of the nearly uniform salinity distribution. Therefore, the pressure at the bottom is increased by $\Delta \gamma h$. The total pressure at station 0 must be compensated by the hydrostatic pressure at station L_i but, as in the case of the stratified estuary, a moment is present which requires a rate of change of momentum of the fluid flowing and results in internal circulation. In view of the smaller moment as compared to the stratified case and assuming the mean salinities at the section to be the same, smaller velocities are to be expected for the internal circulation. However, this moment and hence this circulation must always exist as long as density difference exists between the fluids being mixed. The strength of the circulation is dependent on the density difference and on the magnitude of the freshwater flow. The higher the freshwater flow, the more difficult it is to maintain a nearly uniformly mixed condition. For a given state of tidal action, the salinity will tend from well-mixed toward a partially-mixed state as the freshwater flow is increased and as the circulation currents become more intense within the shorter intrusion length. It is also concluded that there must always be salinity differences over the depth as long as fresh water flows through an estuary. Complete mixing will only be approached as the mean freshwater velocities become negligible either by low discharges or by widening of the estuary.

The preceding description of the basic elements of salinity intrusion in estuaries give, qualitatively, the dynamic reasons for the existence of a large-scale internal circulation pattern by which salinity is transported in estuaries as a result of the density differences existing between sea and fresh water along the intrusion length. As a result of advanced studies by Ippen, Harleman, Keulegan, and others, it is also possible to predict quantitatively the changes in salinity intrusion with variations in freshwater flow and modifications in channel depth. With the relation for intrusion length, investigators have also established an important criterion for shoaling in estuaries (see Chapters V and VI). This general understanding of the intrusion process should greatly enhance estuarine planning as well as predict major consequences of engineering measures with respect to the biological, environmental, and sedimentary questions involved.

Glossary

Lower case letters

- h Mean depth of water in cross section, ft
- h_{so} Maximum height of salinity wedge at ocean entrance, ft
- u Current velocity in horizontal (x) direction, ft/sec
- $\bar{u}$ Temporal mean current velocity component in horizontal (x) direction, ft/sec
- $\bar{v}$ Mean current velocity in vertical (y) direction, ft/sec
- x Horizontal distance, ft
- y Vertical distance, ft

Upper case letters

- D' Apparent diffusion coefficient including effect of density-generated convection currents, ft^2/sec
- D'_o Maximum value of D'_x at estuary entrance (x = 0) including effect of density-generated convection currents, ft^2/sec
- L_i Salinity intrusion distance, ft
- U_f Mean freshwater current velocity toward ocean, ft/sec

Greek letters

- Δ Finite interval period
- γ Specific weight, lb/ft^3

V. SILTATION IN ESTUARIES

The hydraulic regimen of an estuary is determined by the interactions of tides, winds, geometric shape, freshwater discharges, and salinity intrusions. The resultant currents transport sediments from sources to locations where, for various reasons, the currents are no longer sufficient to keep these materials in motion. Salinity intrusions may be one of the causes of this. The preceding chapter dealt with the causes of salinity intrusions and their variability; this chapter discusses their effects.

Wicker and Eaton[38] list seven principal sources of sediments that shoal tidal waterways:

1. The land areas that drain into tidal bodies.
2. The bed of tidal waterways.
3. The littoral drift in motion along beaches adjacent to the mouths of tidal waterways.
4. Industrial and sanitary wastes.
5. Marine life.
6. Deflationary material.
7. Improperly deposited spoil from channel dredging operations.

The rate of supply of upland material depends upon many factors; the type of soil, slope steepness, ground cover, freezing and thawing, amount and distribution of precipitation, the hydraulic characteristics of the stream and the activities of man within the watershed. A watershed with a light soil will erode more rapidly during heavy rainfall than one with a heavy soil or with rock cover. Steep slopes cause more rapid flow of water, thereby experiencing greater erosion. Ground covers, including the grasses, bind the soil together with their roots and tend to slow down the rate of flow across the surface. Freezing causes expansion and cracking, and after thawing the soil is much more susceptible to erosion. Intense rainfalls cause much more rapid flows across the surface than light precipitation. The actual impact of large raindrops even causes soil erosion. Therefore, erosion will be greater in an area where frequent intense rainfall is experienced than in one having an even distribution of precipitation throughout the year. Streams with steep gradients flow more swiftly than those with slight slopes and are more able to carry sediments.

The effect of various sources of sedimentation in tidal waterways will be considered in greater detail in Chapter VI entitled "Hydrologic Implications of Deepwater Channels in Tidal Estuaries."

According to Schultz and Simmons(35), upland discharges which create fresh water-salt water density currents, are the major cause of siltation in estuaries. Upland discharges into many estuaries have been modified by forest clearing, agricultural practices, grazing, the construction and operation of dams and reservoirs for flood control, generation of electric power, municipal and industrial waste discharges, and many other factors. Significant quantities of upland discharge have been diverted from some watersheds to others thereby increasing the upland discharge into some estuaries while reducing that into others.

Effects of Upland Discharge on Estuarine Hydraulics

According to Schultz(35,36), Simmons(35,36), and Tiffany(36), the presence in estuaries of water of varying density causes significant changes in the magnitudes, distributions, and durations of tidal currents. As a result of the density differences between the heavier salt water at the seaward end of the estuary and the fresh water at the upstream end, each type of water tends to assume distributions that approximate a wedge shape with the base of the wedge at the source. The authors point out that the interface of the salt water and fresh water may vary from well-defined to obscure, depending on the degree of mixing of the salt water and fresh water in any given estuary. The transition from salt water to fresh water is well defined where the mixing is slight and occurs within a small percentage of the channel depth. However, where the mixing is appreciable, no definite interface exists.

Estuary Mixing Types. Knowledge of the degree of mixing of salt and fresh water in an estuary is very important, as this appears to control certain important features of the hydraulic and shoaling characteristics of an estuary. The degree of mixing may be separated into three broad categories of highly stratified, partly mixed, and well mixed. However, the transition from one type of mixing to another is gradual instead of well defined. In subsequent paragraphs some of the more important characteristics of the three estuary mixing types are illustrated through the use of current velocity and salinity data obtained by Schultz and Simmons[35] and Schultz and Tiffany[36] in Southwest Pass of the Mississippi River, Savannah Harbor, Charleston Harbor, and the Delaware Estuary.

In all estuaries in which there is appreciable stratification of the salt water and fresh water, the magnitudes, durations, and directions of the currents above the interface are measurably different from those below. Figure 6[35,36,37] shows schematically the distribution of current velocities and directions in a highly stratified estuary of which Southwest Pass of the Mississippi River provides an excellent example. Upstream from the limit of saltwater intrusion the direction of the current throughout the entire depth is downstream at all times (section A, Figure 6)[35,36,37]. In the region of saline intrusion, however, the direction of flow in the freshwater strata is still toward the sea, but the direction of flow in the underlying salt water is upstream at all times (section B, Figure 6)[35,36,37]. The cause of the continuous upstream flow within the saltwater strata, even though the extent of saltwater intrusion may be stable, is the additional hydrostatic pressure produced by the salinity and by the constant erosion of salt water from the interface by the outflowing fresh water. The salt water thus eroded must be replaced to

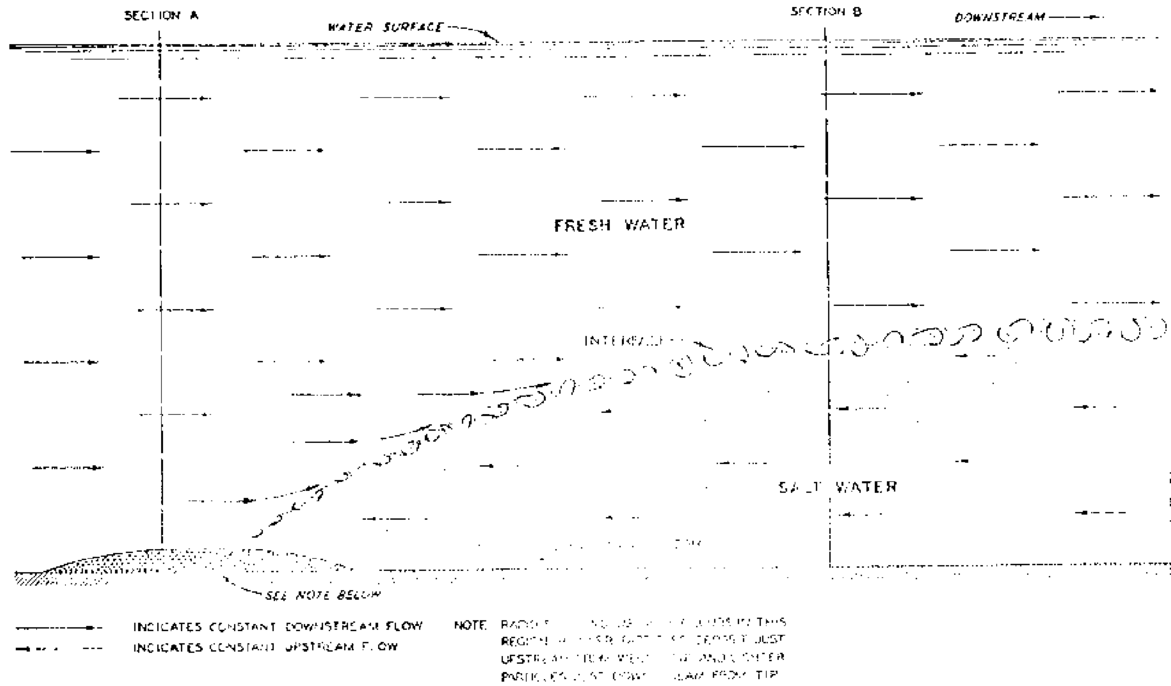


FIGURE 6[1]. Conditions Typical of Highly Stratified Estuary

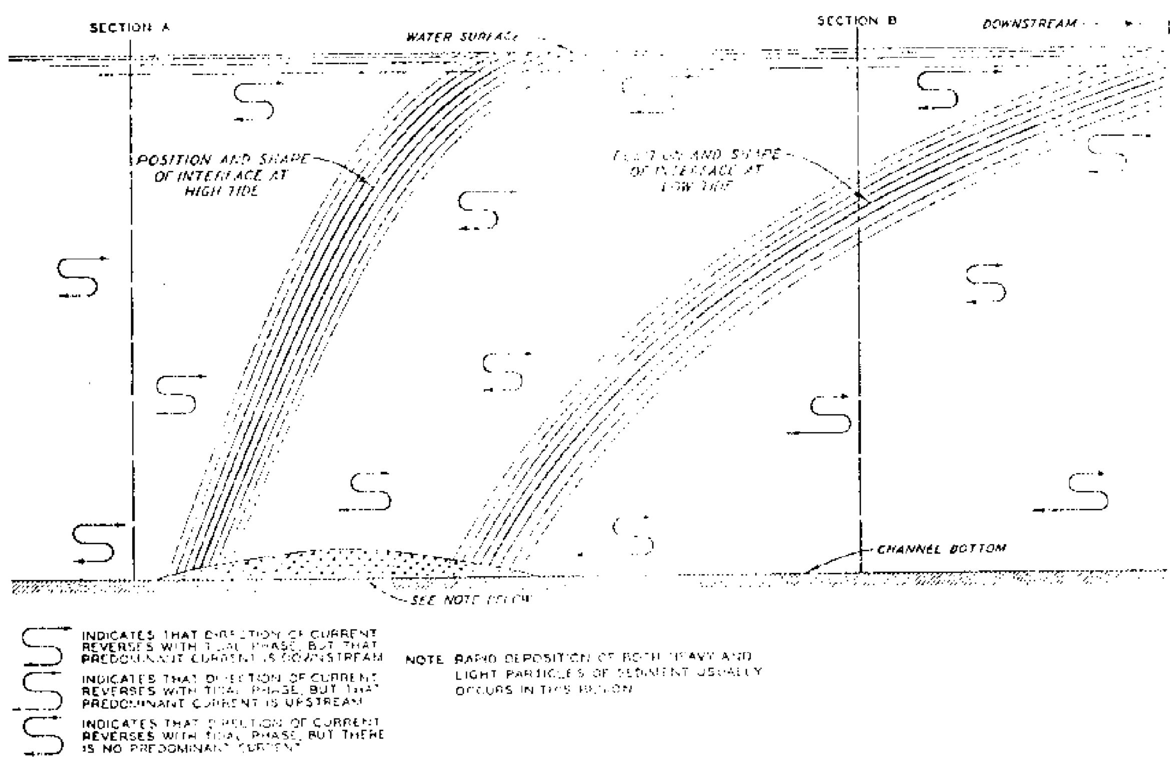


FIGURE 7[1]. Conditions Typical of Partly Mixed Estuary

[1]Modified after References (35), (36), and (37).

maintain stability of the intrusion length, and so a continuous upstream current is generated beneath the interface.

The lengths of the flow direction arrows in Figure 6[35,36,37] indicate the relative magnitudes of currents throughout the highly stratified estuary. Maximum velocities in the freshwater strata occur in the vicinity of the entrance to the estuary and near the surface, while the maximum currents in the saltwater strata occur near the bottom and near the upstream limit of intrusion. Usually, velocities in the fresh water decrease with distance from the surface and those in the salt water decrease with distance from the bottom, with the result that a point of zero velocity occurs in the vicinity of the interface.

Rapid shoaling usually occurs in the region of the saltwater intrusion tip in a highly stratified estuary, as shown in Figure 6[35,36,37]. The heavier particles of sediment, which are moved along the river bed by the outflowing fresh water, come to rest in the vicinity of the intrusion tip. The lighter particles such as colloidal clays, transported largely in suspension in the fresh water, gradually begin a flocculation process with the dissolved salts from the uplands which continues as the material moves downstream. The suspended particles gradually fall through the interface along the length of intrusion and are transported upstream by the saltwater currents to the vicinity of the intrusion tip. The channel reach occupied by the upstream limit of intrusion is therefore a focal point for accumulation of sediment from both upstream and downstream, with the heavier particles depositing immediately upstream of the intrusion limit and the lighter particles just downstream (see Figure 6)[35,36,37]. As the limit of the wedge varies in location with variations of upland discharge, shoaling may take place over a considerable distance.

The distribution of current velocities and directions in a partly mixed estuary, which is probably the most common type found in nature, is shown in Figure 7[35,36,37]. Typical examples of partly mixed estuaries are the Hudson River, Charleston and Savannah Harbors, and the St. Johns River. The interface in the partly mixed estuary advances and retreats with each rise or fall of tide, usually over a distance of several miles. Although the currents in both the freshwater and saltwater strata usually reverse with tidal phase, the downstream currents in the fresher water strata are much stronger than the upstream currents, whereas the upstream currents in the more saline water strata are stronger than the downstream currents. As in the case of the highly stratified estuary, the maximum currents in the fresh water also are usually near the surface and near the estuary entrance, while those in the more saline strata are usually near the bottom and near the upstream limit of saltwater intrusion. Measurements taken by Schultz and Simmons[35] indicate that the salinity at the bottom is much greater than at the surface, particularly at low tide, and that the greatest change in salinity from surface to bottom occurs in about 20 percent of the total depth. The greater density of the water in the lower strata causes the reversal in flow from ebb to flood to occur much earlier at the bottom than at the surface. This results in a duration of the bottom flood that exceeds that of the bottom ebb current. According to Schultz and Simmons[35], the duration of the ebb current at the surface exceeds that of the flood because the fresh water is depleted from the estuary primarily in the surface strata.

As indicated in Figure 7[35,36,37], the region of heaviest shoaling in the partly mixed estuary frequently lies between the high tide and low tide positions of the upstream limit of saline intrusion. However, some cases may extend to the mouth of the estuary, depending on certain conditions which will be explained later. As in the case of the highly stratified estuary, the heavier sediment particles collect near the intrusion limit. In the case of the partly mixed estuary, the lighter particles may be carried well down into the estuary before they enter the predominantly upstream flow in the lower strata, and only in some cases are they then transported back upstream to the vicinity of the intrusion limit. There is little evidence of sorting of the sediment particles in the partly mixed estuary, because the intrusion limit moves back and forth over a large distance with tidal phase which allows mixing of the sediment particles.

Shoaling in Charleston Harbor, an example of the partly mixed estuary, is heaviest in isolated reaches extending to and into the entrance, far downstream from the range of movement of the interface. In cases such as this the controlling features appear to be the predominance of upstream current on the bottom in conjunction with such factors as excessive cross-sectional area, eddies and crosscurrents, and other physical features.

The Delaware and Raritan Estuaries are typical examples of the well-mixed estuary. The distributions of current velocities and directions in these estuaries have similar characteristics to those of the partly mixed estuary. The tidal forces predominate over the freshwater inflow to such an extent that the fresh and salt water are fairly well mixed throughout the vertical. However, an embryo "interface" can usually be detected in certain regions of the estuary as surface salinities are somewhat less than bottom salinities at any given location. Also, careful analysis of current velocity measurements will usually indicate characteristics similar to those of the partly mixed estuary though much less pronounced.

Salinities decrease more or less progressively from sea water at the entrance to fresh water in the upper reaches, and bottom salinities normally exceed those at the surface by 15 to 25 percent. The rate of change in salinity from surface to bottom is nearly constant, unlike the rapid change at some critical depth which is indicative of the partly mixed estuary. In the intermediate and highly saline regions, however, the bottom flood currents usually predominate slightly over the bottom ebb currents.

Since the effects of density differences on the vertical distribution of currents are slight in the case of the well-mixed estuary, the distribution of shoaling does not appear to be directly related to the limits of salinity intrusion except in rare instances. The locations of shoals in well-mixed estuaries appear to be influenced more by such factors as excessive cross-sectional area, nonuniform flow caused by islands and divided channels, and physical features other than limits of salinity intrusion.

Role of Upland Discharge in Establishing Estuary Mixing Type. According to Schultz and Simmons[35] and Schultz and Tiffany[36], the two principal factors that indicate whether an estuary is highly stratified, partly mixed, or well mixed are (a) upland discharge, and (b) turbulent mixing of fresh and saline water in the estuary by tidal action. Normally, the highly stratified estuary exists where the upland discharge is large in comparison with tidal forces, the partly mixed estuary exists where the upland discharge and the tidal forces are about equal, and the well-mixed estuary exists where the upland discharge is small with respect to the tidal forces.

The mean tidal prism of an estuary (the net volume of water which would flow into the estuary from the sea during an average flood-tide period) provides an approximate measure of its tidal forces. Simmons[35] has found from experience that the ratio of mean upland discharge into an estuary, which is defined as the volume of upland water entering an estuary for conditions of mean upland discharge and over the interval of a mean tidal cycle of about 12-42 hours, to its mean tidal prism provides a fairly dependable index as to its mixing types. Where the ratio is about 1.0 or more (average for Southwest Pass of the Lower Mississippi River is about 1.25), the highly stratified type usually exists; where the ratio is about 0.25 (average for Savannah Harbor is about 0.20), the partly mixed type normally exists; and where the ratio is much less than 0.1 (average for the Delaware Estuary is about 0.01), the well-mixed type is normally found. However, the authors point out that, because one reach of an estuary may be partly mixed while another reach may be well mixed under identical conditions of tide and upland discharge, the ratios given above should only be used in a general manner. The ratios do, however, provide a quick and fairly dependable means for predicting estuary mixing types in the absence of detailed measurements of current velocities and salinities.

The tabulation below, which was taken from Schultz and Tiffany(36), shows for San Francisco Bay the classification of different parts of the Bay system, and changes in classification for different freshwater inflows into the Bay system (stations are shown in Figure 8)(36).

Portion of System	Freshwater Inflow	
	5000 cfs	45,000 cfs (mean)
North and south of sta 8	Well mixed	Well mixed
Southeast of sta A	"	"
South of sta S-4	"	"
North of sta G	"	"
East of sta I	"	Partly mixed
East of sta K	"	Partly mixed
	100,000 cfs	200,000 cfs
North and south of sta 8	well mixed	Partly mixed
Southeast of sta A	"	"
South of sta S-4	Partly mixed	"
North of sta G	"	"
East of sta I	"	Highly stratified
East of sta K	Highly stratified	"

If the upland discharge into an estuary does, in fact, play a major role in dictating whether the estuary will be highly stratified, partly mixed, or well mixed, the importance of knowing in advance what the effects of changing the upland discharge into an estuary will be is obvious. For example, an existing partly-mixed estuary may be changed to well mixed by reducing the upland discharge, or it may be changed to highly stratified by increasing the upland discharge. Similarly, a change in the tidal establishment may be sufficient to cause modification of the degree of mixing.

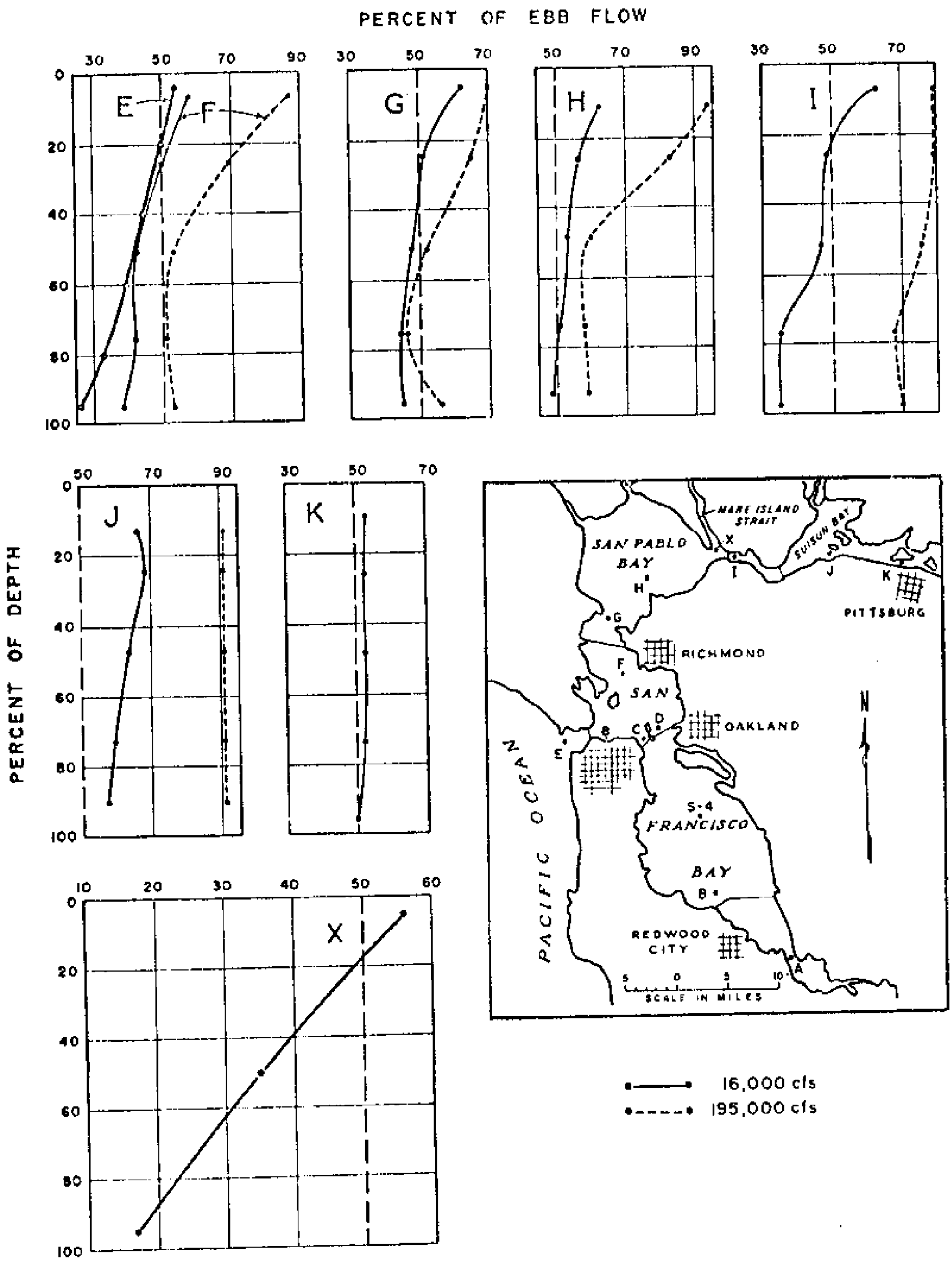


FIGURE 8. Predominance curves, San Francisco Bay

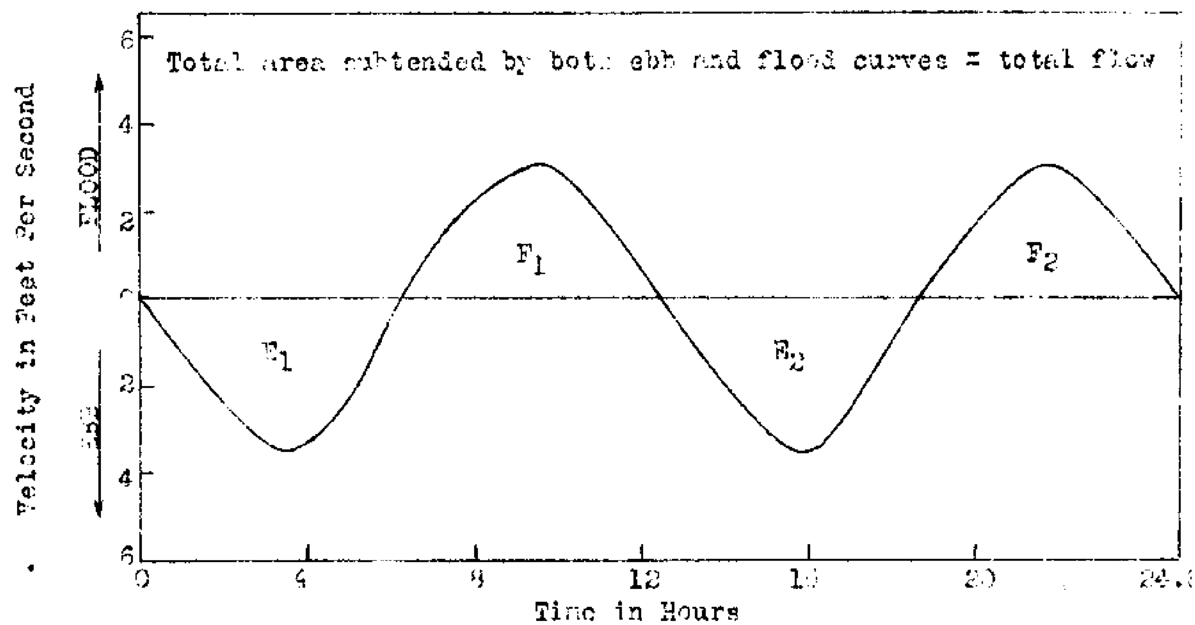
According to Simmons[37] there are cases of record in which the diversion of fresh water from one tributary watershed to another has produced drastic changes in estuary mixing characteristics -- sometimes with disastrous results. Since available information indicates that the pattern of shoaling in estuaries varies with mixing type, it follows that estuarine sedimentation is an important effect of upland discharge.

Minor changes in mixing types are constantly being effected by the deepening of estuary channels for navigation. As channels are dredged deeper and deeper, salt water penetrates farther into the estuary and the degree of vertical stratification is increased because of reduced tidal current velocities. Some of the hydrologic implications of deepwater channels in tidal estuaries are considered in Chapter VI.

In considering the effects of changes in upland discharge on the hydraulics of an estuary, and in turn on its shoaling characteristics, a large number of factors may be used for analysis. For example, Simmons[35,36] points out that a change in upland discharge may be considered in terms of its effect on maximum flood or ebb velocities, mean flood or ebb velocities, duration of flood or ebb currents, etc. However, it is very difficult to interpret the effects of changes in upland discharge on any one hydraulic factor in terms of change of shoaling characteristics. The sediments that cause shoaling in estuaries consist largely of flocculated clays and other finely-grained materials which, once placed in suspension, are transported easily by very weak tides. Experience with shoaling in estuaries, particularly in harbors and dead-end channels, has led investigators to the opinion that such sediments will be transported anywhere that water goes. For this reason, establishment of a single criterion that would define the hydraulic characteristics of an estuary, that can be used to define the principal features of its resulting shoaling pattern, is essential to the engineer responsible for solving hydraulic and shoaling problems in estuaries.

Method for Analyzing Current Velocities. Simmons[35] has developed a method for analyzing current velocity measurements as a means of defining the hydraulic characteristics of an estuary in simple terms. It describes the broad features of the accompanying shoaling pattern and predicts with fair accuracy the effects of proposed changes in upland discharge or tidal prism or hydraulic and shoaling characteristics. Essentially, this method reduces data on the velocities, directions, and durations of the currents into a single expression that defines the direction and degree of predominance at any given location and depth. If current velocity measurements are made at 10 percent increments of depth at a given station over a complete tidal cycle, a conventional plot of velocity versus time for each point in the vertical can be made as shown in Figure 9[36,37]. The total areas enclosed by both the flood and ebb curves provides an index to the total flow at the point of measurement. The area enclosed by the ebb curve is then divided by the combined areas under the flood and ebb curves, and the resultant determines what percentage of the total flow at the point of measurement is downstream. From the percent of flow downstream from each point in the vertical, a second plot is made to define the distribution of the total flow between flood and ebb from surface to bottom for the vertical in question. This plot defines the direction and degree of predominance of flow from surface to bottom. Simmons[37] points out, however, that it is not a graph showing the distribution of discharge from surface to bottom at the vertical involved, nor over the entire cross section.

Application of Method to San Francisco Bay. Figure 8[36] shows San Francisco Bay and flow predominance curves obtained by Schultz and Tiffany[36] using the method described in the preceding paragraph. Current velocity measurements were made (except for station X at the entrance to More Island Strait) in the deepwater channels of the prototype for conditions of approximate



$$\frac{E_1 + E_2}{F_1 + F_2 + E_1 + E_2} = \% \text{ OF FLOW DOWNSTREAM}$$

FIGURE 9[2] Computation of Flow Predominance

[2]Modified after References (36) and (37).

mean tide at stations extending from outside of Golden Gate (station E) to a point nearly 50 miles inside (station K) for a low freshwater inflow into the Bay system of 16,000 cfs (dry season flow) and a high freshwater inflow of 195,000 cfs (wet season flow). Measurements at station X were made in the hydraulic model of the San Francisco Bay system for the low freshwater inflow.

With minor exceptions, the high freshwater inflow caused ebb flow to predominate throughout the depth from station E (Golden Gate) to station J (Suisun Bay). The low freshwater inflow caused flood flows to predominate in the bottom strata from Golden Gate to about the middle of Carquinez Strait (east of station I). This predominance prevailed in the lower 75 to 80 percent of the depth at most stations. At the mouth of More Island Strait, and in areas of San Pablo Bay and Carquinez Strait adjacent to the mouth, Schultz and Tiffany[36], found that the flood current prevailed during a wide range of upland discharges, throughout a large portion of the depth. In fact, flood predominated throughout the entire depth at two stations.

According to Schultz and Tiffany[36], these current characteristics explain why the More Island Strait navigation project experiences the largest amount of shoaling of all the navigation projects within the San Francisco Bay system. During the higher freshwater flows that occur more frequently, flood predominates over ebb along the bottom in San Pablo Bay thereby interrupting seaward movement of sediment in the bottom strata. Consequently, San Pablo Bay is a sediment trap most of the time. Fortunately, at times of rare large river floods, when the largest sediment loads are delivered to the bay, ebb prevails over flood throughout the depth in the entire upper Bay system, and consequently the net transport is seaward. Otherwise, shoaling inside and outside the navigation channels would be much larger than experienced. Nevertheless, Schultz and Tiffany[36] point out that part of the sediment load brought down during large river floods settles out in areas favorable to deposition, and thus remains as a potential source of material, subject to disturbance by waves and movement by tidal currents, to shoal the channels. San Pablo Bay is the largest local source of material causing shoaling in More Island Strait. This is evidenced by the fact that shoaling in the strait is most rapid during the dry season when the river flows and sediment loads are small, and is indicated by reconnaissance type field observations and radioactive tracer tests.

Application of Method to Savannah Harbor. Figure 10[35,36,37] shows the results of computations obtained by Schultz and Simmons[35] for three verticals in Savannah Harbor, Georgia, plotted to show the direction and degree of flow predominance throughout the depth. Station 193 is located near the harbor entrance, Station 153 near the midpoint of saltwater intrusion, and Station 130 near the upstream limit of saltwater intrusion (see Figure 11)[36]. The flow predominance curves indicate that the vertical distribution of flow at Station 193 varies from about 44 percent downstream at the bottom to about 61 percent downstream at the surface; that at station 153 it varies from about 30 percent downstream at the bottom to about 60 percent downstream at the surface; and that at Station 130 it varies from about 49 percent downstream at the bottom to about 70 percent at the surface. The depth of flow which is predominantly upstream represents only about 10 percent of the total depth at Station 130 and almost 70 percent of the total depth at Stations 153 and 193.

Figure 12[35,36,37] gives a second method of representing flow-predominance data. In this figure, the percentages of total downstream flow at surface and bottom for each station are plotted against distance along the channel. As indicated in this figure, flow at the surface is predominantly downstream throughout the harbor, while flow at the bottom is predominantly downstream from the upper end of the improved channel to about Station 130. Downstream from Station 130, however, flow at the bottom is predominantly upstream to and including the harbor entrance. In the vicinity of Stations 160 and 170,

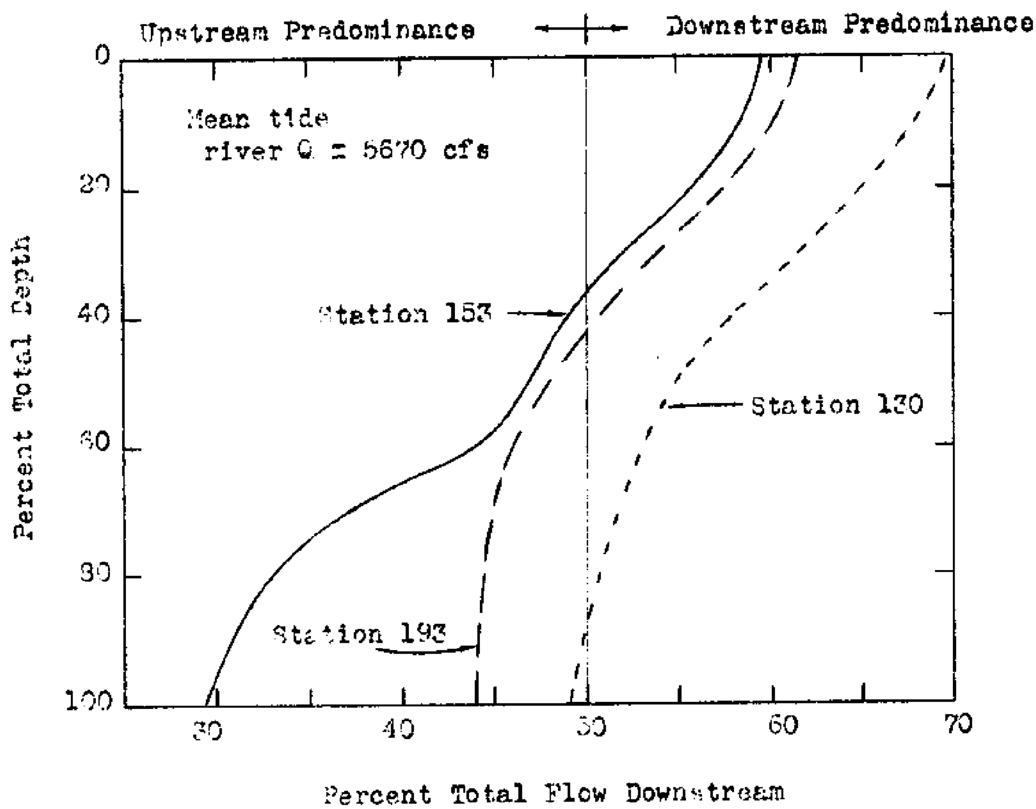


FIGURE 10[3]. Flow Predominance Curves, Savannah Harbor

[3]Modified after References (35), (36), and (37).

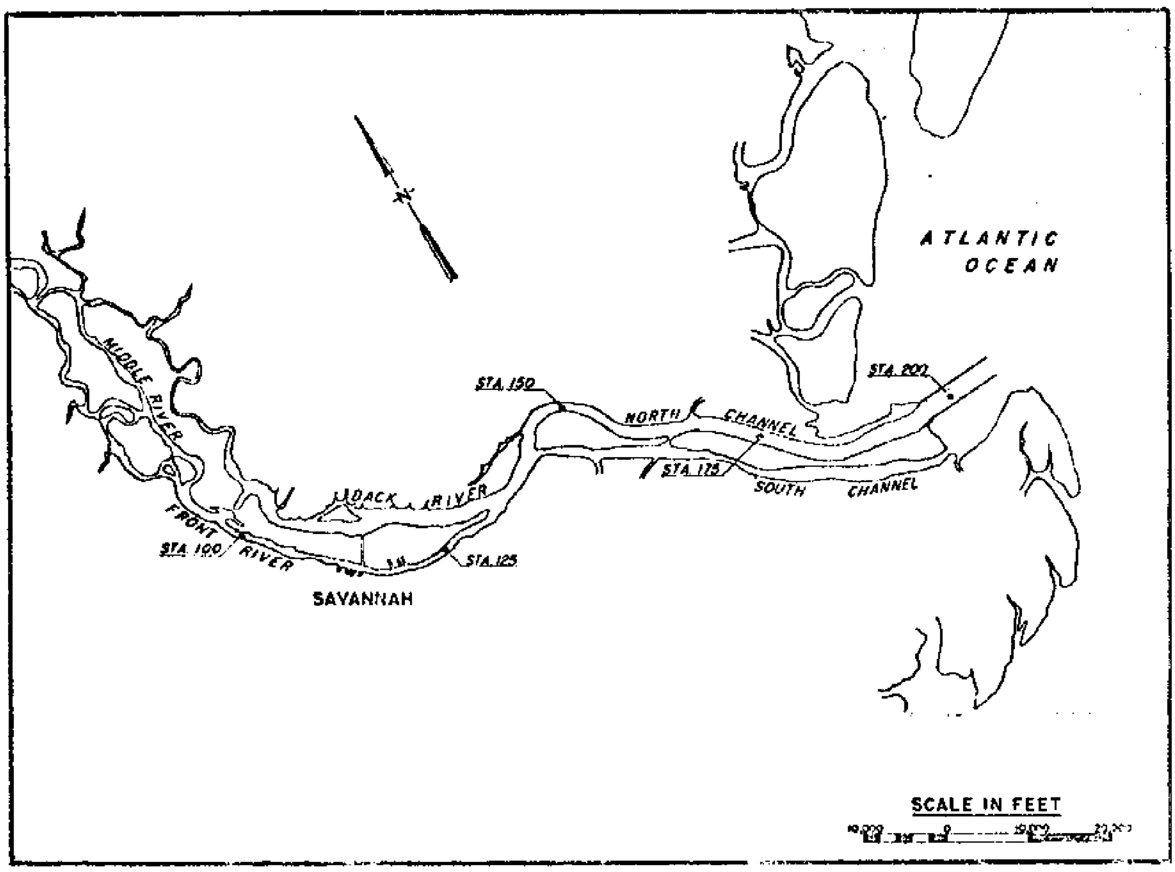


FIGURE 11. Location map, Savannah Harbor

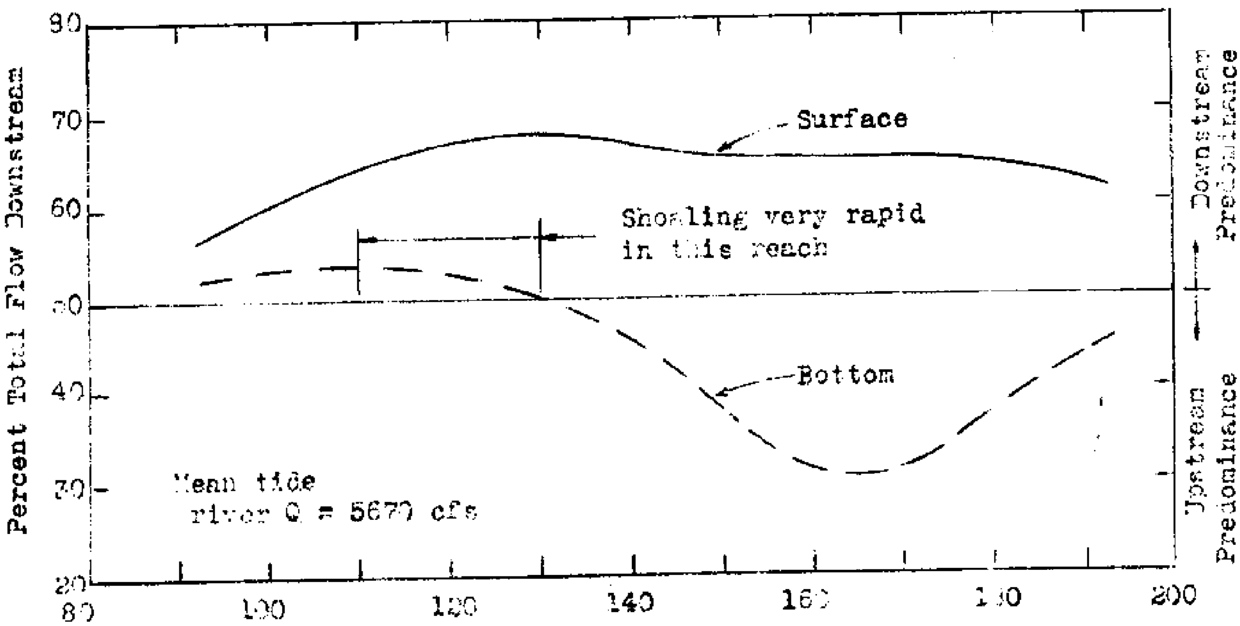


FIGURE 12[4]. Predominance of Flow in Surface and Bottom Strata, Savannah Harbor

[4]Modified after References (35), (36), and (37).

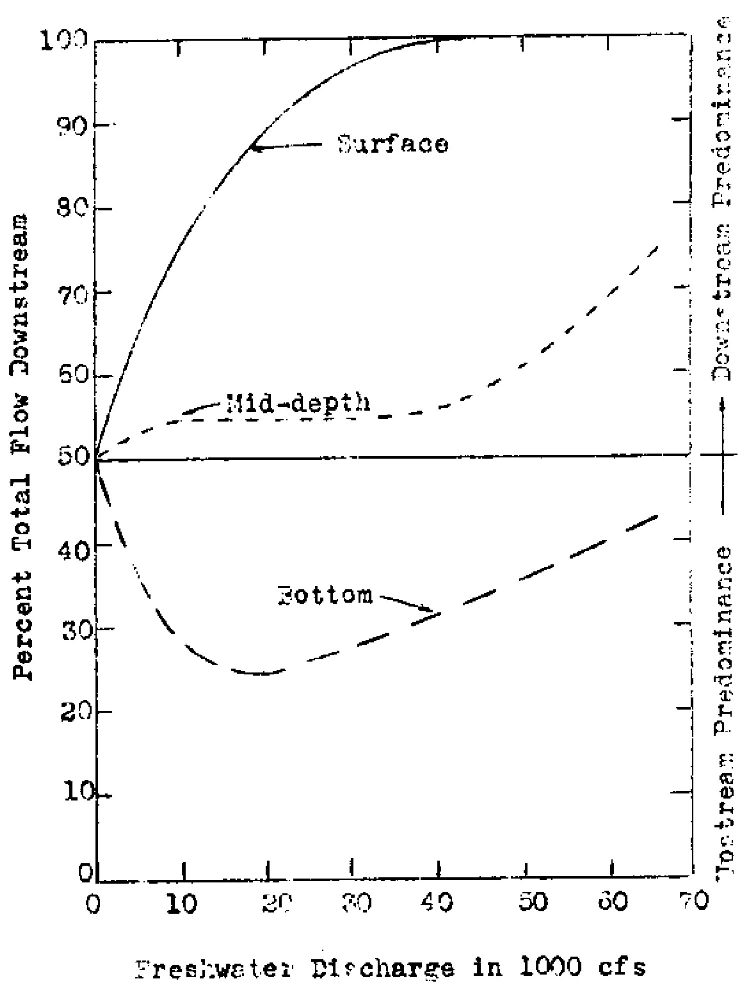


FIGURE 13[5]. Effects of Upland Discharge on Predominance of Flow, Station 190, Savannah Harbor

[5]Modified after References (35) and (36).

about 70 percent of the total flow is upstream and only about 30 percent is downstream.

Figure 13[35,36] shows the effects of upland discharge on predominance of flow at Station 190 in Savannah Harbor. The predominance of flow at surface, mid-depth, and bottom for upland discharges ranging from a low of about 3,000 cfs to a high of 66,000 cfs, are illustrated. These curves indicate that for zero upland discharge the flow is almost exactly 50 percent downstream and 50 percent upstream at all depths. Without upland discharge, no predominance of flow exists in either direction at any depth, because there is no possibility of stratification. As the upland discharge increases, flow in the surface layer is more and more predominantly downstream until an upland discharge of about 40,000 cfs is reached where the direction of flow in the surface layer is downstream throughout the tidal cycle. The percentage of total flow downstream increases from 50 to about 55 at mid-depth as the upland discharge increases from zero to about 10,000 cfs. Flow at mid-depth remains about 55 percent downstream until flow in the surface strata is 100 percent downstream; then there is a sharp increase in the predominance of downstream flow at mid-depth. At the bottom, the percentage of total flow downstream decreases sharply from 50 percent as the upland discharge increases from 0 to about 20,000 cfs. Further increases in upland discharge gradually increase the percentage of downstream flow in the bottom strata. However, for a discharge of 66,000 cfs the total flow downstream in the bottom layer is only about 43 percent as compared to 50 percent for zero discharge.

Another method for plotting flow-predominance data is shown in Figure 14[37]. In this figure, the numerical values of percent total flow downstream are plotted in terms of depth and distance along the channel. Equal values are connected by contours to give an overall picture of the circulation pattern. The numbers of the contours gives a quick index to the regions of

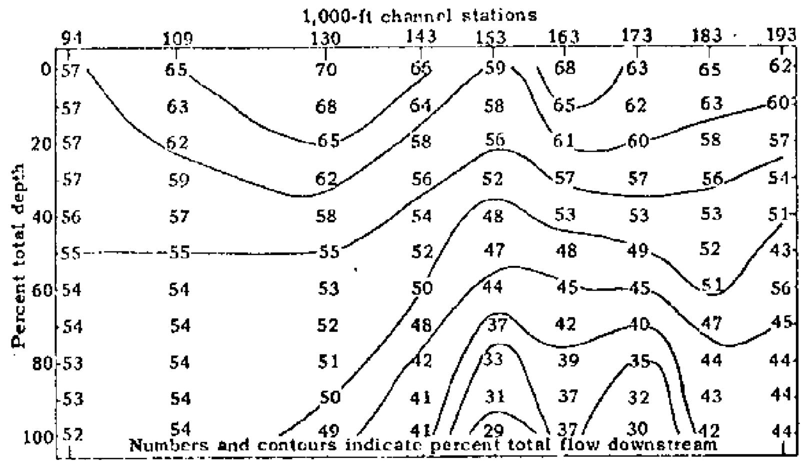


FIGURE 14. Distribution of Flow in Savannah Harbor

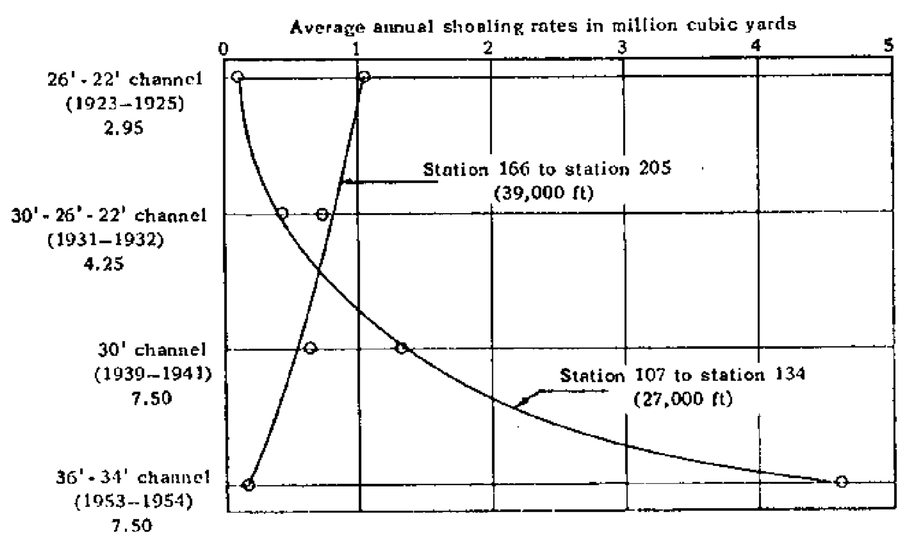


FIGURE 15. Shoaling Characteristics of Savannah Harbor

the harbor in which density effects are most pronounced. For example, only one contour passes between surface and bottom in the freshwater region of the harbor, represented by Station 94, while eight contours pass between the surface and bottom in the vicinity of Station 153, where the density gradient is steepest.

Analyses of these data has led Schultz and Simmons[35] to the following conclusions concerning sedimentation in Savannah Harbor:

(a) sediment entering the upstream end of Savannah Harbor is moved progressively downstream at all depths to the vicinity of Station 130;

(b) sediments moved along the bottom will be deposited in the vicinity of Station 130;

(c) sediments carried by suspension in the upper layer will be transported toward the sea, but a large percentage of these sediments will sink to the bottom strata during times of slack current and will be carried back upstream to the vicinity of Station 130 by the predominant upstream flow in the bottom strata.

These deductions are confirmed by maintenance dredging records for Savannah Harbor which show that the largest shoal in the harbor is located at Station 130 upstream. The average annual shoaling in Savannah Harbor presently amounts to about 7.5 million cubic yards per year, and more than 80 percent of this total occurs in a 4-mile reach of channel which brackets the nodal point for bottom flow predominance as shown in Figure 12[35,36,37].

Figure 15[37] shows the results of an analysis of shoaling rates and locations in Savannah Harbor for four different depths of navigation channels. A 7.4-mile reach in the lower harbor and a 5.1-mile reach in the upper harbor were selected by Simmons[37] as a basis for computing average annual shoaling rates for each channel depth. The total average annual shoaling for the harbor for each channel depth is shown underneath the designated periods in millions of cubic yards.

For the shallower channel depth, shoaling of the downstream reach was 10 times that of the upstream reach which indicates that the major shoal area for this depth was in the lower reaches of the harbor. For the next deeper channel, shoaling of the downstream reach had decreased while shoaling in the upstream reach had increased, the rate of shoaling in the downstream reach being about double that in the upstream reach. For this condition, shoaling of the upstream reach exceeded that of the downstream reach by about 2 times. For the deepest channel, shoaling of the downstream reach was further reduced and that of the upstream reach was greatly increased. For this condition, shoaling of the downstream reach had been reduced to a negligible amount, whereas the upstream reach had become the major shoal area of the harbor.

The trend of total average annual shoaling for the four channel depth also is significant. From the shallowest depth to the next deeper channel, total shoaling in the harbor increased markedly from 3.0 million to 4.2 million cubic yards. A further increase was indicated by the next increment of depth (4.2 million to 7.5 million cubic yards). However, the last increase in channel depth did not cause a further increase in total shoaling. This indicates that essentially all sediments available for shoaling were deposited for the 30-foot channel depth and that the further increase in depth to 34 feet only caused a redistribution of the material with no increase in the total.

According to Simmons[37], the shoaling characteristics of Savannah Harbor are typical of the simple type of partly mixed estuaries, and the effects of changes in channel depth just described are typical of the changed vertical circulation pattern on the distribution of shoaling. As the navigation channel was progressively deepened, salt water penetrated farther upstream and the nodal point for bottom flow predominance moved farther upstream.

Application of Method to Charleston Harbor. Schultz[35,36], Simmons[35,36], and Tiffany[36] point out that, in the more complicated partly mixed estuaries, major shoals usually develop at each nodal point of bottom flow predominance. In the case of Charleston Harbor, the three major shoal areas bracket the three nodal points indicated in Figure 16[36,37]. As in the case of Savannah Harbor, the resultant curves indicate those regions of the harbor in which the currents are predominantly upstream or downstream and in what degree. The surface flow throughout the entire harbor is predominantly downstream (about 65 to 80 percent of the total flow). The bottom flow throughout the lower harbor (see Figure 17[36]) from the jetties to a point about 11 miles upstream is predominantly upstream, the predominance increasing progressively with distance upstream. At mile 9.5, the location of the second largest shoal in the harbor, only 15 percent of the total flow at the bottom is downstream. This changes from downstream to upstream between miles 11 and 9 and again to downstream predominance in the 3/4-mile reach below Wando River. Prior to recent improvements, the shoal at the junction of the Ashley River (where bottom flood currents predominate) amounted to 1.1 million cubic yards per year, that at the junction of the Wando River reached .62 million cubic yards per year, and that at the upstream nodal point (where bottom currents predominate) was .45 million cubic yards per year. The fact that some shoaling occurs in the latter reach is attributed to the upstream and downstream shifting of the freshwater-saltwater interface under variable conditions of tide and freshwater discharge, and to other factors such as excessive cross-sectional area. Also, the coarsest grained sand is found in the shoals in this region of the harbor.

Summary of Effects of Upland Discharge on Estuarine Hydraulics

The upland discharges into many estuaries have been modified in recent years by the construction and operation of various types of projects. In some instances, significant quantities of upland discharge have been diverted

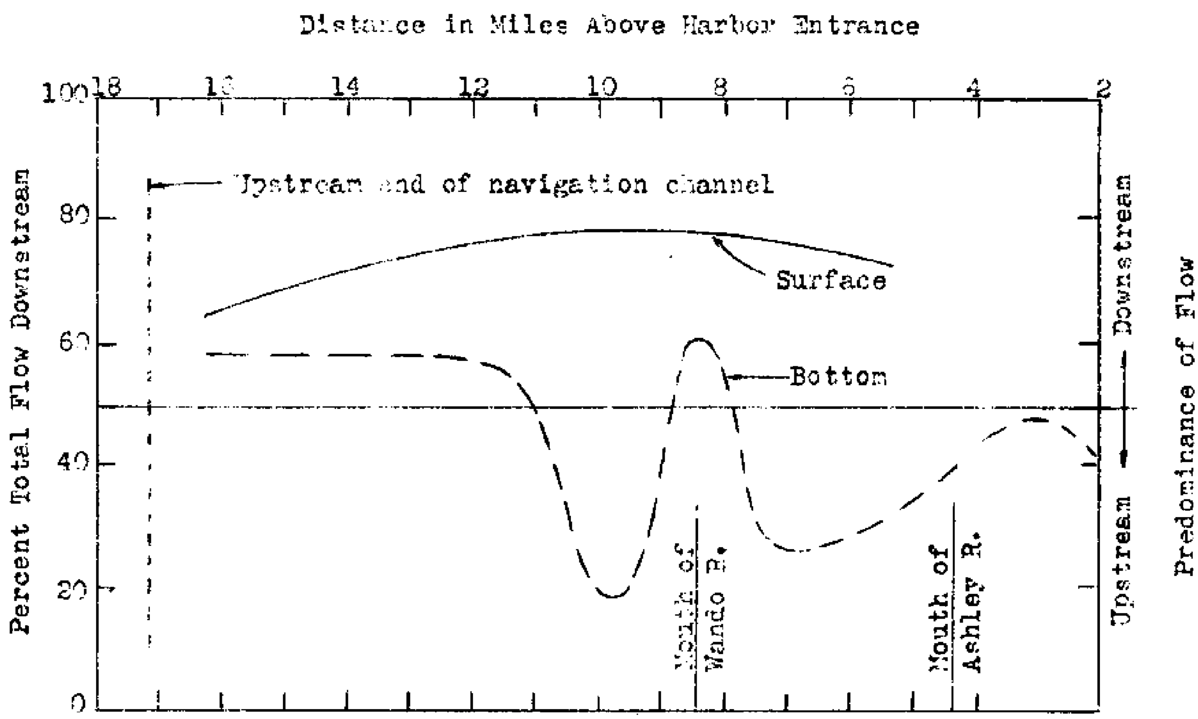


FIGURE 16[6]. Predominance of Flow in Charleston Harbor

[6]Modified after References (36) and (37).

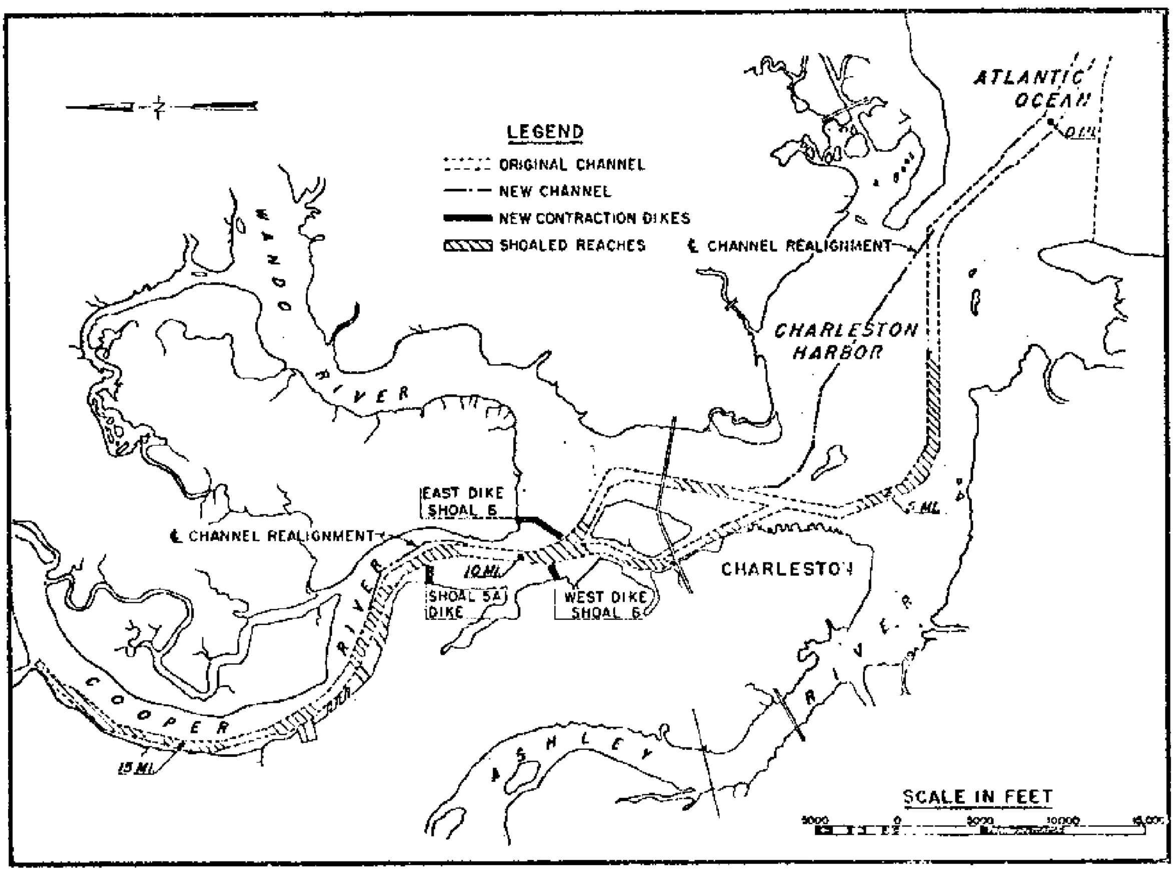


FIGURE 17. Location Map, Charleston Harbor

from one watershed to another thereby increasing the upland discharge into one estuary while decreasing that into another. In the opinion of Schultz and Simmons[35], the changing of upland discharges into estuaries without due consideration of the effects of such changes on hydraulic and shoaling conditions has created serious shoaling problems.

On the basis of their studies, Schultz and Simmons[35] reached the following general conclusions:

"(a) The degree of mixing of salt and fresh water in estuaries plays an important role in establishing their hydraulic regimens. Since it has been demonstrated that the shoaling regimens of some estuaries are related directly to their hydraulic regimens, it follows that the degree of mixing also plays an important role in establishing their shoaling regimens.

(b) Because of incomplete mixing of salt and fresh water in estuaries, the predominance of flow in the bottom strata is almost always upstream while that in the surface strata is downstream; the degree of such predominance is dependent on the degree of mixing, being most prominent in the highly stratified estuary and least prominent in the well-mixed type.

(c) Changes in the upland discharge, tidal prism, and physical configurations of estuaries will frequently change the degree of mixing of salt and fresh water therein and thus affect such important features as the vertical distribution of current velocities, the direction and degree of flow predominance, the amount of shoaling, and the location of major shoal areas.

(d) Available data indicate that lightweight sediments are supplied to estuaries principally through the medium of upland discharge. It therefore follows that upland discharge plays a dual role in estuarine sedimentation, since a large portion of the potential shoaling material is supplied by one of the three principal contributors to the resultant hydraulic regimen.

(e) The magnitude of changes in upland discharge into estuaries usually far exceeds that of changes in tidal prism or physical configuration. For this reason, and because upland discharge is of primary importance, it follows that major changes in upland discharge should be accomplished only after consideration of all probable effects."[1]

It is not implied that the vertical circulation pattern of an estuary is the only factor to be considered in predicting the location of major shoaling areas, or in explaining the reason for shoals which are already in existence. Many other factors must be considered in the overall problem of shoaling, but it appears certain that the vertical circulation pattern is the dominant effect in most estuaries.

Remedial Measures and Improvements

Remedial measures and improvements to reduce siltation in the interior navigation channels of estuaries have been grouped by Schultz and Simmons[(35)] into the following four classes: (a) improved maintenance dredging methods, (b) training and contraction works, (c) channel realignments, and (d) rediversion channels. These remedial measures and improvements, and the effects of improper deposition of spoil from channel dredging procedures as a source of shoaling, are discussed in Chapter VI, "Hydrologic Implications of Deepwater Channels in Tidal Estuaries."

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[1]Schultz, E. A. and Simmons, H. B., "Fresh Water-Salt Water Density Currents, A Major Cause of Siltation in Estuaries," Technical Bulletin No. 2, Committee on Tidal Hydraulics, U.S. Army Corps of Engineers, 1957, pp. 24 and 25.

VI. HYDROLOGIC IMPLICATIONS OF DEEPWATER CHANNELS IN TIDAL ESTUARIES

A tidal waterway is seldom adequate in its natural state to fulfill the needs of navigation. The channel may be shallow or tortuous, the current may be too strong, or it may be exposed to high winds and seas. These conditions may create high vessel transportation costs or make use of the channel impossible. The economic losses thus created generate demands for channel improvements.

Such improvements should not be undertaken without a thorough understanding of the possible consequences. A waterway affected by tidal forces is very complicated. A most common disappointment experienced by an engineer charged with the responsibility for the design of a deeper channel in a tidal waterway is the discovery that the new channel shoals excessively. An understanding of the factors involved in the transportation and deposition of sediments in tidal waterways and the effects of the new channel itself on these factors would help the engineer select the best channel alignment, or perhaps the construction of training works, which would prevent excessive shoaling.

Failure to recognize and evaluate these factors may result in a new channel that so drastically alters the regimen of a waterway that the tide rises higher and falls lower than it did before the improvement. Obviously, higher tides may damage shoreline property and lower tides may result in inadequate channel depths. Salinity intrusions may be increased, requiring the abandonment of water supply sources. Training works designed to prevent excessive shoaling may be ineffective. Jetties and breakwaters may fail to provide adequate shelter, may increase maintenance dredging requirements, and may cause severe erosion of adjacent beaches. Although there are many areas requiring additional investigation, the present state of knowledge is sufficient to minimize the occurrence of such difficulties.

Factors Affecting Tidal Waterways

The tidal phenomena that occurs in any waterway seldom results from a single cause, but are a more or less complex interaction of many factors. If a navigation improvement is desired which would effect a change in the regimen of a waterway, the change in each contributing factor and in the resulting interaction should be determined.

According to Douma and Wicker[9], the principal factors to be considered are: tides, tidal currents, freshwater discharge, volume of sediment, characteristics of beds and banks, wave action, littoral processes, salinity intrusion, and dispersal and flushing of pollutants.

Tides. Obviously the tide is the main generating force that causes the rise and fall of the water surface and the resultant currents. Basic differences in the characteristics of the tides make it dangerous to extend conclusions drawn as a result of a study of a tidal waterway on the east coast to a problem concerning a waterway on the west coast or the gulf coast. As discussed in Chapter II the tide is so greatly affected by the geometry of a waterway that it is almost as dangerous to consider that the tidal aspects of problems within two estuaries located on the same coast may be similar.

The importance of the tides in the design of tidal waterways cannot be overemphasized. It is as important in the life of the waterway as the pulse of blood through the arteries is to human life.

Tidal Currents. Tidal currents are generated by the vertical rise and fall of the water surface and are modified by the geometry of the waterway, freshwater discharges into the waterway, and salinity. As tides vary due to astronomic considerations as well as meteorological variations, a wide assortment of combinations enters into the resultant current.

These currents are the means for the transport of sediments. Local variations in tidal currents will cause either scour or deposition, depending upon their strength and the sediment itself. According to Simmons[(37)], the supply of sediment to navigation slips occurs almost exclusively during the rising phase of tide, during which the local tidal prism of the slip is being filled.

Tidal Theories. The engineer concerned with a problem waterway does not need to analyze basic tide data. However, he does need to know of their characteristics so that he may have an understanding of the factors that will change the tide. As discussed in Chapters II and V, among these factors are included the geometry of the waterway and the upland freshwater discharge.

Freshwater Discharges. As discussed in detail in Chapter V, freshwater discharges into tidal waterways have profound effects on the regimen. They affect the basic tide independently of the effects of geometry, greatly modify the resultant current by lengthening the ebb and shortening the flood, transport upland sediment to the tidal estuary, and interact with salinity intrusion forces to produce a complex modification of the distribution of currents in the vertical circulation pattern. Also, the inflow of fresh water is the means by which a tidal waterway rids itself of pollutants, and it is the factor that retards salinity intrusions.

Volume of Sediment. If the waterway is to remain, the volume of sediment brought down from the watershed must be either removed from the waterway by dredging, or purged out to sea by the currents.

Characteristics of Bed and Banks. The characteristics of the bed and banks of the waterway are very important factors. If they are composed of rock, it will be expensive to provide channel enlargement. Although sandy or silty bottoms and banks are easily dredged, they are also easily scoured by swift currents, thus adding material to the burden to be transported and perhaps deposited in localities requiring frequent maintenance dredging. These factors were discussed in more detail in Chapter V. One of the first investigations that should be made in any navigation study is an investigation of the character and type of material to be dredged.

Wave Action. Wave action should be considered in those channel reaches where the banks are composed of unconsolidated materials. Natural wave action and waves generated by passing vessels may cause bank sloughing which would create excessive amounts of material to be removed from the waterway or unacceptable losses of land destroyed by the erosion.

At the entrance to the waterway, ocean waves will generally affect the configuration of bars which generally extend into and across the opening. Therefore, their directions of approach should be considered in laying out bar channels. Other characteristics of waves such as height, period, and length, are needed for the design of any breakwaters or jetties considered necessary.

Littoral Processes. Littoral processes are the methods employed by nature for molding and remolding shorelines. These processes are significant to investigations of tidal waterways primarily because their product, known as littoral drift, is a given quantity of detritus moving along the shore. This quantity represents the resultant of the erosion and accretion occurring along a section of shoreline.

Littoral movement of material may occur along the shoreline of a waterway subject to wave action. Therefore, it is desirable to investigate the littoral processes of the shoreline of the waterway to determine whether the eroded material will move into the navigable channels of the waterway.

Of greater importance is the effect of the littoral processes in depositing material offshore adjacent to the entrance of a tidal waterway. This material produces bar formations usually found at entrances and are especially hazardous to navigation. Also, bar channels are expensive and difficult to maintain.

As pointed out by Wicker and Eaton[38], the migration cycles of most inlets are very unpredictable. Where the drift rate is large and predominately from one direction, the inlet may migrate in the direction of the drift movement for many years. Where drift rates are more evenly balanced, the migration cycles are much more indefinite and the longitudinal extent of the migration appears to be much less than in the former case. However, the present understanding of inlet behavior is not sufficient to establish quantitative predictions of inlet migration.

Salinity Intrusions. As discussed in Chapter IV, salinity intrusions are caused by the difference in densities of the sea water and fresh water acting singly or together with the flood and ebb flows of the waterway. The dissolved solids in the saline water, which consists mostly of sodium chloride salts, impair the use of the tidal estuary as a source of domestic and even industrial water supply. From Chapter V it was seen that they cause curious changes in the hydraulics of the waterway. It was shown that sediments in transport in a waterway are deposited to form a repetitious shoal at a location not anticipated from the geometry of the estuary. Also, certain dissolved salts will cause flocculation of certain suspended sediments, causing deposition.

Factors that must be recognized in investigating existing or expected changes in salinity intrusions include the tidal characteristics of the waterway, its geometry, and upland discharges.

Major changes in channel dimensions may affect the extent of salinity intrusions (1) by increasing the vertical density gradients or (2) as a result of changes in the tidal regimen. As explained in Chapter V, major alteration in the runoff of fresh water may significantly alter the salinity regimen with resultant modifications of the shoaling pattern.

Dispersal and Flushing of Pollutants. Alteration of the waterway or of the freshwater discharges into the waterway may increase or reduce the concentrations of pollutants. Since some amount of pollution probably will always be with us, it is very important that consideration be given to the characteristics of the waterway in relation to its ability to disperse and flush away pollutants.

Planning Tidal Waterway Improvements

The factors previously discussed should be considered to establish the extent to which each is likely to influence the plan of improvement for a tidal waterway. It may be necessary to include sediment sampling, current observations, and hydrographic surveys in the investigations. Most importantly, in selecting the best method of improvement, preliminary plans should be prepared for all the methods believed capable of producing the desired end result for economic comparison.

Sedimentation in Tidal Waterways

In Chapter V, upland discharges were discussed as being the major cause of siltation in tidal estuaries. In addition to the land areas that help determine the rate of upland discharges, other principal sources of sediments that shoal navigation channels outlined by Wicker and Eaton(38) include the bed of the waterway itself, the littoral drift in motion along beaches adjacent to the mouths of tidal waterways, industrial and sanitary wastes, and improperly deposited spoil from channel dredging operations. In Chapter V it was noted that Schultz and Simmons(35) have grouped the remedial measures and improvements necessary to reduce siltation from these sources of sediments into the following four classes: (a) improved maintenance dredging methods, (b) training and contraction works, (c) channel realignments, and (d) rediversion channels. A discussion of these classes are included in the following section.

Remedial Measures and Improvements

Improvements in Dredging Methods. Some of these sources of sedimentation in tidal waterways outlined by Wicker and Eaton(38) have already been discussed.

The last source (improper deposition of spoil from channel dredging operations) has only recently been recognized as a major source of shoaling in tidal waterways.

According to Schultz and Simmons(35), improvements in dredging and spoiling techniques usually are the least expensive of remedial measures, and therefore should normally be the first step in programs undertaken to reduce shoaling in tidal waterways. However, Johnston and Marcroft(24) says that the results of this thinking have gone off in two widely divergent directions, each of which appears to have merit. Both pertain particularly to situations where the use of a pipeline dredge pumping directly ashore is impracticable.

One of these methods provides for the removal of all the material from the shoal in the channel by a hopper dredge and depositing it behind dikes. A permanently located pipeline dredge, operating in water undisturbed by wave action or currents, would then remove the material deposited by the hopper dredge from a confined rehandling basin.

In contrast to this method, a method has evolved which has resulted in the so-called side-casting (or boom-discharging) plant. This method of dredging is premised on the idea that the most economic method to maintain channels under certain circumstances is to use a plant that can remove material from the channel more rapidly than the natural processes that bring the material to the recurring shoal and do so more cheaply than conventional dredging and disposal methods. Proponents of this method believe that the dredge can remove the natural shoaling material and that portion of the previously dredged material that returns to the shoal so rapidly and cheaply that the method is more economical than conventional dredging and disposal methods.

Training Walls, Contraction Dikes, and Channel Realignments. Training walls may be used to solve shoaling problems by directing the tidal currents into alignment with the course of the dredged channel. Contraction dikes also can be utilized by increasing the velocities sufficiently to increase erosion and decrease sedimentation. Overcontraction can reduce the tidal prism or create velocities that are hazardous to navigation. Reduction of shoaling in one reach may create a new shoaling problem elsewhere. Therefore, Schultz and Simmons[35] recommends that these structures be subjected to careful hydraulic model testing.

Rediversion Channels. According to Schultz and Simmons[35], the only real solution to shoaling problems, if the basic cause of shoaling is density currents, is to prevent the upland discharge from entering the estuary. This can be accomplished by diverting the upland discharge to the sea by some other route. This would not only eliminate the factor which creates the density currents, but also reduces a large portion of the potential shoaling material supplied to the estuary. However, Schultz and Simmons[35] points out that, although this is perhaps the most effective method of improvement, it also usually is the most expensive.

At any rate, as pointed out by Caldwell[14] and Simmons[37], through appropriate studies, careful planning and construction of necessary facilities, and proper supervision and inspection of dredging operations, the overall cost of maintaining estuarine navigation channels can be reduced by a substantial amount.

Hydrologic Studies of the Coastal Waters of North Carolina

At the previously referenced symposium on hydrology of the coastal waters of North Carolina, a paper was presented that considered the general effects that provision of a deepwater channel from the Pamlico River to the ocean would have on the hydrology of the sounds. A tabulation of data on some of the factors which influence tidal flow was included and the changes that may result if a deepwater channel is provided in Pamlico River and connecting sounds to the ocean were discussed. Also, additional investigations that would be required if a project were authorized by Congress were enumerated. This chapter is concluded with a summary of that paper for the purpose of determining some of the factors that should be considered for tidal estuaries in general.

Magnuson, Nels C.

HYDROLOGIC IMPLICATIONS OF A DEEPWATER CHANNEL IN PAMLICO SOUND, NORTH CAROLINA, Proceedings, Symposium on Hydrology of the Coastal Waters of North Carolina, pp. 130-141, May 1967.

At this time, six navigation routes are being considered by the Corps of Engineers (see Figure 18[27]). If any route is determined to be economically justifiable, detailed studies, including a model study if found to be advantageous, would be conducted before a favorable recommendation for improvement would be submitted to Congress.

As shown on Figure 18[27] routes under consideration would either cross Pamlico Sound or Pamlico Sound and Core Sound. Pertinent data on the sounds are given in the following tabulations.

TABLE 1. - DATA ON SOUNDS

Location	Maximum Values			Average depth (feet)	Area (sq. miles)	Volume (acre-feet)
	Width (miles)	Length (miles)	Depth (feet)			
Currituck Sound	8	35	14	5.0	160	512,000
Albemarle Sound					700	5,310,000
Croatan Sound	5	12	19	9.4	46	276,000
Roanoke Sound	3	12	10	5.2	37	122,000
Pamlico Sound	30	70	24	12.5	1,675	13,500,000
Core Sound	6	36	9	4.0	92	236,000
					2,710	19,956,000

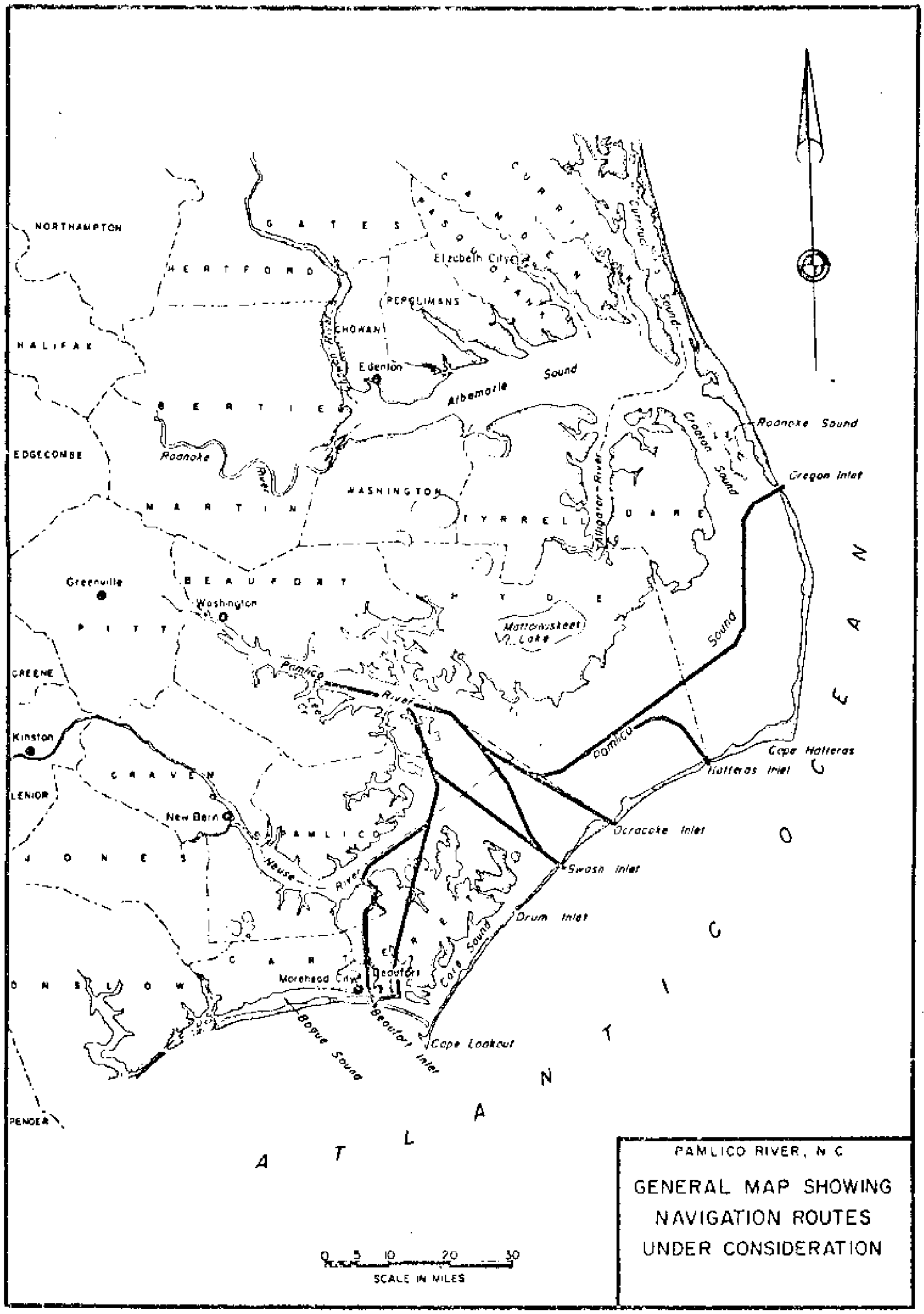
NORTHAMPTON
GATES
HERTFORD
HALIFAX
CHOWAN
PERQUIMANS
Elizabeth City
Edenton
Albemarle Sound
BERTIE
EDGECOMBE
Roanoke River
MARTIN
WASHINGTON
TYRRELL
DARE
Alligator River
Croatan Sound
Roanoke Sound
Oregon Inlet
Greenville
PITT
BEAUFORT
Washington
HYDE
Mattamuskeet Lake
Pamlico River
Pamlico Sound
GREENE
Kinston
LENIOR
CRAVEN
New Bern
PAMLICO
Neuse River
JONES
CARTERET
Morehead City
Beaufort
Core Sound
Bogue Sound
Beaufort Inlet
Cape Lookout
Drum Inlet
Swash Inlet
Ocracoke Inlet
Hatteras Inlet
Cape Hatteras
ONSLOW
PENDER
ATLANTIC OCEAN
SCALE IN MILES
0 5 10 20 30
PAMLICO RIVER, N C
GENERAL MAP SHOWING
NAVIGATION ROUTES
UNDER CONSIDERATION

FIGURE 18

Streams. The major streams tributary to the sounds of North Carolina are the Chowan and Roanoke Islands, which flow into Albermarle Sound, and the Pamlico-Tar and Neuse Rivers, which flow into Pamlico Sound. Because the sounds are interconnected, their outlets are not distinctly defined. However, Oregon Inlet serves as the main outlet for Albermarle, Currituck, Croatan, and Roanoke Sounds and the northern part of Pamlico Sound. Ocracoke and Hatteras Inlets serve as outlets for Pamlico Sound, and Beaufort Inlet is the principal outlet for Core Sound.

Drainage Areas. Drainage areas of streams tributary to these sounds are tabulated below.

TABLE 2. - DRAINAGE AREAS

Area	Square Miles
Albermarle Sound	
Folly Swamp	3
Pasquotank River	402
Little River	97
Perquimans River	170
Yeopin River	46
Queen Anne Creek	7
Pembroke Creek	31
Chowan River	4,929
Roanoke River	9,666
Kendricks Creek	25
Deep Creek	7
Scuppernong River	201
Subtotal (Albermarle Sound)	15,584
Pamlico Sound	
Pamlico River	4,302
Jones Bay	14
Bay River	142
Neuse River	5,598
Subtotal (Pamlico Sound)	10,056
TOTAL	25,640

Runoff. Average annual runoff for ten stations, taken from U.S. Geological Survey records, are listed below.

TABLE 3. - RUNOFF DATA

Station	Drainage area (sq. miles)	Average runoff (c.f.s.)	Runoff per sq. miles
Blackwater River near Franklin, Va.	613.0	646.0	1.05
Nottoway River near Sebrell, Va	1,451.0	1,296.0	0.89
Meherrin River at Emboria, Va.	749.0	650.0	0.87
Roanoke River at Roanoke Rapids, N.C.	8,410.0	8,155.0	0.97
Tar River at Tarboro, N.C.	2,140.0	2,312.0	1.08
Neuse River at Kinston, N.C.	2,690.0	2,960.0	1.10
Ahoskie Creek at Ahoskie, N.C.	64.3	65.5	1.02
Herring Run near Washington, N.C.	15.0	10.8	0.73
Swift Creek near Vanceboro, N.C.	182.0	202.0	1.11
Trent River near Trenton, N.C.	168.0	207.0	1.23

Hydrology

Runoff. Based on the tabulated data, the author estimated that the average flow into Albemarle Sound is 0.95 second-foot and the flow into Pamlico Sound is 1.05 second-feet per square mile. These runoff rates are equivalent to 1.89 and 2.09 acre-feet per day per square mile, respectively. Based on data tabulated above, the flow into Albemarle and

Pamlico Sounds would total 29,500 acre-feet and 23,100 acre-feet per day respectively. This is equivalent to an annual flow of 10,700,000 acre-feet into Albermarle Sound and 8,450,000 acre-feet into Pamlico Sound for a total of 19,150,000 acre-feet.

Rainfall. Rainfall records for the area in the vicinity of the sounds indicate that precipitation averages about 48 inches per year.

Evaporation. Average annual Class A pan evaporation in the sounds is 50 inches and the average annual lake evaporation is 40 inches.

Total Inflow. If precipitation averages 48 inches and evaporation 40 inches, there is a net gain of 8 inches. The total area of the sounds is 1,290,000 acres. The gain for the sounds would then be 860,000 acre-feet. Adding to this the tributary inflow computed above roughly indicates that freshwater inflow totals about 20,010 acre-feet.

Tidal Inflow

Tidal Flow. Data on the cross-sectional area of inlets at the gorge, maximum rates of flow in cubic feet per second, and total inflow and outflow are tabulated on the following page.

TABLE 4. - TIDAL FLOW AND RELATED DATA

Date	Cross Section (sq. ft.) at m.l.w.	Maximum rate of flow (c.f.s.)		Total Flow (acre-ft.)	
		Inflow	Outflow	Inflow	Outflow
		Oregon Inlet			
Sept. 9, 1931	39,000	134,000	89,200	47,800	37,400
Aug. 31, 1932		129,100	102,700	42,700	40,100
Oct. 11, 1932		126,500	127,300	34,900	57,200
Aug. 24, 1937	44,400	180,000	142,000	63,500	55,900
Aug. 14, 1939	56,000	152,000	141,000	37,800	71,500
Apr. 23, 1950	28,000		90,000		38,200
Sept. 27, 1965	66,800	292,000	145,800	98,200	54,200
		Hatteras Inlet			
Apr. 25, 1950				52,700	
		Ocracoke Inlet			
Apr. 27, 1950	82,800			45,400	122,000
May 25, 1958	107,500	285,000		78,400	
May 25, 1958	96,100		273,000		104,000
Oct. 14, 1962	94,100	329,000		125,000	
Oct. 14, 1962	74,400		344,000		129,000
		Beaufort Inlet			
1934				63,600	71,200
Aug. 5, 1935				47,143	
Aug. 6, 1935				71,400	
Oct. 20, 1936				39,000	
Oct. 21, 1936				75,900	

Tidal Range. Tidal ranges for the study area as determined by the U.S. Coast and Geodetic Survey for 1967 are tabulated below.

TABLE 5. - TIDE RANGE, IN FEET

Place	Gorge or Inside Elevations		Ocean	
	Mean	Spring	Mean	Spring
Currituck Beach Light			3.6	4.3
Kitty Hawk			3.2	3.8
Oregon Inlet	2.0	2.4		
Cape Hatteras			3.6	4.3
Hatteras Inlet	2.0	2.4		
Ocracoke Inlet	1.9	2.3		
Ocracoke	1.0	1.2		
Cape Lookout			3.7	4.4
Morehead City	2.8	3.4		
Atlantic Beach			3.6	4.3

According to the author, the mean range in the ocean as determined by the Corps of Engineers was 3.45 feet in 1893 and the extreme range was 4.9 feet. Also, the mean range in the throat was determined to be 2.35 feet. Tide ranges at other points in 1893, which were taken on a line to the northwest from the throat and following Wallace Channel, are tabulated below. This would roughly be the route of the channel through Oracoke Inlet, shown on Figure 18.[27].

TABLE 6. - TIDAL RANGE IN 1893

Distance from Gorge (miles)	Mean Range (feet)
0	2.35
1.5	2.10
3.0	1.40
4.8	0.40
5.7 (Head of Wallace Channel)	0.20
10.0 (Royal Shoal)	0.10

The tide range near the heads of seven other channels, from 4.9 to 6.5 miles from the inlet, was the same as at the head of Wallace Channel (0.2 foot).

No definitive data are available on the present tide range in the sounds. However, U.S. Coast and Geodetic Survey charts indicate that the periodic tide in Pamlico Sound has a mean range of less than one-half foot except near the inlets.

Salinity

Salinity. Pamlico Sound and the sounds directly adjoining it are highly saline, but Albemarle and Currituck Sounds contain relatively fresh water. The average salinity in Pamlico Sound has been estimated at 20,000 parts per million, which is about 60 percent sea water. Data from a Tar-Pamlico River Pollution Survey Report, prepared by the North Carolina Department of Water Resources, Division of Stream Sanitation and Hydrology, are tabulated below.

TABLE 7. - CHLORIDES, IN PARTS PER MILLION

Distance from mouth	7/30/58	8/8/58	9/9/58	Average per Station (PPM)	Average per Station Percent sea water
0.0	3,700	5,200	5,100	4,700	23
10.9	3,200	-	4,000	-	-
12.2	-	3,900	-	3,300	16
18.2	3,200	3,300	2,100	2,300	11
26.9	2,000	2,400	790	1,400	7
37.3	350	88	24	190	1
Flow at mile 37.3 (c.f.s.)	2,000	3,200	1,200	5,160	-

In April 1950, the salinity at Ocracoke Inlet was 34,500 parts per million which decreased progressively to 21,300 parts per million 5.1 miles from the inlet. The mixing in Pamlico Sound has been estimated to be 5 to 6 miles during maximum flood tides and about one-half of that distance during minimum flood tides.

Flushing. The average flushing time of Pamlico Sound has been estimated at about 3 months. As stated previously, the estimated volume of the sounds total 19,956,000 acre-feet and the estimated freshwater inflow averages 20,010,000 acre-feet and the estimated freshwater inflow averages 20,010,000 acre-feet per year. Although there is no direct relationship between the flushing time and freshwater inflow, the fact that inflow is sufficient to completely fill the sound on an average of about once a year indicates that the water would be changed periodically.

Routes Under Consideration

Data from preliminary studies of the six routes under consideration in the Pamlico River study are tabulated below. For estimating purposes, a channel having a depth of 45 feet below mean low water, with a bottom width of 600 feet and 5 to 1 side slopes, is used for the inlet channel, and a channel 40 feet deep, 500 feet wide, with 3 to 1 side slopes, is used for inside channels.

TABLE 8. - VOLUME OF EXCAVATION

Route via	Miles	Excavation (cubic yards)
Oregon Inlet	95	317,600,000
Hatteras Inlet	67	222,100,000
Ocracoke Inlet	51	203,500,000
Swash Inlet	49	189,600,000
Beaufort Inlet (via land cut)	63	250,300,000
Beaufort Inlet (via AIWW)	67	237,100,000

The scope of the Pamlico-Tar River study does not permit investigation of the effects that a deep channel would have on the hydrology of the sound beyond the limits discussed in the author's paper. However, during the preconstruction planning stage, a salinity baseline would be established and the stations on the baseline would be monitored before and after construction of the project. Some of the factors that will be considered by the Corps of Engineers during the course of their investigation are summarized below.

Effect of Deepwater Channel on Salinity in Sounds and Estuary. A channel through the gorge of the dimensions given above would have a minimum cross-sectional area of about 37,100 square feet. Except for one measurement (see Table 4) Ocracoke and Oregon Inlets have always had greater areas than this. Corps of Engineers' estimates indicate that the excavation would increase the cross-section about 9 percent in the Ocracoke Inlet gorge, 3 percent at the mouth of the Pamlico River, and 8 percent in the river at Lee Creek. According to the author, because of the large expanse and volume of the sounds and the indications that the influence of the inlet extends only 5 to 7 miles from the gorge, it appears unlikely that minor enlargement of the area in the gorge would measurably affect the tidal prism or average salinity of the sounds. The large variations in cross-sectional areas, rates of flow, and tidal volumes indicated in Table 4 seem to support this finding. If the hydraulic conditions in Pamlico Sound are not changed significantly, those conditions in Pamlico River also should remain unaltered. The cross-sectional area near Lee Creek is about 150,000 square feet. As stated before, excavation would increase the cross-sectional area about 3 percent at the mouth of the Pamlico River and about 8 percent at Lee Creek.

Effect on Salinity in Navigation Channel. According to the author, although a deepwater channel would have only minor effect on average salinities, it may increase the salinity in the excavated channel. Available data on model studies for the Matagorda Ship Channel, Texas, indicate that salinities in the navigation channel will be much higher than now occur in the bay system, but salinities outside the navigation channel would not be significantly increased.

Geology. A relatively impervious strata exists from about 45 feet below mean sea level to 90 feet below. The Castle Hayne aquifer is about 150 feet below mean sea level in the vicinity of Lee Creek. Above this lies a formation, about 65 feet thick, which contains phosphate ore. A layer of relatively impervious material lies above it, which extends upward to 45 to 50 feet below mean sea level. The existing streambed is approximately 20 feet below mean sea level. If deepened to 40 feet, the cut would barely reach the relatively impervious stratum.

Pumping and Upstream Control. Two other factors that may influence the effect of a deeper channel in Pamlico River are pumping and upstream control. The Texas Gulf Sulphur Company is pumping 65,000,000 gallons a day from the Castle Hayne aquifer. The effect of this operation on water quality is under study by the Texas Gulf Sulphur Company and the state of North Carolina. Secondly, the Corps of Engineers is conducting an investigation of water-resources development on the Tar River, where storage for release during dry periods for water-quality control, is under consideration. According to the author, if such reservoirs were constructed, the quality of water in the Pamlico River would be improved during dry periods.

Spoil. One other factor to be considered is the effect that placement of dredge spoil will have on the sounds. According to the author, the Corps of Engineers expects that if proposed dredging were accomplished, spoil in deep water would be placed to a height of 5 feet above the existing bottom, not less than 1,000 feet from the channel in mounds about one-half mile long and 2,000 feet wide, with openings of 1,000 feet between the spoil deposits. It is estimated that spoil would cover about 15 square miles if the Ocracoke Inlet route is chosen. Only about 0.9 percent of Pamlico Sound would be covered with spoil. If the Ocracoke Inlet route were followed, the dredge spoil would total about 126,000 acre-feet, or less than 1 percent of the volume of Pamlico Sound. Special precautions would be taken during dredging operations to confine suspended solids until final settlement occurs.

Effect of Deepwater Channel. Based on the information summarized above, provision of a deep channel would not appreciably affect the tidal prism of the average salinity in the sounds. The proposed deepwater channel would barely cut into the relatively impervious stratum lying above the phosphate ore which, in turn, covers the Castle Hayne aquifer. Dredge spoil would cover a relatively small area in the sounds and would be spaced to permit circulation of water.

Post-authorization Studies. If a navigation project is authorized, detailed studies would be made during preconstruction planning to determine its effect on the sounds and on the ground water. A model study probably would be required to determine the effect of the deep-draft channel under construction. Some of the factors that would be considered in such a study would include:

a. Channel alignment.

b. Construction and maintenance structures.

c. Shoaling pattern.

d. Location, size, and spacing of spoil-dispersal areas.

e. Required geological exploration along the construction route.

f. Changes in tidal prism.

g. Changes in the salinity of the sounds.

h. Changes in the salinity of the navigation channel.

i. Changes on the regimen of the Pamlico River and the sounds caused by the project.

The authors conclude that a deepwater channel from Pamlico River to the ocean could be provided without disturbing the regimen of the river or sounds, but that it would be desirable to make a model study to explore significant aspects of such a project prior to construction operations.

VII. SUGGESTIONS FOR RESEARCH

Presently, only a limited understanding of many aspects of estuarine hydrology exists. The engineering problems encountered in tidal water developments are complex because of the varied interaction of many forces. The present state of knowledge does not permit the formulation of exact solutions to these problems or even mathematical expressions of many factors and influences. Although most tidal hydraulics subjects, such as shoaling, saltwater intrusion, etc. have been investigated in some localities, sufficient comprehensive studies have not been completed to formulate design methods and procedures for general application. For this reason, heavy reliance has been placed and will continue to be placed on hydraulic model studies, field studies and experience, and engineering judgement in designing essential improvements.

For the reasons discussed above, Douma and Wicker[9] compiled a rather comprehensive list of those hydraulics subjects that are deficient in knowledge and require additional investigations to reach an advanced stage of understanding. The complete list follows, with detailed information included for each section since the entire list is pertinent to this paper.

"a. Tides and currents in tidal waterways:

(1) Existing theories and methods of predicting the magnitude of tides, currents, and surges in a proposed new tidal waterway, or to determine in advance the effect of major physical changes in the tidal regimen, should be more clearly defined regarding their conditions of application.

(2) The known expressions for uniform flow should be reexamined to determine the effects of density differences, varying bottom roughness, waves, etc., on their applicability to tidal waterways.

(3) More information is needed on the effects of geometry and boundary resistance on damping in cooscillating tidal systems.

b. Shoaling processes:

(1) The basic transportation laws for sediments, including muds, need to be established to predict shoaling rates and locations in

proposed new channels or enlargements of existing channels.

(2) The process whereby the fine materials, composing some shoals, pass through successive stages of being in essential suspension, becoming plastic in character, and finally changing to a consolidated mass needs to be more clearly understood.

(3) Greater knowledge is necessary on the mechanics of flocculation and deposition and the effects of repetitive scour and deposition on shoaling rates.

(4) Compaction studies should systematically investigate the effects of pressure, grain-size composition, and temperature on the compaction rate of muddy deposits.

(5) More should be known of the effects of degree of mixing of salt water and fresh water on velocity distribution and turbulence and how these effects influence shoaling processes.

(6) The radioactive tracer technique should be developed further and used more widely to identify the source of materials composing shoals and to establish the relative importance of various shoal materials and sources.

(7) Improved knowledge of the shoaling process and transportation of estuarine sediments should be examined with a view to more efficient use of dredging equipment.

c. Saltwater intrusion:

(1) There is need for more complete knowledge of the characteristics of the saltwater wedge, the flow conditions around it during its advance and retreat, and its effect on newly deposited sediment and that still in suspension.

(2) An appraisal is needed of the significance of physical features and hydraulic regimen of estuaries on the extent of salinity intrusion.

(3) The effect of predominance of upstream flow due to saline intrusions on the shoaling process must be more clearly evaluated.

(4) It should be determined whether shoaling occurs in the region where sediment first encounters the saline water (effect of salt water on flocculation phenomena) regardless of hydraulic characteristics which otherwise might keep the sediment moving seaward.

d. Upland discharge:

(1) Criteria are needed which will permit determination of the freshwater discharge into an estuary necessary to hold saltwater intrusion to a given desired location.

(2) More knowledge is needed on the effect of artificial changes in upland discharge on tidal hydraulic and shoaling characteristics of estuaries.

e. Navigation channels and structures:

(1) Improved criteria are needed to incidate the effects of any plan of improvement on salinity, shoaling, tidal circulation, and pollution in an estuary.

(2) Criteria concerning relatively stable cross sections of channels subject to scour and deposit must be determined to predict long-range adjustments which follow artificial interference with natural channels.

(3) Practical methods of modifying waterways should be investigated to determine whether shoaling can be made to occur in the vicinity of disposal areas of large potential capacity.

(4) Although general criteria are available, increased tidal hydraulics knowledge should permit the development of improved criteria for the planning and design of channels and structures, resulting in greater hydraulic efficiency and reduced maintenance costs.

f. Tidal entrances:

(1) Improved criteria are needed to establish relations between tidal prism, cross-sectional area, flow velocities, wave action, sedimentation characteristics, bar location, and geometry of tidal entrances to assure relatively stable conditions.

(2) More information is needed on the effects of adjacent shores and littoral drift on stability and shoaling of entrances.

g. Navigation requirements:

(1) Determination should be made of the effects of soft bottoms containing fluff material on vessel squat, maneuverability, and machinery.

(2) Bases are needed for establishing economical navigation depths through fluff material.

(3) Improved criteria are needed for establishing economical depths, widths, and turn characteristics of navigation channels.

h. Maintenance dredging:

(1) Basic data should be obtained and analyzed to determine the efficacy of agitation dredging operations under various tidal hydraulic conditions. This should include the settling rates of agitated shoal material.

(2) The use of flocculents should be explored for controlling deposition and consolidating fluff for the purpose of increasing the effectiveness of dredging.

(3) All other maintenance dredging practices should be constantly reviewed to ensure the permanent removal, consistent with economy of operations, of the maximum volume of sediment from waterways.

i. Prototype investigations:

(1) More field measurements and analyses of data obtained therefrom are needed to verify existing theories and model tests and for the purposes of developing new or improved criteria.

(2) More determinations of the undisturbed dry density of shoals need to be made.

(3) More accurate means of measuring the inflow of sediment to an estuary should be developed.

j. Instrumentation:

(1) More research is required for the development of new, or the improvement of existing, methods of sampling muddy sediment deposits, transportation rates, and concentrations.

(2) There is a need for the development of instruments capable of recording turbidity of flow, in-place density of shoal material, and amount of solids being pumped through dredge pipelines."[1]

As evidenced by the above list, considerable research is needed to increase the state of knowledge of factors affecting estuarine hydrology and related phenomena.

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