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	Engineering and Design TIDAL HYDRAULICS	
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15 March 1991

US Army Corps
of Engineers

ENGINEERING AND DESIGN

Tidal Hydraulics

ENGINEER MANUAL

DEPARTMENT OF THE ARMY
US Army Corps of Engineers
CECW-EH-D Washington, DC 20314-1000

Engineer Manual
No. 1110-2-1607 15 March 1991

Engineering and Design
TIDAL HYDRAULICS

1. Purpose. This manual provides current guidance and engineering procedures for the solution of tidal hydraulics problems.

2. Applicability. This manual applies to HQUSACE/OCE elements, major subordinate commands, districts, laboratories, and field operating activities (FOA) having responsibility for design, construction, and operation of civil works projects within areas of tidal influence.

3. General. The subjects covered in this manual range from the fundamentals of estuarine engineering to specific problem solving techniques, including environmental considerations, to a summary of "lessons learned" from completed projects. The problem solving portion of the manual serves as a means of transferring the technical knowledge obtained from recent research efforts in tidal hydraulic engineering.

FOR THE COMMANDER:

ROBERT L. HERNDON
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Chief of Staff

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

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Table of Contents

This manual supersedes EM 1110-2-1607, 21 August 1965.

CHAPTER 1

INTRODUCTION

1-1. Purpose. This manual provides design guidance for the development or improvement of navigation and flood control projects in estuaries. Factors are presented that should be considered in providing safe and efficient navigation facilities with least construction and maintenance costs and/or providing protection from design floods. Considerations for preventing damage to the environmental quality of the estuary are also presented. The design engineer is expected to adopt the general guidance presented in this manual to specific projects. Deviations from this guidance are acceptable if adequately substantiated. It should be noted that coastal structures and approach channels are not included in this manual.

1-2. Appendices. Appendix A is the alphabetical listing of references cited in this manual. Appendix B discusses field data collection considerations along with an example. Appendix C presents an example numerical model investigation. Appendix D presents greater details of sedimentation analysis than provided in Chapter 4. Appendix E is a summary of generic or overall lessons learned from various Corps navigation projects, and Appendix F is a listing of tidal model investigations conducted at the US Army Engineer Waterways Experiment Station (WES). Appendices B through F have been included to provide general guidance and examples.

1-3. Training. The US Army Engineer Division, Huntsville, offers a short-term (1-week) training course entitled "Hydraulic Design for Tidal Waterways" (formerly called "Tidal Hydraulics") within the Proponent Sponsored Engineer Corps Training Program (PROSPECT). The course covers the latest engineering and design considerations for the development and improvement of Corps projects in tidal waters as contained in this manual. Other related courses on the TABS numerical modeling system, referenced in several of the chapters and appendices, are also listed in the PROSPECT Purple Book. Several other PROSPECT courses also are available on various topics directly related to tidal hydraulics. Interested Corps employees should check with their supervisor or Training Officer and the Purple Book for required qualifications and prerequisites for the particular training course. If qualified, the employee should follow the standard training application procedure for his or her District or Division.

1-4. Available Assistance. The USACE Committee on Tidal Hydraulics (CTH) provides expert consultation on problems related to tidal hydraulics. Address inquiries to the Chairman, CTH, WES, ATTN: CEWES-HV-Z, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199.

1-5. References. Required references are listed as follows. Related references are listed in Appendix A.

a. EM 1110-2-1202 (Environmental Engineering for Deep-Draft Navigation Projects).

b. EM 1110-2-1412 (Storm Surge Analysis and Design Water Level Determination).

c. EM 1110-2-1611 (Layout and Design of Shallow Draft Waterways).

d. EM 1110-2-1613 (Hydraulic Design of Deep-Draft Navigation Projects).

e. EM 1110-2-5025 (Dredging and Dredged Material Disposal).

f. ER 1105-2-50 (Environmental Resources).

g. ER 1110-2-1404 (Deep-Draft Navigation Project Design).

h. ER 1110-2-1457 (Hydraulic Design of Small Boat Navigation).

i. ER 1110-2-1458 (Hydraulic Design of Shallow Draft Navigation Projects).

CHAPTER 2

DEFINITION AND FORCING FUNCTIONS OF ESTUARIES

Section I. Definition

2-1. Definition. An estuary is an area of interaction between salt and fresh water. The most common definition used is that of Cameron and Pritchard (1963) that states, "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." Hopkinson and Hoffman (1983) argue that the estuarine influence may extend to the nearshore coastal waters where seawater is diluted by land drainage but beyond the confines of emergent land masses. Using the Cameron-Pritchard definition, the brackish waters of the Amazon and Mississippi Rivers seaward of the river mouths are not estuarine; using the Hopkinson-Hoffman definition, they are. Hopkinson and Hoffman support, from a functional point of view, the extension of the estuarine boundary to include the interface system that couples continent to ocean.

Section II. Classification of Estuaries

2-2. General. To more fully understand what an estuary is, some sort of classification system must be established. Pritchard's definition is one for a positive estuary (Pritchard 1952a), an estuary where freshwater input (river flow and precipitation) exceeds losses due to evaporation. Thus the surface salinities in a positive estuary are lower than in the open ocean. A situation in which freshwater input is less than losses due to evaporation results in a negative estuary, such as Laguna Madre in Texas. Most estuaries are positive; however, a negative situation can occur, resulting in different circulation patterns caused by hypersaline conditions.

2-3. Classification. Estuaries are also classified by topography and salinity structure. Ratio parameters of flow, stratification, and stratification-circulation can be used to identify the salinity structure class.

2-4. Topographic Classification. Pritchard (1952b) has suggested a topographic classification of three groups: coastal plain estuaries, fjords, and bar-built estuaries.

a. Coastal Plain Estuaries. Coastal plain estuaries, or drowned river valleys, were formed as the melting waters from the last ice age flooded the existing river valleys. River flow is normally small compared to tidal prism (the volume of water between high and low tides) and sedimentation has not kept pace with inundation. The resulting estuary has maintained the topography of the former river valley but is relatively shallow (rarely deeper than 100 feet (30 metres)). There are extensive mud flats with a sinuous, deeper central channel. Coastal plain estuaries are generally found in temperate latitudes. Examples are the Chesapeake Bay estuary system in the United States and the Thames and Mersey systems in England.

b. Fjords. Fjords, estuaries that have been formed by glacial erosion, generally occur at higher latitudes, are relatively long and deep, and possess a shallow sill at the fjord mouth and fjord intersections. These shallow sills can restrict the free exchange of ocean and estuary waters, in some cases producing a small tidal prism with respect to river flow. Examples of fjords are Puget Sound (United States), Alberni Inlet (British Columbia, Canada), Sogne Fjord (Norway), and Milford Sound (New Zealand).

c. Bar-built Structures. Bar-built estuaries are formed by the same processes as the drowned river valleys, the difference being that sedimentation has kept pace with inundation, with a characteristic bar forming at the mouth. Associated with depositional areas, bar-built estuaries are shallow with extensive lagoons and waterways inside the mouth. Entrance velocities can be quite high but quickly diminish as the estuary widens. This type of high sediment volume estuary is most often found in tropical or active coastal deposition areas. Examples of bar-built estuaries are the Roanoke River (United States) and the Vellar Estuary (India).

d. Other. A fourth group of estuaries would be those not belonging to the previously mentioned three. This group would include estuaries formed by volcanic eruptions, faulting, landslides, or other processes.

2-5. Classification by Salinity Structures. Most estuary systems are coastal plain estuaries with individually unique salinity and flow characteristics. To understand the circulation of these estuaries, Pritchard (1955) and Cameron and Pritchard (1963) have classified estuaries using stratification and salinity distribution as the governing criteria. The major classifications are highly stratified, partially mixed, and well-mixed (homogeneous) (Figure 2-1).

a. Highly Stratified. A highly stratified, salt wedge type estuary is one in which the outgoing lighter fresh water overrides a dense incoming salt layer. The dense salt wedge will advance along the bottom until the freshwater flow forces can no longer be overcome. At this point, the tip of the salt wedge will be blunt during rising tide and tapered during falling tide. Mixing occurs at the saltwater/freshwater interface by entrainment, a process caused by shear forces between the two moving layers. As small amounts of dense water are mixed in the upper layers, more fluid enters the estuary near the bottom to compensate for the loss, and more fluid leaves the estuary in the upper layers to attain equilibrium of forces (Figure 2-2a). In these river-dominated, poorly mixed estuaries, such as Southwest Pass on the Mississippi River, upstream flow occurs in the salt wedge regardless of tidal phase, with downstream flow on the surface. In the shallower South Pass, also on the Mississippi River, upstream flow occurs in the wedge during flood tide simultaneously with surface downstream flow, while during ebb tide, flow at all depths is in the seaward direction (Wright 1971). Examples are the Mississippi River (United States) and Vellar Estuary (India). Another form of a highly stratified estuary is the fjord type system. Similar to the salt wedge type, in a fjord the lower, almost isohaline, layer is very deep. The freshwater surface layer is almost homogeneous, and only during low-flow periods does the maximum salinity gradient ever reach the surface. Circulation over

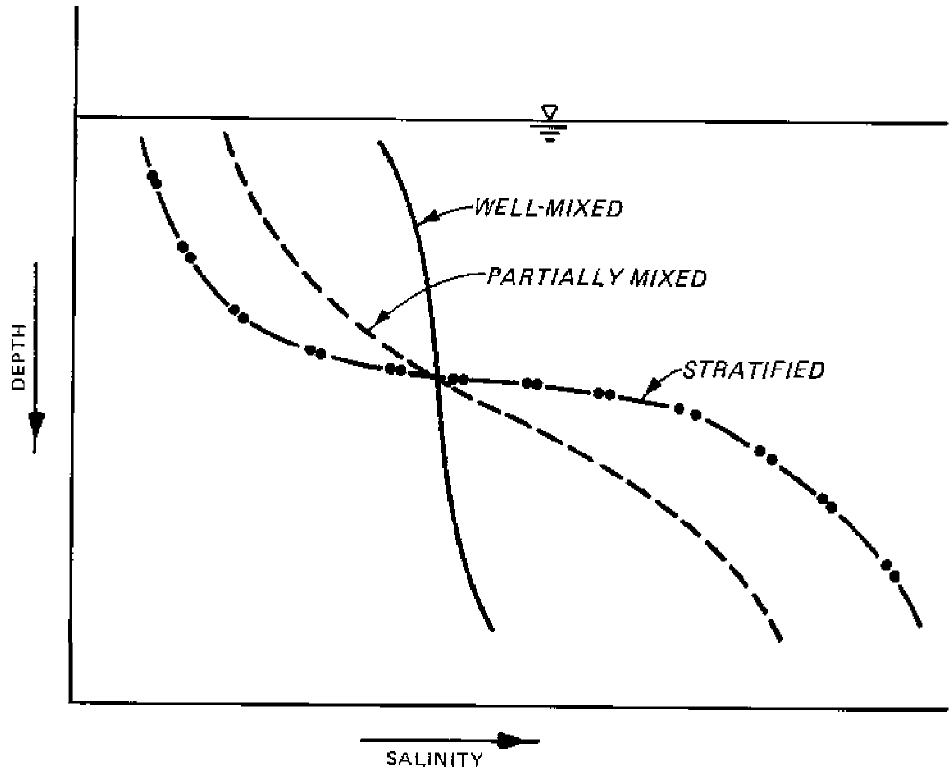

Figure 2-1. Vertical salinity structure. Classification depends on salinity difference between surface and bottom values

the sill may be very different from the rest of the fjord estuary because of large tidal velocities and weaker stratification at the sill. The inflow over the sill is usually a mixture of coastal and outflow water. As the water passes the sill and the tidal action decreases, the denser water settles and frequently results in a layered structure resulting from successive saltwater intrusions (Figure 2-2b). If water renewal is infrequent, anoxic conditions can develop on the bottom. Silver Bay (Alaska, United States) and Alberni Inlet (British Columbia, Canada) are examples.

b. Partially Mixed. A partially mixed estuary is one in which tidal energy is dissipated by bottom friction produced turbulence. These turbulent eddies mix salt water upward and fresh water downward with a net upward flow of saline water. As the salinity of the surface water is increased, the outgoing surface flow is correspondingly increased to maintain riverflow plus the additional upward-mixed saline water. This causes a compensating incoming flow along the bottom. This well-defined, two-layer flow is typical of partially mixed estuaries. The salinity structure is very different from a highly stratified estuary because of the efficient mixing of salt and fresh water. The surface salinity increases steadily down the estuary with undiluted fresh water now occurring only near the head of the estuary. There is

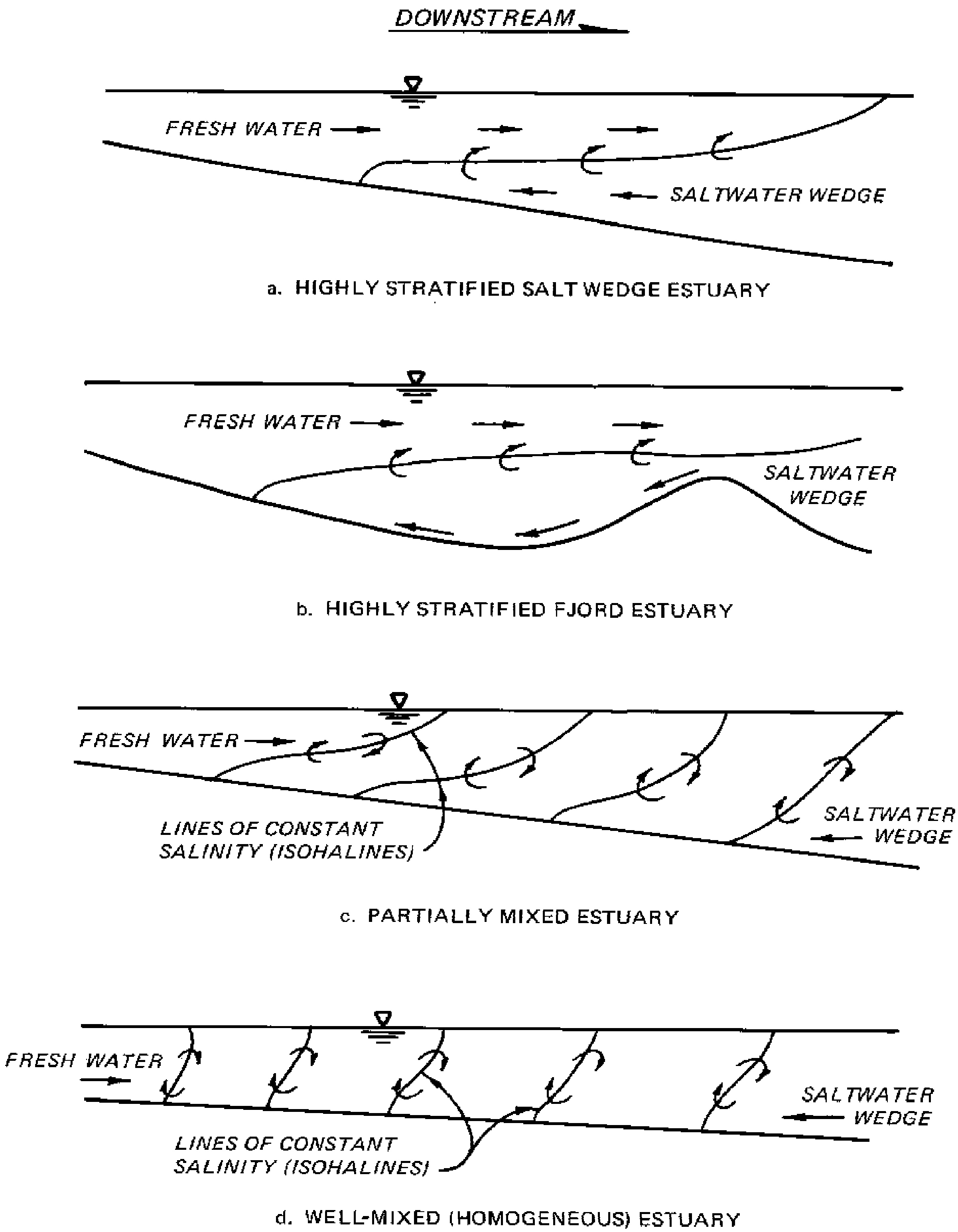

Figure 2-2. Estuary classification by salinity structure

also a longitudinal salinity gradient along the bottom (Figure 2-2c). In a partially mixed estuary, riverflow is low compared to tidal prism. Examples are James River (United States) and Mersey and Southampton Water Estuaries (England).

c. Well-mixed or Homogeneous. In estuaries where tidal flow is much larger than riverflow and bottom friction large enough to mix the entire water column, a vertically homogeneous (well-mixed) estuary results (Figure 2-2d). If the estuary is wide, Coriolis force may form a horizontal flow separation; and in the northern hemisphere, the seaward flow would occur on the right side (looking downstream), while the compensating landward flow would be on the left. This vertically homogeneous, laterally nonhomogeneous condition can be found in the lower reaches of the Delaware and Raritan Estuaries in the United States. A vertically and laterally homogeneous (sectionally homogeneous) condition occurs in narrow estuaries in which salinity increases evenly toward the mouth.

2-6. Stratification Numbers. It is clear that the different types of estuaries are not well defined but are stages on a continuum, which is controlled by the ratio of river and tidal flow. As the estuary progresses from river to ocean, it may pass through several stages of estuary types. At the head of the estuary where tidal range is reduced and riverflow is large, a highly stratified salt wedge condition may result. Farther downstream as tidal amplitudes increase, turbulent mixing occurs, and a partially mixed estuary is created. As tidal flow becomes larger than riverflow, a vertically homogeneous situation may develop. Since these stages depend on riverflow, seasonal flow changes will influence the estuary and its varying stages.

a. Simmons Ratio. Simmons (1955) related flow ratio (the ratio of riverflow per tidal cycle to the tidal prism) to estuary type. When the ratio is 1.0 or greater, the estuary is highly stratified. When the flow ratio is 0.2 to 0.5, the estuary is partially mixed, and when less than 0.1, a well-mixed condition exists. Pritchard (1955) considers estuary depth and width to be factors controlling the flow ratio. As the geometry of an estuary changes, the flow ratio is affected, and the estuary type will also vary. Constrictions cause increased current velocities and produce well-mixed sections, while wider areas tend to be more quiescent and more stratified.

b. Ippen Number. Using the tidal properties of amplitude and phase, Ippen and Harleman (1961) developed a relationship between energy and estuary mixing. This stratification number is a measure of the amount of energy lost by the tidal wave relative to that used in mixing the water column. Increasing values of the stratification number indicate increasingly well-mixed conditions, and low numbers indicate highly stratified conditions. Changes in riverflow, width, and depth will influence the tidal properties, and accurate tidal measurements are necessary to use this method.

c. Hansen Parameter. Hansen and Rattray (1966) chose the parameters of salinity and velocity to develop a means of estuary classification and comparison. Two dimensionless parameters, stratification (ratio of the surface to bottom salinity difference divided by the mean cross-sectional salinity) and circulation (ratio of the net surface current to the mean cross-sectional velocity) are used to construct a diagram. The location on the diagram will identify the estuary stage on the continuous spectrum of estuary type. Type 1 is well-mixed (homogeneous) with net seaward flow at all depths. Type 2 experiences flow reversal and is a partially mixed estuary. Types 3 and 4 are stratified estuaries, type 3 the deep fjord type, and type 4 the intensely stratified salt wedge.

2-7. Flow Predominance. The concept of flow predominance is useful in understanding the effects of density-induced currents on velocites. In a conventional 12-hour plot of velocity versus time, velocity values will be positive (flood flow into the estuary) and negative (ebb flow out of the estuary) (Figure 2-3). To determine flow predominance, the area under the ebb portion of the curve (all negative values) is divided by the total area under the curve (ebb portion plus flood portion). The resultant, ebb predominance, is the percent of the total flow per tidal cycle that is moving in the ebb direction at a given velocity sampling depth. In a highly stratified estuary, the freshwater surface flow will always be ebb dominant, while the bottom salt wedge layer will be strongly flood dominant. Near the entrance of a well-mixed estuary, the bottom flow will be slightly flood dominant, while the surface will be strongly ebb dominant. Further upstream the flow will be ebb dominant throughout the entire depth. In a partially mixed estuary, the bottom flow will be mainly flood dominant within the salinity wedge, and the surface flow predominantly in the ebb direction. Examples of flow predominance in Savannah Harbor, Charleston Harbor, and the Hudson River are presented in "Field Experiences in Estuaries" by H. B. Simmons (Ippen 1966).

2-8. Null Point. Along with the concept of flow predominance is the realization that at some point the net flow may be balanced (no net flow in either direction). This point is called the null point.

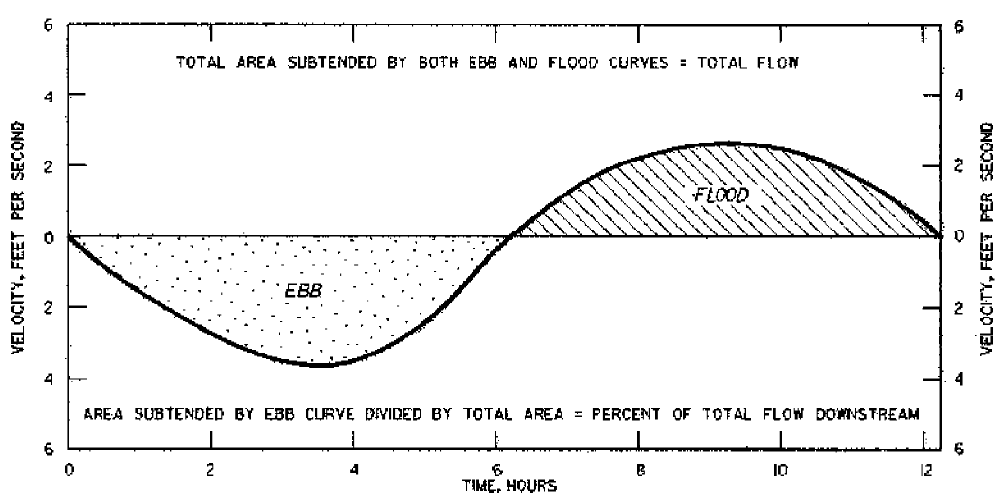

Figure 2-3. Definition sketch: flow predominance

2-9. Salinity Effects on Shoaling. Saltwater intrusion is important to estuary sedimentation because saline water enhances flocculation of suspended clay particles, and density currents tend to move sediments upstream along the bottom. Thus sediments entering the estuary may become trapped instead of moving out to sea. Frequently, shoaling occurs between the high-water and low-water positions of the upstream limit of salinity intrusion. The region most likely to experience heavy shoaling is the reach bracketing the 50 percent value (or null point) of the bottom flow predominance (Schultz and Simmons 1957) (Figure 2-4).

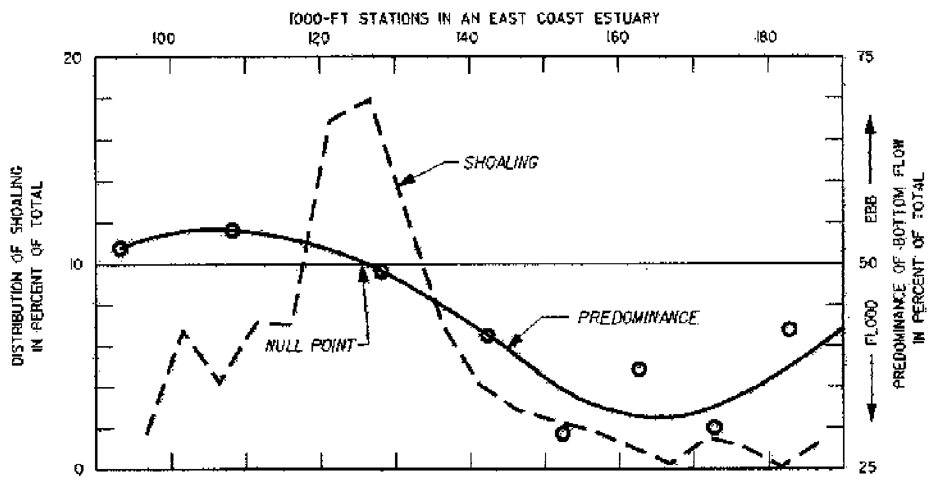

Figure 2-4. Relationship of shoaling and predominance of bottom flow

2-10. Summary. The classification of estuaries uses variables of topography, riverflow, and tidal action as factors influencing saltwater and freshwater mixing. Ultimately the salinity characteristics of an estuary determine the unique features of the system. No two estuaries are alike, but one can hope to find general principles rather than unique details to use when studying and comparing similar systems. Dyer (1973) describes in detail several estuaries with different topographies, tidal ranges, and riverflows, while Cameron and Pritchard (1963), Lauff (1967), and Ippen (1966) have tried to identify the relevant general principles governing estuarine behavior.

Section III. Tides and Other Long Waves

2-11. Tide-Generating Forces. To understand the effect of tides on an estuarine system, a brief comment should be made on the tidal-generating forces and rhythms.

a. Newton's laws of gravitation state that the force of attraction between two bodies is proportional to the product of their masses and inversely proportional to the square of the distance between their centers.

Tidal forces, acting on the surface of the earth, are less than gravitational forces and vary inversely with the cube of the distance between bodies. In our sun-moon-earth system, the sun is the largest body, but because its distance is so great from the earth, its influence on tides is only 46 percent of the moon's.

b. All forces in the sun-moon-earth system are in equilibrium; however, individual particles on the earth's surface are not. In this system of varying distances from each other and different rotation rhythms (the earth once every 24 hours and the moon around the earth once every 24 hours and 50 minutes), these tide-generating forces are never constant. These forces act on land, water, and air. However, the land mass is not as elastic as liquids, and air, although elastic, has such a low density that the effects of the tidal forces, although measurable, are small. The media most free to respond in an observable manner are the earth's water masses, the oceans. Tide-generating forces are the residual forces between attraction (earth/moon and earth/sun) and centrifugal force (due to the rotation of two bodies about a common axis). A detailed description of tidal theories can be found in Darwin (1962) and Defant (1958), and in a more readable form in Wylie (1979) and Marmer (1926).

2-12. Tide Terms. Several basic terms are used to describe tides. High water is the water-surface level at its highest extent during one cycle and is also used to denote the time at which it occurs. Low water is used in the same way for the lowest water level. Where there are two unequal high waters and two unequal low waters in one day, they are distinguished by naming them higher high water, lower high water, lower low water, and higher low water. A tidal current that is flowing landward is termed a flood current, while one flowing seaward is called an ebb current.

2-13. Types of Basic Tides. The basic tide is the cyclic rise and fall of the water surface as the result of the tide-generating forces. There are three types of tides--diurnal, semidiurnal, and mixed--which are a result of tide-generating forces and location on the earth.

a. Diurnal. A diurnal tide is one high and one low water level in a lunar day (24.84 hours). Diurnal tides predominate in the Gulf of Mexico, some parts of the Pacific Ocean, e.g., the Philippines, and certain places in Alaska.

b. Semidiurnal. Semidiurnal tides produce a tidal cycle (high and low water) in one-half the lunar day (12.42 hours) or two nearly equal tidal cycles in one lunar day. Semidiurnal tides occur along the east coast of the United States.

c. Mixed. Mixed tides are a combination of diurnal and semidiurnal characteristics and are found on the west coast of the United States. There is a marked inequality in the heights of the succeeding tides, especially low waters, and there is also an inequality in time. There are usually two high and two low waters each day. Typically, there is a high tide, then a low tide, followed by a scanty high tide and a moderate low tide.

2-14. Spring and Neap Tides. Due to the unequal rotational rhythms of the members of the sun-moon-earth system, their forces are periodically in and out of phase. Every 14.3 days (twice a month) the earth, moon, and sun are aligned in phase. At this time the gravitational forces reinforce each other to form higher than average tides called "spring tides." Also twice a month the moon and sun are at right angles to the earth and the forces are subtracted from each other to form lower than normal tides called "neap tides."

2-15. Influence of Moon and Sun. Another factor influencing the tide is the declination of the moon and sun--their angular distance north or south of the equator. The relationship of the earth's axis to the plane of its orbit around the sun results in an apparent yearly north-south movement of the sun. The plane of the moon's orbit is tilted also, and the apparent north-south migration across the equator occurs every 27-1/3 days. This monthly migration results in observable tidal changes. Figure 2-5 illustrates the differences in tides at various places for a month. During this month, spring tides (new and full moon) happen to occur when the moon is crossing the equator. Neap tides occur at the quarter moon, and apogee (moon furthest from the earth) and perigee (moon closest to the earth) effects are noted. The spring tide occurring at perigee is larger because of the increase in tidal forces. The tides at New York are semidiurnal with a strong spring and neap influence. Tides at Port Adelaide, Australia, go from mixed to semidiurnal when the moon is over the equator, while tides at Seattle, Washington, are mixed at all times. Tides at Los Angeles, California, and Honolulu, Hawaii, are diurnal during neap tide when the moon is south of the equator, semidiurnal during spring tide, and mixed at other times of the month. Tides at Pakhoi, China, are strongly diurnal except when the moon is over the equator.

2-16. Tide Prediction Tables. The National Oceanic and Atmospheric Administration (NOAA) annually publishes "Tide Tables, High and Low Water Predictions" (NOAA, year of interest). The four volumes include the entire maritime world and contain daily tide predictions for 198 reference ports and tidal differences and other constraints for about 6,000 subordinate stations. Each volume, which covers a different section of the world, contains tables for obtaining the approximate height of the tide at any time; local mean time of sunrise and sunset for every fifth day of the year for different latitudes; the reduction of local mean time to standard time; moonrise and moonset for a number of locations; the Greenwich mean time of the moon's phase, apogee, perigee, greatest north and south zero declination, and the time of the solar equinoxes and solstices; and a glossary of terms.

2-17. Tidal Constituents. The tide-producing forces exerted by the moon, sun, and other astronomical bodies are represented by mathematical expressions. There are over 128 tidal constituents used to represent the various wavelengths and frequencies found in nature (Schureman 1940).

2-18. Nonastronomical Forces. Nonastronomical forces can also produce waves. A tsunami, or seismic sea wave, is a very long wave originating from a

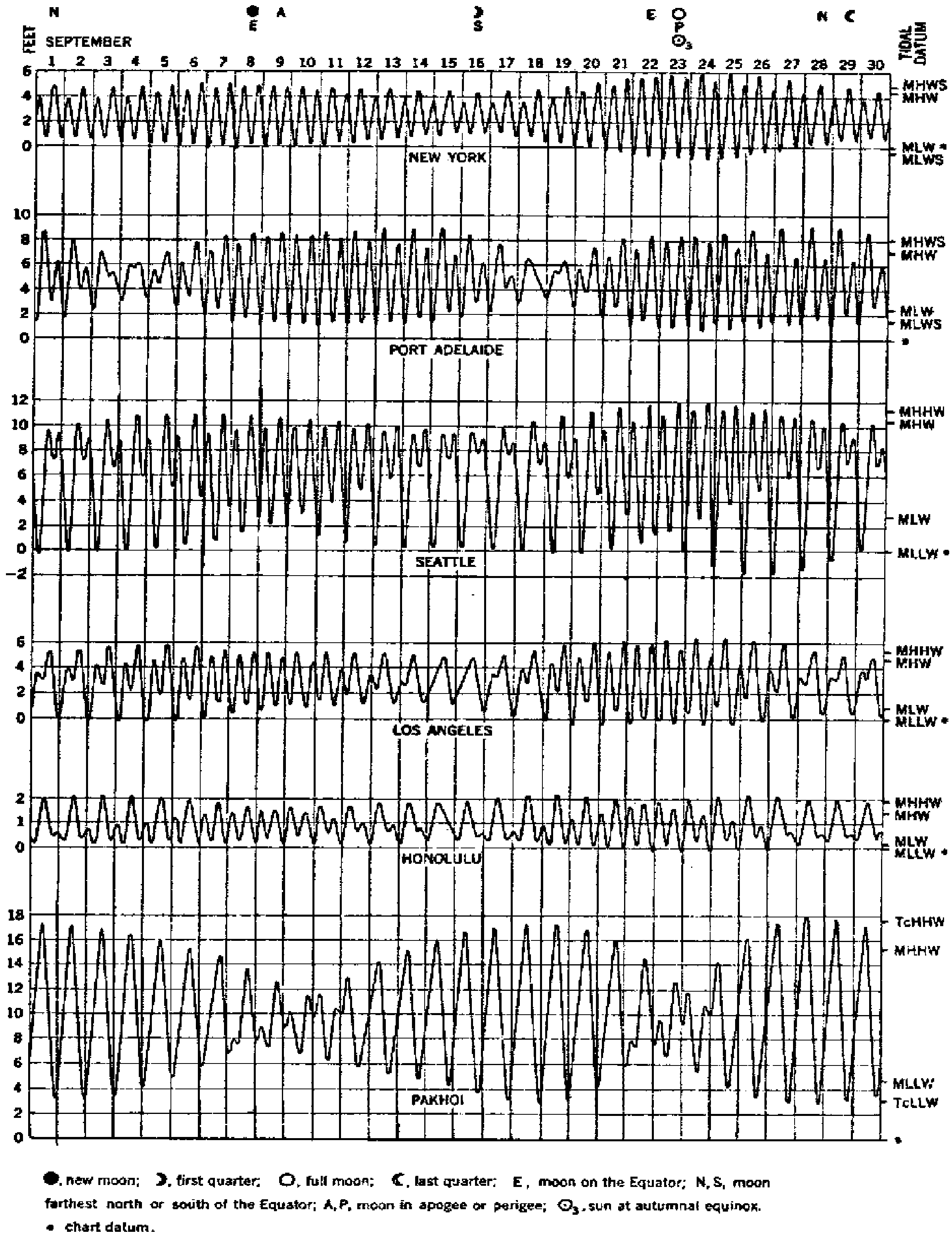

Figure 2-5. Variations in tides by location

disturbance in the seafloor. The wave train generated from such an event (earthquake, mud slide, volcanic explosion) contains huge amounts of energy and moves at high speeds. When it reaches shallow water and the shoreline, it can be extremely destructive. Other nonastronomical waves are produced by boat wakes, explosions, landslides, and any force that can disturb the surface of the water.

2-19. Waveforms. The tide may enter the estuary as a progressive wave manifested by the forward movement of the waveform. The current velocity and water-surface elevations in this waveform are in phase. As the wave progresses up the estuary, the waveform changes shape, the face steepening and the rear slope becoming more gradual. Areas of constriction increase the wave amplitude, and boundary friction is a means of energy dissipation. At some point in time, as the wave reaches the end of the estuary, it may be reflected and the interaction of the forward-advancing progressive wave and the returning reflected wave may produce a standing wave. In a standing or stationary wave, the current velocity and water-surface elevation are out of phase by 90 degrees. Most estuaries are intermediate, displaying characteristics somewhere between progressive and standing wave features.

Section IV. Winds and Wind-Generated Waves

2-20. General. Meteorological factors such as changes in barometric pressure and the uneven heating and cooling of the earth produce pressure differences that result in winds. Winds blowing across the surface of bodies of water transmit energy to the water, and waves are formed. The size of these wind-generated waves depends on the wind velocity, the length of time the wind is blowing, and the extent of open water over which it blows (fetch).

2-21. Wind Effects. The water surface absorbs energy from the wind and from smaller waves to form higher, longer waves. At any point in time, the resultant waves are the summation of all the waves passing through a given location. The concept of wavelength and period no longer applies in such an unsteady environment. Instead, a method of describing waves by means of their energy spectra is used. Tables have been developed relating wind description and its observed effects on the water surface to a classification system such as the Beaufort Scale and the International Code for state of the sea. Examples of these and information on other topics in this section can be found in many publications such as Bascom (1980).

2-22. Setup and Setdown. In addition to the creation of wind waves, wind can also cause a condition known as "setup" or "setdown." Wind stress on the water surface can result in a pushing or piling up of water in the downwind direction and a lowering of the water surface in the upwind direction. When the wind blows landward, water will set up against the land. This setup, superimposed on the normal tidal elevation, causes apparent higher than normal tides. This frequently produces flooding during storm events. A seaward wind will push water toward the sea and away from land, causing a lower than normal water level. When the wind stops, the setup or setdown water surface will return to normal levels. In enclosed waters, this return may occur as successive oscillations that are diminished by friction.

2-23. Seiche. If the surface of an enclosed body of water such as a harbor or bay is disturbed, long waves may be generated that will rhythmically slosh back and forth as they reflect off the opposite ends of the basin. These waves, called seiches, will travel back and forth until the energy is lost to frictional forces. The period of a seiche is dependent upon the size and depth of the basin in which it occurs. If an arriving wave train has a period similar to the natural frequency of a harbor, each arriving wave will increase the intensity of the seiche, producing rougher waters inside the harbor than on the surrounding sea.

2-24. Storm Surge. During a storm, there may be a substantial rise in the sea level along the coast called a "storm tide" or surge caused by wind setup, wave setup, and air pressure drop. The difference in pressure between an atmospheric low-pressure area and the surrounding high-pressure area causes the sea surface to "hump" under the influence of lower atmospheric pressure. The wind-generated storm waves superimposed on the normal tides and storm surge can have disastrous effects on shore structures and produce flooding of the coastal and inland areas.

Section V. Freshwater Inflow

2-25. Freshwater Sources. So far the topographic classification of estuaries, the astronomical tide-generating factors, and the meteorological and seismic wave-generating factors have been discussed. The final critical forcing function of an estuary is the amount of fresh water delivered to the system. This fresh water can be flow from the drainage basin of the river, ground water, discharge from dams and reservoirs, and rain falling on the water surface. The US Geological Survey (USGS), Water Resources Division, in cooperation with state and local governments, collects and disseminates hydrologic data of stream discharge or stage, reservoir and lake storage, ground-water levels, and the quality of surface and ground water. All data are stored in the USGS National Water Storage and Retrieval System (WATSTORE) and are available upon request to the USGS regional office or the USGS in Reston, Virginia.

2-26. Episodic Events. Episodic events that produce extreme quantities of water in a drainage basin can have a significant effect on the freshwater/salinity balance of an estuary. The seaward displacement of the salinity zone by sediment-laden fresh water will result in drastically different salinity and shoaling patterns.

Section VI. Changes in Sea Level

2-27. Sea Level Rise. Sea level rise refers to the rise in sea level or the apparent rise in the ocean surface when compared to a stable landmark. This, however, is a very general description for a more complicated event. The actual rise in the ocean is not one that is readily noticeable, especially when the average value varies 0 to +1 centimetre per year. The geologic record indicates that shifts in climate and the associated changes in sea level are attributed to the global freeze and thaw cycles. These trends are most noted in the Pleistocene Epoch, or ice age, when the ocean level was much lower due to the fact that much of the available water was frozen in the glaciers. Other events and factors can affect the rate of change:

a. The Greenhouse Effect. Overall global warming (postulated by the greenhouse effect) will cause thermal expansion of the seas and melting of snow and ice at increased rates and thus increase ocean levels. The greenhouse effect is not a part of the cyclic warming or cooling periods of natural weather patterns, but is related to man- influenced changes in the atmosphere and ozone layer. Future rates of change caused by warming are unknown.

b. Subsidence. Along coasts consisting of deposited materials, subsidence may occur due in part to consolidation of recent sediments. Subsidence may also occur due to man’s activities, such as withdrawal of oil, natural gas, and water, or by the additional weight of structures.

c. Tectonic Activity. Such events as earthquakes and crustal movements may in fact raise or lower coastal areas somewhat and as a result negate or magnify the rising sea level.

d. Geomorphology of the Area. Some coastlines are termed as sinking (such as the US east coast) whereas some are considered rising (US west coast). Few, if any, reliable measurements are available.

2-28. Apparent Sea Level Rise. Because of these and other factors, it would be more accurate to use the term apparent sea level rise since there is the possibility that the particular area in question may actually be subsiding. Additional reading on this topic can be found in most books dealing with oceanography, geology, and geomorphology.

Section VII. Summary

2-29. Classifying an Estuary. The classic definition of an estuary includes these three characteristics: semienclosed, free connection with the open sea, and fresh water derived from land drainage. These three characteristics govern the concentration of seawater; therefore, salinity is the key to estuarine classification. The mixing of fresh water and seawater produces density gradients that drive distinctive estuarine (gravitational) circulation patterns. These circulation and shoaling patterns differ with each estuary system according to the depth, tidal amplitude and phase at the mouth, and the amount of fresh water flowing into the basin. The tide that approaches the mouth of the estuary is the result of all the astronomical, meteorological, seismic, and man-made factors affecting amplitude and frequency of the wave. As the tide enters the estuary, it is greatly influenced by the river depth, width, and discharge. Tides exhibit wave behavior, usually as a combination of progressive and standing waves, with maximum flood velocity occurring 1-3 hours after high water. Superimposed on this tidal action is the freshwater/ saltwater interaction. Salt water will advance up a system until the tidal flow can no longer overcome the riverflow. Depending on the relationship between tidal flow and riverflow, the estuary can be classified by its salinity structure and resulting circulation patterns.