Excerpt from Fischer et al. "Mixing in Inland & Coastal Waters"

Chapter 7

Mixing in Estuaries

7.1 INTRODUCTION AND CLASSIFICATION

An estuary is where a river meets the sea. Pritchard (1967) has given a more circumscribed definition that "an estuary is a semienclosed coastal body of water which has a free connection with the open sea and within which sea water is measureably diluted with fresh water derived from land drainage." Our purpose in this chapter, however, is to describe mixing in a class of water bodies that do not necessarily fit Pritchard's definition, or any other strict definition of an estuary. We are concerned, for example, with mixing in a tidal bay, like perhaps San Diego Bay, which has so little fresh water inflow that there is no measurable dilution. We are also concerned with mixing in the tidal portions of rivers upstream of the maximum extent of sea water intrusion. The studies we describe are even applicable, to some extent, to mixing on some continental shelves well outside what might be called a semienclosed body of water, but where the effect of river water is still evident. Thus our definition of the bodies of water we are concerned with must be an operational one. In Chapter 5 we discussed mixing in a flow driven by the slope of the water surface; in Chapter 6 we discussed mixing in flows driven primarily by wind stresses and by internal density variations. The flows discussed in this chapter are driven by all three; the primary flow is usually driven by the slope of the tidal wave, but wind stresses and internal density variations are often important. In addition we add a new complication, the flow oscillates. The result is the complex, unsteady and spatially varying flow which we customarily see in what are broadly referred to as "estuaries." Our purpose is to give an account of how the various aspects of this flow lead to different types of mixing, to synthesize the results as best we can, and then to describe some practical methods for studying the distribution of pollutants.

Part of the difficulty in describing estuaries is that the term covers such a diversity of sizes and shapes. A method for classifying estuaries into categories would be helpful, but no single scheme has been found sufficient. Bowden (1967a) and Pritchard (1967) distinguished three major hydrodynamic categories; sharply stratified estuaries such as fjords and salt-wedge estuaries; partially stratified estuaries, in which there is a significant vertical density gradient; and well mixed estuaries (see Fig. 7.1). A second method of classification is geomorphological: coastal-plain estuaries; fjord type estuaries; bar-built estuaries; and the rest. Fjord-type estuaries are generally formed by glacial action; they are usually very deep, narrow, and highly stratified. Coastal plain estuaries are generally formed by the gradual drowning of a river system, and are usually long and narrow with many branches. Bar-built estuaries are formed by the closing off of an embayment by a sand bar, and are generally found along coasts with large littoral drift. "The rest" includes such large closed bays as San

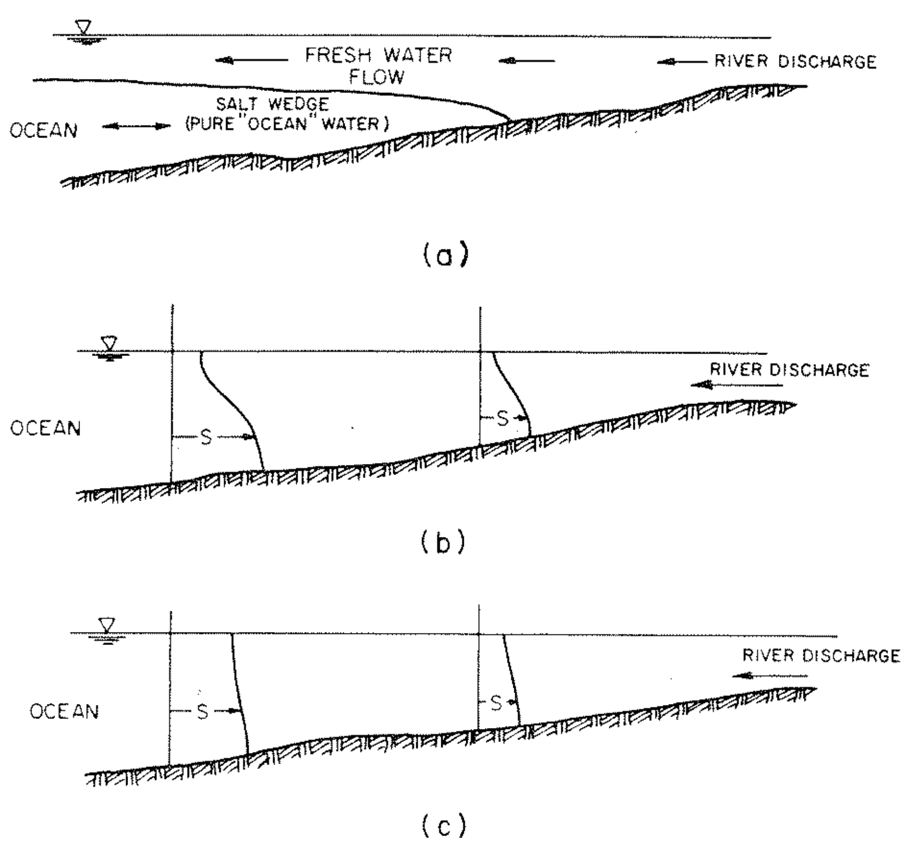

Figure 7.1 Salinity distributions along the axes of (a) a "salt wedge" estuary, (b) a "partially mixed" estuary, and (c) a well mixed estuary.

Francisco Bay, and estuaries formed by channels running across aluvial plains, such as the Columbia. A third possibility is to devise analytical methods of classification. Hansen and Rattray (1966) proposed a method based on the vertical variation of salinity and the strength of the internal density-driven circulation; some of their results are discussed in Section 7.2. A simple geometrical classification can be based on the ratios of length L, width W, and mean depth d. None of these schemes are able to express the unique characteristics of any estuary, however. Estuaries have individual personalities, made up of the distribution of sand bars, points of land, man made jetties and harbors, islands, deep channels, shallow bays, the characters of the tributary rivers, and the seasonal variation of the weather. Before doing a mixing study in an estuary it is best to get to know it.

This chapter begins with an enumeration of various causes of mixing in estuaries, and analytical treatments of them. We then discuss cross-sectional mixing and longitudinal dispersion in the same sequence as in the chapter on rivers, although with much less ability to give dependable results. We close with a discussion of the one-dimensional analysis as a practical tool. The discussion provides essential background to the descriptions of the use of numerical and physical estuary models in the next chapter.

7.2 THE CAUSES OF MIXING IN ESTUARIES

Mixing in estuaries results, as it does in rivers, from a combination of small-scale turbulent diffusion and a larger scale variation of the field of advective mean velocities. In rivers the combination is fairly simple, as explained in Chapter 5; the advective velocity field defines a set of approximately steady stream lines. The main role of turbulent diffusion is to transfer mass between stream lines, and longitudinal dispersion comes about mainly because the flow along different stream lines is going at different speeds. In estuaries we can also try to describe mixing in terms of advection by a mean flow along stream lines and turbulent diffusion between stream lines, but matters are nowhere near as simple as in rivers. The first problem is to differentiate diffusion from advection. If a current meter is held at a fixed point in an estuary and a long record is examined, spectral analysis can disclose fluctuations with a wide range of period. Fluctuations with a period of less than a few minutes can be identified as turbulence, and the transport resulting therefrom can be termed diffusive transport, just as we have done in rivers. The term "advection" can then be assigned to the remaining motion. The advective velocity is not constant, however, either in time, space, or direction. The velocity record obtained at a single point will contain semidiurnal and diurnal tidal variations, wind-induced variations of almost any period, an inertial frequency caused by the earth's rotation, and fluctuations of longer periods caused by the monthly and longer term variation of the tidal cycle and by seasonal variations of meteorological influences and tributary inflows. The direction of the velocity vector will often not be parallel to the channel axis, even if one can be defined. Often the flow is going in different directions at different depths; often the flow is one way near the shore and the opposite way in the center of the channel. Obviously, the analysis of mixing in terms of the interaction of advection and diffusion is much more complicated in estuaries than in rivers.

The proper way to begin seems to be to make things as simple as possible by considering different mechanisms in turn. Most of what is seen in an estuary can be related to one of three sources, the wind, the tide, and the river. Most of the analyses to be found in the engineering technical literature discuss the effect of only one or at most two sources, for example the current driven by the wind in a tideless bay or the circulation driven by the river inflow in a tideless estuary. Taking the literature as a guide, the next three sections discuss in turn the isolated effects of wind, tide, and river. In each case we will discuss qualitatively why and how the source causes mixing, and will quote what analytical results can be found. Later, in Section 7.4, we attempt an analytical synthesis based on a decomposition of the salinity and velocity profiles.

7.2.1 Mixing Caused by the Wind

Wind is usually the dominant source of energy in large lakes, the open ocean, and some coastal areas, but in estuaries it may or may not play a major role. Breaking waves, the most apparent result of wind, have little to do with large scale dispersion. In a long, narrow estuary the flow may be predominantly tidal, and the wind has little chance to generate much current. On the other hand, if the estuary is wide, or consists of a series of bays, wind stresses can generate currents of considerable importance. The wind exerts a drag on the water surface, and will pull floating objects, or even floating pools of oil or warm water, in the wind direction. Thus the dispersion of an oil spill is directly affected by the local wind. On the other hand, if a dissolved substance is distributed throughout the water column and vertical mixing is vigorous what matters is the mean motion of the water column. Thus the effect of wind depends primarily on the currents induced.

Suppose that a uniform wind blows over a wide, shallow basin containing water of constant density, and that the basin is deeper on one side than on the other. The resulting current is demonstrated by the laboratory photograph shown in Fig. 7.2; on the shallow side the current flows with the wind, and on the deep side it flows against the wind. By "current" we mean the vertically averaged mean flow; there is also a vertical velocity profile, not apparent in the photograph, such that the surface velocity is somewhat more in the direction

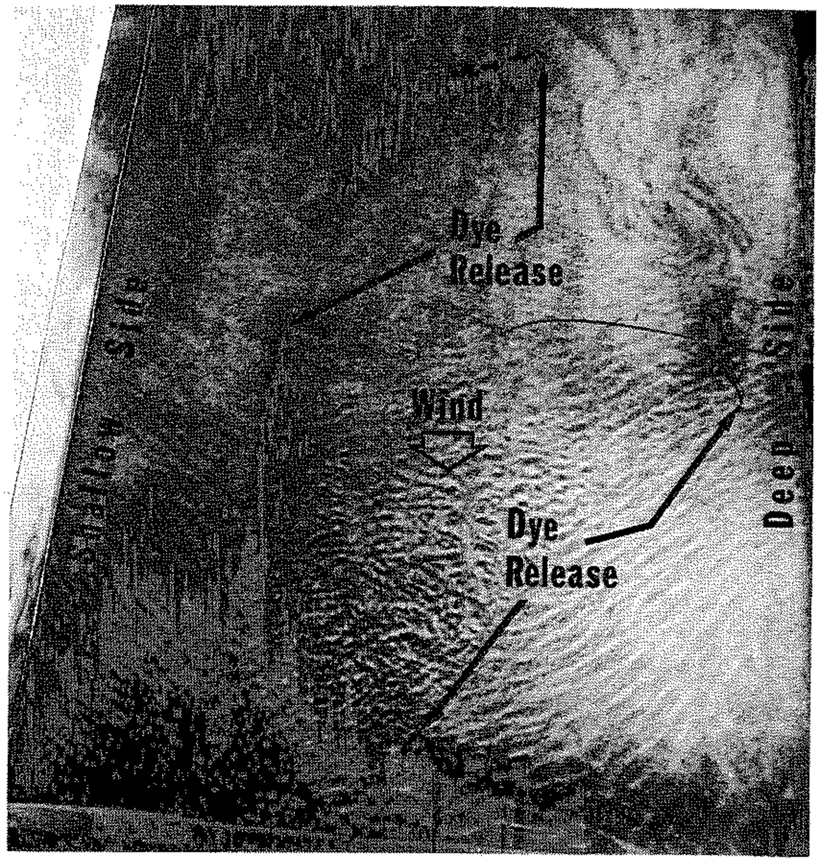

Figure 7.2 A rotational current caused by a uniform wind blowing over a basin of variable depth. The wind is blowing from the top of the picture towards the bottom at a velocity of 4.5 m/sec. The basin is 0.3 cm deep on the left side, sloping uniformly to 5 cm deep on the right side. Four dye plumes can be seen, each released from near the bottom. The plumes show that the flow is in the form of one nearly circular rotor extending throughout the basin. [Photo by R. Spigel, from Fischer (1976a).]

of the wind than the mean flow. The vertical velocity profile causes dispersion around the position of a particle traveling with the mean velocity, for the reasons explained in Chapter 4, and the circulatory current may be viewed as a larger scale mixing mechanism which will be additive to any other mixing mechanisms present because of other sources. For example, if an estuary has a deep channel alongside a shallow embayment, as illustrated in Fig. 7.3, the wind-driven steady circulation in the shallow bay will interact with the tidal current in the channel, and a complete analysis of mixing will have to account for both causes.

The simplest explanation for the current illustrated in Fig. 7.2 is as follows. The wind induces an approximately uniform stress everywhere on the water surface (estimates of the magnitude of the wind stress are given in Section 6.2.1). Therefore the line of action of the wind-induced force is through the centroid of the water surface. The center of mass of the water in the basin is displaced towards the deeper side, since there is more water there. Hence the line of action

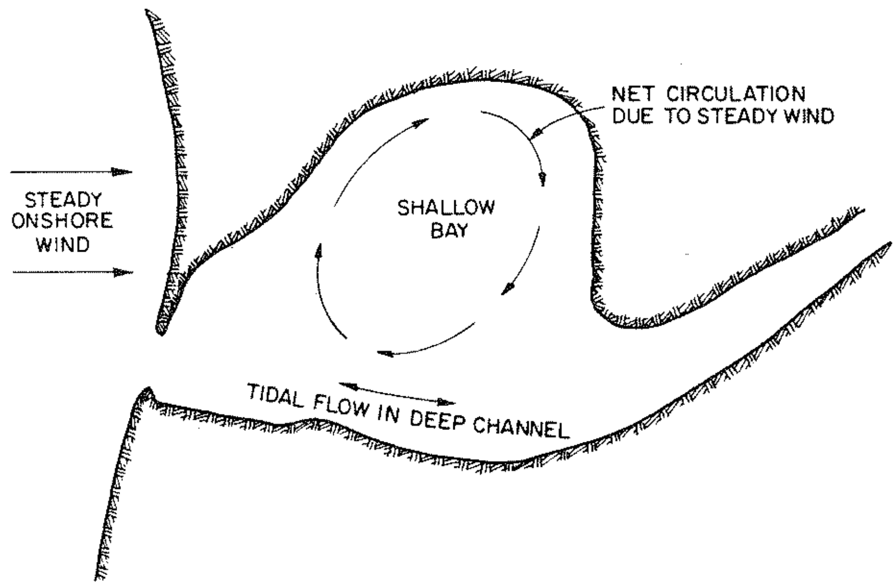

Figure 7.3 A sketch of a steady wind-driven circulation superposed onto the tidal flow in an estuary.

of the force passes on the shallow side of the center of mass of the water, and a torque is induced causing the water mass to rotate.

A more detailed prediction of wind-induced currents, and an examination of transient flows when the wind velocity changes, requires a solution of the equation of motion for the water. Usually the equations are averaged over the vertical, and the resulting depth-integrated two-dimensional equation of motion is solved numerically using any of a number of computer programs. A particularly well documented method is that of Leendertse (1967); some computations of wind-driven currents are illustrated in Fig. 8.1.

7.2.2 Mixing Caused by the Tide

The tide generates mixing in two ways. Friction of the tidal flow running over the channel bottom generates turbulence and leads to turbulent mixing, and the interaction of the tidal wave with the bathymetry generates larger scale currents. Efforts to quantify the rate of turbulent mixing are discussed in Section 7.3; here we discuss the effects of the larger scale currents. These include shear flow dispersion similar to that found in rivers, and in addition other circulations which we will classify by the terms "pumping" and "trapping" and discuss in detail below.

7.2.2.1 The Shear Effect in Estuaries and Tidal Rivers

The most obvious characteristic of tidal flow in most estuaries is that the flow is like a river, but goes back and forth. In Chapter 5 we showed how to apply shear flow dispersion theory to rivers, and in Section 4.3 we showed analytically