CHAPTER 6

CIRCULATION IN ESTUARIES [1]

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In discussing the circulation in estuaries, an apparent paradox must always be kept in mind. In the first place the problems of estuarine circulation are unique, being different from the problems of the open sea, and from the problems of river hydrology. Estuarine circulation and related problems consequently constitute a valid field for investigation. In contrast to this viewpoint is the tremendous range of conditions found in various estuaries - no two are alike. This inherent variability of estuaries discourages generalizations about the circulation.

The paradox thus lies in the recognized fact that estuaries are similar enough to constitute an integrated field of investigation, but at the same time estuaries are so different in details that generalizations are dangerous. The state of our knowledge is still so imperfect that one is never certain whether a general principle or a unique detail is being studied. Therefore it is difficult and sometimes impossible to apply methods which have been found useful in one estuary as the basis for predictions in others.

When asked to present a paper "summarizing the present state of the art and science" it seemed particularly important to attempt to classify our knowledge so as to indicate, on the one hand, principles which are generally applicable and tend to make estuaries similar, and, on the other hand, to contrast the circulation in various estuaries so as to indicate the wide variety of differences which may be encountered. Since our knowledge is meagre, this can be done only in a qualitative way.

Let us first consider what is meant by an estuary. Many definitions have been given, but one suggested by Pritchard (1952a) seems particularly applicable to studies of the circulation. "An estuary is a semi-enclosed coastal body of water having a free connection with the open sea and containing a measurable quantity of sea salt." The most common type of estuary is one in which the enclosed water is fresher than that of the open sea, since the increments of fresh water from precipitation and runoff exceed the loss of water by evaporation. Such locations have an estuarine type of circulation. In some enclosed bodies of water evaporation exceeds precipitation and runoff, and the water becomes more saline than that of the open sea. These may logically be included among estuaries, since the same processes must determine their circulation, even though everything is working in reverse. Redfield (1951) has called the

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circulation in this type of embayment anti-estuarine. Little is known about anti-estuarine circulation (Collier and Hedgpeth, 1950) and the remainder of this paper will deal only with the positive type.

Among the positive type of estuaries in which the water within the estuary is fresher than pure sea water, three major types can be enumerated. The drowned river valley is the common type of estuary of the Atlantic and Gulf coasts. For example, the Delaware, Hudson and Chesapeake Bay systems are drowned river valleys. These estuaries are generally shallow relative to their width and have a tidal range which is substantial in proportion to the total depth. The sides of the estuary slope gradually in a shallow V shape and the surrounding coast is relatively low.

The Scandinavian coasts and the coasts of northern United States and of Canada are frequently indented by fjord type estuaries which present many contrasts. The depth is great relative to the width of the estuary, being not uncommonly equal to the width. There is frequently a sill at the entrance which isolates the deeper water within the estuary from coastal water at equal depths. The estuary is steep sided giving essentially a U shaped trench in contrast to the shallow V shape of the drowned river valley. The total depth of water is generally great relative to the range of tides.

Estuaries may also be formed by the development of an offshore barrier beach, having a narrow entrance to an enclosed bay. Such estuaries are found along the south shore of Long Island, and along our Southern Atlantic coast. The largest estuary of this sort on the Atlantic coast is the Pamlico Sound system in North Carolina. In general these estuaries are even more shallow relative to the width than are the drowned river valleys. However, the entrance to the sea is generally so narrow that the tidal wave is damped and consequently the range of tides in such estuaries is not as great in proportion to the total depth as it is in the drowned river valley. The wave may indeed be sufficiently damped so that within the embayment no predictions of tidal variations are possible.

In each of the above categories, estuaries of various sizes and shapes will be found. It is this variation which discourages generalizations about the circulation in estuaries. All of the positive type estuaries, however, have the following properties in common:

1. Fresh water additions exceed evaporation. The principle of the continuity of volume requires that the circulation remove the excess fresh water at a rate which, over a period of time, equals the rate of addition.

2. There is a gradual increase of salinity from the source of fresh water to the sea. As the salt content increases a greater volume of mixed water must move out in order to transport a unit

volume of fresh water seaward. The principle of continuity of salt requires that the circulation provide enough sea salt to maintain the salinity distribution and to balance the salt removed.

3. The volume of water within the estuary varies periodically with the stage of the tide.

4. The currents within the estuary vary periodically with the stage of the tide. These currents are directly related to the tidal change in volume, though in some locations the relationship may be obscure and unpredictable.

5. Net movements of water, or non-tidal drifts, result from inequalities in the direction, velocity or duration of flood and ebb tidal currents.

The circulation of water is the net result of two processes operating simultaneously and in three dimensions. These are advection and turbulent mixing. Advection is the mass transport of water, whereas turbulence involves random motions of water and the resultant intermixture of adjacent waters. Theoretically, at least, either one of these processes alone could produce a circulation in an estuary which would satisfy the requirements of the continuity of volume and the continuity of salt. Actually the two processes are combined in various ways to produce the diversity of circulation patterns which is so apparent and troublesome to students of estuaries.

To show the range of conditions which may be found in different estuaries the salinity variation with distance for four examples is plotted in Figure 1. In all cases the salinity increases along the length of the estuary, but the shape of the distribution curve is quite different. The ratio between the volumes of water entering the two ends of the estuary during each tidal cycle is informative in connection with this figure. In the Bay of Fundy, where the salinity increases so rapidly, the tidal flow exceeds mean river flow by a factor of about 900. This factor is about 300 for the Raritan system, 150 for the Delaware and the two volumes are nearly equal in the Connecticut. As this ratio decreases the change of salinity with distance becomes more gradual in the upper end of the estuary. It seems probable that the ratio of these two volumes will have a direct effect on the pattern of salinity distribution in all estuaries, though the circulation can be determined by so many combinations of the turbulent and advective processes that no simple relationship can be expected.

Let us consider first the advective processes, neglecting for the moment the horizontal transport resulting from turbulent mixing. In order to remove the fresh water increment there must be a net transport seaward. As the water moves seaward there is continuous admixture of more saline water, and the gross seaward transport of water must increase

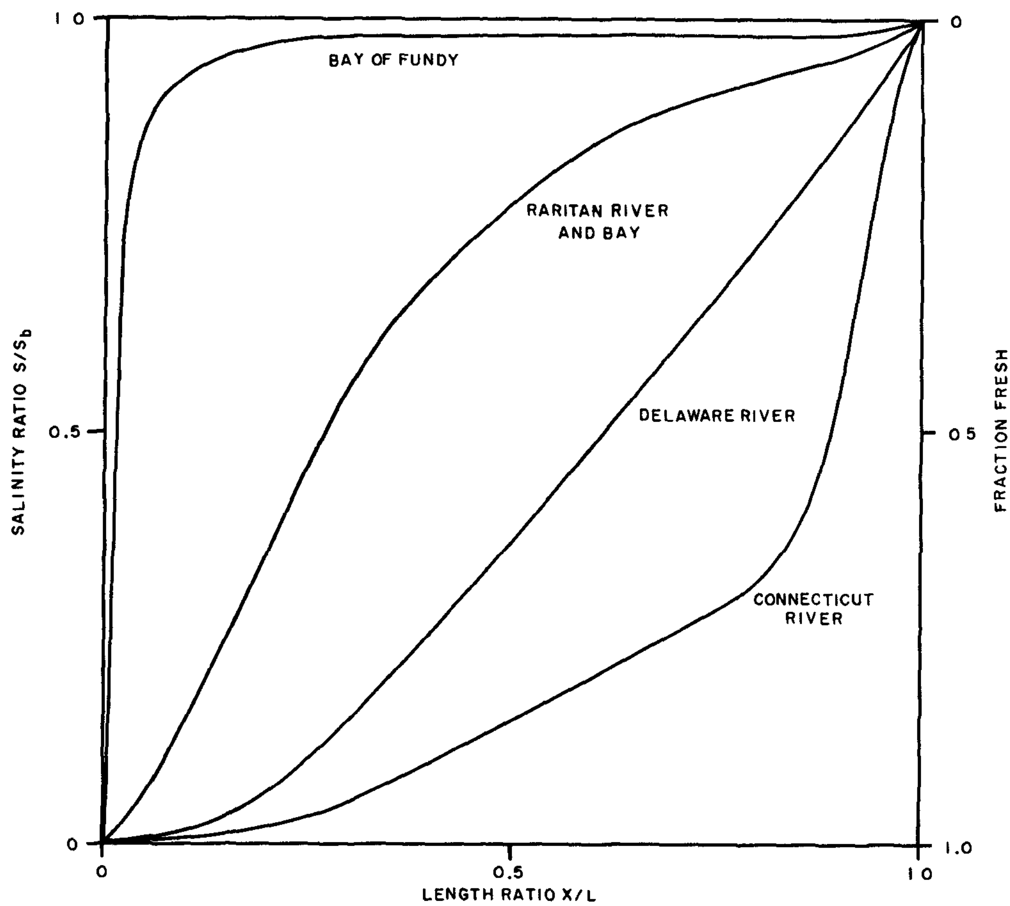

Fig. 1. The distribution of salinity along the length of four estuaries. Data for Delaware Bay from Mason and Pietsch (1940); for Connecticut River from Howard (1940).

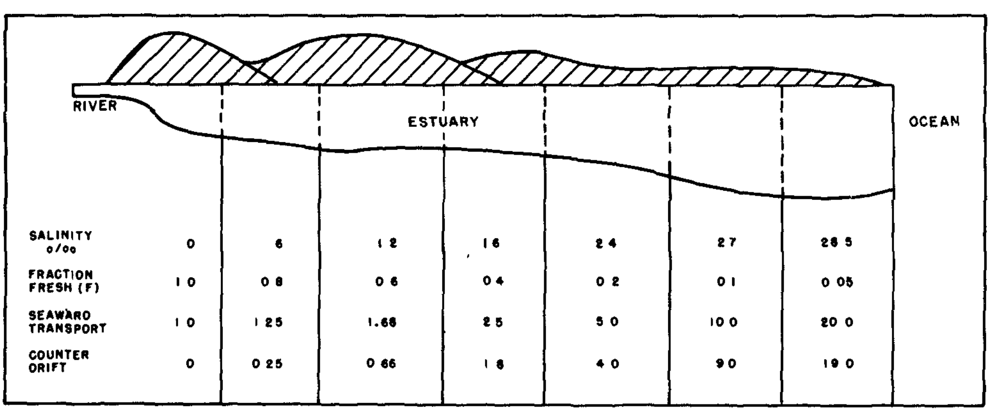

Fig. 2. The changes in mean salinity and in the volume of water which must be transported in order to maintain the steady state distribution in a hypothetical estuary.

directly in proportion to its salt content. At the same time a landward transport of salt must take place to satisfy the salt balance. For example, where the mixture contains half sea water and half fresh water two volumes must move seaward in order to carry one volume of fresh water seaward. A direct consequence of this simple relationship is that the total circulation in the estuary increases enormously in volume as the water moves from the river towards the sea. This is illustrated in a diagrammatic way in Figure 2 which shows the increase in seaward transport of mixed water and the compensating landward transport of salt, expressed in terms of the equivalent volume of pure sea water.

These seaward and landward advective transports may be separated vertically to produce two or three layered flow systems, or they may be horizontally separated. In still other cases there may not be a division into two distinct advective drifts, so that the horizontal transport in one direction must be due to rather large, horizontal mixing processes.

The relative importance of the advective and turbulent mixing processes has been assessed by Pritchard (1952) in the estuary of the James River. In this location the two most important processes were horizontal advection and vertical random mixing. Of secondary, but significant, importance was the vertical advection and lateral random mixing related to the change in width of the estuary with depth. Horizontal random mixing was negligible. The horizontal advection in this case was clearly separated into two layers, with a net seaward transport in the surface and a net landward transport in the deeper layer. Pritchard's measured tidal currents as a function of depth, and the resultant non-tidal drifts are shown in Figure 3.

As mentioned above there may be no separation of the system into two clear advective drifts such as those observed in the James River. As an example of such a case Table I presents the transport of water by the ebb and flood tidal currents in the mouth of the Raritan River. At this location both the surface and deeper water showed seaward non-tidal drifts, and no landward countercurrent was found. The seaward drift calculated from the river flow and the mean fraction of fresh water in the section indicates a volume of gross seaward transport intermediate in magnitude between the surface and deeper transports. In such a case turbulent mixing must be the mechanism which provides the salt required to maintain the salt balance.

The admixture of salt water into the system as the water moves seaward is clearly an important process. Two sets of evidence are available to indicate that the rate of admixture is correlated with the velocity of the tidal currents. These are given in Figure 4. The left-hand figure is from Tully (1949) who was describing the circulation in Alberni Inlet, a fjord type estuary where the deepest layer was essentially completely isolated from a two layered surface system. This shows that the total admixture of salt, whether it resulted from turbulence or from vertical advection, into the surface layers is directly

Table I

Tidal Excursions and Non-Tidal Drifts in Mouth of Raritan River
Negative values indicate seaward motion
(feet per tidal cycle)

Surface:-	Excursion on Flood	$+12.1 \times 10^3$
	Excursion on Ebb	-26.8×10^3
	Non-tidal drift	-14.7×10^3
Bottom:-	Excursion on Flood	$+16.5 \times 10^3$
	Excursion on Ebb	-22.1×10^3
	Non-tidal drift	-5.6×10^3

Average Non-Tidal Drift Calculated from Salinity:

$$NTD = \frac{-R}{FA} = \frac{-23 \times 10^6}{0.12 \times 27 \times 10^3} = -7.1 \times 10^3$$

Where R = River flow (cubic feet per tidal cycle),
F = Average fraction of fresh water,
A = Cross sectional area.

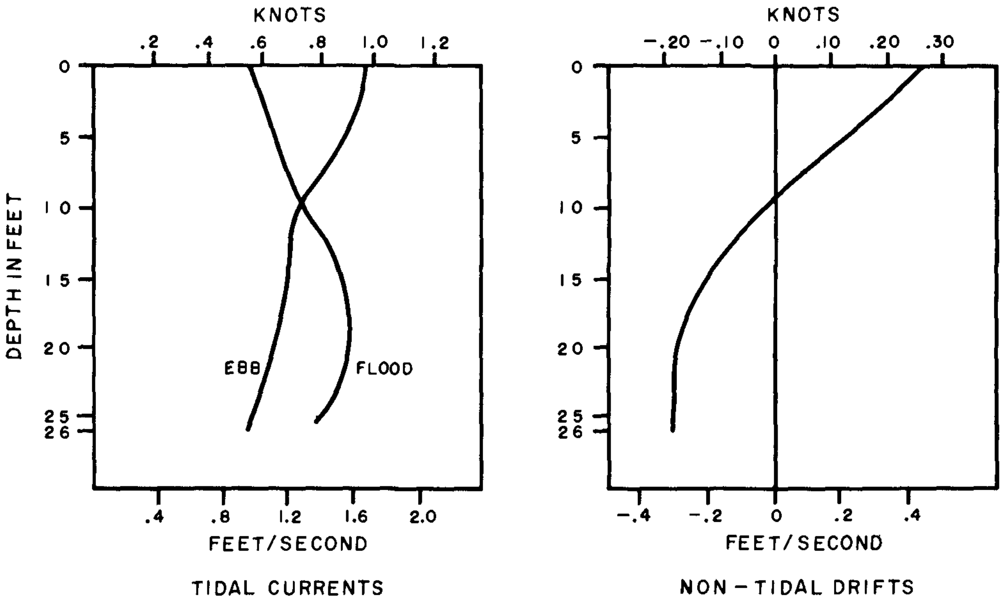

Fig. 3. Tidal currents and non-tidal drifts observed by Pritchard (1952) at various depths in the James River.

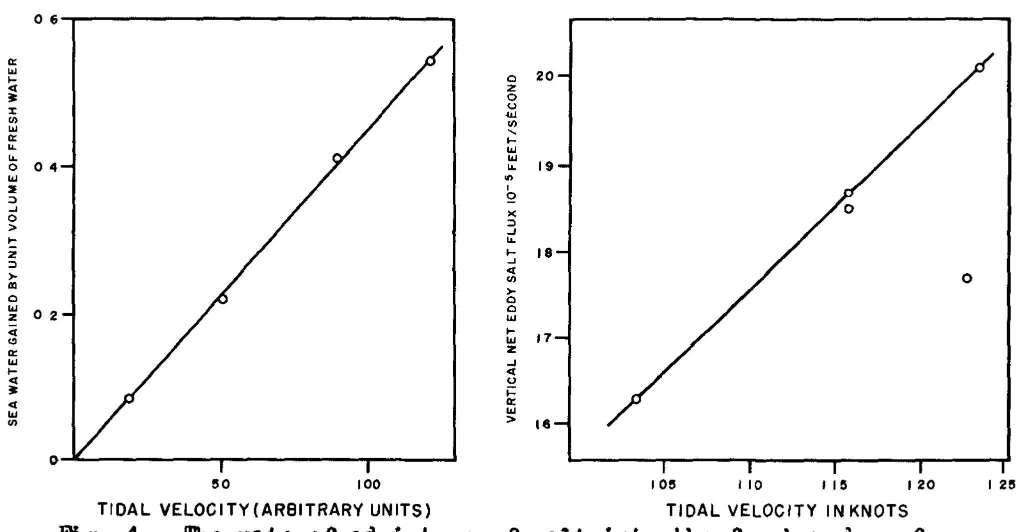

Fig. 4. The rate of admixture of salt into the freshened surface water in Alberni Inlet (at left, Tully, 1949) and in the James River (at right, Pritchard, 1952).

related to tidal velocity. The right-hand figure is from Pritchard's (1952) analysis of the James River, and shows that the random eddy flux, excluding the admixture of salt due to vertical advection, is a direct function of tidal velocity. These relationships between salt entrainment and tidal flow emphasize the importance of tidal currents in effecting the mixing between salt and fresh water.

As the estuary widens the seaward drift of freshened water may be horizontally separated from the landward counter drift. The distribution of salinity in Raritan Bay just off the mouth of the Raritan River illustrates this condition (see Figure 5). A similar effect is shown in Figure 6 for Mount Hope Bay. This effect is the result of the rotation of the earth, and is generally found in the wider parts of estuaries. Even in the narrow parts the effect may be present, but the change from one side to the other is so small that it frequently cannot be detected. In localities where additional river flow enters a bay along one side the distortion of the salinity distribution may be augmented, as it seems to be in the Chesapeake Bay (Pritchard, 1952) and in the Bay of Fundy (Ketchum and Keen, in press), or it may be decreased or completely obliterated, as seems to be the case in the lower Delaware Bay (Mason and Pietsch, 1940).

So far, we have been talking of estuaries in which mixing between salt and fresh water occurs throughout the length of the estuary. We have mentioned cases in which the landward counter drift and the seaward drift are separated vertically or horizontally, and in which only one advective drift can be identified. There are, of course, other possibilities. Tully (1949) clearly describes in Alberni Inlet, a case in which three layers are identifiable, the deepest being essentially isolated from the upper two. Farmer and Morgan (1953) will discuss in the next paper the salt wedge, which is a special case of two layer flow in which vertical mixing is very slight. There is evidence that in some estuaries intense mixing takes place in a certain region and that little additional mixing occurs as the freshened water flows seaward. Hachey (1934) has studied localized mixing phenomena in a small model and applied the results to the conditions in the upper end of Passamaquoddy Bay. There he finds a surface fresher layer mixing with a deep saline layer to produce an intermediate layer of intermediate properties.

In the Strait of Juan de Fuca - Strait of Georgia system in the Pacific Northwest, the San Juan islands, combined with rapid tidal flows, appear to provide a similar localized mixing. The resultant water masses and their distribution are shown in Figure 7. In this case water from mid depths of the Pacific Ocean enters through the Strait of Juan de Fuca unchanged until it is mixed with surface water from the Strait of Georgia in the San Juan channels. This mixed water then becomes the deep water of the Strait of Georgia and the surface water of the Strait of Juan de Fuca (Redfield, 1950). The volume of water flowing into the system from the Pacific Ocean in the countercurrent is about 15 times greater than the volume of fresh water introduced by the rivers. This

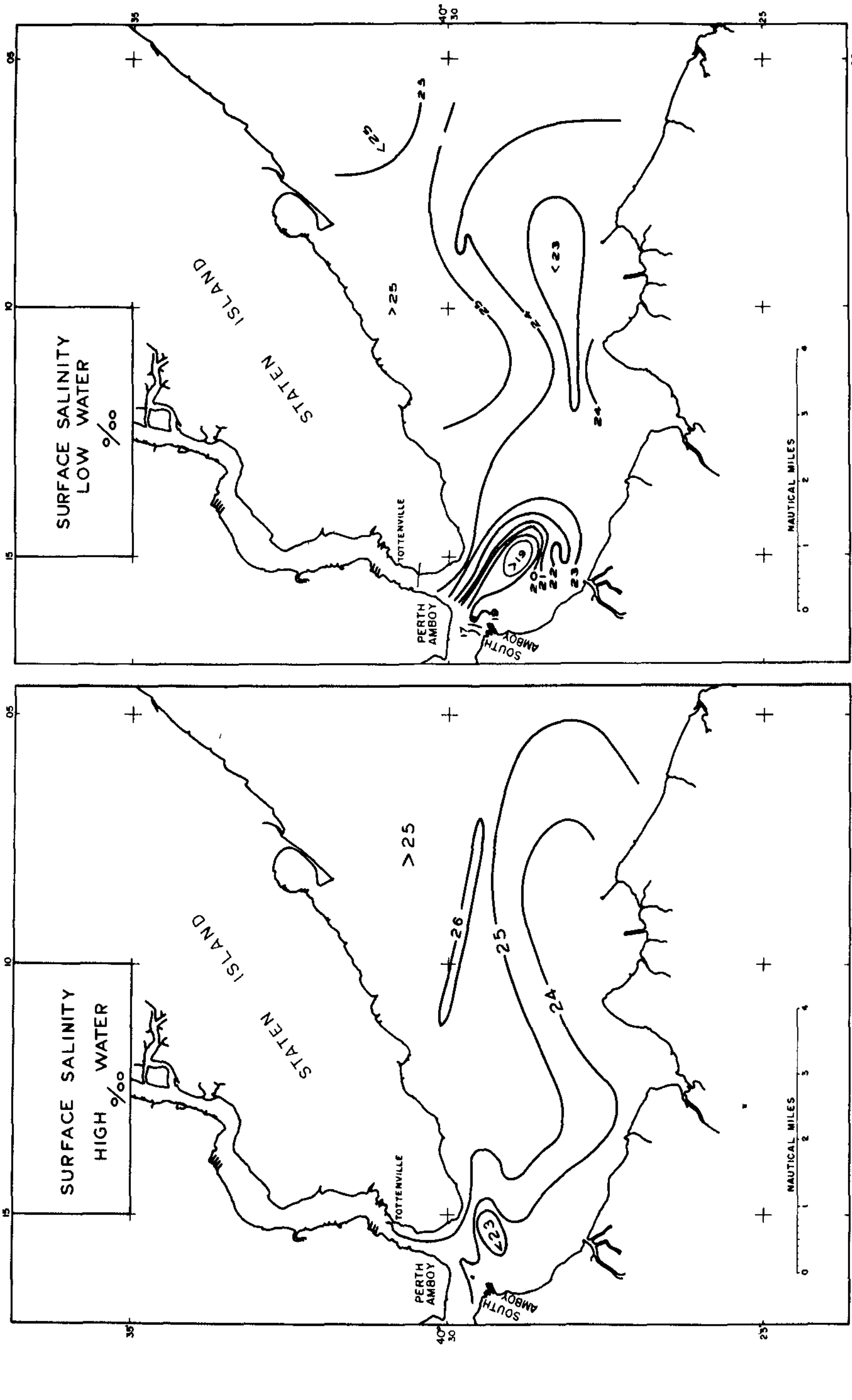

Fig. 5. Surface distribution of salinity at high and at low tide in Raritan Bay.

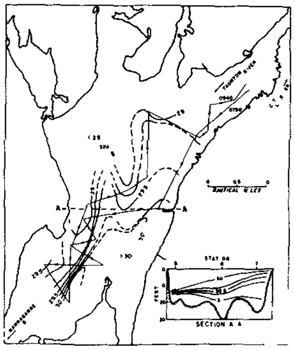

Fig. 6.

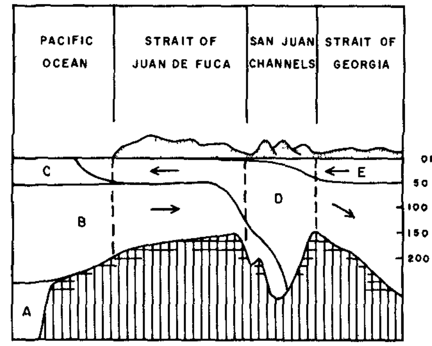

Fig. 7.

Fig. 6. Surface distribution of salinity in Mt. Hope Bay, and a cross section showing the slope of the isohaline surfaces.

Fig. 7. Diagrammatic chart of the distribution of various water masses in a section running from the Pacific Ocean through the Strait of Juan de Fuca to Georgia Strait (after Redfield, 1950).

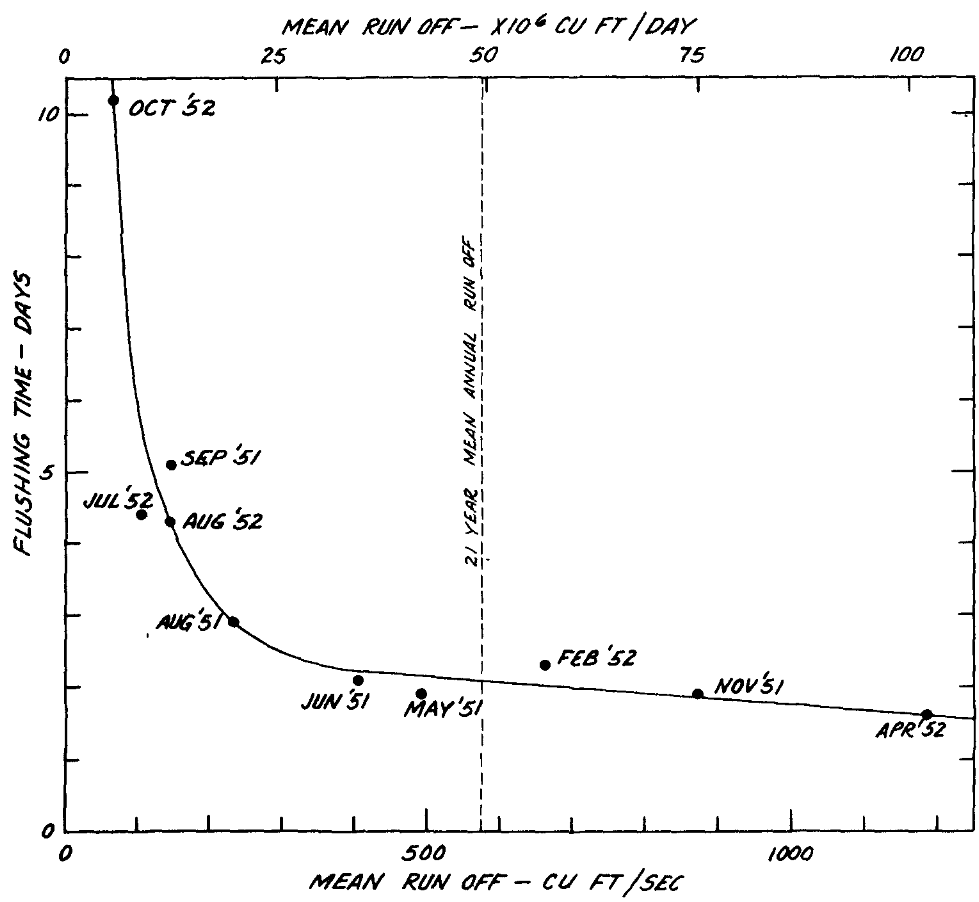

Fig. 8. The relationship between flushing time and river flow in Boston Inner Harbor (after Bumpus, 1952).

is a case of three layered flow in which all three layers have an active part in the circulation.

The importance of the tides as the effective force producing mixing has been emphasized. Empirical predictions of the distribution of fresh and salt water which are based upon the concept of tidal mixing have been shown to be applicable to a variety of estuaries (Arons and Stommel, 1951; Ketchum, 1951, 1951a; Ketchum and Keen, in press). What effect does variation in river flow have upon the circulation? Obviously increased river flow requires an increased transport of fresh water through each part of the estuary. This could be accomplished by increasing the fraction of fresh water in the mixed water which moves seaward, which would result in the movement downstream of the whole pattern of salinity distribution. It could also be accomplished by a more rapid circulation of the water with essentially no change in the salinity distribution. Once again both phenomena exert their influence. In the upper reaches of the estuary the rate of the circulation appears to increase as the river flow increases. Bumpus (1952) has determined the accumulation of fresh water in Boston Harbor and shows that the flushing time decreases from about ten days during low flow to about two days at the mean annual rate of flow. Further increases in runoff had only a slight additional effect on the rate of the circulation. His results are given in Figure 8.

As the water moves seaward, however, the fresh water is a smaller and smaller proportion of the mixture, and the effect of changes in fresh water volume is similarly decreased. In the offing of the Hudson River, for example, where the volume of sea water was about 100 times greater than the volume of fresh water in the mixture, variations in river flow had no measurable effect on the flushing time (Ketchum, Redfield and Ayers, 1951). It seems likely that river flow will, in all estuaries, have a direct effect on the rate of the circulation in the upper reaches, and a progressively smaller effect in the seaward region where the mixture moving seaward contains so much more sea water than fresh.

This paper has attempted to indicate the fundamental similarities in estuaries, and to point out the wide variety of detail in circulation which may be expected. It seems probable that the examples cited are isolated pieces of a continuous range of conditions extending from one extreme to the other. This is almost certainly true of the vertically stratified estuaries. In temperate latitudes, at least, the same geographical estuary can change from the vertically homogeneous type to the vertically stratified type at different seasons of the year as a result of changing runoff and temperature. As yet no unified theory is available which is comprehensive enough to permit application to a wide variety of conditions, though some success in interpreting quasi semi-state conditions in particular estuaries has been achieved. The recently expanded interest in estuarine circulation promises great advances in the art and science of such studies in the future.

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