SALINITY DISTRIBUTION AND CIRCULATION IN THE CHESAPEAKE BAY ESTUARINE SYSTEM[1,2]

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ABSTRACT

The salinity distribution in a coastal plain estuary governs the dynamic structure. In the estuaries studied, the salinity increases with depth, the salinity-depth curve having the general shape of an inverse tangent function. Though there is a layer of relatively rapid increase in salt content with depth, separating an upper less saline layer from a lower more saline layer, this halocline is still sufficiently weak to allow a downward random flux of fresh water as well as an upward random flux of salt. The longitudinal salinity gradient is approximately uniform with depth. The salinity is on the average higher on the right side of the estuary (looking downstream) than on the left.

Superimposed upon the oscillatory tidal motion there is a net circulation in which the upper less saline layer moves seaward and the lower more saline layer moves up the estuary. The boundary between the two layers of net flow has a slight lateral slope, being deeper on the right side of the estuary than on the left.

As a result of considerations of the salt balance, a net upward vertical motion is implied. A combination of the concepts of salt continuity and volume continuity allow the successful computation of the mean net horizontal velocity in the two opposite flowing layers.

INTRODUCTION

The Chesapeake Bay and its tributary estuaries may be classed in a group of coastal indentations called coastal plain estuaries. This type of estuary has been formed by the drowning of a former river valley either as a result of subsidence of the land or of a rise in sea level. This body of water, into which rivers empty, takes the shape of an elongated indentation of the Atlantic Coastline. The depths are relatively shallow, so that mixing of at least moderate magnitude extends to all depths.

The analysis to be presented here is based upon a series of extensive surveys of the physical and chemical properties of the waters of Chesapeake Bay and its major tributaries. The data were collected

[1] Contribution No. 6 from the Chesapeake Bay Institute.

[2] Results of work carried out for the Office of Naval Research of the Navy Department, the State of Maryland (Department of Research and Education), and the Commonwealth of Virginia (Virginia Fisheries Laboratory), under contract with The Johns Hopkins University.

between July 1949 and January 1951. During this period ten separate cruises were undertaken in the Bay and its tributaries, with an average of 120 stations occupied on each cruise.

A total of 5,830 salinity measurements were made, of which approximately 2,027 were obtained by means of the conductivity-temperature-indicator developed at the Chesapeake Bay Institute for rapid *in situ* measurements. Most of the samples were also analyzed for pH, phosphate, dissolved oxygen, and turbidity.

Temperature measurements were made chiefly with the bathythermograph, though an electronic temperature device was used extensively after August 1950. Some 1,200 surface temperatures were obtained by means of a bucket thermometer, and approximately 800 subsurface temperatures were taken by means of reversing thermometers. These thermometer temperatures were employed primarily for calibration of the bathythermographs.

The above data have been compiled in the Chesapeake Bay Institute Data Reports 1 through 7, which are available in the majority of oceanographic libraries in the United States.

Current velocity was measured with a modified Jacobsen drag current meter, which has been described by Pritchard and Burt (1951). Approximately 1,650 individual current measurements were obtained and analyzed for this study, the majority of them from the James River estuary. Current observations made in the Chesapeake Bay by the Coast and Geodetic Survey were also used in the analysis.

TREATMENT OF DATA

For each station the temperature and salinity, as well as other chemical properties, were plotted against depths. Vertical sections and horizontal charts for each survey were then prepared from these individual station curves. The charts showed the distribution of temperature and salinity at the surface and at depths of 10, 20, 30, 40, and 60 feet. In each case consideration was given to the probable effect of tidal motion on the individual measurements.

The study of the salt balance is based upon an extensive field investigation of the James River estuary. Approximately 1,530 salinity and 1,600 current velocity measurements were made during two periods, the first from 17 June through 21 July 1950, the second from 30 August to 3 September 1950. In this analysis it was necessary to use data averaged with respect to the periodic tidal fluctuations.

The James River data were divided into four periods, each period covering at least six tidal cycles. The salinity data were then averaged for each period in such a way that the average vertical gradients were maintained. This was accomplished by averaging with respect to a characteristic inflection point on the vertical salinity curve rather than with respect to depth. While the resulting average curve gives slightly different salinities at individual depths than a straight averaging process would, the mean salinity from top to bottom is the same in both cases.

The current velocities were for the most part directed along the longitudinal axis of the estuary, either in the ebb direction (toward the mouth of the estuary) or in the flood direction (toward the head of the estuary). The appropriate ebb or flood component of all velocity observations was plotted against a time scale for each five feet of depth. (See Fig. 5 as an example of the type of plot.) The areas under the resulting velocity time curve were then planimetered, taking ebb areas as positive and flood areas as negative. The final mean velocity figures for each depth and for each period were obtained by dividing the net velocity-time areas by the total time in each period.

DISCUSSION OF THE OBSERVED DISTRIBUTION OF SALINITY AND CURRENT VELOCITY

The Chesapeake Bay and its major tributaries may be considered an estuarine system composed of a number of estuaries of different size and character leading into the lower Chesapeake Bay. This estuarine system is shown in Fig. 1. The Chesapeake Bay is approximately 165 nautical miles long, extending from the mouth of the Susquehanna at Havre de Grace, Maryland, to the Virginia Capes. If the upper limit of the estuarine region is defined as the mean limit of measurable salt water intrusion, then the area of the Chesapeake Bay estuarine system is 3,014 square miles (nautical).

The 20 and 60 foot depth contours are shown in Fig. 1. Approximately 50% of the estuarine system (i. e., Bay plus tributaries) is less than 20 feet deep. Thirty-five per cent of the total area has depths greater than 30 feet, 18% greater than 40 feet, and only 8% greater than 60 feet. The corresponding figures for Chesapeake Bay alone are 57% of the area greater than 20 feet in depth, 44% greater than 30 feet, 24% greater than 40 feet, and 10% greater than 60 feet.

The Susquehanna River contributes 49% of the annual fresh water inflow into the Bay, but it contributes 87% of that above the mouth of the Potomac. Thus the Bay above the mouth of the Potomac may be considered the estuary of the Susquehanna.

The Potomac River estuary is the second largest in the system, the salt water intruding in measurable quantity nearly 60 miles above Chesapeake Bay proper. The Potomac River contributes about 18% of the total fresh water inflow into the Bay.

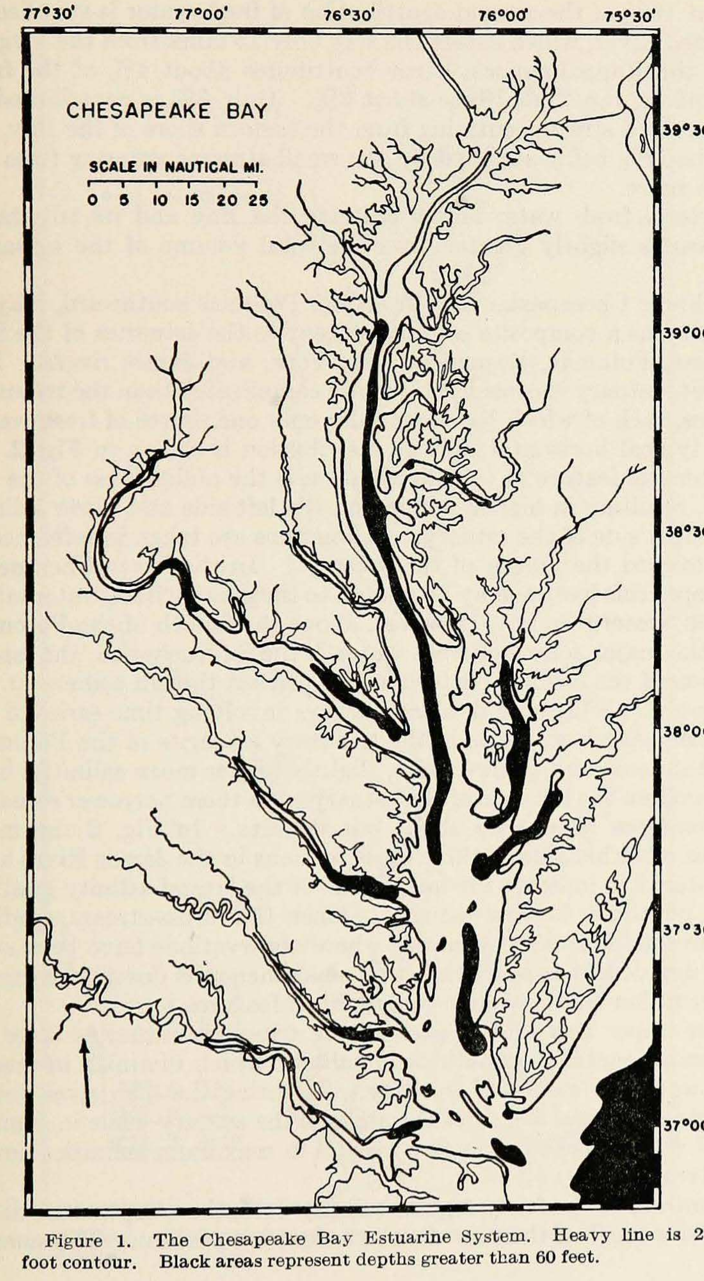

Figure 1. The Chesapeake Bay Estuarine System. Heavy line is 20-foot contour. Black areas represent depths greater than 60 feet.

About 16% of the annual contribution of fresh water is supplied by the James River, which enters the Bay only 15 miles from the Virginia Capes; the Rappahannock River contributes about 4% of the fresh water inflow, the York River about 2%. Only 7% is contributed by the rivers and streams entering from the eastern shore of the Bay, the remaining 4% being supplied by the small streams entering from the western shore.

The total fresh water inflow entering the Bay and its tributaries each year is slightly greater than the total volume of the estuarine system.

The lower Chesapeake Bay, from the Potomac southward, may be considered as a composite estuary, parent to the estuaries of the Susquehanna, Potomac, Rappahannock, York, and James rivers. This composite estuary is considerably more complicated than the tributary estuaries, each of which has essentially only one source of fresh water.

The typical horizontal salinity distribution is shown in Fig. 2. A characteristic feature of this distribution is the obliqueness of the isohalines, resulting in higher salinity on the left side and lower salinity on the right side of the estuary. (Directions are taken in reference to facing toward the mouth of the estuary.) In the lower Chesapeake Bay proper this feature may be related to the greater fresh water inflow from the western shore. However, above the mouth of the Potomac, where the major source of fresh water is the Susquehanna, the lateral distortion of the salinity pattern is also present though somewhat less pronounced. Whenever detailed surveys involving time series of observations have been made in the tributary estuaries of the Potomac, Rappahannock, and James rivers, slightly higher mean salinities have been found on the left side of the estuary. In these narrower estuaries the differences have been slight but definite. In Fig. 2 the mean salinities on either side of three cross sections in the James River have been entered to indicate the magnitude of the lateral salinity gradient in this relatively narrow estuary. Since this cross-stream gradient has been found in other estuaries where observations have been sufficiently detailed, it appears that this phenomenon is due to the earth's rotation rather than peculiar geographical features.

In the upper Bay and in each of the tributary estuaries there are considerable seasonal variations in salinity which diminish in magnitude toward the mouth of the Bay. In spring the high river flow is reflected in minimal salinities throughout the estuary while in summer and fall the decreased river flow results in maximum salinities during the latter season.

In contrast to the fairly regular salinity field, the temperature distribution over much of the year shows no clear-cut pattern. The summer

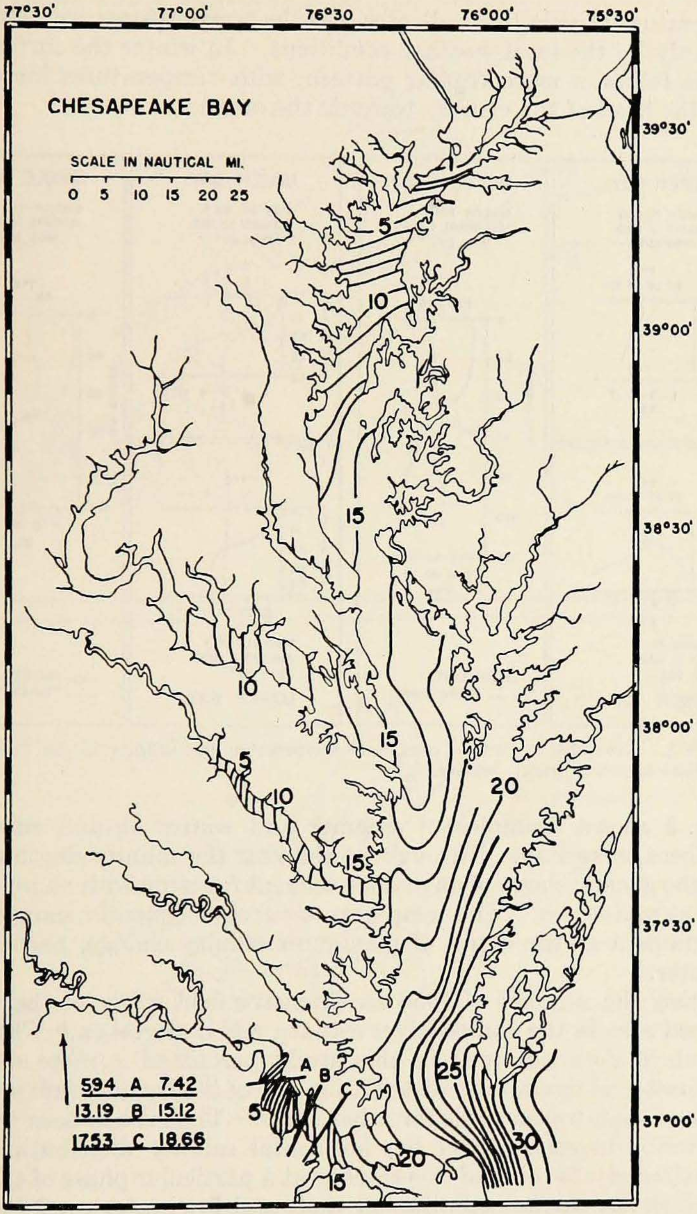

Figure 2. Typical surface salinity pattern in Chesapeake Bay and tributary estuaries.

temperature distribution indicates that the temperatures are controlled primarily by the local weather conditions. In winter the surface isotherms follow a more regular pattern, with temperatures increasing from the head of the estuary towards the ocean.

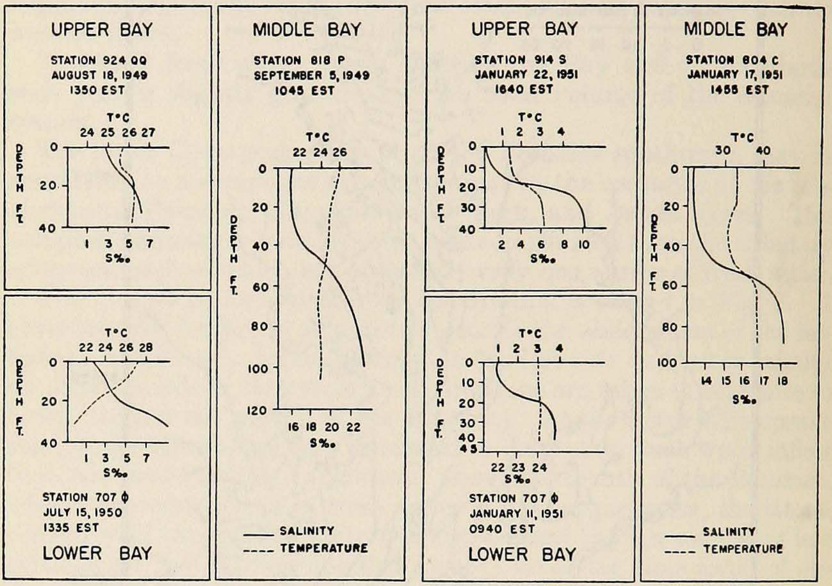

Figure 3. Examples of vertical profiles of temperature and salinity in the Chesapeake Bay: (left) summer; (right) winter.

Fig. 3 shows examples of summer and winter station curves in the Chesapeake Bay. Throughout the year the salinity-depth curves have the general shape of an inverse tangent function with an inflection point at mid-depth. The temperature curves frequently show a positive gradient at the depth of maximum salinity change, particularly in winter.

During the summer of 1950 an extensive field study of the oyster seed bed area in the James River estuary was undertaken. The large amount of data obtained in this study permitted a more detailed examination of the salinity distribution and of the concomitant physical structure than was possible for other areas. Thus it has been possible to describe in some detail the horizontal salinity distribution over approximately 15 miles of this estuary at a particular phase of the tide. Figs. 4 shows surface salinities at high and low water on 2 September 1950. Though the general features of distribution are the same

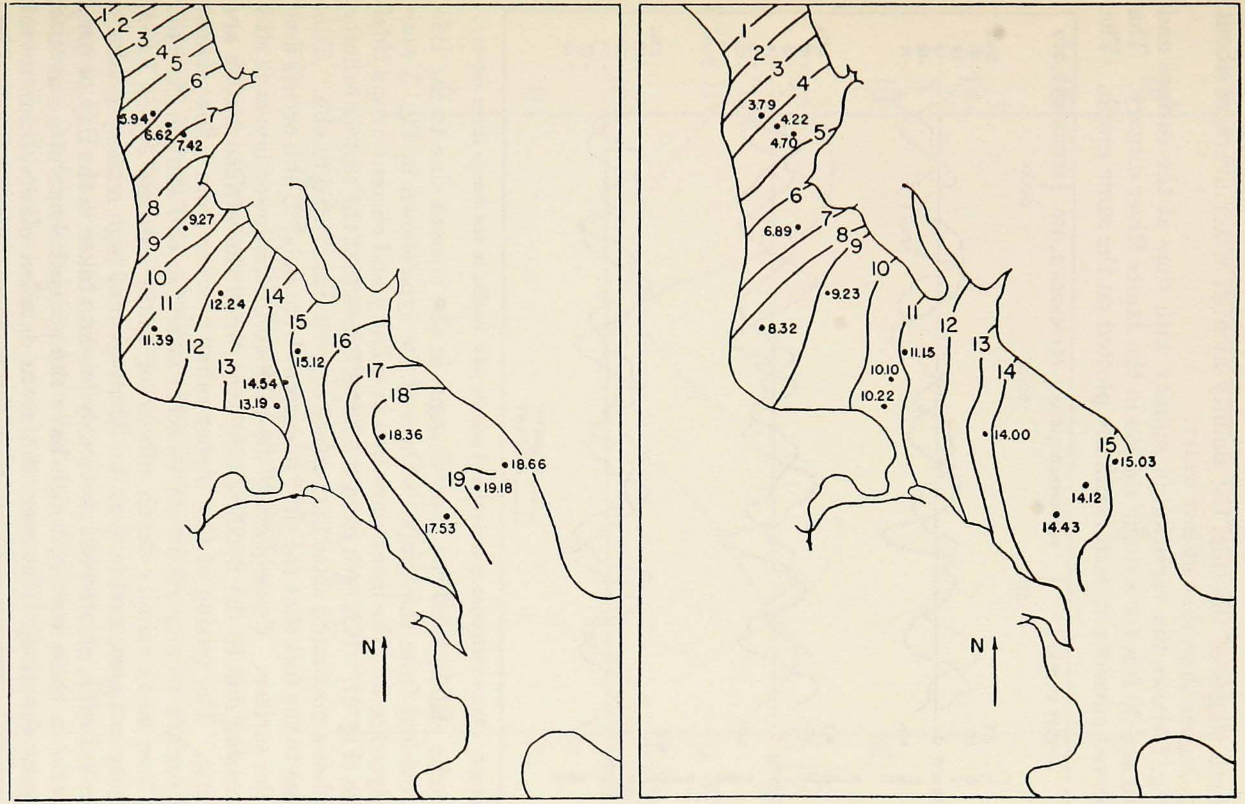

Figure 4. Surface salinity distribution in the James River estuary: (left) high water; (right) low water.

at both stages of the tide, the salinity at high water averages about 4°/₀₀ higher than that at low water.

Fig. 5 shows the variation in salinity with time at the surface and at 10 and 20 feet for a single station in the James River estuary. The observed currents at each depth are plotted on the same graph. The

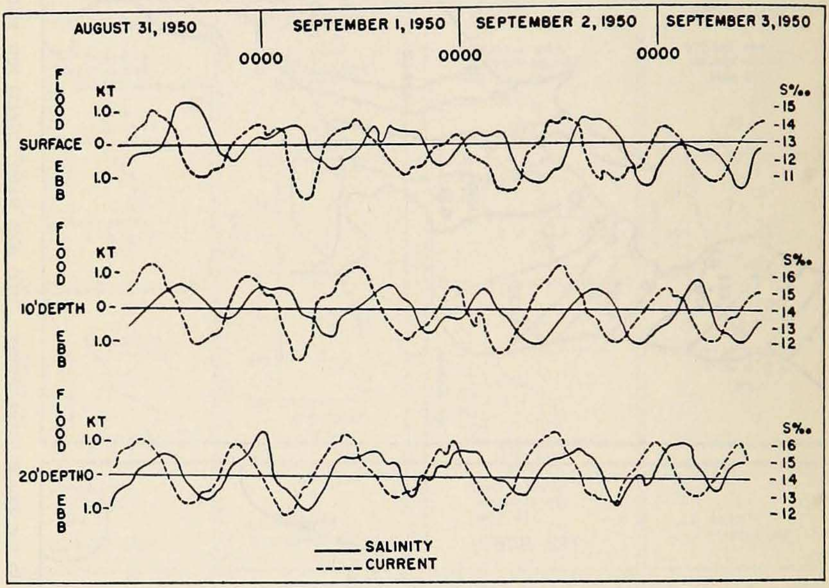

Figure 5. Time variations in current and salinity at a station in the James River estuary.

periodic character of the time changes in the current due to the tide are evident from this graph. Data of the type shown in Fig. 5 were analyzed to find the mean variation in salinity and current over a tidal cycle (Fig. 6). It is seen from the latter figure that the surface salinity reaches a maximum after the surface current has shifted to ebb. This is due to the fact that the shift in current from flood to ebb occurs first at the surface. Consequently the salinity in the lower layers is still increasing due to the flooding tide even when the surface waters are ebbing. The mixing of this higher salinity water from below causes the surface salinity maximum to occur after the ebb shift in current.

Three mean salinity-depth curves for stations in the James River estuary are presented in Fig. 7. The region of high salinity gradient at mid-depths, pointed out previously for data taken in the Bay proper, appears in these curves, which have the general shape of an inverse tangent function. However, the more detailed observations reveal regions of increased gradient near the surface and near the bottom.

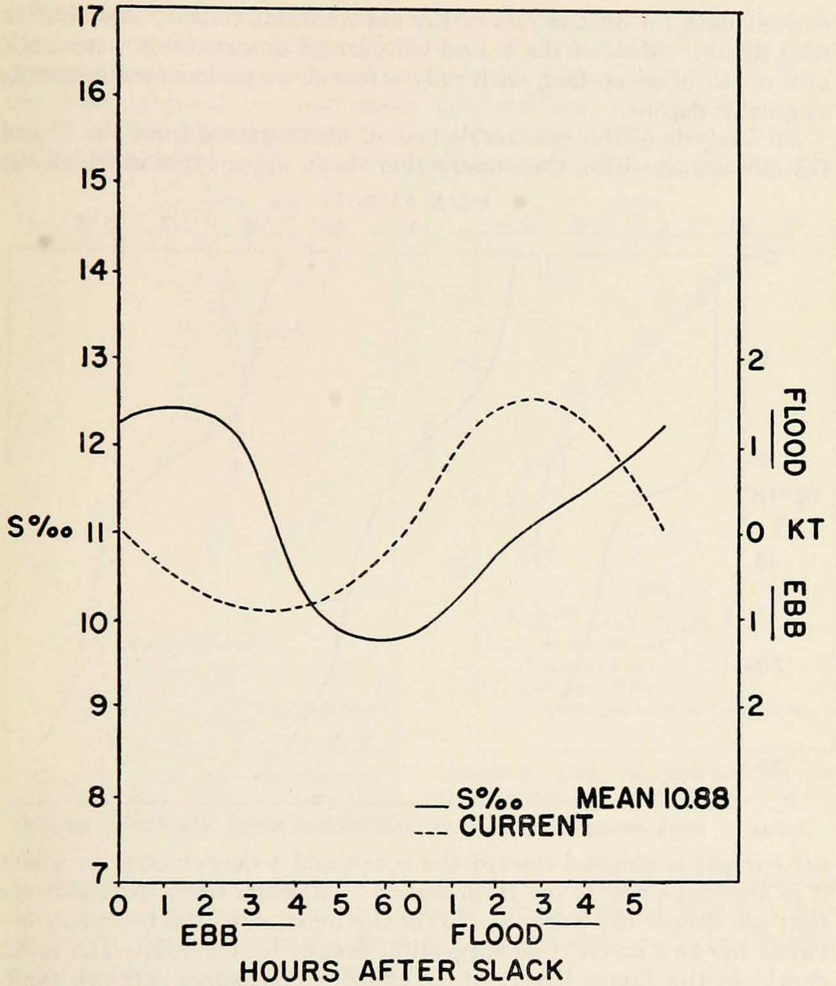

Figure 6. Mean time variation of salinity and current for one tidal cycle.

Although the surface gradient disappears under conditions of high winds, it is present in the mean picture.

Tidal currents, varying in maximum magnitude from one-half to three knots, occur in the estuaries of the Chesapeake Bay system. Although the Coast and Geodetic Survey (1930) has made extensive measurements of the surface currents because of their importance to navigation, no previous attempt has been made to obtain sufficient current data for an analysis of the net nontidal velocity distribution with depth. Most of the C and GS current observations were made at a depth of seven feet, with only a few short period measurements at greater depths.

An analysis of the few usable sets of observations from the C and GS shows that within the estuary there is an upper layer in which the

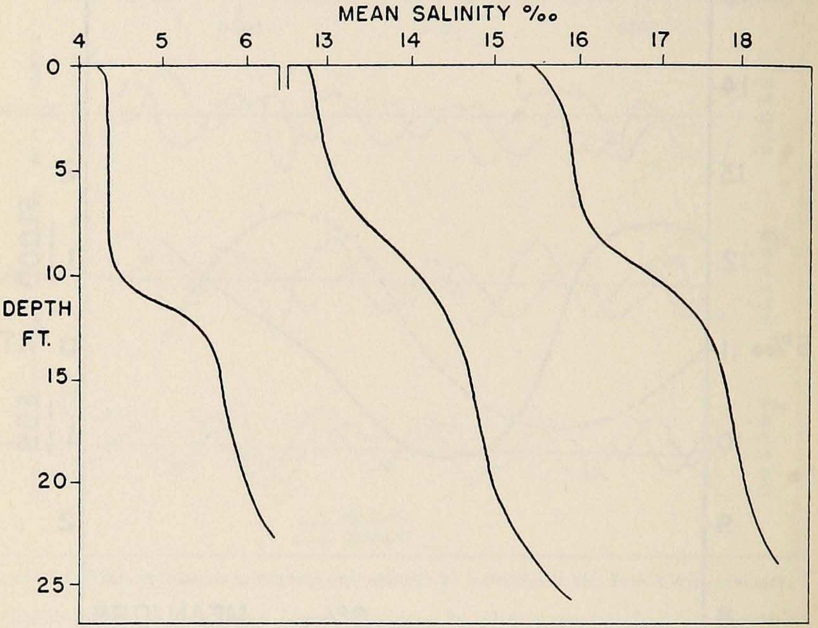

Figure 7. Mean salinity-depth curve at three stations in the James River estuary.

net current is directed toward the ocean and a deeper layer in which it is directed towards the fresh water. Although these data indicate that the deeper the water the lower the location of the boundary between the two layers, this suggestion cannot be verified. The mean depths in the James River, where extensive measurements are available, do not vary sufficiently to show such a relationship.

During the study of the James River oyster seed bed area in the summer of 1950, serial current measurements were obtained at five-foot depth intervals at some 12 stations. Only three of these stations were located in the relatively deep water of the channel, the others being located over the oyster bars on either side. The current data from these three stations showed that there is an upper layer with a net motion toward the mouth of the estuary and a deeper layer with a net motion toward the head of the estuary.

Continuous observations were obtained for three periods between 18 June and 21 July 1950. Mean current data for each of the three periods at one of the stations are shown in Figs. 8 and 9. In Fig. 8 the mean ebb-velocity and mean flood-velocity are plotted against depth. The ebb velocities are relatively large on the surface and decrease with depth, while the flood velocities are relatively small on the

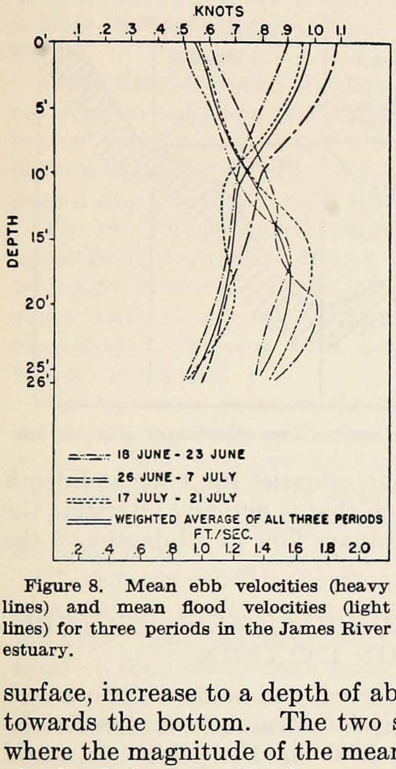

Figure 8. Mean ebb velocities (heavy lines) and mean flood velocities (light lines) for three periods in the James River estuary.

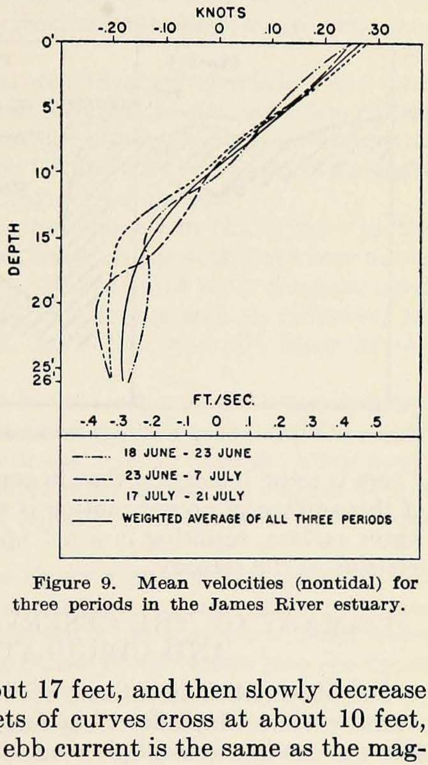

Figure 9. Mean velocities (nontidal) for three periods in the James River estuary.

surface, increase to a depth of about 17 feet, and then slowly decrease towards the bottom. The two sets of curves cross at about 10 feet, where the magnitude of the mean ebb current is the same as the magnitude of the mean flood current.

The net velocity-depth curve for each period is shown in Fig. 9. Above ten feet the current is directed down the estuary and is designated as positive; below ten feet the current is directed up the estuary and is designated as negative.

All of the current data produced similar curves. Although the shallow water stations gave only the upper portion of the curve, they served to reveal the cross-sectional structure. Fig. 10 gives the variations in depth of the boundary between the upper and lower layers in a section across the James River. This boundary, which is designated as the surface of no net motion, appears to slope upwards from the right of the estuary to the left. This results in a thicker layer with positive flow on the right (low mean salinity) than on the left (high mean salinity).

This slight slope in the surface of no net motion, as well as the lateral salinity gradient, suggests the influence of the earth's rotation.

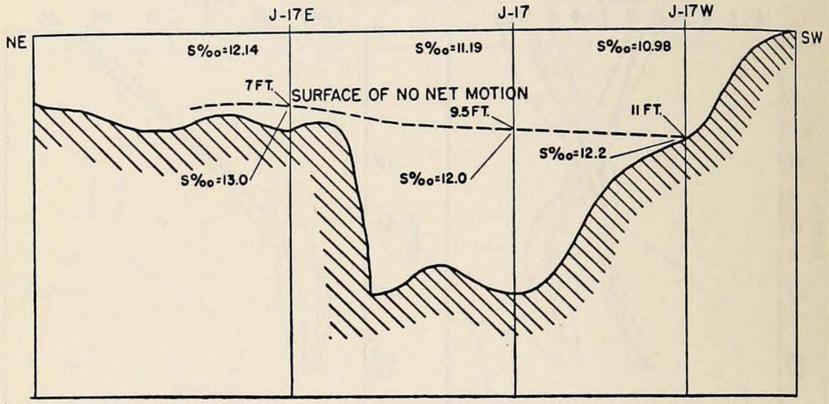

Figure 10. Cross section in James River estuary showing slope of surface of no net motion.

There is some indication that in certain estuaries the slope and depth of this surface of no net motion is such that it actually intersects the water surface, resulting in a net up-estuary flow at all depths on the left side of the estuary.

SUMMARY OF THE OBSERVED PHYSICAL STRUCTURE AND CIRCULATION PATTERN

The observed distributions, as discussed, can be fitted into a consistent picture which describes the physical structure and the circulation pattern in a coastal plain estuary in the midlatitudes. As an aid in the presentation, a geographically simplified model estuary will be discussed. This estuary is elongated and a river brings in fresh water at the head. The smooth straight shore lines diverge from each other toward the mouth of the estuary. The bottom slopes smoothly upward from the sea towards the head.

Consider a coordinate axis with its origin in the fresh water at the head of the estuary. The x_1 axis is directed horizontally down the central axis of the estuary toward the mouth. The x_2 axis points vertically downward. The lateral coordinate is x_3 and is directed from the center of the estuary toward the right-hand shore.

The distribution of salinity governs the dynamic structure. The salinity increases from zero at the head of the estuary to nearly that of sea water at the mouth. The isohalines are not perpendicular to the x_1 axis but run rather obliquely across the estuary, the salinities on the right side being slightly lower than those on the left.

The vertical salinity profile has the general shape of an inverse tangent curve. Close to the bottom and to a lesser extent near the surface the curve departs from a typical tangent shape due to boundary effects.

From the standpoint of physical structure and circulation the estuary may be considered as having two layers. In the upper layer there is a net horizontal flow down the estuary, in the lower a net horizontal flow up the estuary. The boundary between the two layers has a slight lateral slope, with the right side deeper than the left.

The net-velocity-depth curve is exponential in character. In the upper layer it decreases from a maximum on the surface to zero at the boundary between the two layers. In the lower layer the horizontal component of velocity is directed in the negative x_1 direction, its magnitude increasing with depth until the frictional layer at the bottom is reached.

The boundary between the two layers occurs close to but does not necessarily coincide with the inflection point on the salinity-depth curve. Thus the upper layer is of lower salinity than the lower layer. The volume of flow in the upper layer must exceed the volume of flow in the lower layer by an amount equal to the inflow of fresh water from the river.

Though the salinity distribution shows a seasonal variation, it may be considered to be in steady state during any particular season. Since the upper layer is transporting seaward a net amount of fresh water equal to the inflow, there must be a flow of salt water into the upper layer to maintain the salinity distribution. This is accomplished by a net transfer of water of relatively higher salinity from the lower to the upper layer. Hence there must be a negative vertical velocity across the boundary between the two layers. The volume of flow in the upper layer increases toward the mouth and that in the lower layer decreases toward the head. A schematic presentation of the volume transport in a longitudinal section down the central axis of the estuary is shown in Fig. 11.

Though the tidal currents constitute the most obvious water movements, they are considered here as being primarily responsible for supplying the energy needed for the vertical and horizontal mixing. The tidal currents in the estuary are of the reversing type, directed up and down its longitudinal axis. The observed net horizontal current

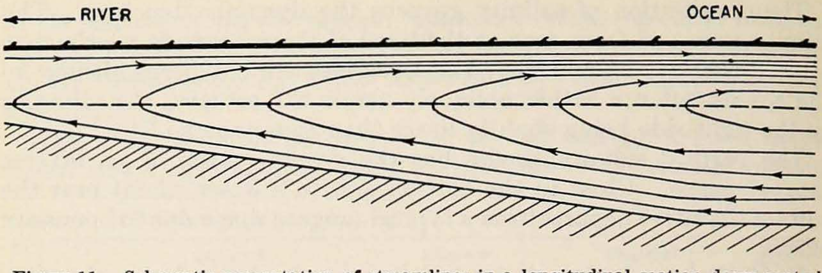

Figure 11. Schematic presentation of streamlines in a longitudinal section down central axis of the estuary.

is obtained by averaging the total current observations over one or more complete tidal cycles.

PRELIMINARY INVESTIGATION OF THE SALT BALANCE

The studies in the James River are sufficient to evaluate certain features of the salt balance. Though a detailed analysis of the processes which control the salinity distribution is now in preparation, some preliminary results are reported here.

Neglecting molecular diffusion, the instantaneous local rate of change of salt concentration, s, is given by

$$\partial s/\partial t = -\frac{\partial(v_i s)}{\partial x_i}. \qquad (i = 1, 2 \text{ and } 3) \tag{1}$$

Consider a segment of the estuary bounded at either end by a cross section. Designating the total salt content within the segment by $S = \iiint_V s dV$, where V is the volume of the segment, we have from (1)

$$\text{(2)}\quad \partial S/\partial t = \frac{\partial}{\partial t}\left\{\iiint_V s dV\right\} = -\iiint_V \frac{\partial}{\partial x_i}(v_i s) dV$$

$$= -\iint_\sigma v_i s d\sigma_i,$$

where $\iint_\sigma f d\sigma_i$ represents the integral over the bounding surfaces of the segment. Now taking the time mean of equation (2), and introducing sums of a mean term and a random term for both the instantaneous velocity and salinity, (2) becomes

$$\text{(3)}\quad <\partial S/\partial t> = -\iint_\sigma <v_i s> d\sigma_i = -\iint_\sigma \bar{v}_i \bar{s} d\sigma_i - \iint_\sigma <v_i' s'> d\sigma_i.$$

For steady state, $<\partial S/\partial t> = 0$, and hence

$$\text{4)}\quad \iint_\sigma \bar{v}_i \bar{s} d\sigma_i + \iint_\sigma <v_i' s'> d\sigma_i = 0.$$

The first term of equation (4) represents the net flux of salt into the segment due to advection through the boundaries. The second term represents the net flux of salt due to random motion through the boundaries. Oceanographers have called this latter term "diffusion" and have replaced the terms of the type $<v_i's'>$ by terms of the type $A_i \partial \bar{s}/\partial x_i$, where A_i is the eddy diffusivity.

If the segment under study is bounded by the surface, bottom, and sides of the estuary, then only the horizontal terms in equation (4) need be considered, since there can be no motion through the upper and lower boundaries. Equation (4) then becomes

$$\int\int_\sigma \bar{v}_1 \bar{s} d\sigma_1 + \int\int_\sigma <v_1's'> d\sigma_1 = 0 \,. \tag{5}$$

Observations of mean salinity and velocity are available for ten separate cases, such that for each case the first term in equation (5) can be evaluated. It is convenient, both for the present discussion and for later analysis, to consider this first integral in two parts: one term involving the upper layer where the velocity is positive, the other term involving the lower layer where the velocity is negative. The value of the integral $\int\int_\sigma <v_1's'> d\sigma_1$, as determined from equation (5), was in all cases less than 5% and in seven of the ten cases less than 1% of either of the two parts of the first term in equation (5).

This analysis is important in that the salinity balance within a segment bounded by the surface and the bottom is maintained primarily by horizontal advection, the horizontal diffusion being of only slight importance.

The fact that the horizontal diffusion term appears small suggests that the concepts employed to determine the net flow across the sill of certain basins (Sverdrup, Johnson and Fleming, 1946: 146–150) may be used in computing the net flow in both the upper and lower layers of this coastal plain estuary. Neglecting horizontal diffusion, equation (5) becomes

$$\int\int_\sigma \bar{v}_1 \bar{s} d\sigma_1 = 0 \,. \tag{6}$$

For nondivergent flow, $\partial \bar{v}_i/\partial x_i = 0$. Taking the integral over the volume V, and applying Green's formulae, we have

$$\int\int_\sigma \bar{v}_i d\sigma_i = 0 \,, \tag{7}$$

which, when applied to a segment of the estuary bounded by the surface, by the bottom and sides, and by two cross sections, becomes

$$\int\int_\sigma \bar{v}_1 d\sigma_1 = 0 \,. \tag{8}$$

Equations (6) and (8) represent surface integrals taken over the two cross sections that bound the segment. At the uppermost section, in fresh water, the value of the integral in equation (8) is simply the river flow. At the lower section, within the estuarine region, the surface integrals in both of the above equations may be considered in two parts: one term involving integration over the upper layer, where the net velocity is in the positive x_1 direction, and the second integral involving integration over the lower layer, where the net velocity is in the negative x_1 direction. Equations (7) and (8) may then be solved simultaneously for the mean value of the velocity in each layer.

River-flow data from gaging stations of the U. S. Geological Survey are available for the James River at Richmond and for the two tributary streams, the Appomatox and the Chickahominy, which enter the James below Richmond. If the reported river flow is used directly in the computation of mean velocities, slightly high results are obtained. By correcting the river-flow data for an estimated evaporation excess of 0.01 foot per day, computed current velocities correspond closely to the observed ones.

Table I gives the results of such determinations at three stations on the James River estuary for four different periods of observations. In each of the ten cases presented, careful observations of velocity were made at each five feet of depth. Average velocities for the upper and lower layer were determined from these observed values; these are also given in Table I. Positive values designate down-estuary flow; negative values designate up-estuary flow.

TABLE I. Computed Mean Velocities and Observed Mean Velocities for a Series of Stations in the James River Estuary (ft/sec)

		Computed Velocities		*Observed Velocities*		*River*
Station	*Date (1950)*	*Upper Layer*	*Lower Layer*	*Upper Layer*	*Lower Layer*	*Flow* $ft^3\ sec^{-1}$
J-24A	18 to 23 June	.33	−.23	.31	−.20	4357
	26 June to 7 July	.33	−.24	.32	−.22	3685
	17 to 21 July	.39	−.27	.35	−.25	4610
J-17	18 to 23 June	.23	−.24	.21	−.20	4357
	26 June to 7 July	.22	−.23	.22	−.24	3685
	17 to 21 July	.22	−.22	.22	−.22	4610
	30 August to 3 Sept	.19	−.22	.19	−.18	2823
J-11	18 to 23 June	.29	−.23	.30	−.24	4357
	26 June to 7 July	.34	−.28	.34	−.28	3685
	17 to 21 July	.35	−.29	.33	−.27	4610

The computed velocities exceeded the observed by an average difference of 4.8%. The individual differences varied from −5 to 20%. This error of approximately 5% is only slightly larger than that to be expected from neglecting the small term involving the random horizontal transfer of salt.

The standard deviation between the observed and computed velocities was less than 0.02 ft/sec, which is certainly close to the limits of accuracy of the observations. Thus it appears that, within the accuracy of the observations of the various parameters, it is possible to determine the mean down-estuary flow in the upper layer and the mean up-estuary flow in the lower layer from the river flow, the salinity distribution, and the cross-sectional dimensions.

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