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NEW DIMENSIONS IN ESTUARY CLASSIFICATION[1]

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ABSTRACT

Results of recent theoretical studies are used as a basis for a new two-parameter system of estuarine classification. The classes are delineated by the magnitudes of the relative stratification and circulation parameters associated with changes in the salt balance mechanism.

The theoretical results depend on a knowledge of the eddy coefficients of viscosity and diffusivity. Tentative relationships between these coefficients and the bulk parameters of tidal current, river flow, and geomorphology, which are obtained from experimental data, may be used to determine the salinity and net current distributions in partially mixed and well-mixed coastal plain estuaries.

INTRODUCTION

Estuaries, in the traditional sense, are regions of transition from river to ocean. They are characterized by the possibility of tidal motions communicated from the sea, and by gradients of salinity and density associated with the progressive admixture of river water and seawater. Often they are elongate in form so that lateral variations are relatively insignificant, as will be assumed herein. The action of gravity upon the density difference between seawater and freshwater tends to cause vertical salinity stratification and a characteristic convective flow that has come to be known as "estuarine circulation," or gravitational convection.

Geomorphology, freshwater flow, and tides are the dominant variables determining the distributions of salinity and circulation within the estuary. Estuaries traditionally have been classified according to their geomorphology and their salinity stratification. The terms commonly applied are: coastal plain and fjord to express the geomorphology; and salt wedge or highly stratified, partially mixed or moderately stratified, and well-mixed or vertically homogeneous to express the relative salinity stratification (Stommel and Farmer 1952; Cameron and Pritchard 1963).

The classification as a sequence of mixing types has been applied usually to coastal plain estuaries. Improvements for navigation have removed local anomalies sufficiently that fairly constant top-to-bottom salinity difference is maintained over major portions of these estuaries by local tide and river flow. Several investigators have noted that the flow ratio of a coastal plain estuary (ratio of the volume of upland water entering the estuary during a tidal cycle to its tidal prism) is a fairly dependable index

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to its mixing type. Schultz and Simmons (1957) observe that where this ratio is of the order of 1.0 or greater we normally find the highly stratified type of estuary in which ideally the river water flows out over a wedge-shaped layer of nearly motionless saline water; where the ratio is of the order of 0.25 we normally find the partially mixed type; and where the ratio is appreciably less than 0.1 we normally find the well-mixed type in which the top-to-bottom salinity difference may be undetectable. These workers caution, however, that this rule applies only in a very general way, and they provide only a vague definition of their criteria for judging mixing types.

In fjord estuaries, on the other hand, the stratification sequence is not so much one of differences in control of stratification by local conditions of tide and river flow as of progressive change along the estuary. Characteristics of fjord estuaries have recently been reviewed by Pickard (1961), Saelen (1964), and Rattray (1964). Near the freshwater source, characteristically at the head of the fjord, the estuaries are highly stratified, not unlike salt-wedge estuaries except for greater depth of the underlying saline water, and the nontidal circulation is confined primarily to the near-surface region. As the surface layer flows seaward it entrains higher-salinity water from below, progressively reducing the relative stratification. Where there are shallow sills or lateral constrictions the mixing process may be augmented locally to an extent that vertical stratification is nearly destroyed. In such an outer well-mixed portion of a fjord the circulation is similar to that in a coastal plain estuary, although with the greater fjord depth the circulation may often be more sensitive to subtle influences such as seasonal changes in density of the oceanic source water.

Stommel and Farmer (1952) concluded that classification of estuaries in terms of salinity stratification had dynamical significance. The data available at that time suggested that well-mixed estuaries have a net flow seaward at all depths and that the upstream salt flux occurs by horizontal diffusion. Reversal of the pressure gradient with depth in partially mixed estuaries, on the other hand, was thought to maintain upstream flow in the bottom layer. Although this conclusion has been for several years a working rule for interpretation of data from estuaries, recent theoretical models developed by the authors (Hansen and Rattray 1965) show that the relative development of stratification and gravitational convection in estuaries depends upon two dimensionless parameters, and indicate that the situation is not so simple as it once appeared. Observations made in the Mersey estuary (Bowden 1963; Price and Kendrick 1963) provide direct evidence that gravitational convection can occur in estuaries that approach vertical homogeneity as well as in estuaries with more evident stratification. We propose therefore a two-parameter classification, in which estuarine dynamics are explicitly included.

The relative development of stratification and gravitational convection does provide insight into the comparative importance of horizontal diffusion and advection for the upstream salt flux in estuaries. Extremes of this relationship have already been recognized and used by oceanographers and engineers. Stommel (1953), apparently as a result of his conclusion regarding the absence of gravitational convection in well-mixed estuaries, proposed a method using the observed salinity distribution to evaluate longitudinal dispersion of pollutants in estuaries of this type. Bowden's (1965) analysis of the "shear effect" now makes it clear that the validity of the method proposed by Stommel does not require the absence of gravitational convection, so long as the pollutant of interest also varies only in the longitudinal direction. On the other hand, Knudsen's hydrographical theorem (Proudman 1953) has long been used to evaluate the water exchanges through straits to landlocked basins on purely advective principles. One of the early results of the James River studies was Pritchard's (1952) report that this method is also applicable to partially mixed coastal plain estuaries.

SALT BALANCE RELATIONSHIPS

The significance of theoretical dimensionless parameters in determining the partition of upstream salt flux among the river discharge, gravitational convection, and diffusive modes for coastal plain estuaries was shown by Hansen and Rattray (1965). The pertinent results are expressed in their equations (15), (16), (17), and (18) which relate the distributions of salinity and longitudinal current to the controlling parameters. These equations are

$$\frac{u}{U_f} = -\frac{\partial\phi}{\partial\eta}, \qquad (1)$$

$$\frac{S}{S_0} = 1 + \nu\xi + \frac{\nu}{M}\left[(\eta - ½) - ½(\eta^2 - ⅓) - \int_0^\eta \phi d\eta + \int_0^1 \int_0^\eta \phi d\eta' \, d\eta\right], \qquad (2)$$

and

$$\phi(\eta) = \frac{1}{2}(2 - 3\eta + \eta^3) - \frac{T}{4}(\eta - 2\eta^2 + \eta^3) - \frac{\nu Ra}{48}(\eta - 3\eta^3 + 2\eta^4), \qquad (3)$$

where

x, z	are the longitudinal and vertical coordinates,
u	is the longitudinal time-mean velocity,
u_s	is the longitudinal time-mean velocity at the surface $z = 0$,
τ_w	is the surface wind stress,
g	is the acceleration due to gravity,
B, D	are the width and depth of the estuary,
A_v	is the vertical turbulent viscosity,
K_h, K_v	are the horizontal and vertical turbulent diffusivities,
K_{h0}	is the value of K_h at $x = 0$,
S	is the time-mean salinity,
S_0	is the sectional mean of S,
ϕ	is a streamfunction,
ρ, ρ_f	are the densities of estuarine water and freshwater,
k	is $(1/\rho_f)(\partial\rho/\partial S)$,
R	is the river discharge rate,
U_f	is the integral mean velocity ($R \div$ cross-sectional area of the estuary),
T	is the dimensionless wind stress $= BD^2\tau_w/A_vR$,
Ra	is the estuarine Rayleigh number $= gkS_0D^3/A_vK_{h0}$,
M	is the tidal-mixing parameter $= K_vK_{h0}B^2/R^2$,
ξ	is a dimensionless horizontal coordinate $= Rx/BDK_{h0}$,
η	is a dimensionless vertical coordinate $= z/D$,
ν	is a constant representing the diffusive fraction of the total upstream salt flux.

Differentiation of equation (2) with respect to ξ and substitution for ξ yields

$$K_{h0}\frac{\partial S}{\partial x} = \nu\frac{RS_0}{BD} = \nu U_f S_0,$$

and shows that the diffusive upstream salt flux at $x = 0$, $K_{h0}\ \partial S/\partial x$, is the fraction ν of the total salt flux given by the product of the sectional mean velocity and the sectional mean salinity. The remaining upstream salt flux is the result of the gravitational convection in the estuary. The diffusive fraction, ν, is related to M, Ra, and T by

$$1{,}680M(1-\nu) = (32 + 10T + T^2)\nu + (76 + 14T)\frac{Ra}{48}\nu^2 + \frac{152}{3}\left(\frac{Ra}{48}\right)^2\nu^3. \qquad (4)$$

These features from the mathematical models are conveniently expressed in dimensionless form by a circulation parameter, the ratio of the net surface current[3] to the mean freshwater velocity through the section, u_s/U_f; and a stratification parameter, the ratio of the top-to-bottom salinity

[3] It is essential to represent estuarine behavior by two independent parameters (or three independent parameters where wind stress is important). It is unfortunate that the net surface current may be somewhat difficult to measure in the field, but the ratio u_s/U_f is the simplest available measure of the circulation. With the help of equations (1) and (2), any other information on the vertical dependence of the time-mean current can be used as a measure of u_s/U_f.

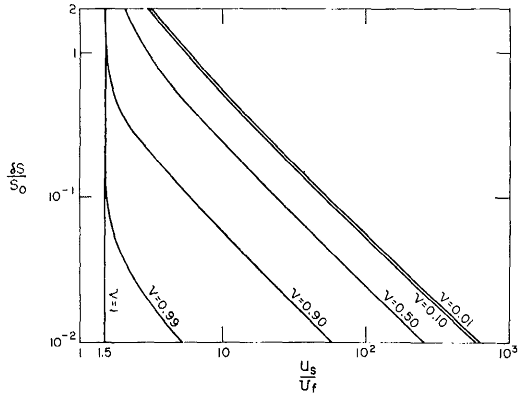

FIG. 1. Fraction of horizontal salt balance by diffusion, as a function of salinity stratification and convective circulation in a rectangular channel.

difference to the mean salinity over the section, $\delta S/S_0$. The diffusive fraction, ν, of total upstream salt transfer in a rectangular channel implied by these stratification and circulation parameters is shown by Fig. 1. When $\nu = 1$, gravitational convection ceases and the upstream salt flux is entirely by diffusion; as $\nu \to 0$, diffusion is unimportant and the upstream salt flux is almost entirely by gravitational convection in a two-layered flow. For values of ν between 0.9 and 0.1, advective and diffusive fluxes both are important in the horizontal salt balance. The exact positions of the isopleths of ν depend upon the boundary conditions of the particular theoretical model employed for their evaluation, but variations from the indicated relationships are expected to be small. It is clear from Fig. 1 that, contrary to what has been stated or implied in the literature, the advective component of salt flux is not necessarily proportional to salinity stratification.

CLASSIFICATION IN TERMS OF STRATIFICATION AND CIRCULATION

We conclude that a useful purpose can be served by classifying estuaries in terms of two parameters, the stratification and the circulation, although we recognize that not all significant differences in the vertical distribution of properties in estuaries can be expressed in terms of these two parameters alone. A plot of the values of stratification and circulation for estuaries will be called a stratification–circulation diagram in analogy to the temperature–salinity (T–S) diagram for the description of ocean water masses.

We have identified seven types of estuaries, basically following the conventional usage initiated by Stommel and Farmer, but further differentiating physically significant differences of regime.

In Type 1 the net flow is seaward at all depths and the upstream salt transfer is effected by diffusion. Type 1a is the archetypical well-mixed estuary in which the salinity stratification is slight, while in 1b there is appreciable stratification. For Type 2 the net flow reverses at depth and both advection and diffusion contribute importantly to the upstream salt flux. The stratifications in Types 2a and 2b correspond to those for Types 1a and 1b, respectively. Type 3 is distinguished from Type 2, primarily by the dominance of advection in accounting for over 99% of the upstream salt transfer. In Type 3b estuaries, the lower layer is so deep that in effect the salinity gradient and the circulation do not extend to the bottom, an important qualitative difference from other types of estuaries. Fjord estuaries are generally of Type 3b until mixed to the extent that they assume the Type 3a characteristics of small stratification. In Type 4 (salt-wedge) estuaries, the stratification is still greater and the flow grades from a thick upper layer flowing over and little influenced by a thin lower layer, to a shallow surface layer flowing with little influence over a deep lower layer.

A certain arbitrariness necessarily remains in the separation of classes. The a and b separation of classes is a matter of convenience for expressing the relative stratification of the estuaries, and the transition between Types 3 and 4 has little observational or theoretical basis. The uppermost boundary represents conditions of freshwater outflow over a stagnant saline layer.

Data points from several estuaries are plotted in terms of these coordinates in Fig. 2. These data are specific to particular places and sets of conditions in the respective estuaries and vary from section to section and from time to time. Entire estuaries, under any given set of conditions, are characterized in the stratification–circulation diagram by a line, rather than a point, which may cross class boundaries putting different parts of the estuary into separate classes. Data from two stations in the James River show two points on such a line. Similarly, a section of an estuary must be expected to change its characteristics in response to external factors, such as seasonal changes in freshwater input. The points for the Mississippi River, Columbia River, and Silver Bay illustrate the nature of these changes. In the last two cases, the changes in runoff have caused these sections of the estuaries to change classes.

The dashed lines through the data points for Silver Bay and the Strait of Juan de Fuca show the relation between the salinity and velocity ratios for purely advective horizontal salt flux (Knudsen's relation) for a region with no local freshwater inflow, and thus show the lines along which points should fall in a reach of a fjord. Comparison of the orientation of these lines with the isopleths of ν on Fig. 1 shows that the latter are, in a sense, generalizations of the Knudsen lines which include horizontal diffusion of salt as a constant fraction of the total upstream salt flux. These data also suggest that a change in river flow is equivalent in a general way to a change in position along the estuary.

RELATIONSHIP OF STRATIFICATION AND CIRCULATION TO BULK PARAMETERS IN WELL-MIXED AND PARTIALLY MIXED ESTUARIES

The mathematical models for well-mixed and partially mixed estuaries from which Fig. 1 is derived [equations (1)–(4)] show the relationship of relative stratification and circulation to the governing variables in terms of two dimensionless parameters.

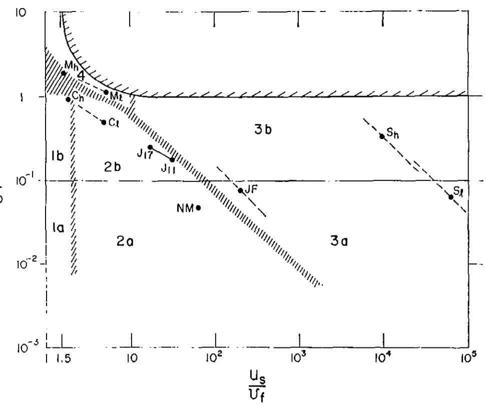

FIG. 2. Proposed classification with some examples. (Station code: M, Mississippi River mouth; C, Columbia River estuary; J, James River estuary; NM, Narrows of the Mersey estuary; JF, Strait of Juan de Fuca; S, Silver Bay. Subscripts h and ℓ refer to high and low river discharge; numbers indicate distance (in miles) from mouth of the James River estuary.)

Although these parameters are not readily measurable because they contain eddy coefficients for viscosity and diffusion, they will depend upon the bulk parameters of river flow, tides, and geomorphology.

The essential features of these bulk parameters are expressed by three quantities having the dimensions of velocity: the river discharge per unit area of cross section of the estuary, U_f; the rms tidal current speed, U_t; and the "densimetric velocity," $U_d = \sqrt{gD\Delta\rho/\rho}$, where $\Delta\rho$ is the density difference between river water and seawater.

Theoretical studies (Stommel and Farmer 1952; Ippen and Keulegan 1965) have identified an interfacial or densimetric Froude number as an important parameter in the dynamics of highly stratified estuaries. For extension to mixed estuaries where discrete upper and lower layers are not discernible, we define the densimetric Froude number by $F_m = U_f/U_d$. This parameter expresses the ratio of forced river flow to potential for density-induced internal circulation. We find that it correlates with the parameter νRa, which expresses a similar relation in our theoretical models.

Ippen and Harleman (1961) concluded from their work with hydraulic flumes that the flow ratio does not correlate well with stratification in estuaries and proposed instead a "stratification number" based upon tidal energy dissipation in the estuary. Our studies lead us to believe that no single parameter is adequate to portray the compound tendency of gravitational convection to generate stratification and of vertical mixing from turbulent tidal currents to destroy it. The coupling between the circulation and salinity distribution is included in the mathematical theory; the ratio $P = U_f/U_t$, proportional to the flow ratio, will be shown to be, within the limits of present data, a simple and adequate measure of the tidal mixing expressed by the theoretical tidal mixing parameter M/ν.

Fig. 3 shows the correlations obtained between these pairs of parameters for estuaries where observations can be interpreted in terms of the theoretical models. The indicated straight-line relationships, not necessarily the best fit, are

$$\nu Ra = 16 F_m^{-3/4} \tag{5}$$

and

$$M/\nu = 0.05 P^{-7/5}. \tag{6}$$

Considerable uncertainty attaches to values of νRa less than 100 because it is difficult to distinguish density effects from the influence of boundaries on the velocity profile when the former are slight. The correlation of larger values of νRa with F_m is good. The greatest departures from the relationship between P and M/ν are in the cases of the Mississippi River mouth where the theoretical models are inappropriate because tidal currents are not the dominant cause of vertical mixing and of the Strait of Juan de Fuca wherein the salinity stratification is not strongly dependent upon local mixing conditions.

Equations (5) and (6) can be combined with equations (1)–(4) from the theoretical models to compute the dependence of stratification and circulation on F_m and P in partially mixed and well-mixed estuaries. Fig. 4 shows the isopleths of F_m and P superimposed on the stratification–circulation diagram. Use of this figure permits determination of the stratification and circulation, and therefore the classification of an estuary from knowledge of its bulk parameters when the estuary falls within the appropriate classes.

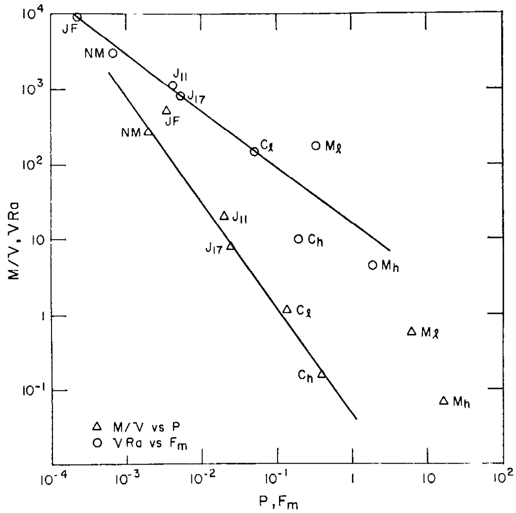

FIG. 3. Correlation of bulk parameters with theoretical parameters.

DISCUSSION

Although the necessity for a two-parameter system for classification even of narrow, elongate estuaries appears well founded, the quantitative relation of circulation and stratification in estuaries to the tidal mixing parameter and the densimetric Froude number must be considered as tentative. Too few direct observations of circulation in estuaries have been made to permit conclusive judgment of whether these simple parameters are adequate for prediction of vertical distributions of properties in all estuaries.

The flow ratio defined by Schultz and Simmons is approximately equal to $2P$. It is apparent from Fig. 4, therefore, that so far as tidal mixing is concerned these results are consistent with their observations. For constant values of the flow ratio there may still be considerable variation of stratification with F_m owing to the stratifying influence of the nontidal velocity distribution.

The parameters P and F_m also appear to extrapolate in a general way to be indicative of the behavior in fjord estuaries, but

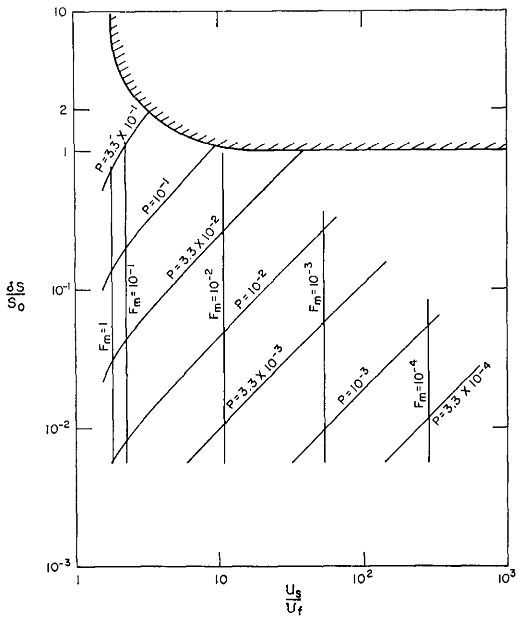

FIG. 4. Stratification–circulation diagram showing isopleths of the bulk parameters F_m and P.

there are as yet insufficient theoretical and observational bases to relate the stratification and circulation of fjords to the bulk parameters. In fjords, the vertical mixing can be neither attributed to tidal currents nor ignored. Figs. 1 and 2 suggest that Knudsen's theorem is probably valid for fjord circulations, but there is no external basis for prediction of the salinity and velocity profiles or even for identification of the respective flow layers.

If the proposed parameters are adequate, then one has recourse to equations (1)–(6) as a basis for estimation of complete vertical profiles of mean salinity and velocity in well-mixed and partially mixed estuaries. The vertical distribution of salinity is sufficiently easy to observe to be useful as a partial test of the method. Further work in which the mathematical models are generalized to encompass the influence of various boundary conditions and shapes (to be presented elsewhere) will permit an improved estimate of these vertical profiles.

The circulation in sea straits with known salt and water budgets is similar to that in estuaries although the density transition and exchange flow may be between adjacent water masses neither of which is either fresh or oceanic. The resulting distribution of properties depends largely upon the relative density difference and vertical stratification of the source waters. Conditions in the Bosporus, for example, approach those in salt wedges except that the upper layer has a salinity (18‰) characteristic of the Black Sea surface water. Where the supply of low-density water is less or the mixing over shallow sills is much greater, the stratification more closely resembles that in mixed estuaries. The latter situation frequently occurs in the outer reaches of fjord estuaries; the Strait of Juan de Fuca is an example. In either case the circulation in straits is basically a two-layer flow similar in many cases to that found in coastal plain estuaries, and the techniques for salt-wedge and mixed estuaries are applicable to strait circulations if the relevant parameters are expressed in terms of the density difference between the source waters.

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