CHAPTER 86

CONSTITUENT TRANSPORT IN ESTUARIES

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During the last two decades considerable progress has been made in analyzing the diffusion process in estuaries. Unfortunately, certain difficulties (e g prediction of diffusion coefficients) still prevent common application of the diffusion method An old technique, related to the diffusion concept, can however, frequently give useful information regarding constituent mixing and transport velocities in natural estuaries

RESIDENCE TIME

Conventionally the residence or detention time refers to the arithmetic mean time spent by all water particles within a certain length of a channel. The residence time of constituent particles in an estuary can be defined as the average length of time the constituent particles will remain within a certain region or reach of the estuary The constituent residence times will change with the location of the constituent sources and sinks and thus generally differ from the conventional residence times.

In the case of a one-dimensional estuary the constituent residence time may be defined as the mean time a constituent will spend traversing a specified section of the estuary For a steady state system the mean time must be

$$dT = \frac{\text{mass of constituent in a section of infinitesimal length (dx)}}{\text{avg mass rate of constituent transport through the section}}$$

where T = mean constituent residence time This expression can also be written

$$dT = \frac{A\bar{c}dx}{A\overline{uc}} \qquad \ldots . (1)$$

where A = local cross sectional area, u = local advective ("fresh water") velocity, c = constituent concentration, and the bar denotes the mean values of the parameters taken over a finite interval of time. The axioms of turbulent stresses as proposed by Reynolds (reference 1) can be used to reduce the term $A\overline{uc}$

$$A\overline{uc} = A\,\overline{u}\,\overline{c} + A(\overline{u'c'}) \qquad \ldots.(2)$$

where u' and c' are the instantaneous deviations from the mean values In equation (2) the total constituent transport is expressed as the sum of an advective and a diffusive constituent transport The equation for molecular diffusion further states that the rate of diffusive transport is proportional to the mean constituent gradient This is known as Fick's First Law and can in one-dimension be written

$$\overline{u'c'} = -E\frac{\partial \overline{c}}{\partial x} \qquad \ldots. (3)$$

where E = variable, overall longitudinal diffusion coefficient (ft^2/sec). The applicability of equation (3) in well-mixed estuarine situations is now generally accepted.

When the equations (2) and (3) are substituted in equation (1) the equation for constituent residence time per unit length of estuary results

$$\frac{dT}{dx} = \frac{\overline{c}}{\overline{u}\,\overline{c} - E\,\frac{\partial \overline{c}}{\partial x}} \qquad \ldots (4)$$

When the advective transport overshadows the diffusive transport, equation (4) reduces to the usual detention time equation for plug flow.

To avoid using a diffusion coefficient it is convenient to introduce an integrated form of the steady state, one-dimensional continuity equation for conservative constituents in estuaries (references 2, 3 and 4)

$$AE \frac{\partial \bar{c}}{\partial x} = A \bar{u} \bar{c} - \sum_{o}^{x} S_s \qquad \ldots . (5)$$

where $\sum_{o}^{x} S_s$ is the summation of sinks and sources of the constituent landward of the point x. Eliminating E between equations (4) and (5)

$$\frac{dT}{dx} = \frac{A \bar{c}}{\sum_{o}^{x} S_s} \qquad \ldots (6)$$

A useful observation can be made regarding constituent residence times in natural estuaries. The linearity of equation (5) implies that, for steady conditions, the constituent concentration throughout the estuary is directly proportional to the source strength Thus equation (6) demonstrates that the constituent residence time is independent of the source strength

In Figure 1 are plotted the approximate maximum and minimum integrated residence times for silica and advective flow for the 1961-62 water year in Northern San Francisco Bay. In general, silica can be said to represent a typical landward source constituent in Northern San Francisco Bay. Since silica and "fresh water" essentially have identical source locations the differences in their transport velocities and residence times therefore represent the diffusive transport of silica.

TRANSPORT VELOCITY

When the expression dT/dx is inverted it gives the constituent transport velocity. Inverting equation (4)

$$\frac{dx}{dT} = u - \frac{E}{\bar{c}} \frac{\partial \bar{c}}{\partial x} \qquad \ldots . (7)$$

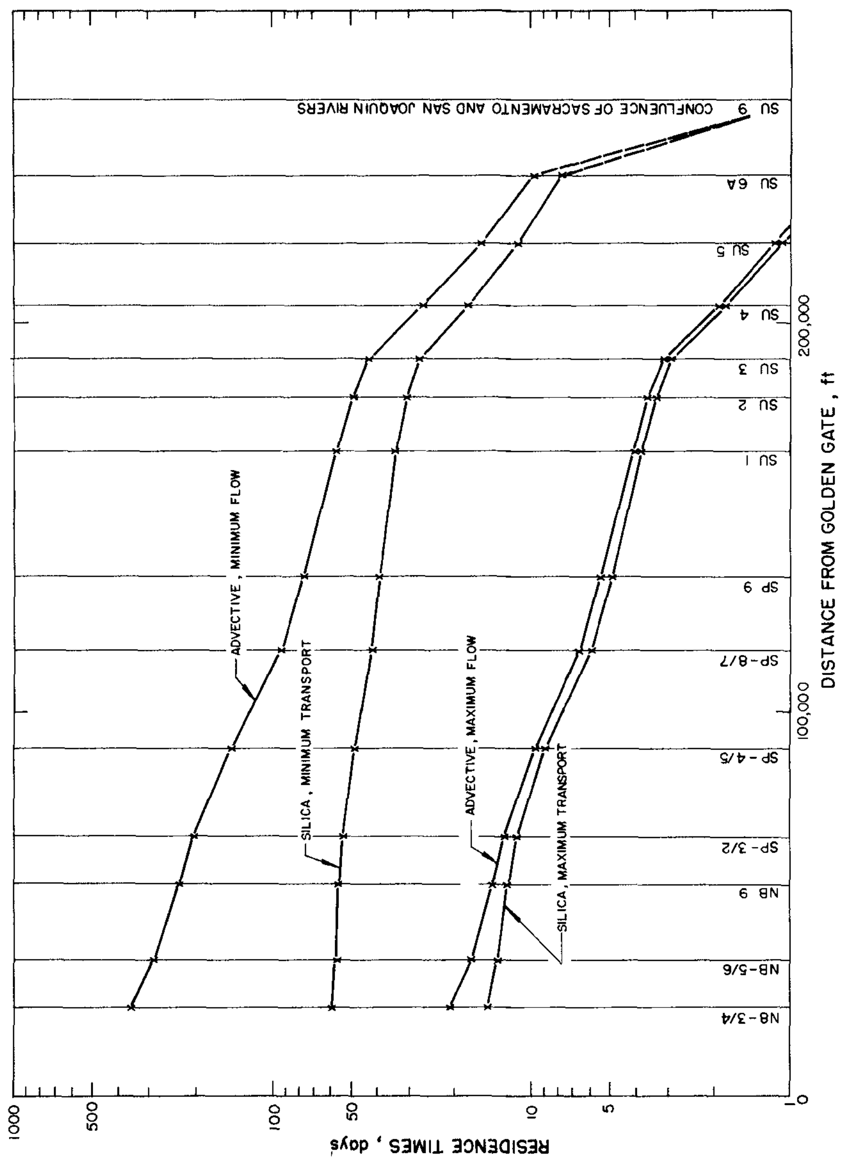

FIGURE 1 RESIDENCE TIMES IN NORTHERN SAN FRANCISCO BAY FOR THE 1961-62 WATER YEAR

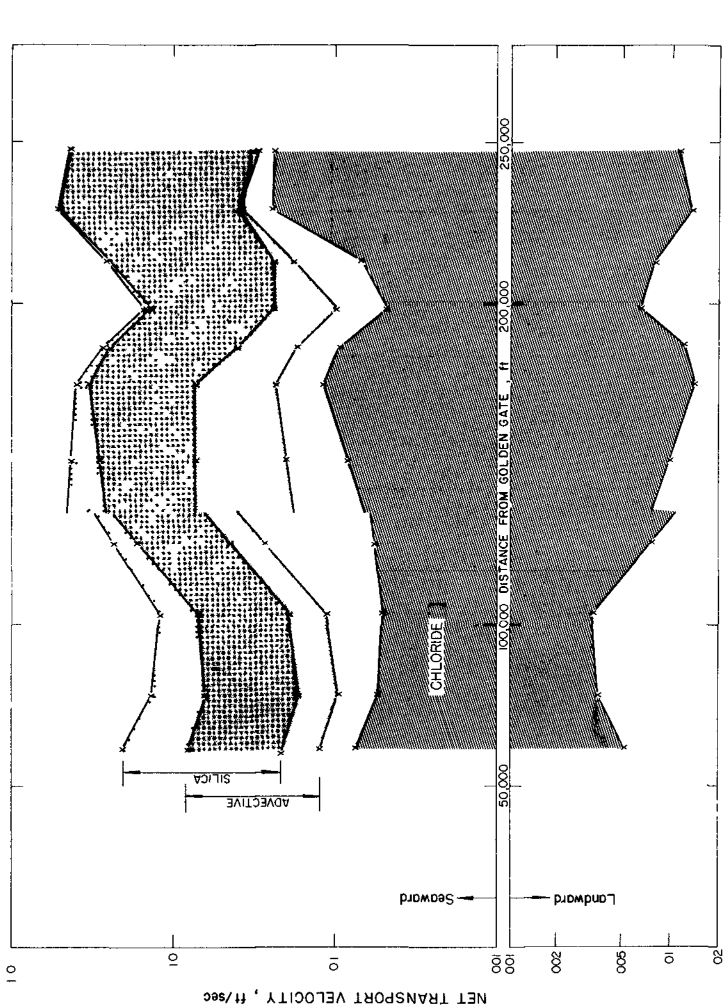

FIGURE 2. RANGE OF NET TRANSPORT VELOCITIES IN NORTHERN SAN FRANCISCO BAY FOR THE 1961-62 WATER YEAR

When the constituent concentration gradient is zero the expression reduces to the advective velocity The significance of the diffusive transport term can be calculated from equation (7). To obtain an expression, void of E, for the local constituent transport velocity equation (6) is inverted

$$\frac{dx}{dT} = \frac{1}{A\ \bar{c}} \sum_{o}^{x} S_s \qquad .... (8)$$

With a minimum of data available equation (8) can be used to evaluate steady state, one-dimensional constituent transport in an estuary Since the constituent transport in most natural estuaries is not strictly one-dimensional it is usually advisable to divide the estuary into several sections and to stepwise perform the computations (see Figures 1 and 2)

In Figure 2 is plotted the range of transport velocities for silica, chloride, and "fresh water" for the 1961-62 water year in Northern San Francisco Bay A discontinuity in the data is present between San Pablo Bay and Carquinez Strait owing to differences in observation periods.

CONCLUSION

The linear characteristic of the one-dimensional mass continuity equation for constituents (conservative or first order decay) in estuaries shows that the constituent residence times or transport velocities are independent of the constituent source strength This fact permits computation of representative constituent transport velocities using artificial or natural tracers with typical discharge locations

The evaluation procedure outlined above requires a minimum of data and labor; e g no knowledge of diffusion coefficients In estuaries and bays with predominantly one-dimensional constituent transport the procedure gives practical information regarding the mixing and exchange mechanism.

In Northern and Southern San Francisco Bay dissolved silica (SiO_2) was found to be a good representative tracer naturally discharged by rivers and streams.

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