Salinity of surface water in a partially-mixed estuary, and its dispersion at low run-off

Estuarine mixing
Salinity variations
Flushing times
Dispersion coefficients
England coast
Mélange estuarien
Variations de salinité
Temps de dilution
Coefficients de dispersion
Côte d'Angleterre

R. J. Uncles, A. J. Bale, R. J. M. Howland, A. W. Morris, R. C. A. Elliott
Natural Environment Research Council, Institute for Marine Environmental Research, Prospect Place, The Hoe, Plymouth PL1 3DH, UK.

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ABSTRACT

Surface salinity at any geographical position in the Tamar Estuary undergoes large seasonal variations. It is shown that these variations are a consequence of variable freshwater inputs to the estuary, and that axial distributions of surface salinity can be estimated with reasonable accuracy from the freshwater inputs using simple regression formulae.

Flushing times and axial dispersion coefficients are computed for low run-off, spring tide conditions, when the estuary approaches the well-mixed state. The observed dispersion coefficients are compared with those predicted from theoretical considerations. Various shear dispersion mechanisms are investigated, as well as those due to tidal "random walk", and tidal "trapping". The estimated cross-estuary mixing due to tidal "random walk" is much greater than that which can be attributed to turbulence alone. Assuming this enhanced cross-estuary mixing, it is shown that the observed dispersion in the upper estuary can be attributed to transverse oscillatory shear. Dispersion in the lower estuary is more complex, and for low run-off, spring tide conditions, the most important individual process appears to be tidal "trapping".

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RÉSUMÉ

Salinité de l'eau superficielle dans un estuaire partiellement mélangé et sa dispersion par faible débit.

La salinité superficielle à toutes les positions géographiques de l'estuaire du Tamar subit des grandes variations annuelles. On constate que ces variations résultent des apports variables d'eau douce, et que les répartitions axiales de salinité superficielle peuvent être estimées avec une assez bonne précision à partir des apports d'eau douce, en utilisant des formules de régression simple.

Les temps de dilution et les coefficients de dispersion axiale sont calculés pour les conditions des marées de vives-eaux et des débits faibles, lorsque l'estuaire est presque homogène verticalement. Les valeurs observées des coefficients de dispersion sont comparées avec leurs valeurs théoriques. Quelques mécanismes de dispersion par cisaillement sont étudiés, ainsi que ceux produits par le « random walk » de marée et le « trapping » de marée. Le mélange estimé en travers de l'estuaire, causé par le « random walk » de marée, est beaucoup plus grand que celui attribué à la turbulence seule. En supposant un mélange intense en travers de l'estuaire, on montre que la dispersion observée en amont peut être attribuée au cisaillement oscillatoire transversal. La dispersion en aval est plus complexe et, dans les conditions de faible débit et de marée de vives-eaux, le phénomène le plus important paraît être le « trapping ».

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INTRODUCTION

The purpose of this paper is to present and interpret data on seasonal variations in surface water salinity in a typical partially mixed estuary, and to investigate its dispersion properties under low run-off, spring-tide conditions. No new insights into dispersion processes are provided; rather, orders of magnitude for these processes are estimated in a real situation. Various shear-dispersion mechanisms are considered, as well as those due to tidal "random walk" and tidal "trapping" (Fischer *et al.*, 1979). Surface salinity data cannot generally be used to estimate total estuarine salt content, nor cross-sectionally averaged salinity in a partially mixed estuary. Nevertheless, these data can be used to investigate flushing times and axial dispersion coefficients at very low freshwater run-off during spring tides, when the water column is very nearly homogeneous.

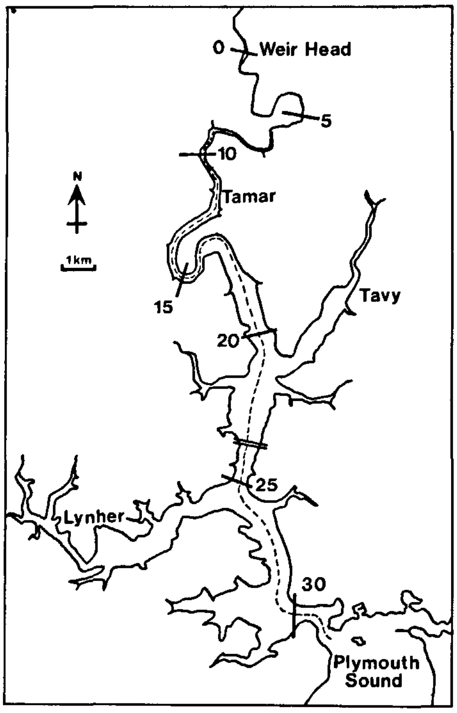

Figure 1
Chart of the Tamar Estuary, showing distance scale in kilometres along its axis.

The data for this study were taken from observations in the Tamar, which is a medium-sized estuary in the south west of England (Fig. 1). It is 31 km long from its seaward boundary with Plymouth Sound ($x=31$ km), to its limit of salinity intrusion at Weir Head ($x=0$). The Tamar Estuary carries freshwater run-off from four main sources. These are the River Tamar at Weir Head ($x=0$), an industrial source at $x=3$ km, and the sub-estuaries of the Tavy ($x=21$ km) and Lynher ($x=25$ km). The River Tamar carries the largest freshwater flows. Typical monthly averaged flows decrease from a maximum of 38 $m^3 sec.^{-1}$ during January to a minimum of 5 $m^3 sec.^{-1}$ during June. On average, the Tavy contributes an input of about 30% of the River Tamar input, and the Lynher about 20%. The industrial source contributes a negligible amount except during very low summer run-off, when it is typically 20% of the River Tamar input.

The tidal regime of the Tamar Estuary has been documented by George (1975). Tides are semi-diurnal with mean neap and spring ranges of 2.2 and 4.7 m, respectively. Volumes of the estuary at high and low water for mean springs and neaps have been plotted by George (1975). These data have been used to specify estuarine volumes and cross-sectional areas in this paper.

A substantial increase in knowledge of the water chemistry in the Tamar has taken place in recent years (Bale *et al.*, 1983; Loring *et al.*, 1983; Mantoura, Mann, 1979; Morris, 1978; Morris, Bale, 1979; Morris *et al.*, 1978; 1981; 1982). This paper is the first quantitative description of physical mixing processes and salinity variability in the Tamar, although the results and methods used here are of general importance to an understanding of this type of estuary.

METHODS

Salinity data

Data were derived from 27 axial surveys of the near-surface water chemistry of the Tamar during 1977 and 1978 (details are given in Morris *et al.*, 1982). Generally, between 40 and 100 observations were made along the axis of the estuary at arbitrary positions and states of the tide on each survey. Each set of measurements was completed within a single tidal cycle. A tidal correction method was used to provide a quasi-synoptic axial distribution of surface salinity. The method is described by Mollowney (1973), and is not repeated here. Axial distributions of salinity were estimated for each lunar hour. Averaging the time-series over a tidal cycle provided an estimate of the axial distribution of tidally averaged salinity, S, for each survey.

Regression analysis

A function, F, is introduced and approximated by a multiple regression equation with independent variables Q^{-1} (Q is run-off) and RQ^{-1} (where R is the tidal range, which has a mean value of 3.45 m):

$$F=-S\left[A\frac{\partial S}{\partial x}\right]^{-1}=F_1(R-3.45)/Q+F_2/Q+F_3. \quad (1)$$

Q is averaged over the week preceding each survey, this being a characteristic flushing time for the Tamar (*see* later). Equation (1) defines the dispersion coefficient as a linear function of Q and R. The area, A, is a tidally averaged value which is plotted later. This technique has been described in detail for the Severn Estuary (Uncles, Radford, 1980). Multiple regression analysis yields the coefficients F_1, F_2, and F_3. The analysis shows that F_1 (the coefficient describing spring-neap variability) is generally not significantly different from zero. Only seasonal variability can be determined from these data. Therefore, the analysis was repeated using linear regression [equation (1) with $F_1=0$].

RESULTS

Salinity variations

Coefficients F_2 and F_3 [$F_1=0$ in equation (1)] have been derived for $x=0.5$ (1) 29.5 km. Of the thirty linear regressions, 18 are significant at the 99.9% confidence level, five at the 99% level, and one at the 90% level. The six regressions at positions nearest Weir Head are not statistically significant. Here, coefficients F_2 and F_3 are arbitrarily equated to values at $x=6.5$ km.

The axial distribution of salinity can be deduced from equation (1):

$$\frac{\partial S}{\partial x} = -S/AF. \qquad (2)$$

This equation can be solved using simple finite-differences provided the freshwater run-off, Q, is known, and using values of F_2 and F_3 given by equation (1). The non-zero salinity at one axial position, x, must also be known.

Axial distributions of salinity for three surveys are drawn in Figure 2. Freshwater run-off at Weir Head for these surveys, Q_0, were: *a*) 1.8 $m^3 sec.^{-1}$, which is less than half the minimum, mean monthly summer run-off;

b) 19 $m^3 sec.^{-1}$, which is approximately the yearly average value;

c) 74 $m^3 sec.^{-1}$, which is more than twice the maximum, mean monthly winter run-off.

Also shown in Figure 2 are the corresponding distributions obtained using equation (2). Observed salinity data at $x=30$ km were used for boundary values for the low and medium freshwater run-off distributions. The boundary value for high run-off was estimated using trial and error. Observed and computed distributions are generally in good agreement. Deviations between observed and computed values could be a consequence of non-steady conditions. Equations (1) and (2) assume that salinity is in equilibrium with the freshwater run-off. Consequently, when run-off is rapidly changing with time a steady-state model of salinity cannot be accurate. This good agreement between observed data and "modelled" regression data (over a wide range of freshwater flows) is important. It demonstrates that the major variability of surface salinity is due to variations in freshwater run-off.

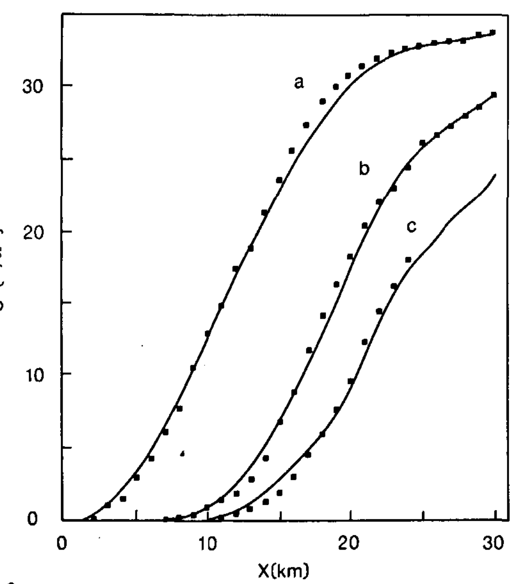

Figure 2

Observed (■) and computed (—) tidally averaged salinity, S, along the axis of the Tamar (x) for: (a) $Q_0=1.8\,m^3 sec.^{-1}$; (b) $Q_0=19\,m^3 sec.^{-1}$ and (c) $Q_0=74\,m^3 sec.^{-1}$.

Simmons's ratio and flushing

The Simmons's ratio, P, provides an indication of the extent to which an estuary is vertically stratified, where:

$$P=u_f/u_T. \qquad (3)$$

Here, u_T is the r.m.s. tidal current, and u_f the cross-sectionally averaged current due to freshwater run-off (Q/A). When $P\sim10^{-2}$ (or less) vertically mixed conditions generally exist (Simmons, 1955). When $P\sim10^{-1}$ (or more) then partially mixed conditions can be expected, with vertical stratification.

P is drawn in Figure 3 for the low run-off survey plotted in Figure 2, for which $Q_0=1.8\ m^3 sec.^{-1}$ and $R=4.6$ m (mean spring tides). For this low freshwater run-off (small u_f) and strong tidal flow (large u_T), $P\sim10^{-2}$ or less down-estuary of $x=8$ km (*see* Fig. 1). Vertically mixed conditions can be expected for most of the estuary. For average run-off conditions ($Q_0=18\ m^3 sec.^{-1}$), vertically mixed conditions can be expected only in the most seaward sections of estuary. The same conclusions follow if the Estuarine Richardson Number (Fischer *et al.*, 1979, p. 243) is considered rather than the older Simmons's ratio.

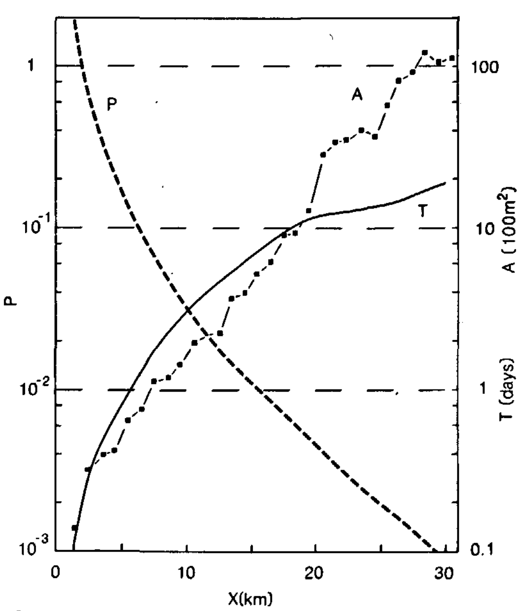

Figure 3

Simmons' ratio, P, and flushing time, T (days), along the axis of the Tamar for $Q_0=1.8\,m^3 sec.^{-1}$. Also shown is the tidally averaged, cross-sectional area A ($100\,m^2$).

Because of vertical stratification, the total salt (and fresh water) content of the Tamar can only be accurately estimated from surface salinity data at very low run-off during spring tides. The flushing time, T, for the survey when $Q_0=1.8\ m^3 sec.^{-1}$ is shown as a function of distance along the estuary in Figure 3. T is defined at a position x as the time required for up-estuary freshwater inputs to replace the up-estuary volume of fresh water. At the mouth, T is three weeks; up-estuary of $x=15$ km (*see* Fig. 1), T is less than one week.

Errors will be incurred in computing the freshwater content of the estuary from surface salinity data for larger values of the run-off. Salinity of deeper water will be higher than surface values. Therefore, both the total freshwater content and the flushing time deduced from surface salinity will be overestimated. For mean freshwater discharge ($Q_0 = 18$ m^3 sec.$^{-1}$), and neglecting stratification, surface salinity data indicate a flushing time of one week. In reality, it will be somewhat less than this, and much less during high winter freshwater inputs. On average, a typical flushing time for the Tamar is roughly one week.

Dispersion coefficients

In a steady-state, the down-estuary transport of salt due to freshwater-induced currents must be balanced by an up-estuary dispersion of salt with coefficient D:

$$QS + DA\frac{\partial S}{\partial x} = 0,$$

which can be rewritten using equation (1):

$$D = QF. \tag{4}$$

This balance assumes that S is the cross-sectionally averaged salinity. Because of stratification, D can only be deduced with confidence from surface salinity data at low run-off during spring tides. The dispersion coefficients have been computed from equation (4) using data from eight spring-tide surveys for which Q_0 was less than 3 m^3 sec.$^{-1}$ ($Q_0 = 2.3 \pm 0.4$ m^3 sec.$^{-1}$ and $R = 4.6 \pm 0.4$ m expressed as means and standard deviations over the eight surveys). Results for D showing means and standard errors are given in Figure 4. A spatially averaged value of D under low run-off, spring-tide conditions is 70 m^2 sec.$^{-1}$. The dispersion coefficients can be computed directly from equation (4) using the regression relationships for F. Results for $Q_0 = 2.3$ m^3 sec.$^{-1}$ are not significantly different from those deduced from actual survey data and presented in Figure 4. The mechanisms whereby hydrographical and topographical properties interact to produce the large axial variability in D (*see* Fig. 4) are considered in the following sections.

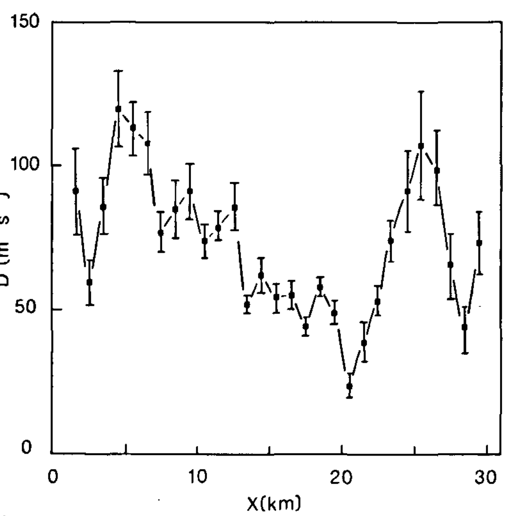

Figure 4
Axial dispersion coefficients, D *(m^2 sec.$^{-1}$), along the axis of the Tamar. Means and standard errors are shown for data from eight spring tide, low run-off surveys, for which* $Q_0 = 2.3 \pm 0.4$ *(standard deviation) m^3 sec.$^{-1}$.*

DISPERSION MECHANISMS

When tidal range is small compared with the depth of an estuary ($\sim$0.3 or less), the effective dispersion coefficient over a tidal cycle due to shear processes, D_s, may be written (Fischer, 1972):

$$D_s = D_v + D_t + D_{xy} + D_{xz}. \tag{5}$$

Subscripts denote dispersion due to vertical oscillatory shear (D_v, Elder, 1959), transverse oscillatory shear (D_t, Holley *et al.*, 1970), transverse residual circulations (D_{xy}, with y the transverse, cross-estuary coordinate, Fischer, 1972), and vertical residual circulations (D_{xz}, with z the vertical, depth coordinate, Prych, 1970). This nomenclature is similar to that used by West and Broyd (1981), who summarized current understanding of shear dispersion processes in the Mersey, Conway, Tay, Usk and Thames Estuaries. For many estuaries, and in particular in the Tamar, the assumption of small tidal range is not valid in the upper reaches. However, it is still useful to consider the breakdown of processes given by equation (5), especially where one process is dominant (*see* later) and can be isolated for subsequent experimental and theoretical study.

In addition to these shear processes, dispersion coefficients, D_r and D_p, can also be defined due to tidal "random walk" (Zimmerman, 1976; Uncles, 1982) and tidal "trapping" (Okubo, 1973), respectively. It is assumed that D_r and D_s are additive, so that [*see* equation (4)]:

$$D = D_s + D_r. \tag{6}$$

A review of these dispersion mechanisms is given by Fischer *et al.* (1979).

The ratio of the tidal period, T_0 (12.4 hr), to the time-scale for vertical mixing, T_v, is given by:

$$\tau_v = T_0/T_v = T_0\,\varepsilon_{sz}/d^2. \tag{7}$$

Here, d is the tidally averaged depth, and ε_{sz} is the vertical eddy diffusivity for the dispersing solute, which is taken to be constant with both time and depth through the water column. We introduce a numerical factor, f_{sz} (West, Broyd, 1981):

$$\varepsilon_{sz} = f_{sz}\,\varepsilon_{sz0} \tag{8}$$

where (Elder, 1959):

$$\varepsilon_{sz0} = 0.07\,du_*,$$

with u_* the tidally averaged absolute value of the friction velocity, which is taken to be (Proudman, 1953):

$$u_* = 0.05\,u,$$

in which u is the tidally averaged, absolute value of the tidal current speed.

The vertical eddy viscosity, ε_{mz}, is given by:

$$\varepsilon_{mz} = f_{mz}\,\varepsilon_{mz0} = f_{mz}\,\varepsilon_{sz0}. \tag{9}$$

Table

Expressions for shear dispersion coefficients. Rapid and slow mixing are applicable to D_v *and* D_t. *The density of seawater is denoted by* ρ.

	D_v	D_t	D_{xz}	D_{xy}
Rapid mixing	$5.9\, du_*/f_{sz}$ Elder (1959)	$2.7\, u\, W^2/df_{sy}$ Fischer *et al.* (1979)	$\dfrac{2.23\times 10^{-6} d^5 (\partial S/\partial x)^2}{u_*^3 f_{sz} f_{mz}^2}$	$\dfrac{1.48\, d^3 (W/2)^2 (\partial S/\partial x)^2}{\rho^2 u_*^3 f_{mz}^2 f_{sy}}$
Slow mixing	$2.2\times 10^4 u^3 f_{sz}/d$ Holley *et al.* (1970)	$9.0\times 10^5 u^3 f_{sy}\, d/W^2$ Fischer *et al.* (1979)	Prych (1970)	Fischer (1972)

The ratio of the tidal period to the time-scale for cross-estuary mixing, T_t, is given by:

$$\tau_t = T_0/T_t = T_0\, \varepsilon_{sy}/W^2. \quad (10)$$

Here, W is the tidally averaged estuarine width, and ε_{sy} is the transverse eddy diffusivity for solute:

$$\varepsilon_{sy} = f_{sy}\, \varepsilon_{sy0}, \quad (11)$$

with $\varepsilon_{sy0} = 0.15\, du_*$, where ε_{sy0} is the transverse eddy diffusivity due solely to turbulence in the tidal currents (Fischer, 1972; Fischer *et al.*, 1979).

The Table gives expressions for the shear dispersion coefficients, and their sources of reference. Expressions are given for conditions of rapid mixing (τ_t, $\tau_v > 1$) and slow mixing (τ_t, $\tau_v < 0.2$). In the case of intermediate mixing, D_v and D_t can be derived from data in Fischer *et al.* (1979, p. 98). Axial and transverse dispersion coefficients due to tidal "random walk" are given in Uncles [1982, equation (3), p. 407]. The axial dispersion coefficient due to tidal "trapping" is given by Okubo (1973) and Fischer *et al.* [1979, equation (7.6), p. 242].

APPLICATION TO THE TAMAR

The dispersion coefficients are expressed in terms of the estuarine variables *d*, W, *u* and $\partial S/\partial x$. These quantities are defined at each position (x) as mean values over that distance of tidal excursion which is centred on x. Low run-off, spring tide conditions are considered, corresponding to data shown in Figures 3 and 4.

Vertical shear and mixing

Vertical shear dispersion due to oscillatory tidal currents and gravitational residual currents, D_v and D_{xz}, are given in the Table. In strictly homogeneous conditions, $f_{sz} = 1 = f_{mz}$ for a passive solute [equations (8) and (9)]. However, there is some evidence that even small, stable deviations from vertical homogeneity greatly suppress vertical turbulence, and thus reduce f_{sz} and f_{mz}. Data in West and Broyd (1981), for a number of estuaries, indicate $f_{sz} \simeq 0.1$ and $f_{mz} \simeq 0.2$. These low values are also used here in order to give a maximum weighting to D_v and D_{xz}, and to subsequently show that these theoretical values are still too small to explain the observed dispersion coefficient (Fig. 4).

Time-scales for vertical mixing [equation (7)] at any position (x) in the estuary are always much less than the flushing time of the estuary. This means that a patch of solute which is introduced into the estuary will have sufficient time to mix vertically during its passage through the estuary, and will thus be subject to vertical shear dispersion with a coefficient ($D_v + D_{xz}$). During spring tides, and under conditions of low run-off, ($D_v + D_{xz}$) decreases from about 10 $m^2 sec.^{-1}$ at the mouth, to less than 3 $m^2 sec.^{-1}$ in the upper estuary. These values are much smaller than those shown in Figure 4.

Transverse shear and mixing

Assuming that the only cross-estuary mixing mechanism is turbulence due to tidal currents, then $f_{sy} = 1$ in equation (11). In this case, the time-scale for cross-estuary mixing, given by T_t in equation (10), would vary from 10 days in the upper estuary, to 200 days near the mouth. This time-scale greatly exceeds the flushing time of the estuary (Fig. 3), so that a patch of solute which was introduced into the estuary could not mix over the width, and transverse shear mechanisms would not affect its subsequent dispersion (*see* also Dronkers, 1982). The axial shear dispersion coefficient, D_s, would be given by:

$$D_s = D_v + D_{xz},$$

which is plotted in Figure 5 as the theoretical shear dispersion coefficient in the Tamar for $f_{sy} = 1$.

Figure 5 also shows D_s [equation (5)] as a function of distance along the Tamar when $f_{sy} = 10$ and 50. A value of $f_{sy} = 10$ leads to cross-estuary mixing time-scales

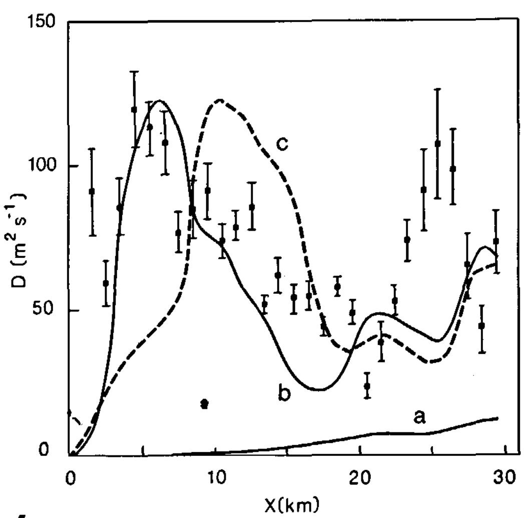

Figure 5

Predicted axial dispersion coefficients due to shear processes, D_s, *for (a)* $f_{sy} = 1$; *(b)* $f_{sy} = 10$ *and (c)* $f_{sy} = 50$. *Observed coefficients are also shown.*

which are comparable to the flushing time, $T_f \sim T$, and may be considered a minimum for which transverse shear dispersion can be effective. All of the theoretical curves for D_s in Figure 5 incorporate vertical shear dispersion ($D_v + D_{xz}$), which is given by the curve for $f_{sy}=1$. In the upper estuary, $x<20$ km, the only significant shear dispersion mechanism is transverse oscillatory shear, D_t; transverse residual shear, D_{xy}, is negligible, even when low values of $f_{mz}=0.2$ and $f_{sz}=0.1$ are used. Considering the upper estuary in Figure 5, curves of D_s for $f_{sy}=10$ and 50 have a similar shape. $D_s=0$ at the head ($x=0$) because shear dispersion due to river flow has been ignored, and because tidal currents and their associated shear vanish at the head. The initial increases in $D_s(D_s \simeq D_t)$ with x results from increasing estuarine width, which provides additional scope for cross-estuary variations. The maximum in D_s is approached when the longer cross-estuary mixing time-scale due to increasing width becomes comparable with the tidal period. Eventually, as the estuary becomes wider with increasing x, a patch of solute experiences little cross-estuary mixing during a tidal cycle, and as shown in Figure 5, the dispersion coefficient rapidly decreases (Holley *et al.*, 1970).

In the lower estuary, $x>20$ km, transverse residual shear dispersion, D_{xy}, becomes more important then D_t for the assumed values of f_{sy}, although the total shear dispersion, D_s, is significantly smaller than the observed values (*see* Fig. 5).

In order for shear dispersion coefficients to reach values which are comparable with observed values in the upper estuary, it is necessary for $f_{sy}>10$, i.e.: the cross-estuary mixing to be much greater than that due to turbulence alone. Two possible cross-estuary mixing mechanisms are tidal "random walk" (Uncles, 1982), and transverse dispersion due to cross-estuary buoyancy-driven currents (Smith, 1980).

Tidal "random walk"

This dispersion is generated by tidally-induced residual current eddies. Such eddies are known to exist in the Tamar (George, 1975), although quantitative data on eddy size are lacking. In the Severn Estuary it is found that the average width of residual current eddies is one third of the estuary's width (Uncles, 1982). It is assumed that this is also the case for the Tamar. Observations of currents in the Tamar yield depth-averaged residual current speeds which are typically about 5 cm sec.$^{-1}$ at spring tides. These currents are thought to be due to horizontal residual current eddies. During spring tides the average amplitude of the tidal excursion is 3.9 km. Using these values gives an axial dispersion coefficient due to tidal "random walk" which decreases from 8 m^2 sec.$^{-1}$ at the mouth, to less than 1 m^2 sec.$^{-1}$ in the upper estuary. Therefore, axial dispersion due to tidal "random walk" is small. The transverse dispersion coefficient decreases from 0.9 m^2 sec.$^{-1}$ at the mouth to 0.03 m^2 sec.$^{-1}$ near the head. This gives values of f_{sy} which vary along the estuary; a spatially averaged value is $f_{sy}=28$.

The large cross-estuary dispersion coefficient near the mouth of the estuary (0.9 m^2 sec.$^{-1}$), can be compared with observed values of 0.25 and 0.4 m^2 sec.$^{-1}$ in San Francisco Bay (Ward, Fischer, 1971), and an estimated value of 0.5 m^2 sec.$^{-1}$ for the Mersey (Fischer, 1972). Ward (1976) reports observations on the growth of a dye patch during an ebb flow in the Fraser Estuary, British Columbia, which give $f_{sy}=11$. However, we know of no observations of cross-estuary mixing which extend over one or more tidal cycles, and which could be used to compare actual values of f_{sy} with those estimated here from tidal "random walk".

In addition to cross-estuary dispersion due to tidal "random walk", there is also the possibility of cross-estuary, buoyancy-driven currents producing transverse dispersion and increasing the mixing (Smith, 1980). Smith's (1980) analysis cannot be applied to the Tamar because the calculated cross-sectional mixing time-scales predicted by the theory are less than one tidal cycle, thereby violating the assumption of slow cross-sectional mixing, on which the theory is based. Nevertheless, it appears that this is an important source of cross-estuary mixing, which augments that due to turbulence and tidal "random walk", and which further implies that $f_{sy} \gg 1$.

Axial dispersion coefficients, ($D_s + D_r$), derived using the estimated values of f_{sy} due to "random walk", are plotted in Figure 6. Up-estuary of $x=20$ km, the theoretical dispersion is almost entirely due to transverse oscillatory shear, and is very close to the observed values. The non-zero dispersion at the head is due to the velocity of the fresh-water flow; the effects of this contribution rapidly decrease down-estuary, as the cross-sectional areas increase and the freshwater-induced velocities decrease. Down-estuary of $x=20$ km the contributions to the axial dispersion from vertical shear processes and tidal "random walk" are comparable, and each amounts to 5-10 m^2 sec.$^{-1}$. Contributions due to transverse buoyancy-driven currents and transverse oscillatory shear are also comparable, and each amounts to about 10-20 m^2 sec.$^{-1}$. None of these mechanisms is able to explain the observed maximum in D which occurs at $x \simeq 25$ km (*see* Fig. 1), and this phenomenon is considered in the next section.

Tidal "trapping"

A parcel of water whose mean position during a tidal cycle is centred on $x=25$ km (the down-estuary maximum in D), oscillates between $x=21$ to 29 km during spring tides. This section of estuary comprises two sub-estuaries (Tavy and Lynher), as well as a number of intertidal embayments and a dockyard. The complexity of the estuary in this region is evident from Figure 1. Up-estuary of $x=20$ km the bank topography is much simpler, and "trapping" is likely to be insignificant.

Therefore, the possibility arises that the sub-estuaries and embayments in the lower estuary provide "traps" for solute which is relased in this region. In particular, a solute which is released at $x=25$ km, and at mid-tide, will experience the complete array of "traps" during a

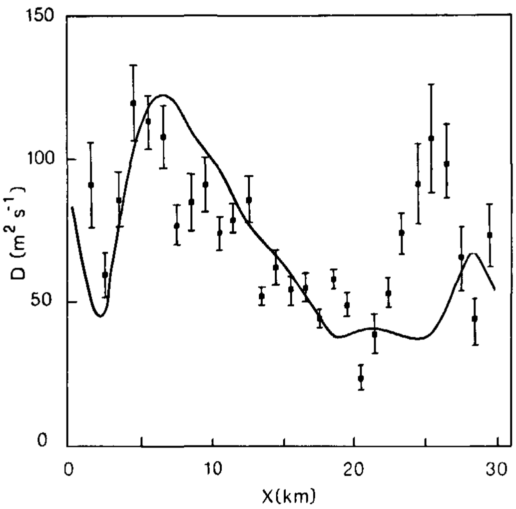

Figure 6

Predicted axial dispersion coefficients due to shear and tidal "random walk". The presence of tidal "random walk" leads to enhanced cross-estuary mixing, $f_{ty} \gg 1$. Observed coefficients are also shown.

tidal cycle, so that the associated dispersion will reach a maximum. The ratio of "trap" volume to main estuary volume in the lower reaches at spring tides is 0.4. Each embayment and sub-estuary fills, and effectively empties, during one tidal cycle, so that the exchange time is T_0. The peak, cross-sectionally averaged tidal current in the lower reaches during spring tides u_0, is 0.47 m sec.$^{-1}$. Using these values gives (Fischer *et al.*, 1979, p. 242):

$$D_t = 0.71\,(D_s + D_r) + 67 \text{ m}^2 \text{ sec.}^{-1}$$
$$\simeq 100 \text{ m}^2 \text{ sec.}^{-1},$$

using an average value of $(D_s + D_r) = 50$ m^2 sec.$^{-1}$ in the lower estuary (Fig. 6). This value is very close to the observed maximum in D which is situated near $x \simeq 25$ km. A solute which is released further up-estuary at mid-tide will experience only a fraction of the complicated down-estuary topography, and the "trapping" and its associated dispersion will decrease, as shown in Figures 4 to 6.

CONCLUSIONS

Surface salinity in the Tamar Estuary undergoes large seasonal variations. These are highly correlated with freshwater run-off to the system. Axial distributions of surface salinity can be estimated with reasonable accuracy from the freshwater inputs using simple regressional relationships, not only for mean inputs, but also for very high and very low values. However, exceptions to this must occur in cases of highly transient freshwater inputs, when salinity distributions will be far from steady-state. This correlation between flow and salinity means that the major variability of surface salinity can be attributed to variations in freshwater run-off.

Examination of the Simmons's ratio demonstrates that the Tamar is generally a partially mixed estuary. Because stratification is expected to be negligible at very low run-off during spring tides, surface salinity data for surveys satisfying these conditions have been used to investigate flushing times and axial dispersion coefficients. Under these rather extreme conditions the flushing time for the whole estuary is about three weeks. On average, the flushing time is expected to be roughly one week. The axial dispersion coefficients under low freshwater input, spring tide conditions are typically 70 m^2 sec.$^{-1}$. Large variations in these coefficients occur with distance along the estuary, and the reasons for this variability have been examined using currently available theoretical expressions for estuarine dispersion.

The observed dispersion in an estuary is a consequence of several different dispersing mechanisms. These include shear dispersion, tidal "random walk" and tidal "trapping". Individual contributions to the dispersion coefficient have been estimated for the Tamar under low run-off, spring tide conditions. Vertical shear dispersion due to both oscillatory tidal currents and gravitational residual currents appears to be very small throughout the estuary; values decrease from less than 10 m^2 sec.$^{-1}$ at the mouth, to less than 3 m^2 sec.$^{-1}$ in the upper estuary.

The contribution of transverse shear dispersion to the dispersion coefficient depends on the cross-estuary mixing time-scale. If turbulence due to tidal currents were the only cross-estuary mixing mechanism, then mixing across any section would take longer than the observed up-estuary flushing time, and transverse shear dispersion would be negligible. In this case, it would not be possible to explain the existence of the large dispersion coefficients which are observed in the upper estuary in terms of the mechanisms examined here. However, the estimated cross-estuary mixing due to tidal "random walk" is much higher than that due to turbulence alone, and leads to mixing time-scales which are much less than the flushing times of the estuary. Mixing is also augmented by cross-estuary buoyancy-driven currents, although the extent of this mixing is unknown. With enhanced mixing the up-estuary dispersion is dominated by transverse oscillatory shear in the tidal currents, and the theoretically derived axial dispersion coefficients are comparable with observed values (*see* Fig. 5 and 6). Axial dispersion coefficients due to tidal "random walk" and tidal "trapping" are estimated to be very small in the upper estuary.

In the lower estuary, the axial dispersion coefficients due to vertical shear processes and tidal "random walk" each amount to about 5-10 m^2 sec.$^{-1}$. Dispersion coefficients due to transverse oscillatory and residual current shear are also small, and each amount to 10-20 m^2 sec.$^{-1}$. The observed maximum in the down-estuary dispersion coefficient ($\simeq 100$ m^2 sec.$^{-1}$), appears to be a consequence of tidal "trapping".

A large body of theory on estuarine dispersion has been formulated in the last twenty years. Some of this has been briefly reviewed here. It is clear from our work on low run-off dispersion in the Tamar (when conditions are simplest), that a major limitation on the application of this theory is the lack of knowledge on cross-estuary circulation patterns and mixing, and that this is an area for extensive research effort in the future.

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