Reprinted from

ESTUARINE COASTAL AND SHELF SCIENCE

ACADEMIC PRESS
London Orlando San Diego
New York Toronto Montreal
Sydney Tokyo

Published by Academic Press Inc. (London) Limited in association with the Estuarine and Brackish-water Sciences Association

Instructions to Authors

(1) *Estuarine, Coastal and Shelf Science* is an international, multidisciplinary journal devoted to the analysis of biological, chemical and physical phenomena occurring in waters from the outer edge of the continental shelf to the upper limits of the tidal zone.

The journal features original papers from such disciplines as zoology, botany, geology, sedimentology, physical oceanography, numerical models and chemical processes. Papers include analysis of species distribution in relation to varying environments; waste disposal, groundwater runoff, estuarine and fjord circulation patterns, physical oceanography and meteorological forcing of semi-enclosed and continental shelf water masses, wave processes and sediment movements.

(2) *Submission of manuscripts.* All manuscripts are to be submitted in English and in the first instance must be sent to one of the three co-editors. All papers concerned with life sciences should preferably be sent to *Professor E. Naylor, School of Animal Biology, University College of North Wales, Bangor, Gwynedd, North Wales, U.K.*, or alternatively, *Dr M. Grant Gross, Chesapeake Bay Institute, The Johns Hopkins University, Baltimore, Maryland, 21218, U.S.A.* Papers primarily concerned with marine physics and earth sciences should be sent to *Dr Nicholas C. Flemming, Institute of Oceanographic Sciences, Wormley, Godalming, Surrey, U.K.*, though papers on sediments or chemistry may also be sent to Dr Grant Gross. Papers submitted to *Estuarine, Coastal and Shelf Science* should preferably be less than 14 printed pages in length, equivalent to 10 000 words without diagrams, or the equivalent in words and diagrams. Major articles up to 15 000 words or equivalent will be accepted at the discretion of the Editors, but there may be a delay in publication of long papers. There are sections for short notes and observations, book reviews, and correspondence.

(3) *Preparation of typescripts.* Typescripts should be submitted in duplicate, using one side only of the paper. Typing should be double spaced throughout the text, including tables, figure legends and reference lists, with a margin of 4 cm on each side. Number consecutively all pages, including title page, abstract, text, references, legends and tables.

(4) *Keywords.* Up to 8 subject-defining Keywords are allocated to each paper immediately preceding the abstract. Authors should select preferred Keywords from the list published in Issue 5 (2), 1977, pp. i-xl and submit them with the Ms if possible. Keywords should be arranged in order of importance, with the geographical or sea area always last.

(5) *Illustrations.* These include figures and plates. Legends for these should be typed in numerical order on a separate sheet, one for figures and one for plates. Illustrations should be designed with the size of the journal page and column in mind. Each illustration should be identified by the name of the author and its number, and its top should be indicated. Magnification should be given by a scale line where appropriate. Unsatisfactory illustrations will be returned to the author. Original illustrations are discarded following publication unless author has requested their return in advance.

Maps, line drawings and diagrams should be prepared with India ink on white drawing paper, tracing paper, or tracing linen. Several drawings grouped on a page as one figure are distinguished as (a), (b), (c), etc. Figures which must be printed larger than page size

Estuarine, Coastal and Shelf Science (1985) **20**, 147–167

Observed Fluxes of Water, Salt and Suspended Sediment in a Partly Mixed Estuary

R. J. Uncles, R. C. A. Elliott and S. A. Weston

Natural Environment Research Council, Institute for Marine Environmental Research, Plymouth PL1 3DH, U.K.

Received 19 April 1983 and in revised form 12 March 1984

Keywords: estuarine circulation; anchor stations; water balance; salt balance; sediment balance; England coast; Tamar Estuary

Observations of the residual fluxes of water, salt and suspended sediment are presented for seven stations along the Tamar Estuary. The data include measurements over single spring and neap tidal cycles, and are generally applicable to medium or high run-off conditions.

Surface to bed differences in salinity are typically of the order of several parts per thousand. Gravitational circulation is an important component of residual flow in the deep, lower reaches of the estuary. Here, Stokes drift is insignificant. In the shallow upper reaches, the major residual currents are generated by Stokes drift and freshwater inputs. Data are compared with predictions from Hansen and Rattray's (1966) model of estuarine circulation.

Salt fluxes due to tidal pumping and vertical shear are directed up-estuary at spring tides, tidal pumping being dominant. Tidal pumping of salt is also directed up-estuary at neap tides, although it is insignificant in the lower reaches, where vertical shear dominates.

Tidal pumping of suspended sediment is directed up-estuary near the head at spring tides, and probably contributes to the formation of the turbidity maximum. The existence of the turbidity maximum is predicted using a simplified model of the transport of water and sediment. The model shows that an additional mechanism for the existence of the turbidity maximum is an up-estuary maximum in the tidal current speeds (and thus resuspension). In the lower reaches, transport of suspended sediment is directed down-estuary at both spring and neap tides, and sediment is essentially flushed to sea with the fresh water.

Introduction

Analyses are presented of the residual fluxes of water, salt and suspended sediment in the Tamar, which is a partly mixed estuary in the southwest of England (Figure 1). Observations were made over spring and neap tidal cycles, generally under average to high run-off conditions. Stations were located in the deep channels of seven cross-sections, which were situated between the head and mouth of the estuary (stations 1, 2, 2a to 6 in Figure 1). The residual fluxes are interpreted in terms of the transport due to residual flows of water, tidal pumping and vertical shear. The effect of tidal pumping of sediment, and the existence of an up-estuary maximum in tidal current speed, are shown to account partially for the existence of a turbidity maximum in the upper reaches of the Tamar.

0272–7714/85/020147+21 $03.00/0

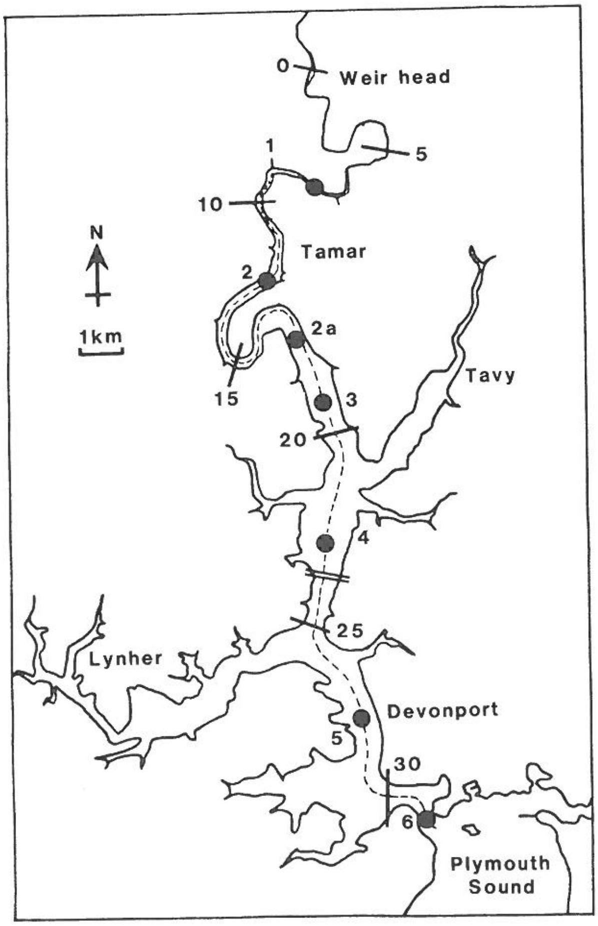


Figure 1. Sketch chart of the Tamar estuary, showing its sub-division into 5 km intervals, and station positions (●).

Estuarine circulation has been studied experimentally for many years (e.g. Pritchard, 1954; Bowden, 1962; Bowden & Gilligan, 1971; Collar, 1978; Lewis, 1981; Lewis & Lewis, 1983), and reviews of much of the earlier work are given by Dyer (1973) and Officer (1976). The importance of gravitational circulation and its role in partially maintaining the salt balance in partly mixed estuaries is well known (Hansen & Rattray, 1966; Rattray & Dworski, 1980). In the shallow, up-estuary reaches of mesotidal and macrotidal, partly mixed estuaries, tidal pumping also appears to be an important source of salt transport (Uncles & Jordan, 1979; Hughes & Rattray, 1980; Lewis & Lewis, 1983). Nevertheless, considerable uncertainty still exists as to the way in which the water and salt budgets are maintained.

Even less is known about the sediment balance. The residual transport of suspended sediment, and the formation of the turbidity maximum, have often been attributed to gravitational circulation and the existence of its associated null point (Festa & Hansen, 1978; Officer & Nichols, 1980; Officer, 1980). However, the possible importance of tidal resuspension of bottom sediments in mesotidal and macrotidal estuaries has been recognized for some time (see Officer, 1981, and the references cited therein). In the Gironde Estuary, the turbidity maximum appears to be largely the result of three coupled processes (Allen *et al.*, 1980): (a) asymmetry in the tidal currents, in which flood currents exceed ebb currents (see Uncles, 1981, for an analysis of this feature of estuarine flow), (b) suspension of eroded bottom sediments, and (c) the existence of an up-estuary maximum in this erosion of bottom sediments. Our work shows that these processes are also important in the Tamar.

The observations presented here are of significance in that they contribute to our knowledge of the magnitudes of the mechanisms affecting the water, salt and sediment budgets in a typical partly mixed estuary.

Definitions and variables

Residual fluxes of water, salt and suspended sediment through a water column can each be separated into their various components. These components result from distinct physical processes, and their analytical descriptions have been derived theoretically many times (see, for example, Bowden & Sharaf El Din, 1966; Fischer, 1972; Dyer, 1974; Lewis, 1979; Uncles & Jordan, 1979). The axial (x) component of motion along the estuary is considered here, with H, U and Q the instantaneous depth, current and rate of volume transport per unit width ($Q=H\overline{U}$), respectively. It is shown in Uncles & Jordan (1979) that the residual rate of transport of water per unit width of water column is:

$$<Q> = <H\overline{U}> = h(\overline{u}_{\mathrm{E}}+\overline{u}_{\mathrm{S}}) = h\overline{u}_{\mathrm{L}}, \tag{1}$$

in which diamond brackets denote a tidal average, and the overbar a depth average, and where:

$$h = <H>, \tag{2}$$

$$\overline{u}_{\mathrm{E}} = <\overline{U}>, \tag{3}$$

$$\overline{u}_{\mathrm{S}} = <\tilde{H}\tilde{U}>/h, \tag{4}$$

with

$$\tilde{U} = \overline{U} - <\overline{U}> \text{ and } \tilde{H} = H - <H> \tag{5}$$

and

$$\overline{u}_{\mathrm{L}} = <Q>/h. \tag{6}$$

A one-dimensional analysis of the depth-averaged Eulerian, Stokes and Lagrangian residual currents in the Severn Estuary ($\overline{u}_{\mathrm{E}}$, $\overline{u}_{\mathrm{S}}$, $\overline{u}_{\mathrm{L}}$) has been given by Uncles & Jordan (1980). Similar studies have been reported by van de Kreeke (1978) and Ianniello (1981). A freshwater-induced residual current can also be defined, $\overline{u}_{\mathrm{F}}$. If $<A>$ is the tidally averaged area of a cross-section, and $<Q_{\mathrm{F}}>$ the tidally averaged rate of input of freshwater volume up-estuary of this section, then:

$$\overline{u}_{\mathrm{F}} = <Q_{\mathrm{F}}>/<A>. \tag{7}$$

The residual transport of salt per unit width of column is (in ‰ cm s^{-1}, see Uncles & Jordan, 1979):

$$F = F_L + F_{TP} + F_V \tag{8}$$

where F_L is due to the residual flow of water, $\bar{u}_L$, and F_{TP} and F_V are due to tidal pumping and vertical shear, respectively. If S denotes the instantaneous salinity, and $s = \langle S \rangle$, then:

$$F = \langle H\overline{US} \rangle / h, \tag{9}$$

$$F_L = \bar{u}_L \bar{s}, \tag{10}$$

$$F_{TP} = \langle \tilde{Q}\tilde{S} \rangle / h, \tag{11}$$

and

$$F_V = \langle H\overline{U'S'} \rangle / h, \tag{12}$$

where

$$S' = S - \bar{S} \quad \text{and} \quad U' = U - \bar{U}. \tag{13}$$

The residual transport of suspended sediment per unit width of column is (in ppm cm s^{-1}, where ppm = parts per million by weight of water):

$$G = G_L + G_{TP} + G_V. \tag{14}$$

Subscripts have the same meaning as those for the salt flux [equation (8)]. If P denotes the instantaneous suspended sediment concentration, and $p = \langle P \rangle$, then:

$$G = \langle H\overline{UP} \rangle / h, \tag{15}$$

$$G_L = \bar{u}_L \bar{p}, \tag{16}$$

$$G_{TP} = \langle \tilde{Q}\tilde{P} \rangle / h, \tag{17}$$

and

$$G_V = \langle H\overline{U'P'} \rangle / h, \tag{18}$$

where

$$P' = P - \bar{P}.$$

Observations and treatment of data

Measurements in the shallower water (stations 1 to 4 in Figures 1 and 2) were made from a flat bottomed seatruck which was moored fore and aft in the deepest part of each cross-section. Measurements in the deeper water (stations 5 and 6 in Figures 1 and 2) were made in the same way, but using conventional small boats. Current velocity, salinity and suspended sediment concentrations were recorded throughout the column, usually from 0·5 m below the surface to 0·5 m above the bed. Measurements were made at half-hourly intervals over a complete tidal cycle. Tidal heights were recorded using a tide pole at the shallower stations. Tidal heights at stations 5 and 6 were estimated from a recording tide gauge at Devonport (Figure 1). Currents were measured using an NBA direct

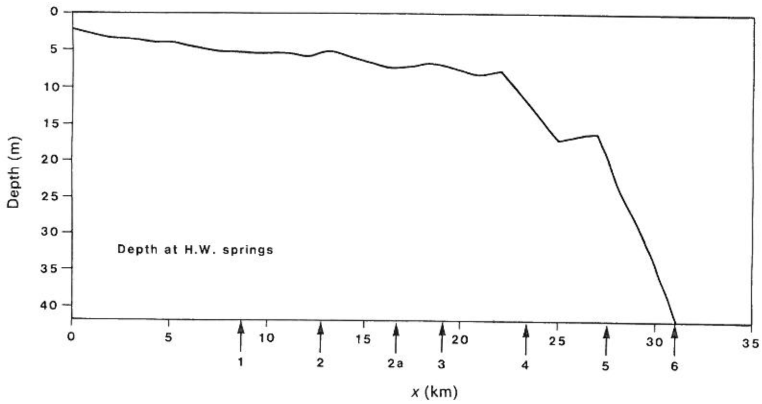


Figure 2. Depth of deep channel along axis of Tamar at mean high water springs. Distance along estuary and station positions are shown.

reading current meter, equipped with a depth sensor. Salinity was measured with an MC5 salinometer, and sediment concentration with a Partech suspended solids meter.

It is convenient to measure (or interpolate) data at fixed fractions of the instantaneous non-dimensional depth, η($\eta = 0$ and 1 at the surface and bed, respectively). The procedure for interpolating such data to standard fractional depths has been discussed previously (Kjerfve, 1975), and is only briefly outlined here. In this work, standard fractional depths were taken to be $\eta = 0{\cdot}1\ (0{\cdot}2)\ 0{\cdot}9$. Cubic splines were used for interpolating data for velocity and salinity. Extrapolation of data was sometimes necessary to estimate near-bed or near-surface values. Near-bed values for velocity were estimated by fitting a logarithmic boundary layer to the data (Kjerfve, 1979). Near-surface values were estimated by assuming a local parabolic profile for velocity. This parabola was chosen to reproduce the two observations closest to the surface, and to have zero slope with respect to depth at the surface (simulating zero stress there). The same technique was used for extrapolating data for salinity, both for estimating near-surface and near-bed values (simulating zero diffusive flux of salt at the surface and bed). Data for suspended sediment were invariably rather 'noisy', both through the water column and through time, especially when concentrations were low ($\sim$10 ppm or less). Therefore, linear interpolation was used to define these data at the standard fractional depths. This method has the advantage of not amplifying errors or inherent variability in the measured data. When extrapolated values were required near the surface or bed, then these were assumed to be equal to those values which were measured closest to the surface or bed. This is a crude approximation, but is not unreasonable; detailed measurements of suspended sediment concentrations in the bottom 2 cm to 100 cm of water column have not indicated any near-bed layers of dense sediment, nor the formation of fluid mud, even during spring tides when strong resuspension can occur (Mr P. G. Watson, personal communication).

A tidal average was formed by integrating observed data or derived data (for example fluxes) at each fractional depth over an M_2 tidal period of 12·42 h. This was compared with the tidal average formed by integrating data over the observed tidal period (the time between successive high waters or low waters). Differences between results obtained using these two averaging periods were insignificant, so that only data derived from the former are presented. The accuracy with which tidal averages of currents and fluxes were

TABLE 1. Basic properties of anchor stations 1 to 6 (spring tides, S; neap tides, N; mid tide, M; see text for explanation)

Station	Date	$R^\star$	$\bar{u}_T$(cm s^{-1})	h(m)	$Q_F^\star$	$\bar{u}_F$(cm s^{-1})	$\bar{s}$(‰)	$\bar{p}$(ppm)
1 S	16 Sep 1981	1·5	54	3·3	0·2	2·7	4·1	350·0
1 N	5 Nov 1981	0·6	22	3·0	1·2	17·0	0	7·5
2 S	29 Sep 1981	1·4	56	3·7	1·0	4·8	5·9	290·0
2 N	20 Jan 1982	0·7	24	3·6	1·1	6·2	5·2	9·8
2a S	12 Dec 1977	1·5	64	4·0	2·2	4·4	9·1	170·0
2a M	15 Dec 1977	1·2	48	3·8	1·2	2·7	12·9	65·0
3 S	10 Dec 1977	1·4	52	4·6	2·8	3·2	16·2	150·0
3 N	20 Nov 1981	0·7	28	3·7	3·7	5·1	10·8	64·0
4 S	12 Nov 1981	1·5	55	6·9	0·7	0·4	26·1	—
4 N	18 Jan 1982	0·7	26	6·3	1·1	0·7	25·3	3·3
5 S	16 Oct 1981	1·5	45	28·0	1·3	0·4	30·4	5·8
5 N	6 Oct 1981	0·6	15	29·0	2·8	0·8	30·6	2·2
6 S	13 Oct 1981	1·5	53	33·0	1·6	0·6	31·8	6·6
6 N	8 Oct 1981	0·5	19	32·0	2·4	1·1	32·5	1·8

derived was estimated by generating synthetic data for each station. For a given set of data, each measurement of a variable was perturbed about its observed value by adding the product of a standardized random normal variate with the standard deviation of the variable. The standard deviation was taken to be half the instrument error. Instrument errors, as specified by the manufacturer, were: current speed (± 5 cm s^{-1}), current direction ($\pm 10°$) and salinity ($\pm 0{\cdot}1$‰). We estimated errors in the depth of an observation and in the suspended sediment concentration to be ± 10 cm and $\pm 10\%$ of the observed concentration, respectively. These errors are assumed to be 95% confidence intervals (two standard deviations). The random perturbation of each data set was repeated 10 times, and the synthetic data were used to derive tidal averages (equal to the observed values) and their standard deviations. All water, salt and sediment fluxes derived and presented in this paper are plotted with 95% confidence intervals where these are larger than the plotting symbols.

A summary of background data for stations 1 to 6 is given in Table 1. This shows, (a): the date of observations, (b): the ratio of the observed tidal range at Devonport to the long-term mean value (3·45 m), $R^\star$, (c): the root mean square depth averaged tidal current, $\bar{u}_T$, (d): the mean depth, h, (e): the ratio of the observed rate of freshwater inputs to the yearly averaged value, $Q_F{}^\star$, (f): the freshwater induced residual current, $\bar{u}_F$ [see equation (7)], (g): the tidally averaged, depth-averaged salinity, $\bar{s}$, and (h): the tidally averaged depth-averaged suspended sediment concentration, $\bar{p}$.

Generally (see Table 1) the observations were carried out at a similar tidal state ($R^\star \simeq 1{\cdot}5$ for springs and $R^\star \simeq 0{\cdot}6$ for neaps). With the exception of station 1 (springs), the run-off into the estuary during the periods of observations was comparable with, or exceeded, the yearly averaged flows ($Q_F^\star \gtrsim 1$). The salinity was zero at all states of the tide at station 1 during neaps. Data on suspended sediment concentrations were not collected at station 4 (springs).

Results

The physical behaviour at a point in the estuary depended upon tidal range, freshwater inputs, and axial position. In the shallow water up-estuary of station 3 (where tidally averaged depths were typically less than a few metres, see Table 1 and Figures 1 and 2), the Eulerian residual currents, u_E, were directed down-estuary throughout the water column. These currents were driven by freshwater inputs ($u_F > 0$) and surface slopes generated by Stokes drift ($u_S < 0$, see Uncles & Jordan, 1980). At spring tides, two-layer flows occurred in the Lagrangian residual current, u_L, although the up-estuary, near-bed currents were small. These appeared to be weak circulations produced by vertical variations in the Stokes drift during spring tides, as found by Lewis & Lewis (1983) for the Tees Estuary, despite Ianniello's (1977) result that the Lagrangian residual currents arising from Stokes drift tend to oppose gravitational circulation (at least in simple model estuaries).

Significant vertical gradients in salinity occurred throughout the estuary, with typical bed to surface differences in salinity amounting to several parts per thousand. In the deep water at stations 5 and 6, during neap tides and for high run-off ($Q_F^* \sim 2$–3, see Table 1), a fairly pronounced two-layer salinity stratification developed. Generally, the vertical profiles of salinity were similar to those observed for other partly mixed estuaries (see, for example, Bowden, 1962). The axial distribution of salinity also had a similar form to that exhibited by other estuaries. Under low run-off conditions, and at high water, the interface between riverine and brackish water was situated near Weir Head (Figure 1); a sharp increase in salinity (the 'tail') was then followed by a much more gradual increase with distance towards the mouth. With increasing run-off the freshwater–brackish water interface moved down-estuary, and the axial salinity gradients became much more uniform throughout the estuary, and much less steep.

The suspended sediment concentrations showed a large spring–neap variability ($\bar{p}$ in Table 1). Spring tide concentrations of sediment in the upper estuary were much higher than during neap tides owing to resuspension of bed sediments in the faster peak currents. In addition to this transient, local resuspension, a pronounced maximum in the axial distribution of suspended sediment concentration (the turbidity maximum) existed throughout the tidal cycle in the low salinity region ($S < 1‰$); this maximum was carried back and forth by the tidal currents (see later). The behaviour of the turbidity maximum over a spring–neap cycle, during low run-off conditions, is illustrated by Morris *et al.* (1982, p. 182). Resuspension of bed sediments did not appear to occur in the lower estuary, and suspended sediment concentrations were always low and were the sum of marine-derived particles, and particles suspended in the more turbid, fresher water derived from further up-estuary. Bed sediment in the lower estuary appeared to have a much higher resistance to erosion than sediment in the upper estuary.

During neap tides the slower currents were unable to resuspend significant amounts of bottom sediment, so that suspended concentrations were generally low (Table 1). However, large concentrations did occur during high run-off conditions (as at station 3, neaps, in Table 1), when there was, apparently, a high suspended sediment load due to soil erosion in the catchment area supplying freshwater discharges to the estuary.

The following sections deal with an analysis of the residual fluxes of water, salt and suspended sediment at these anchor stations. The vertical structure of currents and salinity are considered later.

Residual currents

A summary of data for $\bar{u}_S$, $\bar{u}_F$ and $\bar{u}_L$ during spring tides is given in Figure 3(a). The freshwater-induced current, $\bar{u}_F$, is given by equation (7). These data are plotted on the same distance scale for convenience; the tidal states were very similar (Table 1), although

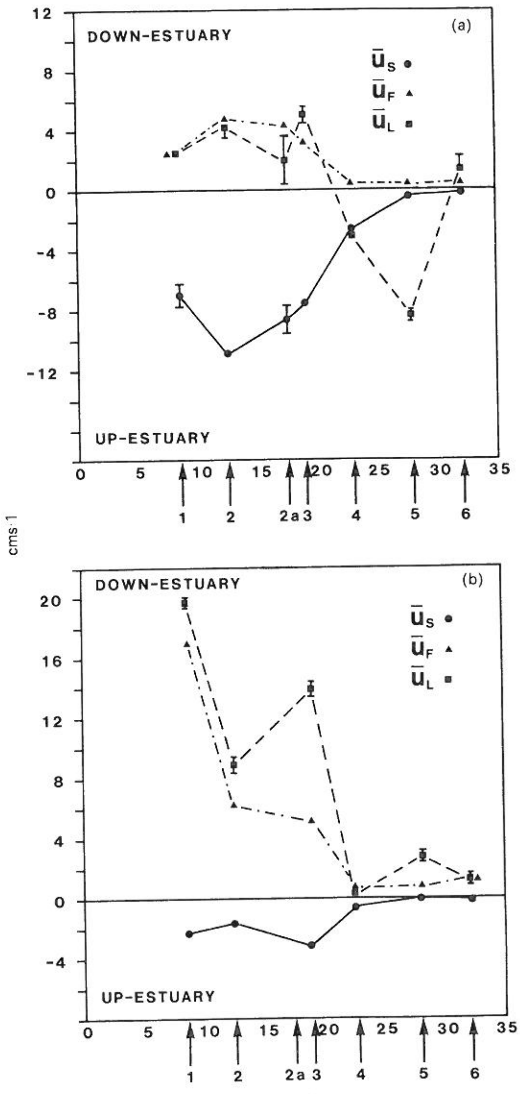


Figure 3. Observed depth-averaged values of Stokes drift (●), freshwater-induced current (△), and Lagrangian residual current (■). (a) Spring tide data, (b) Neap tide data. 95% confidence intervals are shown for the Stokes drift and the Lagrangian residual current.

the individual periods of observations were generally subjected to very different meteorological conditions.

The Stokes drift, $\bar{u}_S$, was directed up-estuary [Figure 3(a)], and decreased from about 10 cm s^{-1} near the head to less than 0·5 cm s^{-1} near the mouth. The mechanism whereby $\bar{u}_S$ is generated in the Severn Estuary has been described by Uncles & Jordan (1980). The same mechanisms apply in the Tamar.

If conditions were uniform over each cross-section, and if a steady-state existed, then the freshwater induced currents would equal the observed Lagrangian currents, $\bar{u}_L = \bar{u}_F$ [see equations (6) and (7) with constant depth, h, over the cross-section, and with

$<Q_F> = <Qb>$, where b is the width]. In the upper estuary $\bar{u}_L \sim \bar{u}_F$ [at, and up-estuary of, station 3 in Figure 3(a)]. In the lower estuary (stations 4 and, particularly, 5), $\bar{u}_L$ and $\bar{u}_F$ are very different. Because only light winds were blowing during these periods, it is reasonable to ascribe the large imbalances between $\bar{u}_L$ and $\bar{u}_F$ to cross-sectional variations in the topography, and also, perhaps, to the existence of horizontal circulation patterns generated by non-linear tidal processes (Zimmerman, 1978; Uncles, 1982*a*, *b*).

Data for neap tides are given in Figure 3(b). Freshwater inputs were higher during these periods, so that $\bar{u}_F$ was higher than for the observations at spring tides [Table 1 and Figure 3(a)]. The Stokes drift, $\bar{u}_S$, was again directed up-estuary, but was much smaller than for spring tides; values decreased from about 2 cm s^{-1} near the head, to about 0·1 cm s^{-1} in the lower estuary. These small values were due to the much smaller frictional dissipation of the tide during neaps (Uncles & Jordan, 1980). The Lagrangian currents and freshwater-induced currents were directed down-estuary [Figure 3(b)]. This is in contrast to the spring tide data at stations 4 and 5, and implies that possible horizontal circulation patterns were less important at neap tides, as would be anticipated if these circulations were generated by tidal non-linearities.

Residual fluxes of salt

The residual flux of salt per unit width of water column is given by equation (8). If conditions were uniform over a cross-section, and if a steady-state existed, then from equation (10):

$$F_L = \bar{u}_L\bar{s} = \bar{u}_F\bar{s} = F_F. \tag{19}$$

so that F_L is the flux of salt, down-estuary, carried by freshwater-induced currents. In steady-state, the residual flux of salt over any cross-section would be zero [$F=0$ in equations (8) and (9)], and equation (8) would become:

$$-1 = F_{TP}/F_F + F_V/F_F. \tag{20}$$

F_F is defined by equation (19), and can be computed from data in Table 1. F_{TP} and F_V have been estimated from the observations [using equations (11) and (12)].

Data for F_{TP}/F_F (the non-dimensional salt flux due to tidal pumping) and F_V/F_F (that due to vertical shear) are given in Figure 4(a) for the spring tide observations. Salt fluxes F_{TP} and F_V were always directed up-estuary (the negative direction), and tidal pumping was generally dominant. The sum of these fluxes is also shown in Figure 4(a); this sum was less than -1, so that tidal pumping and vertical shear were, between them, greater than that required to balance the down-estuary advection of salt due to freshwater inputs (F_F). Because this excess up-estuary flux of salt occurred at each station, it was unlikely to have been a consequence of unsteady conditions, but was probably due to the observed fluxes in the deep sections of each cross-section being larger than those in the shallower sections. Cross-sectionally averaged values might have been closer to a balance [as given by equation (20)].

The observations determined F_L rather than F_F, and these are equal only if $\bar{u}_F = \bar{u}_L$[equation (19)]. Figure 3(a) shows that at stations 4 and 5 $\bar{u}_L$ was negative, and much greater in magnitude than $\bar{u}_F$. Therefore, the observed fluxes of salt due to depth averaged residual flows were much larger than those due to run-off, and, at stations 4 and 5, were directed up-estuary. However, the residual flow at one station in a cross-section must have been nearly balanced by opposing residual flows in other parts of the cross-section (in steady-state, and in absence of freshwater inputs, the cross-sectionally

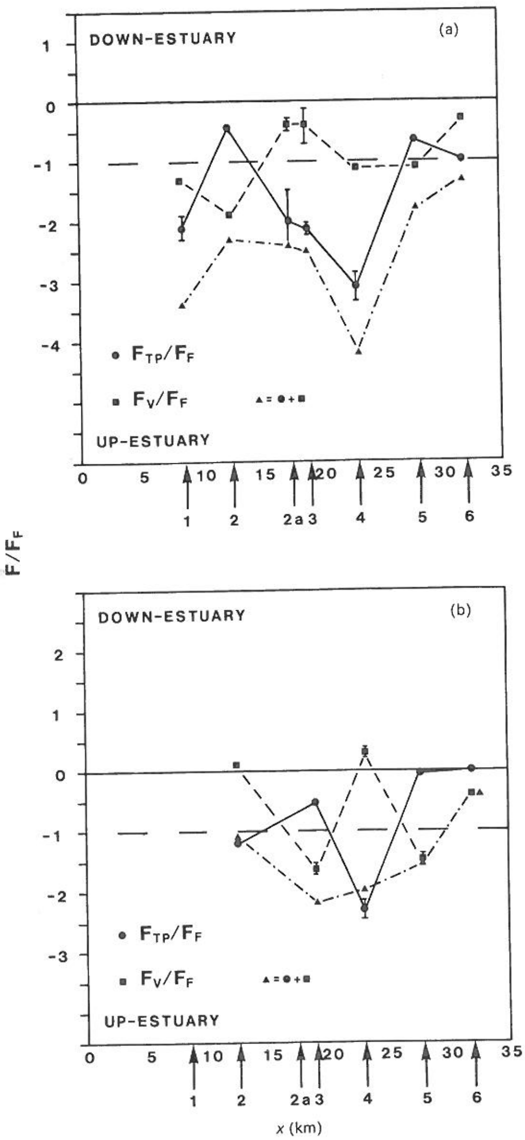


Figure 4. Observed depth-averaged values of the non-dimensional salt fluxes due to tidal pumping (●), vertical shear (■), and their sum (▲). (a) Spring tide data. (b) Neap tide data. 95% confidence intervals are shown for the tidal pumping and vertical shear.

averaged Lagrangian residual current would be zero). If these cross-estuary circulations were correlated with salinity, then a net contribution to the cross-sectionally averaged salt flux would exist due to transverse shear (Fischer, 1972); the existence of such a correlation cannot be inferred from these data. Uncles *et al.* (1983) undertook a theoretical investigation of such shear dispersion mechanisms in the Tamar. Spring tide, low run-off conditions were considered. It was found that the up-estuary dispersion of salt in the upper reaches could be attributed to transverse shear—provided the cross-estuary mixing were equal to a physically plausible (but unmeasured) value which greatly exceeded that due to turbulence. Clearly, the analysis of observations over estuarine cross-sections is necessary before one can state, with confidence, the relative importance of tidal pumping and these various shear mechanisms. Dyer (1978) has presented calculations of the cross-sectionally averaged salt fluxes during spring tides for the Thames and the Gironde Estuaries. Dyer's method of analysis differs from that used here, but his data can be interpreted in terms of the same flux mechanisms. For both estuaries, tidal pumping of salt (the sum of terms 3, 4 and 5 in his Table 1, p. 139) was found to be much larger than that due to vertical and transverse shear.

Components of the residual fluxes of salt did not show any strikingly systematic behaviour for the neap tide observations [Figure 4(b)]. This was partly because of faster winds and greater freshwater inputs during these periods. The already weak vertical mixing at neap tides was further reduced by the increased stratification resulting from large freshwater inputs. Thus, wind-stress had a significant influence on the movement of near-surface water. Nevertheless, tidal pumping was always directed up-estuary, although it was negligible at stations 5 and 6 in the deep, lower reaches of the estuary (Figure 2). Here, in the deep channel, the salt transport due to vertical shear was dominant. Further up-estuary the tidal pumping was comparable with that required to balance the down-estuary flux of salt due to freshwater inputs [F_F, the line drawn as -1 in Figure 4(b)].

The salt flux due to vertical shear was directed down-estuary at stations 2 and 4 [Figure 4(b)]. At station 4 the vertical profile of residual current was the reverse of the gravitational circulation, which accounted for the down-estuary flux of salt due to vertical shear. This reversal of flow was possibly due to an up-estuary wind, with an average speed of 6 m s^{-1}. The salt flux due to vertical shear was also down-estuary at station 2 [Figure 4(b)] and, again, there was an up-estuary wind of 6 m s^{-1}. This down-estuary transport can only be ascribed to cross-estuary variations in the flow, attributable to the wind-stress, although its precise cause is unknown. Vertical shear dominated tidal pumping at station 3. This was a result of high run-off during these observations, coupled with slow tidal currents (see data for station 3, neaps, in Table 1), which produced flow conditions which were similar to those in a salt-wedge estuary (Dyer, 1973).

Residual fluxes of sediment

The residual flux of suspended sediment is given by equation (14). If conditions were uniform over a cross-section, and if a steady-state existed, then from equation (16):

$$G_L = \bar{u}_L \bar{p} = \bar{u}_F \bar{p} = G_F, \tag{21}$$

and equation (14) would become

$$G/G_F - 1 = G_{TP}/G_F + G_V/G_F \tag{22}$$

Data for G_{TP}/G_F (dimensionless tidal pumping) and G_V/G_F (dimensionless vertical shear) during the spring tide observations are drawn in Figure 5(a). Tidal pumping of sediment was much larger than that due to vertical shear and freshwater-induced currents. The pumping was directed up-estuary at stations 1 and 2, and down-estuary elsewhere. At these stations the oscillatory tidal currents [$\tilde{U}$ in equation (5)] were strongly asymmetrical, with flood currents exceeding ebb currents. This is a characteristic feature of estuarine tidal flows in shallow water (Kreiss, 1957; Uncles, 1981). At

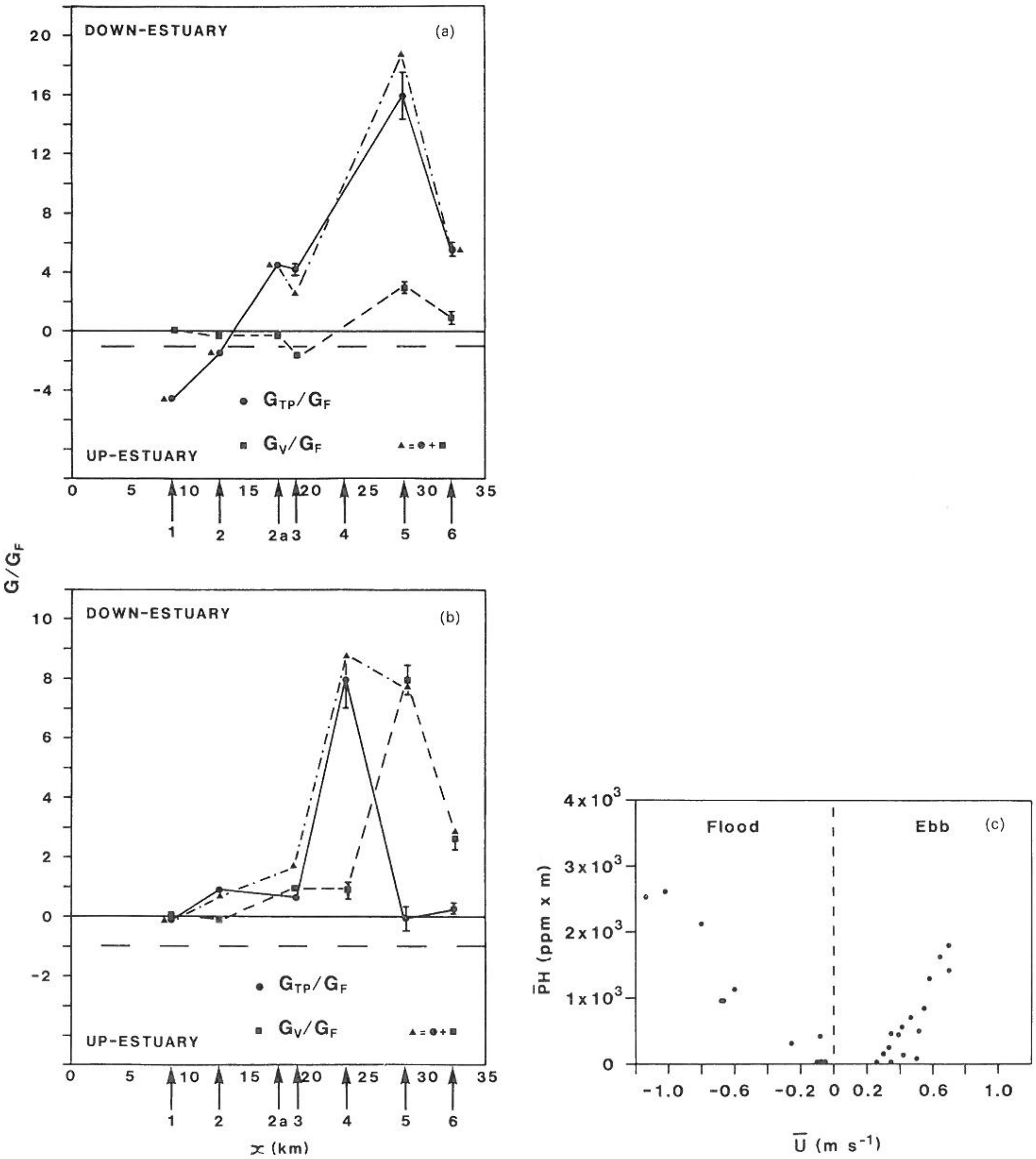


Figure 5. Observed depth-averaged values of the non-dimensional suspended sediment fluxes due to tidal pumping (●), vertical shear (■), and their sum (▲) at (a) spring tides, and (b) neap tides. 95% confidence intervals are shown for the tidal pumping and vertical shear. (c) Suspended sediment load, $\overline{PH}$, versus depth-averaged current, $\overline{U}$, during spring tides at station 1.

station 1 the stronger flood currents produced enhanced resuspension of bottom sediment, which was subsequently transported into the estuary. Ebb currents produced less resuspension and less transport of sediment, so that the residual transport was directed up-estuary. The run-off was much higher at station 2, and peak ebb and flood current speeds were almost equal. Nevertheless, more suspended sediment was transported up-estuary on the flood than down-estuary on the ebb. It is thought that this was due to flood-dominated resuspension down-estuary of station 2, where the freshwater-induced Eulerian currents were less effective on the ebb owing to the increased cross-sectional area of the estuary. Tidal resuspension of bed sediment was also important at stations 2a and 3. However, during these observations the freshwater inputs were so high (see Table 1) that ebb currents greatly exceeded flood currents; therefore, resuspension and sediment transport were greater during the ebb tide, leading to a down-estuary residual flux of suspended sediment due to tidal pumping. Tidal pumping was also directed down-estuary at stations 5 and 6, although resuspension did not, apparently, occur at these stations. Here, due to mixing of turbid estuarine water with low turbidity coastal water, the suspended load during the ebb tide exceeded that during the flood tide, leading to a down-estuary residual transport of sediment.

At stations 1 to 3 [Figure 5(a)] the concentrations of suspended sediment generally increased from surface to bed, owing to tidal resuspension from the bed. Salinity also increased from surface to bed. Transport due to vertical shear was, therefore, directed up-estuary, as it was for salt [Figures 4(a) and 5(a)]. At stations 5 and 6 the concentrations of suspended sediment decreased from surface to bed (in the opposite sense to salinity) so that transport due to vertical shear was directed down-estuary.

The observed fluxes of suspended sediment at neap tides [Figure 5(b)] were either negligible, or else directed down-estuary. Resuspension did not, apparently, occur at neap tides, and suspended sediment concentrations correlated with the concentration of fresh water. Therefore, sediment was dispersed in a similar way to fresh water (oppositely to salt), with residual fluxes due to both tidal pumping and vertical shear tending to be directed down-estuary. It is of interest to note that, over both spring and neap tidal cycles, suspended sediment was transported out of the estuary at station 6 under medium to high run-off conditions.

Considering further the sediment fluxes during spring tides; the relationship between depth-averaged current, $\overline{U}$, and the mass of suspended sediment in the water column (proportional to $\overline{P}H$) during spring tides is shown in Figure 5(c) for station 1. The importance of tidal pumping is evident in view of the marked asymmetry between the suspended load for flood and ebb currents. Dyer (1978) has presented data on sediment fluxes in the Gironde and Thames Estuaries during spring tides. For both estuaries, tidal pumping (calculated from the sum of terms 3, 4, and 5 in his Table 1, p. 139) greatly exceeded vertical shear (as for the Tamar). For the three sections in the Gironde, tidal pumping of sediment was directed down-estuary at the two seaward sections, and up-estuary at the section located in the vicinity of the turbidity maximum (as for the Tamar). In the Thames, the section was located in the vicinity of the turbidity maximum, and tidal pumping was again directed up-estuary.

Estuarine type

A classification scheme for estuaries was proposed by Hansen & Rattray (1966), who related estuarine 'type' to its position on a stratification–circulation diagram. The stratification parameter is given by $\delta s/\overline{s}$, where δs is the difference between bed and surface tidally averaged salinity: $\delta s = s(1) - s(0)$. The circulation parameter is $u_E(0)/\overline{u}_E$, where $u_E(0)$ is the residual current at the surface. Hansen & Rattray's theory is linear, so that the Stokes drift is zero; it also assumes steady-state conditions, and uniformity over the estuarine cross-section. These conditions mean that [see equations (1)–(7)]:

$$\overline{u}_S = 0 \qquad \text{and} \qquad \overline{u}_E = \overline{u}_L = \overline{u}_F.$$

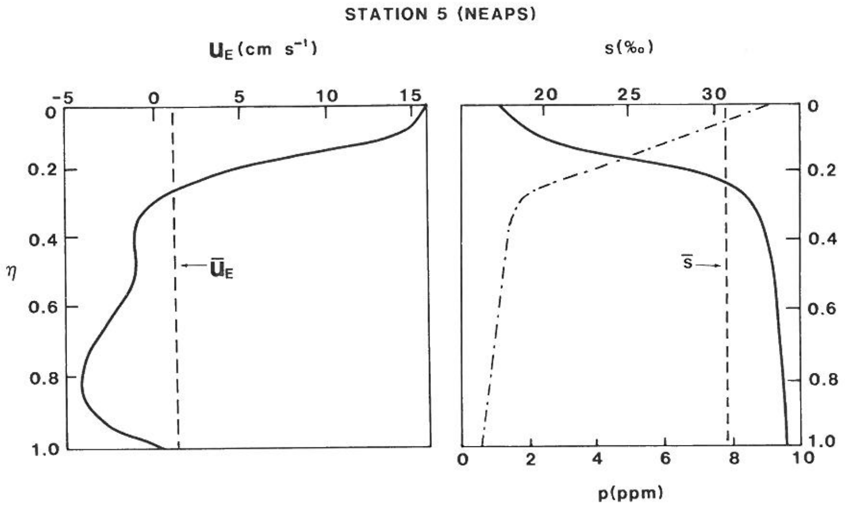


Figure 6. Tidally averaged current, u_E, salinity s(———), and suspended sediment concentration p(—·—·—), against non-dimensional depth, η, for station 5 (neaps).

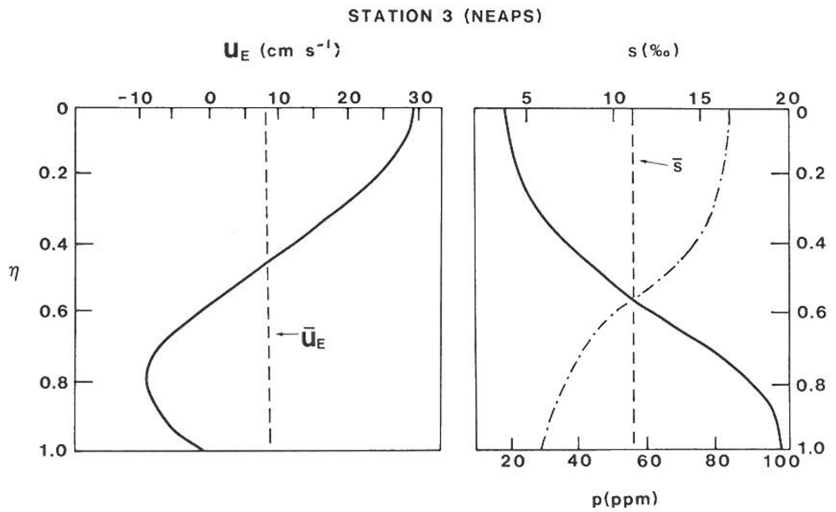
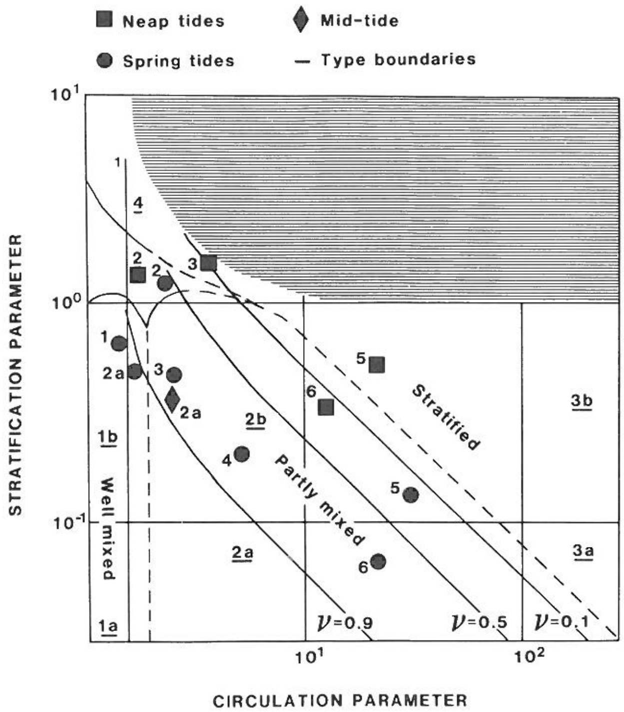


Figure 7. Tidally averaged current, u_E, salinity s(———), and suspended sediment concentration p(—·—·—), against non-dimensional depth, η, for station 3 (neaps).

If steady-state conditions existed during our observations, and if uniformity existed over each cross-section, then the observed depth-averaged residual currents at each station would have been:

$$\bar{u}_E = |\bar{u}_S| + \bar{u}_F. \quad (23)$$

To interpret our data in terms of Hansen and Rattray's theory it was necessary to shift each observed profile of residual current (velocity against depth) along its velocity axis until the depth-averaged velocity corresponded to that given by equation (23). The redefined surface current, $u_E(0)$, could then be determined from the velocity scale. Results of this procedure are shown in Figures 6 and 7 for station 5 (neaps) and station 3 (neaps),



Hansen and Rattray estuary classification

Figure 8. Hansen and Rattray estuary classification for stations 1, 2, 2a, 3, 4, 5 and 6. Spring tides (●), neap tides (■), mid tide at station 2a (◆). Broken lines delineate classification boundaries; full lines show contours of constant ν.

respectively. Both sets of observations corresponded to high run-off conditions (Table 1). Station 5 (neaps) exhibited a strong gravitational circulation under high run-off conditions, with $u_E(0)/\bar{u}_E = 20$ and $\delta s/\bar{s} = 0{\cdot}5$ (Figure 6). A strong correlation existed between freshwater concentrations and suspended sediment concentrations (Figure 6). At station 3 (neaps) $u_E(0)/\bar{u}_E = 4$ and $\delta s/\bar{s} = 1{\cdot}5$ (Figure 7). There was, again, a strong correlation between freshwater concentrations and suspended sediment concentrations.

Data on salinity stratification and circulation from these observations are plotted on the Hansen and Rattray diagram in Figure 8. The estuarine 'type' at a station depended strongly on position, run-off and tidal range. At the deep water stations, 5 and 6, during periods of medium to high run-off, it appeared that the gravitational circulation made an important contribution to the up-estuary salt balance (the fraction of up-estuary salt flux not due to vertical shear, ν, is such that $\nu \sim 0{\cdot}5$ or less in Figure 8). Qualitatively, this is consistent with data on salt fluxes presented in Figure 4(a), (b). Up-estuary of station 3 the classification scheme implies that the estuary was well mixed or transitional under these conditions, with most of the up-estuary salt flux being due to processes other than vertical shear. An exception is station 3 (neaps), which fell into the salt-wedge classification. This was a consequence of the high run-off and slow tidal currents. Similarly, because of high run-off, slow tidal currents, and deep water, station 5 (neaps) fell into the fjord-like classification. According to this classification scheme, the Tamar may be considered partly mixed in the lower reaches (during average run-off conditions) and transitional or well mixed in the upper reaches.

Observed and computed circulation and stratification parameters have been compared. The method used is an extension of Hansen and Rattray's (1966) theory which takes into account Stokes drift (Rattray & Uncles, 1983). The predicted circulation parameter increases from head to mouth, as shown in Figure 8. Generally, predicted values are in reasonable agreement with observations. However, the predicted salinity stratification would provide only a very rough guide to the actual stratification.

Formation of turbidity maximum

Tidal pumping of sediment during spring tides would appear to provide a mechanism for the production or enhancement of the turbidity maximum in the upper estuary [see Figure 5(a), stations 1 and 2]. The extent to which this possibility can be quantified is briefly examined here using a simplified one-dimensional model to describe the transport of water and suspended sediment. According to Figure 5(a), the transport due to vertical shear is negligible compared with that due to tidal pumping. Therefore, a depth averaged model of the sediment transport is not unrealistic for this exploratory study. The effects of cross-estuary variations on sediment transport may be important, but are currently unknown and impossible to quantify.

The model simulates the one-dimensional region between $x=0$ and $x=20$ km (see Figure 1), and is based on the conservation equations for water volume, momentum and sediment, which are, respectively:

$$\frac{\partial A}{\partial t}+\frac{\partial}{\partial x}(A\overline{U})=0, \tag{24}$$

$$\frac{\partial \overline{U}}{\partial t}+\overline{U}\frac{\partial \overline{U}}{\partial x}=-g\frac{\partial \zeta}{\partial x}-k\overline{U}|\overline{U}|/H, \tag{25}$$

and

$$\frac{\partial \overline{P}}{\partial t}+\overline{U}\frac{\partial \overline{P}}{\partial x}=(\dot{m}_e-\dot{m}_d)/H. \tag{26}$$

The estuary is assumed to be laterally uniform. Symbols $A, \overline{U}$, H and $\overline{P}$ have been defined in equations (1)–(18). Additional symbols are k (drag coefficient), ζ (surface elevation relative to Ordnance Datum Newlyn), and $\dot{m}_e$ and $\dot{m}_d$ (the rates of erosion and deposition of sediment). Lateral inputs of fresh water are negligible in this region, and have been omitted. Except for our omission of axial density gradients, equations (24) to (26) are essentially one-layer versions of the two-layer equations used by Odd & Owen (1972) in their work on the Thames Estuary. For resuspension, Odd & Owen assumed that (using a quadratic stress law):

$$\dot{m}_e=\begin{cases} M[(\overline{U}/\overline{U}_e)^2-1], & \overline{U}\geqslant\overline{U}_e, \\ 0 \quad , & \overline{U}<\overline{U}_e. \end{cases} \tag{27}$$

Resuspension is observed to occur at spring tides in the upper estuary when $\overline{U}_e \simeq 50$ cm s^{-1}. For deposition, Odd & Owen (1972) assumed that (using a quadratic stress law):

$$\dot{m}_d=\begin{cases} \overline{P}\,\overline{V}_s\,[1-(\overline{U}/\overline{U}_d)^2], & \overline{U}\leqslant\overline{U}_d, \\ 0 \ , & \overline{U}>\overline{U}_d, \end{cases} \tag{28}$$

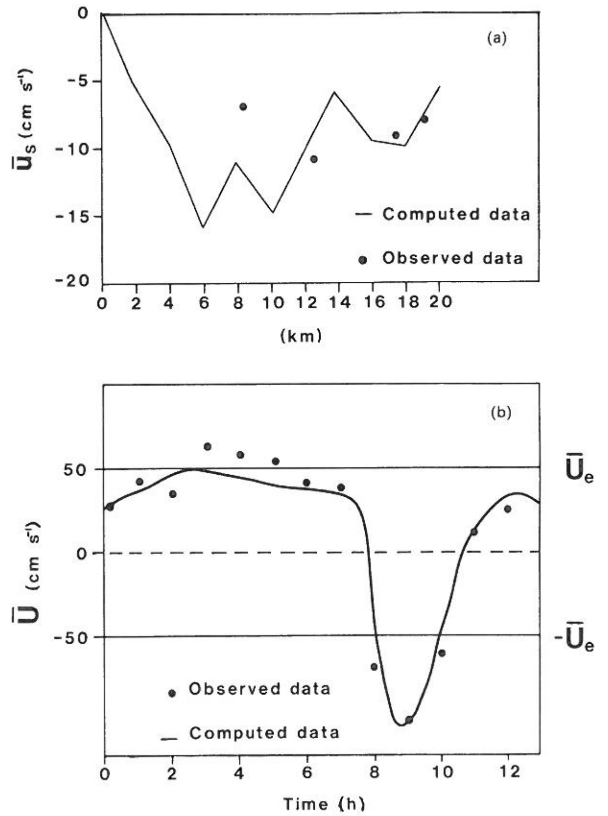


Figure 9. Observed (●) and computed (—) currents for conditions corresponding to station 1 (springs). (a) Stokes drift as a function of distance along the axis. (b) Currents during a tidal cycle at station 1; $\overline{U}_e$ is the speed at which erosion is assumed to occur.

where $\overline{V}_s = 2 \times 10^{-3}\,\overline{P}$ (in mm s^{-1}) for 50 ppm $< \overline{P} <$ 3000 ppm (during spring tides). On the basis of flume data, Odd & Owen (1972) took the depositional stress [$\tau_d = \rho k\,\overline{U}_d^{\,2}$ in equation (28)] to be 0·6 dyne cm^{-2}, or $\overline{U}_d = 14 - 10$ cm s^{-1} (for $k = 3 \times 10^{-3}$–6×10^{-3}). In absence of similar data on sedimentation processes for the Tamar, we also use these relationships and their associated parameter values.

Equations (24) to (26) are solved on a finite-difference grid which uses a 1 km node spacing. Boundary conditions on the elevations (ζ at $x = 20$ km) are determined from tidal height data for observations made during one month in 1981 (Hydrographer of the Navy). The boundary condition at the head is that the down-estuary rate of transport of water equals the freshwater input at Weir Head. The topography of the estuary is modelled such that each cross-section is replaced by a rectangle of constant width, equal to the observed mean width of the section. Depth, relative to mean water level, is found by dividing the observed averaged cross-sectional area by the mean width.

The results of running the hydrodynamical model for conditions corresponding to station 1 (springs) are shown in Figure 9(a), (b). The Stokes drift is plotted as a function of distance along the estuary in Figure 9(a), and the tidal current (ebb positive) as a function of time at station 1 (springs) in Figure 9(b). The comparisons between observed and computed currents are reasonable. The value of the drag coefficient, k, is 6×10^{-3}. The computed tidal currents [Figure 9(b)] show a long, slow ebb, and a short, fast flood. This

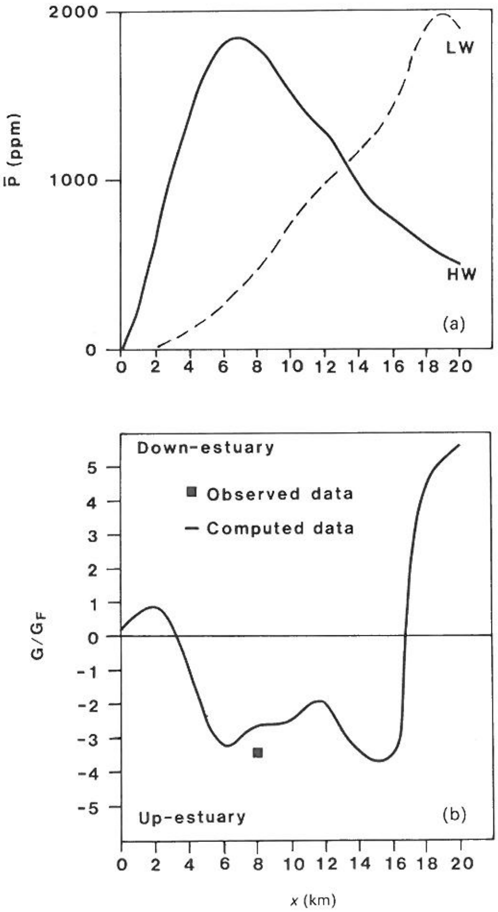


Figure 10. Computed concentrations and fluxes of suspended sediment along the axis of the estuary for conditions corresponding to station 1 (springs). (a) Concentrations at high water and low water. (b) Non-dimensional sediment flux; observed value (■); observed data for stations 2, 2a and 3 are not plotted because they correspond to different run-off conditions.

is typical of estuarine flows under low run-off conditions (Uncles, 1981; Kreiss, 1957). The critical erosion velocity for resuspension of sediment is not exceeded during the ebb, but is greatly exceeded during the flood.

Considering the solution of equation (26), boundary conditions are such that the freshwater inputs satisfy $\overline{P}=0$ at Weir Head. Conditions are not required at the down-estuary boundary during the ebb flow. On the flood, it is assumed that the down-estuary, axial gradient of suspended sediment concentration at this boundary is zero. The rate of erosion [M in equation (27)] is arbitrarily taken to be 30 ppm cm s^{-1}. Qualitative features of the results are not sensitive to the choice of M in the range tested (10–50). It is not the intention to accurately simulate observed data here, but rather to reproduce gross effects.

Solutions corresponding to conditions at station 1 (springs) and for infinitely repeating tidal cycles of the form shown in Figure 9(b), are plotted in Figure 10(a). These suspended sediment concentrations are plotted for high water and low water stages of the tide. A geographical maximum in the suspended load occurs at all times throughout the tidal cycle, and is advected up and down-estuary with the tidal currents. This maximum is generated partly by the fact that a maximum occurs in the tidal current speeds at approximately $x = 10$ km. An additional factor is the residual up-estuary pumping of sediment shown in Figure 10(b). Near the mouth of the model ($x = 20$ km in Figure 1), and near its head, the residual flux of sediment is directed down-estuary. The residual flux of sediment is directed up-estuary in the central reaches, and is thus able to accumulate sediment on the estuary's bed, and in the turbidity maximum.

The model has also been used to investigate the possible effects of high freshwater inputs on the turbidity maximum and sediment fluxes. For freshwater inputs of the order of, or greater than, typical yearly averaged values, residual fluxes of suspended sediment are directed down-estuary everywhere. Erosion is primarily the result of large ebb currents produced by the freshwater flow. A turbidity maximum persists in the upper estuary because currents and, therefore, resuspension maximize there. Finally, if the model is run for neap tides during low run-off, then very little erosion of bed sediment occurs, although a distinct turbidity maximum (~ 10 ppm) is still formed near the head. This maximum is the result of a maximum in the speeds of the neap tidal currents near the head. In reality, gravitational circulations will also contribute to the formation of the turbidity maximum under certain conditions (Festa & Hansen, 1978; Officer & Nichols, 1980; Officer, 1980).

Summary

Under medium to high run-off conditions the Tamar is, generally, a partly mixed estuary. In the deeper sections of each cross-section the observations showed surface to bed differences in salinity of the order of several parts per thousand. Gravitational circulation was an important component of the residual flow in the deep, lower reaches of the estuary. In this region, the depth-averaged residual currents during spring tides greatly exceeded those due to freshwater flows, and were possibly due to tidally-induced residual circulations. Stokes drift was extremely small.

In the shallow, upper reaches of the estuary, the Eulerian residual currents were directed down-estuary under conditions of medium to high run-off. These currents were primarily due to freshwater flows and compensation currents generated by Stokes drift. The Stokes drift reached values of the order of 10 cm s^{-1} during spring tides, although neap tide values were much smaller. The circulation parameters deduced from Hansen and Rattray's model were in reasonable agreement with observations, although predicted salinity stratification provided only a rough guide to observed values.

Salt fluxes due to tidal pumping and vertical shear were always directed up-estuary in the deep channels at spring tides, and tidal pumping was generally dominant. The up-estuary salt flux due to these processes always exceeded that required to balance advection by freshwater flows. This implied that salt fluxes in the shallower parts of a cross-section were smaller than those in the deeper sections, or even reversed. The observations at neap tides were more difficult to interpret, mainly owing to stronger winds and greater freshwater inputs. Nevertheless, tidal pumping was always directed up-estuary, although it was negligible in the lower reaches of the estuary, where transport due to vertical shear dominated.

The suspended sediment concentrations showed a large spring–neap variability. Spring tide concentrations in the upper estuary were much higher than during neap tides

owing to resuspension of bed sediments. A turbidity maximum occurred at spring tides in the low salinity region of the estuary. Concentrations in the lower estuary were always small. During spring tides, tidal pumping of sediment was much larger than transport due to vertical shear. This pumping was directed up-estuary near the head, and probably contributed to the turbidity maximum. An additional mechanism for the existence of the turbidity maximum was the existence of a maximum in the tidal current speeds (and thus resuspension) in this region. Further down-estuary the tidal pumping was directed out of the estuary, and sediment was flushed to sea with the fresh water. Fluxes of suspended sediment at neap tides tended to be directed down-estuary, the sediment again being dispersed in a similar way to fresh water. These features of the sediment dynamics were reproduced qualitatively using highly simplified, one-dimensional models of the water and sediment budgets.

The inaccuracies in the tidal averages which arise from instrument errors are generally very small, as one would expect due to the random nature of such errors. The effects of non-simultaneity of data are more difficult to gauge. Nevertheless, the consistency of the data between stations which were subject to similar tidal conditions but different (medium to high) run-off conditions, suggests that the results provide a general view of the estuary's behaviour for medium to high freshwater inputs.

Acknowledgements

This work, which forms part of the estuarine ecology programme of the Institute for Marine Environmental Research, a component of the Natural Environment Research Council (NERC), was partly supported by the Department of the Environment on contract DGR 480/48.

References

Allen, G. P., Salomon, J. C., Bassoullet, P., Du Perihoat, Y. & De Grandpre, C. 1980 Effects of tides on mixing and suspended sediment transport in macrotidal estuaries. *Sedimentary Geology* **26**, 69–90.

Bowden, K. F. 1962 Estuaries and coastal waters. *Proceedings of the Royal Society, Series A* **265**, 320–325.

Bowden, K. F. & Gilligan, R. M. 1971 Characteristic features of estuarine circulation as represented in the Mersey Estuary. *Limnology and Oceanography* **16**, 490–502.

Bowden, K. F. & Sharaf El Din, S. H. 1966 Circulation, salinity and river discharge in the Mersey Estuary. *Geophysical Journal of the Royal Astronomical Society* **10**, 383–399.

Collar, R. H. F. 1978 Estuary circulation: assessment and application. *Proceedings of the Royal Society of Edinburgh* **76B**, 37–54.

Dyer, K. R. 1973 *Estuaries: A Physical Introduction*. John Wiley, Chichester, Sussex. 140 pp.

Dyer, K. R. 1974 The salt balance in stratified estuaries. *Estuarine and Coastal Marine Science* **2**, 273–281.

Dyer, K. R. 1978 The balance of suspended sediment in the Gironde and Thames Estuaries. In *Estuarine Transport Processes* (Kjerfve, B., ed.). The Belle W. Baruch Library in Marine Science, No. 7. 331 pp.

Festa, J. F. & Hansen, D. V. 1978 Turbidity maxima in partially mixed estuaries: A two-dimensional numerical model. *Estuarine and Coastal Marine Science* **7**, 347–359.

Fischer, H. B. 1972 Mass transport mechanisms in partially stratified estuaries. *Journal of Fluid mechanics* **53**, 671–687.

Hansen, D. V. & Rattray, M. 1966 New dimensions in estuary classification. *Limnology and Oceanography* **11**, 319–326.

Hughes, F. W. & Rattray, M. 1980 Salt flux and mixing in the Columbia River Estuary. *Estuarine and Coastal Marine Science* **10**, 479–493.

Hydrographer of the Navy. Hydrographic Department, Crossway, Taunton, Somerset, U.K.

Ianniello, J. P. 1977 Tidally induced residual currents in estuaries of constant breadth and depth. *Journal of Marine Research* **35**, 755–786.

Ianniello, J. P. 1981 Tidally-induced residual currents in Long Island and Block Island Sounds. *Estuarine, Coastal and Shelf Science* **12**, 177–191.

Kjerfve, B. 1975 Velocity averaging in estuaries characterized by a large tidal range to depth ratio. *Estuarine and Coastal Marine Science* **3**, 311–323.

Kjerfve, B. 1979 Measurement and analysis of water current, temperature, salinity and density. In *Estuarine Hydrography and Sedimentation* (Dyer, K. R., ed.). Cambridge University Press, Cambridge. 230 pp.

Kreiss, H. 1957 Some remarks about non-linear oscillations in tidal channels. *Tellus* **9**, 53–68.

Lewis, R. E. 1979 Transverse velocity and salinity variations in the Tees Estuary. *Estuarine and Coastal Marine Science* **8**, 317–326.

Lewis, R. E. 1981 Estuary mixing. *The Chemical Engineer*, Aug–Sep, 381–383.

Lewis, R. E. & Lewis, J. O. 1983 The principal factors contributing to the flux of salt in a narrow, partially stratified estuary. *Estuarine, Coastal and Shelf Science* **16**, 599–626.

Morris, A. W., Bale, A. J. & Howland, R. J. M. 1982 The dynamics of estuarine manganese cycling. *Estuarine, Coastal and Shelf Science* **14**, 175–192.

Odd, N. V. M. & Owen, M. W. 1972 A two-layer model of mud transport in the Thames Estuary. *Proceedings of the Institution of Civil Engineers*, paper 7517S, 175–205.

Officer, C. B. 1976 Physical oceanography of estuaries (and associated coastal waters). John Wiley, Chichester, Sussex. 465 pp.

Officer, C. B. 1980 Discussion of the turbidity maximum in partially mixed estuaries. *Estuarine and Coastal Marine Science* **10**, 239–246.

Officer, C. B. 1981 Physical dynamics of estuarine suspended sediments. *Marine Geology* **40**, 1–14.

Officer, C. B. & Nichols, M. N. 1980 Box model application to a study of suspended sediment distributions and fluxes in partially mixed estuaries. In *Estuarine Perspectives*. Academic Press, London. 329–340.

Pritchard, D. W. 1954 A study of the salt balance in a coastal plain estuary. *Journal of Marine Research* **13**, 133–144.

Rattray, M. & Dworski, J. G. 1980 Comparison of methods for analysis of the transverse and vertical circulation contributions to the longitudinal advective salt flux in estuaries. *Estuarine and Coastal Marine Science* **11**, 515–536.

Rattray, M. & Uncles, R. J. 1983 On the predictability of the ^{137}Cs distribution in the Severn Estuary. *Estuarine, Coastal and Shelf Science* **16**, 475–487.

Uncles, R. J. 1981 A note on tidal asymmetry in the Severn Estuary. *Estuarine, Coastal and Shelf Science* **13**, 419–432.

Uncles, R. J. 1982*a* Computed and observed residual currents in the Bristol Channel. *Oceanologica Acta* **5**, 11–20.

Uncles, R. J. 1982*b* Residual currents in the Severn Estuary and their effects on dispersion. *Oceanologica Acta* **5**, 403–410.

Uncles, R. J. & Jordan, M. B. 1979 Residual fluxes of water and salt at two stations in the Severn Estuary. *Estuarine and Coastal Marine Science* **9**, 287–302.

Uncles, R. J. & Jordan, M. B. 1980 A one-dimensional representation of residual currents in the Severn Estuary and associated observations. *Estuarine and Coastal Marine Science* **10**, 39–60.

Uncles, R. J., Bale, A. J., Howland, R. J. M., Morris, A. W. & Elliott, R. C. A. 1983 Salinity of surface water in a partially-mixed estuary, and its dispersion at low run-off. *Oceanologica Acta* **6**, 289–296.

van de Kreeke, J. 1978 Mass transport in a coastal channel, Marco River, Florida. *Estuarine and Coastal Marine Science* **7**, 203–214.

Watson, P. G. (personal communication) Institute for Marine Environmental Research, Plymouth, U.K.

Zimmerman, J. T. F. 1978 Topographic generation of residual circulation by oscillatory (tidal) currents. *Geophysical and Astrophysical Fluid Dynamics* **11**, 35–47.

should be avoided, as they are inconvenient and expensive. Authors may submit original drawings if small enough, or very clear glossy photographs of them. Care should be taken not to overload maps with irrelevant detail, or to use excessive amounts of space to convey little information. The smallest symbols or letters used should not be less than 1·5 mm high after reduction. The author should supply one or two extra copies of each figure suitable for sending reviewers (photocopies, etc. which may be folded).

Plates are page size units, often consisting of several photographs. The plates are numbered consecutively, and individual photographs on a plate are designated (a), (b), (c), etc. Authors should use the minimum number consistent with adequate presentation of the subject. Photographs must be sharp and clear, printed on glossy paper and not smaller than their publication size. They should not be mounted. Copies of photographs for sending to reviewers need not be of the same high quality as the originals, but they must be clear (Xerox copies are usually inadequate).

Tables should be numbered in the order of their position in the text and typed on separate sheets. A brief title should be typed directly above each table.

(6) *References.* In the text, references to the literature cited should list the author's name, year of publication and preferably the specific page numbers in this form: (Smith, 1928, p. 36). Under the heading References cited at the end of the text should be listed all literature cited, double-spaced, arranged alphabetically by authors and chronologically under each author. Initials should be typed after surnames. Publication date should be given directly after the last author. The order should be as follows:

(a) Single authors.

(b) Two authors. References for which there are two authors should be arranged first alphabetically and then chronologically. For text citations, use both author's names and the year. Do not use *et al.* for two-author references.

(c) Three or more authors. References with three or more authors should be arranged chronologically. For all text citations use the surname of the first author only followed by *et al.* and the date.

If more than one reference by the same author or authors published in the same year is cited, use *a*, *b*, etc., after the year in both text and reference list, e.g. (1963*a*). Journal titles, in reference list should be cited in full. Full title of the paper, journal, volume number and page number should be given.

(7) *Proofs.* Copy editing of manuscripts is performed by the staff of the publishers. The author is asked to check page proofs for typographical errors and to answer queries from the copy editors. No other changes are permitted in proof unless the author is prepared to pay for them.

(8) *Copyright/offprints.* Authors submitting a manuscript do so on the understanding that if it is accepted for publication, exclusive copyright in the paper shall be assigned to the Publisher. In consideration for the assignment of copyright, the Publisher will supply 50 offprints of each paper. Further offprints may be ordered at extra cost at the proof stage. The Publisher will not put any limitation on the personal freedom of the author to use material contained in the paper in other works.

Printed in Great Britain by Henry Ling Ltd., at the Dorset Press, Dorchester, Dorset