CHAPTER TWO HUNDRED FOUR

Lateral Distributions of Water, Salt and Sediment Transport in a Partly Mixed Estuary

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The transverse structure of the residual transport of water, salt and suspended sediment in the upper reaches of the Tamar Estuary is investigated. Data were obtained at three cross-sections for spring and neap tides. The transport for each variable is analyzed in terms of the governing physical processes.

Introduction

The objectives of this paper are to investigate transverse variations in the transport of water, salt and suspended sediment in the upper reaches of the Tamar Estuary, which is a partly mixed estuary in the southwest of England (Figure 1). Tides are semi-diurnal, with mean neap and spring ranges of 2.2 and 4.7 m, respectively.

Observations of the transverse structure of currents and salinity have been made for some other estuaries, generally with a view to investigating dispersion processes (4,6,7,8,10,11). In this work we present data on the transverse variations in the advective, tidal pumping and vertical shear components of the salt and sediment transport.

Observations

Three sections (1, 2 and 3 in Figure 1) were worked for spring and neap tidal cycles. Velocity, temperature, salinity and suspended sediment were profiled at either four or five positions over each section. Some of these stations dried out near low water. Measurements were made at half-hourly intervals from a seatruck anchored in the centre of a section, and at approximately three-quarter-hourly to hourly intervals at the remaining stations. Transverse topography at the experimental sections is shown in Figure 2. Positions of the high and low water lines for the spring and neap tide surveys are drawn, together with the station positions. The mean, axial, depth averaged current speeds in the deepest parts of the sections were roughly 0.4 - 0.5 m s^{-1} during spring tides, and less than half this at neap tides.

Table 1 shows background data for sections 1 to 3. Up-estuary flows are negative. The estimated residual flow due to diurnal inequality over each observed tidal cycle is given, together with the sum of flows due to run-off and inequality, Q.

None of the sections were vertically well mixed for salinity, and

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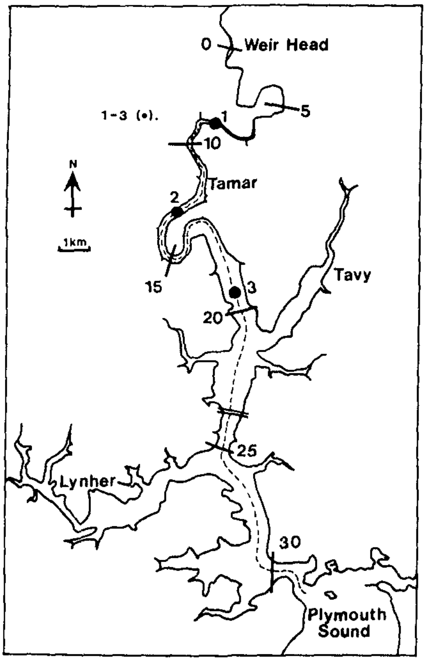

Figure 1. Sketch chart of the Tamar Estuary, showing its sub-division into 5 km sections and the locations of sections 1 to 3.

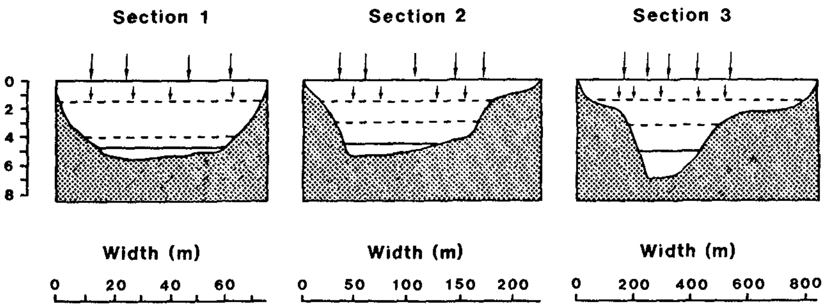

Figure 2. Transverse topography at sections 1 to 3, showing station positions and depths (m) below the high water springs line.

TABLE 1: Background data for sections 1-3, springs (S) and neaps (N). Residual flows due to daily-averaged run-off, diurnal inequality and their sum, Q, are shown (negative up-estuary).

Section	Date	Tidal Range (m)	Run-off ($m^3\ s^{-1}$)	Inequality ($m^3\ s^{-1}$)	Q ($m^3\ s^{-1}$)
1(N)	18/5/82	2.3	3.7	-0.5	3.2
2(N)	19/3/82	1.6	41.8	-1.8	40.0
3(N)	18/2/82	1.8	21.3	3.8	25.1
1(S)	25/5/82	4.9	3.6	0.0	3.6
2(S)	27/4/82	4.6	5.9	0.0	5.9
3(S)	26/2/82	4.9	25.9	14.3	40.2

section 2 (Neaps) was strongly stratified, owing to high run-off (see Table 1). Consequently, at section 2 (Neaps) the residual (tidally averaged) current was directed down-estuary throughout the column. The residual currents at sections 1 and 3 (Neaps) showed classical gravitational circulation. At spring tides, the stronger residual tidal wave (Stokes) transport generated compensating down-estuary residual currents which greatly reduced the gravitational circulation at all sections.

Concentrations of suspended sediment were much higher during spring tides, and increased towards the bed. Therefore, local resuspension of sediment was important. During neap tides, concentrations were typical of those associated with freshwater and marine inputs, although the slight increase in suspended sediment with depth at section 1 (Neaps) showed that a small amount of local resuspension occurred.

Calculation of Transport

If $\bar{Q}$ is the volume transport of water per unit width, $\bar{Q} = H\bar{U}$, where H is total depth, U velocity and the overbar denotes a depth average, then the residual transport is given by:

$$\langle \bar{Q} \rangle = \langle H\bar{U} \rangle = Q_E + Q_S = Q_L$$

in which the diamond bracket denotes a tidal average, and where:

$$Q_E = \langle H \rangle \langle \bar{U} \rangle \tag{1}$$

$$Q_S = \langle \tilde{H}\tilde{\bar{U}} \rangle \tag{2}$$

with $\tilde{U} = \bar{U} - \langle\bar{U}\rangle$ and $\tilde{H} = H - \langle H\rangle$

and $$Q_L = Q_E + Q_S \quad (3)$$

Therefore, Q_E is the Eulerian residual transport per unit width, Q_L is the residual transport of water per unit width, and Q_S is the residual transport associated with the tidal wave (equivalent to the Stokes transport for one-dimensional flows (12)). On intertidal areas, Q_E is also defined from equation (1), except that the substitution $\bar{U} = 0$ is made during times when a station is not submerged; Q_S is then defined from equation (3) rather than from equation (2).

The residual, depth averaged rate of transport of salt per unit width is (in ppt $m^2\ s^{-1}$):

$$F = F_L + F_{TP} + F_V \quad (4)$$

where F_L is due to the residual flow of water, Q_L, and F_{TP} and F_V are due to tidal pumping and vertical shear, respectively (5, 9, 13). If S denotes the instantaneous salinity and $\tilde{S} = \bar{S} - \langle\bar{S}\rangle$, then:

$$F = \langle H\overline{US}\rangle \quad (5)$$

$$F_L = Q_L\langle\bar{S}\rangle \quad (6)$$

$$F_{TP} = \langle\tilde{Q}\tilde{S}\rangle \quad (7)$$

and $$F_V = \langle H\overline{U'S'}\rangle \quad (8)$$

where $S' = S - \bar{S}$ and $U' = U - \bar{U}$. Fluxes are taken to be zero in these tidal averages when a station is not submerged on the intertidal areas.

The residual, depth averaged rate of transport of sediment per unit width is (in ppm $m^2\ s^{-1}$, where ppm = parts per million by weight of water):

$$G = G_L + G_{TP} + G_V \quad (9)$$

Subscripts have the same meaning as those for the salt transport (equation (4)). If P denotes the instantaneous suspended sediment concentration, and $\tilde{P} = \bar{P} - \langle\bar{P}\rangle$, then:

$$G = \langle H\overline{UP}\rangle \quad (10)$$

$$G_L = Q_L\langle\bar{P}\rangle \quad (11)$$

$$G_{TP} = \langle\tilde{Q}\tilde{P}\rangle \quad (12)$$

and $$G_V = \langle H\overline{U'P'}\rangle \quad (13)$$

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

Results

The cross-sectionally averaged currents, salinity and suspended sediment load over a tidal cycle are shown in Figure 3. An overbar is used to denote a cross-sectional average, rather than a depth average, in this figure. The cross-sectional area is denoted by A. Cross-sectional values were deduced by interpolating observed data onto a rectangular grid of points covering each section. The interpolation program has been widely used for such problems (2, 3). The program was also used to extrapolate data from the outer stations on each section (Figure 2) to the banks. Extrapolation is least accurate for the velocity, owing to its large spatial variations. Because of this, a condition of zero velocity was applied at the bed over the region of extrapolation, and on the banks, so that the problem reverted to one of interpolation.

Typical maximum current speeds were of order 1 m s^{-1} during spring tides. Speeds were less than half of this during neap tides. Currents

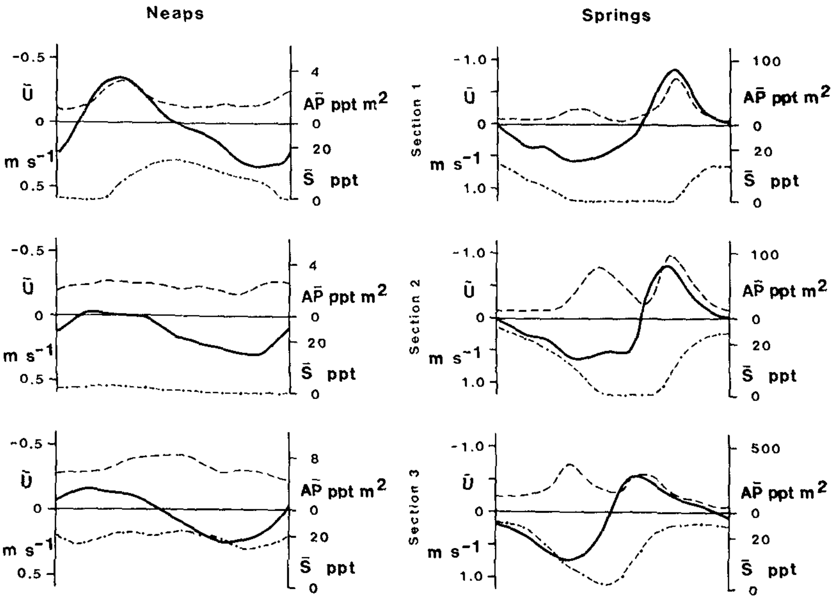

Figure 3. Tidal cycles of sectionally-averaged velocity (——), sediment load (- - -) and salinity (• - • - •).

were much more distorted during spring tides. At sections 1 and 2 the flood currents exceeded the ebb currents and were of shorter duration.

This tidal asymmetry is typical of estuarine flows in shallow water (14,1). At the seaward section (section 3) the tidal asymmetry was very small and the down-estuary-directed Eulerian residual current was sufficiently strong to generate an ebb-dominated flow.

Asymmetry in the tidal currents affected the suspended sediment load during spring tides. At sections 1 and 2 the enhanced flood currents produced more resuspension and a higher suspended sediment load than during the ebb tides (Figure 3). At section 3 the suspended load maximized during the ebb tide. Sediment loads during spring tides were very much higher than during neap tides. There is some indication that slight resuspension of sediment occurred during maximum flood currents at section 1 (Neaps).

Cross-sectionally averaged salinity is shown in Figure 3. Near the head, at sections 1 and 2, the salinity was zero near low water as the fresh water-brackish water interface swept through the section. Salinity was very low throughout the tidal cycle at section 2(Neaps) owing to the high freshwater run-off (Table 1).

Water Transport

Transverse distributions of the residual rates of transport of water per unit width of estuary are shown in Figure 4. Data are given for neap

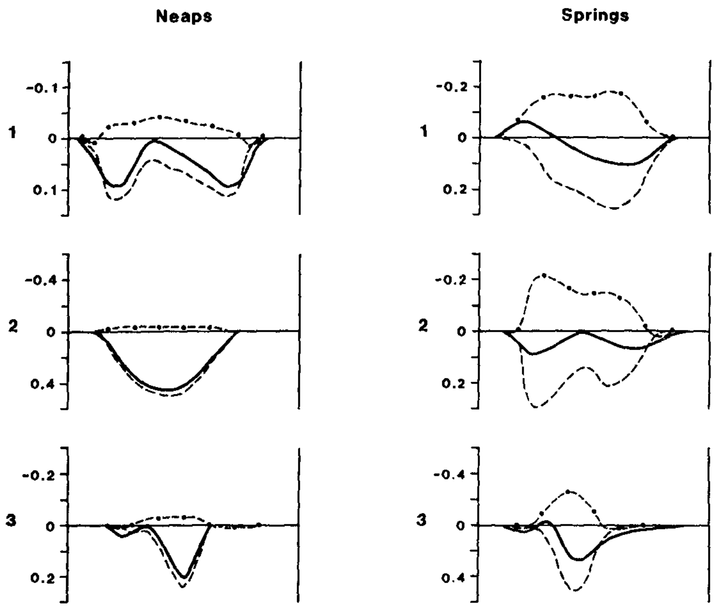

Figure 4. Lateral profiles of residual water transport per unit width (m^2s^{-1}). Stokes (-.-), Eulerian (- - -), Total (——).

and spring tides at sections 1 to 3. The tidal wave (Stokes) transport Q_S was directed up-estuary over the deeper parts of each cross-section, and was small and directed down-estuary over the intertidal areas. This transport was much higher during spring than neap tides. The Eulerian transport Q_E was always directed down-estuary, and was driven by surface slopes generated by the overall up-estuary tidal wave transport, as well as those due to freshwater inputs to the estuary, density effects and non-linear tidal effects. At section 2 (Neaps) the Eulerian transport had a simple river-like form, with fastest speeds in the deeper, central part of the section. Physical conditions were governed by the high run-off at that time.

Transverse distributions of the total residual rates of water transport per unit width Q_T were similar to those for the Eulerian transport at neap tides, owing to the smaller tidal wave (Stokes) transport. The distributions at sections 1 and 3 (Neaps) and 2 and 3 (Springs) showed a systematic pattern of circulation. Transport in the central, deeper part of the section was small, whereas over the shallower subtidal and intertidal areas the transport was stronger and directed down-estuary. This pattern consisted of three components: a run-off induced residual flow which was directed down-estuary everywhere; a density-driven component which was down-estuary in the shallow subtidal and intertidal areas, and up-estuary in the deeper, central parts of a section; and a tidally-induced component, which acted to enforce the density-driven flow. The density-driven and tidally-induced flows opposed the river-like circulation in the centre of the sections, leading to small transport there. The opposite occurred in the shallow areas.

Salt Transport

Transverse distributions of the residual rate of salt transport per unit width (ppt m^2 s^{-1}) are given for sections 1 to 3 in Figure 5. Rates of transport due to vertical shear (F_V in equation (8)), tidal pumping (F_{TP} in equation (7)) and advection (F_L in equation (6)) are shown.

Transport due to vertical shear was always directed up-estuary, and was largest in the deeper, central parts of a section. Here, the vertical variations in both currents and salinity were largest, and pronounced gravitational circulations occurred. Transport due to tidal pumping was directed up-estuary in the deeper parts of a section, but sometimes reversed direction in the shallow areas. With the exception of section 1 (Neaps), this down-estuary transport due to tidal pumping was extremely small, and is thought to be due to the reduced phases of the tidal currents (a response to the increased frictional drag in these areas) relative to those in the deeper regions.

The advective transport of salt due to the residual flow of water had a very similar pattern to the residual flow of water (compare Figures 4 and 5). This is because of the relative insignificance of transverse variations in salinity when compared with sectionally-averaged values. Thus, the advective transport of salt tended to be small in the deeper parts of a section, and large and directed down-estuary in the shallower areas. Rates of transport due to vertical shear and tidal pumping were large and directed up-estuary in the deeper part of a section. Therefore, the residual transport was directed up-estuary in the central, deeper part of a section, and directed down-estuary in the shallow regions.

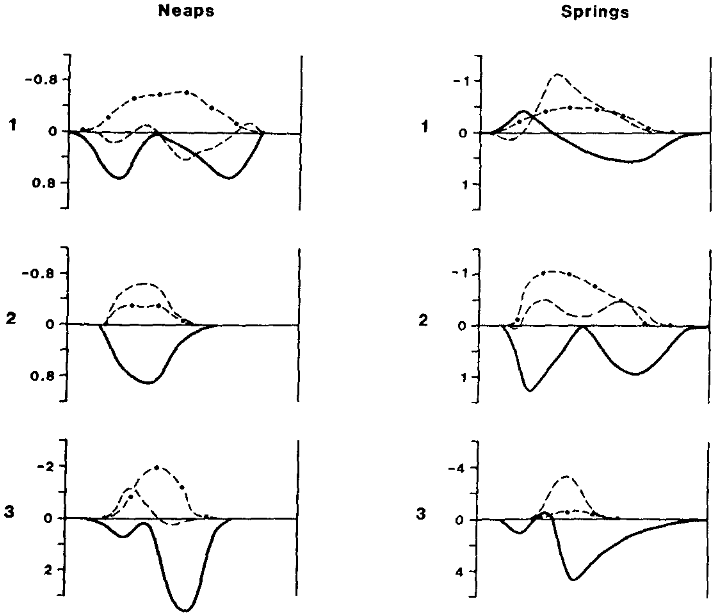

Figure 5. Lateral profiles of residual salt transport per unit width (ppt m^2 s^{-1}). Advection (——), Pumping (- - -), Shear (-.-).

Sediment Transport

Transverse distributions of the residual sediment transport per unit width (ppm m^2 s^{-1}) are given for sections 1 to 3 in Figure 6. Rates of transport due to vertical shear (G_v in equation (13)) were negligible and are not plotted. This is because of the low and fairly uniform concentrations of suspended sediment during neap tides; marine and freshwater concentrations were comparable (5-10 ppm). During spring tides the much higher concentrations were generated by local resuspension at maximum flood and ebb currents, and temporal correlations of the vertical shear transport were small.

The advective transport of suspended sediment due to the residual flow of water had a very similar pattern to the residual flow of water (compare Figures 4 and 6). Transport during spring tides was between one and two orders of magnitude larger than during neap tides.

Tidal pumping of sediment was directed up-estuary at section 1, and was considerably larger during the spring tide. The residual, up-estuary transport due to tidal pumping was a consequence of enhanced re-suspension of sediment, and associated up-estuary transport during peak flood currents (see also Figure 3). Flood currents also exceeded ebb currents at section 2 (Springs), and up-estuary tidal pumping occurred in the shallow areas. However, weak down-estuary pumping occurred in the deeper part of the section. This was possibly due to the absence of easily erodible bed sediment in the deepest part of the section. Tidal pumping of non-locally suspended sediment acted in the opposite way to that for salt (salinity increased down-estuary, whereas suspended sediment concentrations decreased), and so pumped sediment out of the estuary. Asymmetry between flood and ebb currents was small at section 3 (Springs). Here, the associated up-estuary pumping in the shallow areas was weak, and the down-estuary pumping in the deeper part of the section was large.

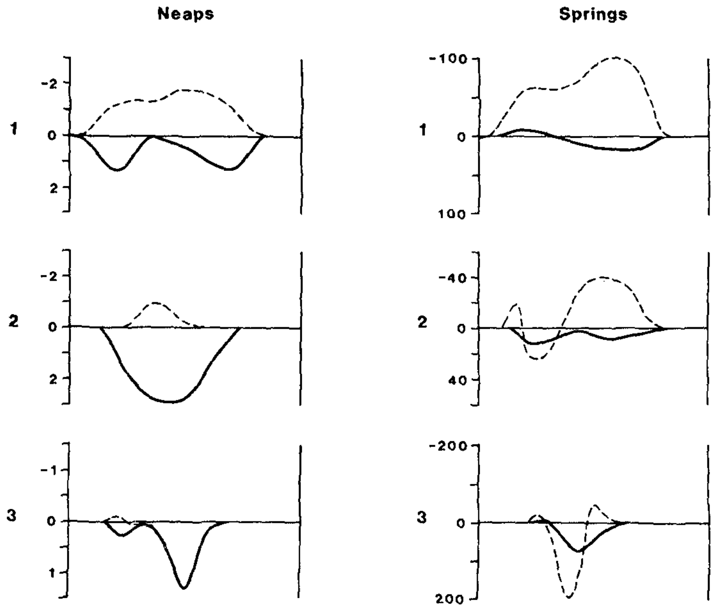

Figure 6. Lateral profiles of residual sediment transport per unit width (ppm m^2 s^{-1}). Advection (——), Pumping (- - - -).

Conclusions

Spring tidal currents showed a strong asymmetry in the upper reaches of the estuary with flood currents exceeding ebb currents. Maximum current speeds were more than twice those at neap tides. Suspended sediment concentrations at spring tides were between one and two orders of magnitude higher than those at neap tides, owing to strong local resuspension of sediment in the faster tidal currents.

The residual, tidal wave (Stokes) transport of water was much higher during spring tides. The transport was directed up-estuary in the deeper parts of a section, but could reverse direction in the shallow intertidal areas. The Eulerian residual transport was always directed down-estuary. The total residual rate of transport tended to be directed down-estuary over the shallow and intertidal areas, whereas in the deeper parts of a section it tended to be smaller, and could be directed up or down-estuary.

Tidal pumping of salt was directed up-estuary in the deepest part of a section, whereas it was small and could be directed down-estuary in shallow and intertidal areas. This was possibly due to reduced phases of the tidal currents (slack water occurring earlier) in the shallow areas. Vertical shear transport of salt was always directed up-estuary, and was largest in the deeper regions where vertical stratification was more pronounced and gravitational circulation was present. Residual salt transport due to local advection by the residual flow of water closely followed the pattern of residual water flow, owing to the relative insignificance of cross-estuary variations in salinity. The total residual transport of salt was directed up-estuary in the deeper parts of a section, and down-estuary in the shallower regions.

Tidal pumping dominated the suspended sediment transport during spring tides. Pumping was directed up-estuary over the whole section near the head. This was because of the much stronger flood currents (and associated erosion stresses) and the existence of a plentiful supply of bed sediment for erosion and resuspension. The asymmetry in the tidal currents was weaker further down-estuary. Tidal pumping was directed down-estuary in the deeper part of a section. This is thought to be due to the absence of easily erodible bed sediment in the deep channel. In absence of local resuspension, the tidal pumping of sediment acted in the opposite way to the tidal pumping of salt (salinity decreased up-estuary whereas suspended sediment concentrations increased). Fine sediment was present in the shallow and intertidal areas further down-estuary, and the tidal pumping there was weak but directed up-estuary.

Vertical shear transport of sediment was very much smaller than that due to pumping and advection. Pumping dominated advection at spring tides, whereas the reverse was true at neap tides. Transport was much smaller at neap tides, but weak resuspension and tidal pumping occurred near the head.

Acknowledgements

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Appendix - References

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