Estuarine sedimentation
Sediment transport
Turbidity maximum
Estuaries
British Isles

Sédimentation estuarienne
Transport du sédiment
Maximum de turbidité
Estuaires
Grande-Bretagne

Seasonal sediment movement in the Tamar estuary

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

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ABSTRACT

Seasonal movements of sediment in the Tamar Estuary have been estimated by recording variations in sediment levels at 30 sites evenly distributed along the length of the estuary through a 14 month period. A marked seasonal migration was observed in which sediment was gradually accumulated in the upper estuarine turbidity maximum zone during the spring and summer months. In winter, this sediment was redistributed into localised depositional sites in the mid-estuarine region. Regressions of sediment accumulation against river flow indicate that internal cycling of sediment is primarily driven by changes in river flow. Particle fluxes and the total amount of material involved in this seasonal migration have been calculated and the potential mobile sediment replacement time has been estimated.

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RÉSUMÉ

Mouvements saisonniers du sédiment dans l'estuaire du Tamar

Les mouvements saisonniers du sédiment dans l'estuaire du Tamar ont été estimés par enregistrement des variations de niveau du sédiment sur 30 sites également répartis le long de l'estuaire pendant une période de 14 mois. On a observé une migration saisonnière marquée, pendant laquelle le sédiment s'accumulait peu à peu dans l'estuaire en amont au printemps et en été. En hiver, ce sédiment était redistribué aux sites de dépôt localisés au milieu de l'estuaire. Les régressions de l'accumulation sédimentaire comparées au flux du fleuve, indiquent que le recyclage du sédiment est principalement causé par des changements de flux du fleuve. Les flux de particules et la quantité totale de matière dans cette migration saisonnière, sont calculés, et la période de remplacement potentiel du sédiment mobile est estimée.

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INTRODUCTION

Dissipation of high tidal energy inputs in macrotidal estuaries like the Tamar promotes a vigorous mixing of particles between sediment and water column while generating substantial internal movements of sediment and maintaining a well-developed turbidity maximum in the upper reaches (Allen *et al.*, 1976; 1980; Morris *et al.*, 1982 *b*; Uncles *et al.*, 1984). These particle transport processes give rise to a complexity of internal transport routes for heterogeneously reactive chemical constituents and, consequently, to the development of significant internal cycling and temporary retention mechanisms. Thus,

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a complete understanding of chemical behaviour in an estuary is dependent on the availability of quantitative information on mobile sediment and suspended particle dynamics in the system. This requirement has been emphasised particularly by studies of trace element distributions in the Gironde Estuary (Etcheber *et al.*, 1981; Jouanneau, 1982; Elbas-Poulichet *et al.*, 1984). Complex chemical behaviour attributable to high internal particle mobility is also evident from studies of the Tamar Estuary (Morris *et al.*, 1982 *a*). To further our understanding of chemical interactions in this estuary, we have assessed the extent and rate of large scale sediment transport associated with the seasonal migration of the turbidity maximum zone. This has been achieved by monthly observations of changes in sediment level using vertical poles in the manner described by Pickrill (1979) and Frostick and McCave (1979).

The results show a marked seasonal migration of sediment in which particles are gradually accumulated in the upper estuary throughout the summer to be redispersed down-estuary when river flow increases during autumn and winter. Particle fluxes and the total amount of material involved in this seasonal migration have been calculated and the potential mobile sediment replacement time has been estimated.

THE STUDY SITE

The Tamar Estuary, situated in the south west of England, extends 31 km from a weir at Gunnislake to its mouth at Plymouth Sound (Fig. 1). The physical hydrography of the Tamar Estuary has been described by George (1975) and Uncles *et al.* (1983; 1984). Chemical characteristics have been described by Butler and Tibbitts, 1972; Morris, 1978; Morris *et al.*, 1978; 1981; 1982 *a*; 1982 *b*; 1982 *c* and Loring *et al.*, 1983.

Extensive intertidal mudflats are typical of the lower estuary between 20 and 30 km from the weir; these flats have shallow slopes and are relatively firm. Between 8 and 20 km the mud banks, though less extensive, are much steeper and the consistency of the superficial mud is more fluid, reflecting the increased tidal reworking of the mud in this region. Above 8 km the river narrows and has been canalised in parts; mud banks are less prominent and sedimentation occurs more uniformly over the estuary section. The sediment here is characterised by extreme fluidity. No significant sedimentation of silt occurs above 3 km where the estuary takes on predominantly riverine characteristics.

MATERIALS AND METHODS

Thirty wooden poles, each 2 m long and 4 cm square, were treated with a wood preservative and driven vertically into the intertidal mud at roughly 1 km intervals along the estuary. The poles were positioned such that they were uncovered at tidal elevations between low water neaps and low water springs. After allowing one month for site recovery from disturbance during installation, measurements of sediment level relative to each pole were taken monthly during spring tides at low water. The study was started in December, 1981 and continued for 14 months.

Assuming that each pole yielded data representative of the entire 1 km segment of the estuary in which it was situated (Fig. 1)., monthly changes in sediment altitude were converted to sediment volume (m^3 wet sediment per 1 km segment) by multiplying by the surface area of that segment. Some segments contained two poles, in which case the values were averaged. For two cases where poles were lost or discarded, information was obtained by interpolation between adjacent segments. Estimates of the monthly flux of sediment through each lateral segment boundary (m^3 wet sediment $month^{-1}$) were obtained by cumulatively summing the riverine sediment flux and the changes in volume of sediment per segment along the estuary from the weir.

The monthly averaged inputs of riverine sediment (Tab. 1) were estimated from data collected by the South West Water Authority at Gunnislake by

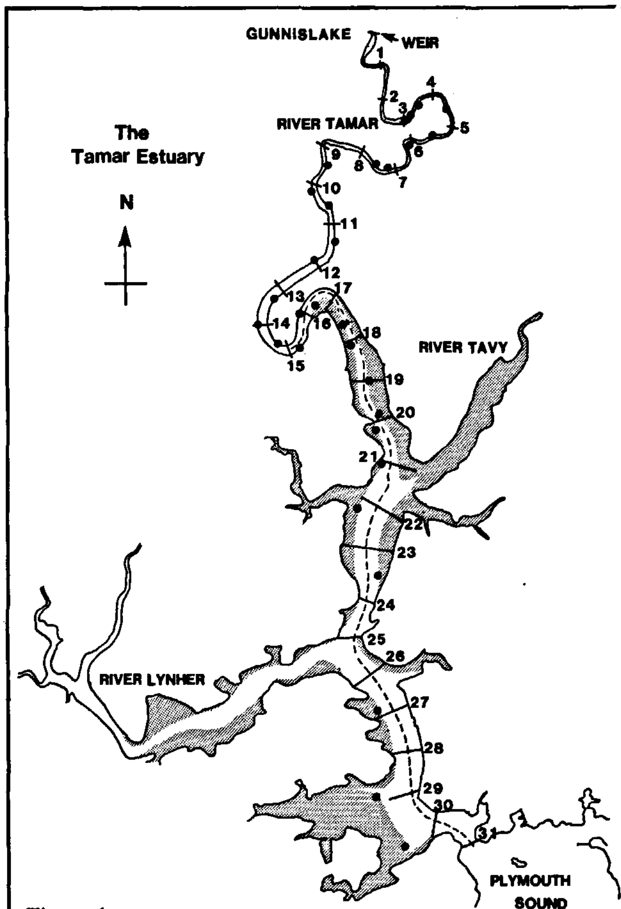

Figure 1
Sketch map of the Tamar Estuary system showing the location of the mud poles (●) and the unit kilometer segments used in the sediment flux calculations. Major areas of mud banks are stippled.

Table 1
Monthly mean river flow and flux of riverine particles (converted from mass units to volume of wet sediment using a factor of 424 kg of suspended solids/m³ of wet sediment determined for Tamar sediments).

Month	Monthly mean river flow ($m^3 . sec^{-1}$)	Riverine sediment volume influx (10^3 $m^3 .month^{-1}$)
January	37.4	5.85
February	28.5	2.81
March	54.5	17.78
April	8.9	0.34
May	3.3	0.11
June	6.6	0.15
July	6.8	0.12
August	4.7	0.09
September	7.9	0.38
October	51.9	7.26
November	70.1	19.11
December	69.4	21.18

summing the product of daily mean river flow and a daily value for suspended solids derived from a regression of suspended solids measurements against river flow.

RESULTS

Monthly changes in sediment altitude at each pole are listed in Table 2 and depicted as a series of axial profiles in Figure 2. The data were effectively normalised by the addition of an altitude factor equivalent to the largest net negative change in sediment altitude relative to the initial measurement at each pole. This maintains the relationships

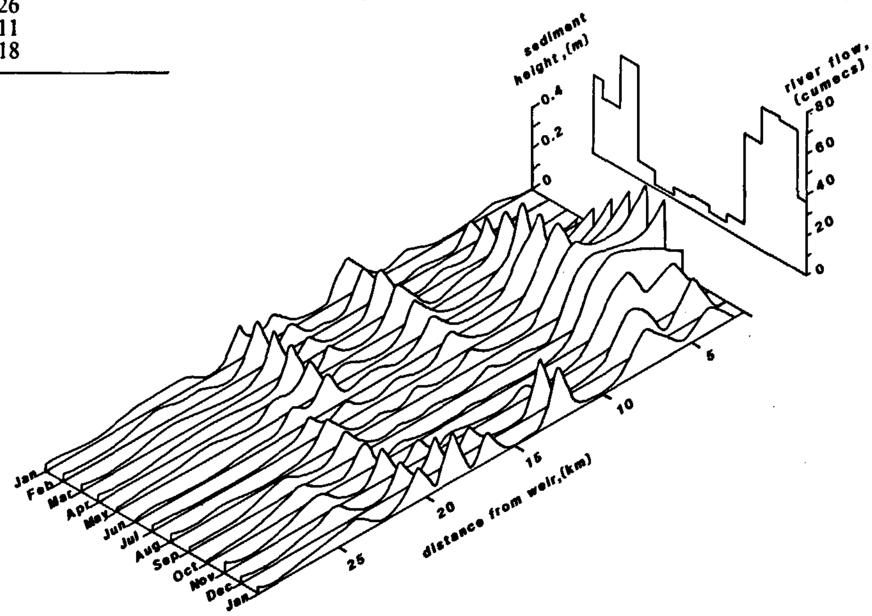

Figure 2
A series of thirteen, monthly axial profiles of sediment elevation in the Tamar Estuary. Mean monthly river flow at Gunnislake is represented on the same time scale.

Table 2
Positions of mud pole sites, monthly changes in sediment elevation at each site, and area of each 1 km segment of the estuary.

Pole No	Position of pole (km below weir)	Segment of estuary (km below weir)	Area of segment (m^2)	Monthly changes in sediment altitude (cm) J-F	F-M	M-A	A-M	M-J	J-J	J-A	A-S	S-O	O-N	N-D	D-J
1	3.1	3-4	4.0×10^4	0	0.8	1.5	11.1	8.9	9.0	7.9	−2.9	−18.8	−15.0	−2.4	0
3	3.6	4-5	4.0×10^4	−3.4	−0.7	0.1	6.0	7.8	5.5	5.3	0.9	−0.5	−0.8	−3.2	−8.3
6	6.2	5-6	5.0×10^4	−1.2	−0.1	0.1	4.3	0.3	12.0	8.7	3.7	2.7	−15.4	−13.8	−0.9
7	7.2	6-7	5.5×10^4	10.5	8.1	8.6	9.0	−0.9	0.7	−3.8	−0.6	5.0	−4.6	−14.6	−6.9
8	7.6	7-8	6.0×10^4	−0.2	4.6	4.6	3.9	11.1	1.5	−1.6	0.5	4.4	−0.9	−4.6	−4.0
9	9.4	8-10	1.4×10^5	−1.9	1.6	1.7	−2.8	2.3	−2.2	−2.2	−2.3	4.8	−1.8	−2.2	−0.6
10 α 11	10.2, 10.5	10-11	9.0×10^4	−0.1	0.2	0.8	0.9	0.4	−3.1	0.1	1.3	−1.8	−0.1	1.0	−1.5
12	11.4	11-12	1.3×10^5	0.5	0.1	1.1	−2.5	−1.5	−2.0	−1.9	−1.7	−0.6	0.3	−0.8	1.9
13	12.0	12-13	1.7×10^5	1.0	2.6	−2.2	−1.2	−3.2	−2.6	−4.0	−2.9	−4.9	5.2	17.6	0.8
14	13.3	13-14	1.6×10^5	−0.2	1.0	2.9	−1.5	1.5	−2.0	−0.7	−2.4	−0.8	−0.1	0	0.3
16	14.7	14-15	2.8×10^5	−0.2	0.2	0.4	−0.2	−0.1	−0.1	0.1	−0.2	1.0	−1.2	−1.0	0.3
17	15.2	15-16	3.1×10^5	0.2	−0.1	1.0	−0.8	3.2	0.3	−0.8	3.6	−2.4	1.9	−0.9	−0.8
18	15.9	16-17	2.7×10^5	0.7	−0.7	−1.0	−1.8	−3.5	−3.3	−1.7	−0.1	0.9	3.6	7.7	0.7
20	17.7	17-18	4.0×10^5	−0.3	−1.5	−3.0	2.2	1.0	−0.8	1.1	−0.5	−2.1	−0.6	−0.3	0.7
21	18.1	18-19	4.8×10^5	7.6	0.5	−2.6	−1.9	−1.4	−7.9	−8.5	−1.1	4.3	7.4	6.0	6.0
22 α 23	19.0, 19.9	19-20	6.6×10^5	5.2	0.6	0.1	0.8	−1.5	−3.1	1.8	−0.8	−4.3	0.1	1.8	1.3
24	20.2	20-21	8.9×10^5	1.3	1.9	2.0	5.1	0.8	0.6	2.5	0.2	0.6	0.1	−0.8	1.6
25	21.0	21-22	8.9×10^5	0	−1.0	0.5	−0.3	0.5	−0.1	0.6	−0.2	−2.9	−0.9	−0.6	3.8
26	22.2	22-23	8.9×10^5	−1.3	−0.2	0.6	−1.8	−0.3	−1.1	−0.1	0.5	−1.3	−1.1	−0.2	−0.3
27	23.6	23-25	9.2×10^5	2.2	−1.1	−1.8	0.9	−4.4	−1.8	0.8	8.2	1.3	0.1	−0.4	−1.5
28	26.9	25-27	1.4×10^6	0.5	0.4	0	−0.2	−2.5	−0.8	1.9	0.3	1.1	0.4	−0.6	−0.2
29	28.9	27-29	1.6×10^6	−1.5	−0.9	0.4	0.3	0.3	0.1	−0.5	−0.3	−0.4	0.1	−0.4	−0.5
30	30.0	29-30	9.8×10^5	−0.1	−0.4	−1.0	−0.5	−1.2	2.5	1.4	−2.6	−1.3	4.0	−1.8	−0.3

between consecutive observations at each pole but compares sites by reference to a common plane (indexed at 0 m) defined by the maximum extent of sediment erosion at each site.

Figure 2 shows that, from January to April, mobile sediment was absent in the upper 5 km of the estuary but was present to depths of 10 to 20 cm in localised depositional areas between 10 and 20 km from the weir. From mid to late summer, the mobile sediment in the mid-estuarine region (10 to 20 km from the weir) was gradually eroded and marked accumulations, up to 40 cm in depth, were recorded in the upper 8 km of the estuary. From October onward this process was reversed, the sediment in the upper estuary became depleted and localised accumulations developed again in the mid-estuarine region.

Linear regressions of sediment accumulation per 1 km segment against mean monthly river flow showed a progressive transition from highly significant inverse correlations for the upper estuary (between 4 and 8 km from the weir) through a zone of insignificant correlations (between 9 and 12 km) to variable conditions in the region between 13 and 20 km below the weir. However, significant correlations within this latter zone were positive.

Although observations were carried out down to 30 km, only relatively small seasonal fluctuations in sediment altitude were observed below 20 km (Tab. 2). In this region, the much greater area per 1 km segment produced unacceptably large errors in the assumptions of uniform deposition and erosion and topographical complications were introduced by the major tributaries. Hence, interpretation of sediment behaviour was not attempted and derivation of sediment fluxes was restricted to the upper 20 km of the estuary.

Monthly sediment fluxes across each boundary showed a regular seasonal pattern (Fig. 3). Throughout the winter months, October to March, riverine inputs were substantial (Tab. 1) and, except for February when river flow was reduced, the fluxes were predominantly negative (*i.e.* down-estuary). From April, concomitant with a marked reduction in river flow and input of riverine particles, the fluxes became positive (*i.e.* up-estuary) although in the months June to August, corresponding to the period of lowest river flow, a divergence of fluxes occurred at 11 to 13 km with positive fluxes continuing in the upper estuary and negative fluxes in the lower estuary.

DISCUSSION

A pronounced cyclic migration of mobile sediment has been recorded in which sedimentary material was accumulated uniformly in the upper 8-10 km of the estuary during the spring to late summer months to be redistributed, in localised depositional regions of the mid-estuary (12-20 km from the weir), during high run-off conditions in late autumn and winter.

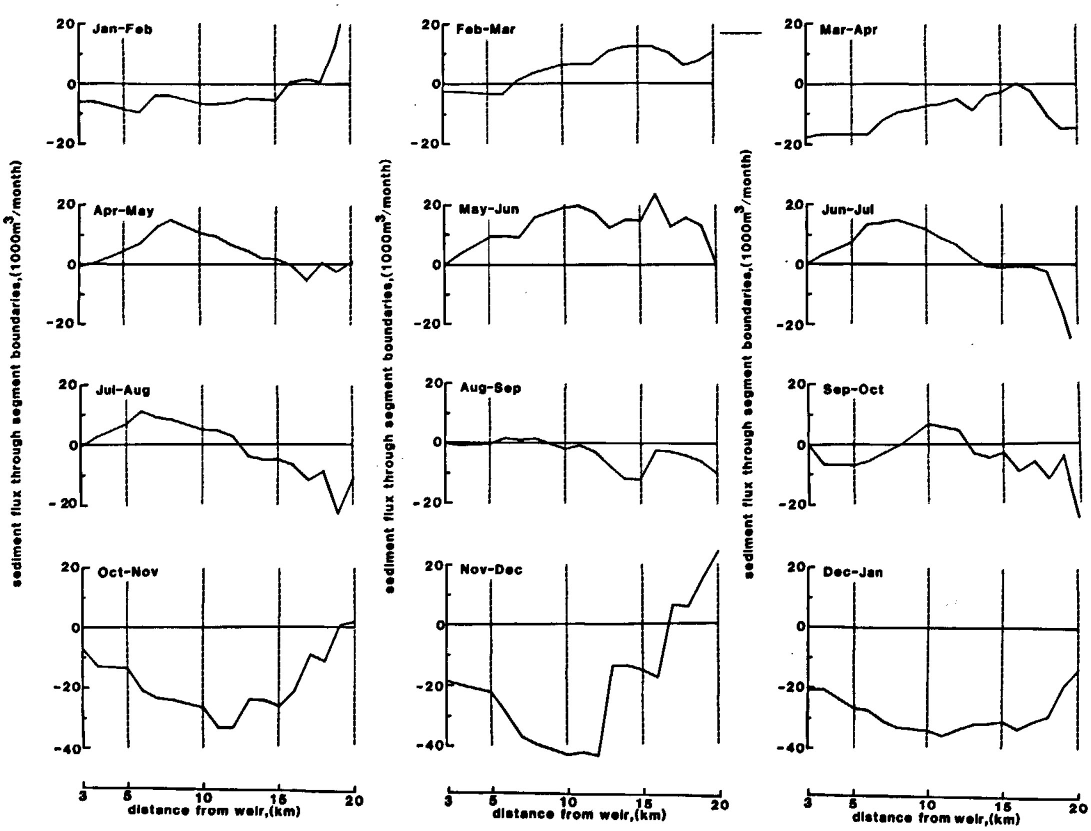

Figure 3

Fluxes ($10^3 m^3$ month^{-1}) of estuarine sediment through each unit kilometer segment boundary. Up-estuarine fluxes are denoted positive.

Regressions of net sediment accumulation against river flow show that sediment transports to and from the upper estuary were correlated with seasonal changes in river flow (Fig. 2; Tab. 1) which is consistent with the conclusions of Allen *et al.* (1976; 1980).

The turbidity maximum in the upper reaches of the Tamar Estuary is generated and maintained by a combination of tidal pumping and locally enhanced tidal bed stress (Uncles *et al.* 1984) in a manner similar to that described for the Gironde and Aulne Estuaries by Allen *et al.* (1980). Except for periods of exceptionally high river flow, tidal currents in the estuary are asymmetric such that peak flood velocities exceed those of the ebb, especially in the upper estuary. Hence, settling particles which oscillate between suspended and deposited states under the influence of periodic tidal sediment disturbance are subject to net transport up-estuary. Consequently, a zone of particle accumulation is generated in the upper estuary at the point where river current transport balances the tidal current effect. This zone of accumulation tends to coincide with the limit of salt intrusion but extends increasingly further into the freshwater as river discharge decreases. Independently, the estuarine gravitational circulation acts to augment the accumulation of particles in the upper estuary by developing a convergent null point in the non-tidal residual circulation just seaward of the limit of salt intrusion (Postma, 1967; Schubel, 1969; Festa, Hansen, 1978).

Tidally produced bed stresses in the Tamar increase up-estuary because magnification of tidal currents by convergence of the estuarine cross-section outweighs the frictional tidal energy dissipation (Uncles *et al.*, 1984). Hence, the upper estuarine zone of accumulation of mobile particles is also subject to locally enhanced tidally controlled resuspension. Together, these processes determine the sharp localisation and high relative magnitude of suspended particle mass in the upper estuary and its characteristic variations through semi-diurnal and spring-neap tidal cycles.

We have demonstrated here that the tendency for settlable particles to accumulate within the turbidity maximum zone leads to substantial net local sediment deposition but, because the zone of accumulation migrates seasonally, a permanent sediment trap is not produced. Nevertheless, transient sediment shoals are important factors in the overall dynamics of the turbidity maximum phenomenon. The volume of sediment accumulated temporarily, from April to September, in the upper 3-10 km of the estuary was approximately 116 × 10^3 m^3 (calculated from the data in Table 2) and even if the total riverine influx of suspended material through this period was deposited in this zone, its contribution would have amounted to little more than 1 × 10^3 m^3 (Tab. 1). It follows that the deposition of material in the upper estuary during summer was fuelled predominantly by tidal pumping of estuarine sediment from below 10 km. Furthermore, the tidally averaged amount

Table 3

*Correlation coefficients for the regression loss or gain of sediment volume per 1 km segment of the estuary against mean monthly river flow at Gunnislake. Significant correlations at the 95% confidence interval are denoted **

Segment of estuary (km below weir)	Correlation coefficient (r)
3-4	−0.29
4-5	−0.80*
5-6	−0.79*
6-7	−0.73*
7-8	−0.39
8-9	−0.57*
9-10	−0.08
10-11	0.25
11-12	0.12
12-13	0.49
13-14	0.70*
14-15	0.47
15-16	−0.09
16-17	0.45
17-18	−0.18
18-19	−0.23
19-20	0.64*
20-21	0.46
21-22	−0.27

of material in suspension in the upper estuary, high turbidity zone (equivalent to a sediment volume of *ca.* 2 × 10^3 m^3) was replaceable by this up-estuarine flux in about 3 days. Thus, particles transported to and trapped within the turbidity maximum zone were rapidly incorporated into the accumulating sediment shoal. Following the down-estuary migration of the turbidity maximum zone in autumn, the seasonally deposited shoal was eroded by river currents. Constituent particles were transported down-estuary to be reaccumulated directly within the relocated turbidity maximum zone, deposited further seaward where they were subject to up-estuarine tidal pumping, or lost permanently from the system.

The influx, between October and March, of fresh riverine suspended material to the estuary was equivalent to a sediment volume of 74 × 10^3 m^3 (Tab. 1). Thus, material delivered to the estuarine mixing zone in winter from up-estuary of the limit of salt intrusion comprised fresh riverine material and recycling estuarine material, roughly in the proportion 1 : 1.6. Partial deposition of this flux, within the estuary below 10 km, supplies the source material for subsequent up-estuarine transport and accumulation during the following summer. It is apparent that, without hydrodynamic selectivity, 39% of the material contributing to the turbidity maximum and its associated sediment shoals would be replaced annually by the fresh riverine influx, giving a half-life for turnover of 1.4 years. However, only a proportion of the particles in the influx will have settling characteristics appropriate for selective retention and most of it is delivered episodically, during short periods of river spate when export of sediment from the estuary is strongly favoured. It is probable therefore that the trapped material comprising the turbidity maximum and its associated sediment shoals has a residence half-life which is considerably longer than 1.4 years.

This seasonally cyclic internal translocation of substantial amounts of sediment within the upper estuary can significantly affect the transports and fluxes of heterogeneously reactive chemical constituents, especially if solubility-controlling redox reactions are involved. An appreciable proportion of the riverine input of dissolved Fe, Mn and other trace metals is scavenged by suspended particles in the high turbidity, low salinity region of the Tamar Estuary (Bale, Morris 1981; Morris *et al.*, 1982 *a*; Ackroyd, 1983). Net deposition of particles in this zone leads to accumulation of these elements in the sediment, where early diagenesis facilitates their resolubilization to the pore waters. Subsequent release to the water column is effected when the site of particle accumulation migrates under the influence of changing river flow, exposing the temporary accumulated shoal to erosive forces. In summer, the primary zone of release of seasonally accumulated components lies down-estuary of the turbidity maximum. Net remobilization of sediment and associated pore water is generated by tidal pumping and is relatively gradual and widespread so that augmentation of reactive constituents in the estuarine water column is significant but relatively unobtrusive. In winter, seasonally accumulated sediment and pore water are remobilized into the river up-estuary of the turbidity maximum. Erosion of this deposit is controlled by the river current and is, correspondingly, much less regular, being highly accentuated by short periods of river spate. Such episodic events produce sharp temporary disruptions in water quality which pervade the entire estuary (Morris *et al.*, 1982 *a*) and are highly important factors in the mass budgets for sediment and reactive chemical constituents in the system.

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