Water and Environment Journal
Promoting Sustainable Solutions

Water and Environment Journal. Print ISSN 1747-6585

Observations of turbidity in the Thames Estuary, United Kingdom

Steve Mitchell[1], Lars Akesson[2] & Reginald Uncles[3]

[1]School of Civil Engineering and Surveying, University of Portsmouth, Portsmouth, UK; [2]Environment Agency, London, UK; [3]Plymouth Marine Laboratory, Plymouth, UK

Keywords
flood; flow monitoring; hydrology; marine and coastal environment; sediment.

Correspondence
Steve Mitchell, University of Portsmouth, Civil Engineering and Surveying, Portland Building, Portsmouth PO1 3AH, UK. Email: Sbmitch1@gmail.com

doi:10.1111/j.1747-6593.2012.00311.x

Abstract

Two years of data of water level, salinity and turbidity have been analysed to understand the response of the estuarine turbidity maximum in the Thames to variations in tidal range and freshwater flow. We show the increase in turbidity in spring, together with a sudden decrease in autumn after fluvial flooding. In order to try to understand the mechanisms, we also present data from individual tides. During dry periods, there is a period of slack water around high tide when settling occurs. There is little equivalent settling at low tide, nor is there any significant settling during wet weather periods, pointing to the importance of tidal asymmetry at certain times of year. We also present an empirical relationship between peak tidal water level and turbidity during flood tides, which clearly shows the greater landward transport of sediment under spring tides, although this is moderated by the availability of erodible material.

Introduction

An estuarine turbidity maximum (ETM) is a common phenomenon in many estuaries and consists in a region of high suspended sediment concentration (SSC) that usually lies somewhere near the freshwater–saltwater interface. It is of interest to environmental managers and consultants because of its effect on patterns of siltation and erosion, primary production through the attenuation of light, and on water quality via a sediment oxygen demand. We herein focus on the behaviour of the ETM in a macrotidal estuary (the Thames, UK) using continuous monitors to measure SSC and salinity to study the behaviour of the ETM under various different conditions of freshwater flow and tidal range. There is a lack of data in such systems due to problems of access, representativeness and cost. Despite the importance of large estuaries and the challenges related to navigation, water quality and ecology, among other issues, we still do not fully understand the response of the ETM to changes in hydrological regime, nor can we fully explain the mechanisms that cause this response. A number of authors have pointed to the relative importance of gravitational circulation and tidal pumping in systems of this kind (Mitchell *et al*. 1998; Wai *et al*. 2004; Chernetsky *et al*. 2010), but it is fair to say that no two estuaries are the same in terms of the relative importance of these two mechanisms. An understanding of the particular mechanisms involved is therefore important for the validation of numerical models (e.g. Chauchat *et al*. 2009; Chernetsky *et al*. 2010), and the provision of good-quality data is important for their calibration.

Descriptions of macrotidal estuaries with respect to their ETMs in terms of their magnitude and migration include the Seine (Brenon & Le Hir 1999), the Scheldt (Chen *et al*. 2005), the Gironde (Doxaran *et al*. 2009) the Tamar (Uncles & Stephens 1993; Uncles *et al*. 1994), the Tay (McManus 2005), the Trent/Ouse system (Mitchell *et al*. 1998; Uncles *et al*. 2006) and the Severn (Uncles 2010). Grab samples taken from the bed of the Tamar reveal the dependence of the position of the ETM on the location of an area of mobile bed sediment that forms the source of the ETM (Uncles *et al*. 1996). The continuing processes of erosion and deposition over each tidal cycle prevent this pool from settling to become part of a consolidated bed. The high ebb velocities caused by high freshwater flow conditions after a prolonged heavy rainfall event also lead to a local 'flushing' effect, whereby the residual (tidal average) transport of sediment is seawards (hereafter 'downstream'), thus effecting a seaward migration of the ETM (Nichols 1993). Conversely, low dry-season freshwater flows lead to a relocation of the ETM landwards (hereafter 'upstream', e.g. Grabemann & Krause 1989). Garel *et al*. (2009) pointed to the importance of changes in the degree of vertical stratification that were caused by these changes in hydrological regime. More recent studies on the Konkoure estuary in Equatorial Guinea (Capo *et al*. 2009) and in two

Indian estuaries (Rao *et al*. 2011) showed a similar ETM response to changes in freshwater flow and in the former case, the effects of construction of an impoundment reservoir on flow regime and ETM characteristics were also noted.

In the absence of significant changes in freshwater flow, an estuary can exhibit substantially different patterns of sediment transport in response to changes in tidal range alone (Castaing & Allen 1981; Vale & Sundby 1987). The simultaneous measurement of surface SSCs at 20 different locations in the Tay estuary revealed a typical downstream net flux on neap tides and an upstream net flux on spring tides, the understanding of which has important consequences for the scheduling of harbour dredging (Dobereiner & McManus 1983). In contrast, extensive harbour development at the mouth of the Seine estuary at Le Havre has led to the effective canalisation of the main channel. The higher tidal currents that have resulted from this have caused sediment, which previously would have remained in the estuary, to be deposited in shelf mud zones off the estuary mouth (Avoine *et al*. 1981). Findings on the ETM response in the Trent/Ouse system indicate a strong dependence of SSC on both tidal range (Arundale *et al*. 1997) and freshwater flow (Mitchell *et al*. 1998; Uncles *et al*. 2006).

A review of literature available that describes the characteristics of the tidal Thames with respect to the transport of fine sediment and the turbidity maximum is available in Uncles & Mitchell (2011). Baugh *et al*. (in press) provided a description of some field measurements made in the tidal Thames taken over a few tidal cycles using acoustic Doppler current profiling. Baugh & Littlewood (2005) used a three-layer model to simulate fine-sediment transport in the Thames and found a tidal- and width-averaged ETM of approximately 600 mg/L and 150 mg/L in the Mud Reaches at spring tides and neap tides, respectively. The studies that have been published to date have been very successful in identifying the transport of sediment that occurs over individual tidal cycles, but generally fail to describe the longer-term migration of sediment via the ETM and its related processes.

The aim of the present work is to use 2 years of data (2008 and 2009) obtained from fixed-point continuous monitors to show the effects of changes in tidal range and freshwater flow on the behaviour of the ETM in the Thames and to bring out some of the likely mechanisms in the light of previous knowledge gained from other similar systems.

Study site and methods

The Thames is a turbid, strongly tidal estuary on the east coast of the United Kingdom that discharges water into the North Sea. It has particular importance to the economy of the United Kingdom in that it passes through the capital city of London. Its width decreases markedly upstream of Southend and Sheerness (the inner estuary, Fig. 1). The tidal Thames is approximately 110-km long from its seaward limit at a location approximately 80 km downstream of London Bridge to its tidal limit at Teddington Weir at approximately 30 km upstream of London Bridge (Fig. 1). The seaward limit is arbitrarily taken to be the dashed line on Fig. 1 [prior to 1964, this was the seaward limit of the Port of London Authority (PLA)], to the east of which a sudden widening occurs. The mean freshwater flow at Kingston is approximately 67 m^3/s, and the difference in water level between high water (HW) and low water at London Bridge varies from 4.6 m at mean neap tides to 6.6 m at mean spring tides (ATT 2010).

As a whole, the river Thames has a catchment area of 16 133 km^2 and a population of over 13 million. As such, it is the most heavily populated catchment in the whole of the UNITED KINGDOM. The non-tidal Thames is 235 km in length and is a source of drinking water to large numbers of households and local industries. Numerous discharges from wastewater treatment plants help to maintain the flow in the fluvial section during periods of dry weather.

The data presented herein relate to (1) observations made by fixed continuous monitors and (2) data collected during boat-based surveys. A series of nine continuous monitors (YSI 6600 series multiparameter sondes), owned and operated by the Environment Agency of England and Wales, are permanently located at a number of stations along the length of the estuary. These are all positioned near the bank of the channel for easier access and are attached to pontoons or floating jetties. They thus reflect the conditions about 1 m below the surface throughout the tide. These monitors record temperature, conductivity and turbidity at 15-min intervals, as well as other parameters not discussed here (ammonia and dissolved oxygen, among others). Not all the determinands are monitored at all the 'water quality' stations listed in Table 1. The data obtained from the continuous monitors are sent using burst telemetry to transmit the data after each reading has been made. Servicing of the monitors is carried out approximately once per month, during which the sensors are cleaned and any necessary maintenance is undertaken. Conductivity and temperature measurements were used herein to obtain instantaneous estimates of salinity using the practical salinity scale (UNESCO 1983), which by convention, is not given a unit here.

A programme of boat-based surveys is also undertaken approximately every 2 weeks, during which near-surface samples of water are obtained and stored in bottles for later analysis. These provide a useful means of 'ground-truthing' the data provided by the continuous monitors. For the present work, it was possible to compare the results of the SSCs obtained from the boat-based surveys with results obtained from the continuous monitors at the same location, although not at the same time. This is of particular importance for the validation of the optical turbidity data provided

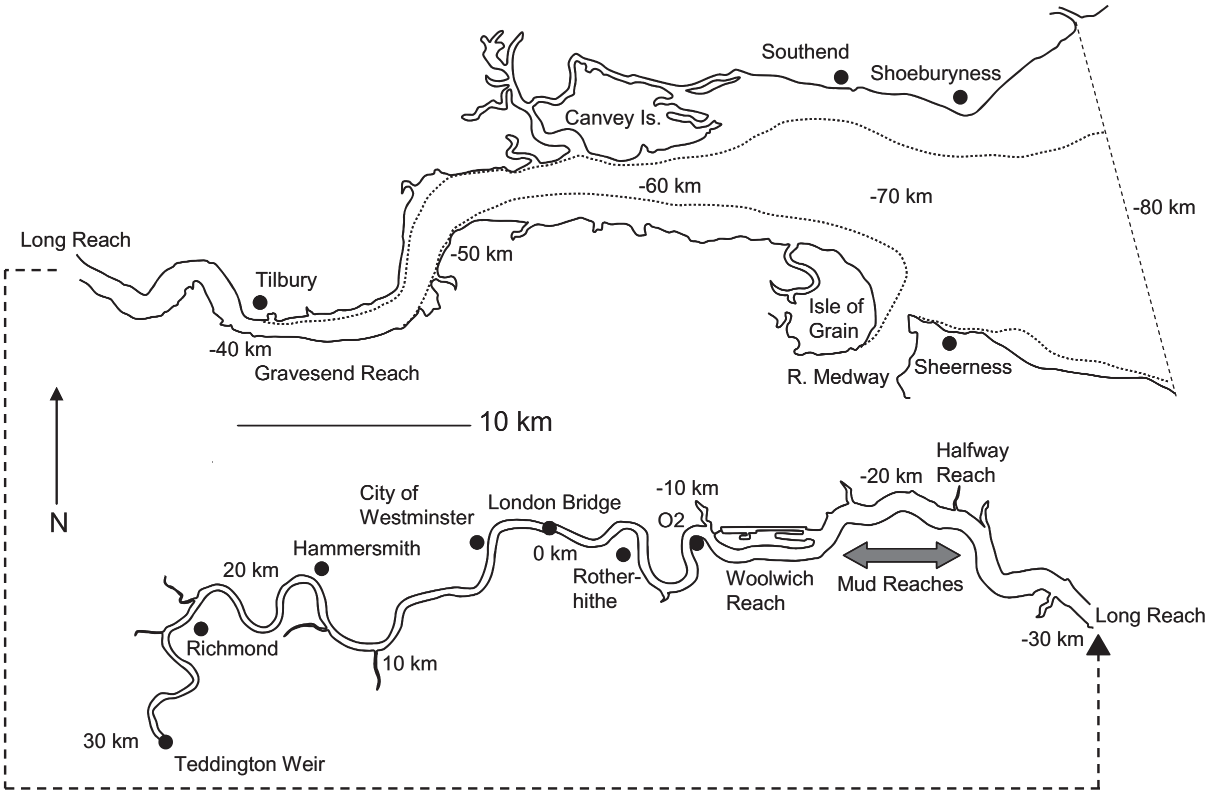

Fig. 1. Map of Thames estuary.

Table 1 Location of sampling points in the Thames estuary

Station	Approximate distance upstream of London Bridge (km)	Parameter
Richmond	25	Water level
Chelsea Bridge	6.5	Water level
Westminster	3.5	Water level
Tower Bridge	–1	Water level
Charlton	–12.2	Water level
Silvertown	–13.7	Water level
Erith	–26.6	Water level
Tilbury	–35	Water level
Southend	–69.7	Water level
Sheerness	–75	Water level
Kew	20.9	Water quality
Chiswick	19	Water quality
Hammersmith	14	Water quality
Putney	11.9	Water quality
Cadogan Pier	7.5	Water quality
Chelsea	6.5	Water quality
Woolwich	–14.7	Water quality
Erith	–26.6	Water quality
Purfleet	–30	Water quality

by the continuous monitors, given the general levels of uncertainty associated with the correlation between turbidity and SSC (Bunt *et al*. 1999).

Another set of monitors (Fig. 1) is located along the tidal reaches of the Thames in order to measure water level. Like the first set, they collect data at 15-min intervals, but for historical and practical reasons, they are located at different sites to the monitors that measure water quality. These gauges are monitored at 1-min intervals but are generally considered at 15-min intervals via the National Flood Forecasting System of the Environment Agency. The gauges are mostly Vega (http://www.vegacontrols.co.uk) radar level gauges connected to Serck Proteus (www.schneider-electric.com.au) outstations. They are monitored by the Thames Barrier Tideway Telemetry System of the Environment Agency using either leased lines or radio links. Maintenance and ownership of the gauges are shared with PLA. Mechanical and electrical maintenance are carried out by the Environment Agency, and level maintenance is usually carried out by the PLA, with occasional surveys being made by the Environment Agency to check their accuracy. It was possible to use the data obtained from these water level monitors to interpret the tidal variation in the parameters of interest here, to see, for example, the intertidal and intratidal variation in salinity and turbidity. These monitors are also owned and operated by the Environment Agency, who also provided data on daily mean freshwater flow measured at Teddington Weir (Kingston-upon-Thames).

Results

In view of the large amount of data obtained during the present study, only a subset of the results are shown here, which generally relate to the continuous monitor at Chiswick Bridge (Fig. 1). The results (2006–7) of the ground-truthing for turbidity along the whole estuary are shown in Fig. 2. Although not contemporaneous, these show reasonable agreement between turbidity in nephelometric turbidity units (NTU) and SSC if a turbidity–SSC correlation of 1 NTU : 1 mg/L is used, and are in good general agreement with the values of SSC modelled by Baugh & Littlewood (2005). Of course, the 1 : 1 relationship assumed here masks a considerable degree of scatter as explained by Bunt *et al*. (1999), and many authors have discussed the inconsistencies of this relationship between different estuaries. Some discussion of the relationship and the scatter involved in the Humber estuary (Mitchell & West 2002, their fig. 6) and a South Coast estuary (Mitchell *et al*. 2004, their fig. 2) shows the nature of the inconsistencies, but it is nevertheless useful to assume some sort of relationship in order to make progress with our understanding of sediment transport in estuarine systems in general, and the Thames in particular. We do not provide a similar direct comparison of salinities, but these results are available on request.

In order to understand the nature of the hydrological regime in the period of the study, we show the freshwater flow, measured at Kingston, for the period 2008–09 (Fig. 3). Although both years experienced wet winters, of key importance to the present study is the difference between 2009, which had a dry summer, and 2008, which did not. Figures 4 (2009) and 5 (2008) show the gradual increase in salinity and sediment during low freshwater flow and downstream flushing under higher freshwater flow. The more prolonged low summer freshwater flows in 2009 than in 2008 allow more sediment to be moved upstream on each spring tidal cycle earlier in 2009 than in 2008. In 2009, peak tidal SSC rose above 200 NTU at Chiswick Bridge for the first time during the spring tide at the end of June. Inspection of the similar record at Cadogan Pier (Fig. 1, data not shown) provides some evidence that a similar SSC was achieved there in late May 2009. This is interesting because it gives an indication of the rate at which the sediment is transported upstream under these conditions. It should be noted that the values of salinity presented here must be viewed with caution, in that the method used is only valid for values of salinity greater than 2. For much of the time, the salinity at Chiswick is rather less than this value, but the results are presented with that in mind.

Some further understanding of the mechanisms of transport of sediment may be obtained by inspection of the variation in salinity and SSC over individual tidal cycles. In selecting the tidal cycles in Fig. 6, some effort was made to ensure their representativeness of the general case. Under low freshwater flows (Fig. 6a), the arrival of each flood tide causes a large increase in SSC due to the higher magnitude of the flood currents compared with the ebb currents that immediately preceded the flood tide. At the end of the flood tide, there is clearly a period of slack water, during which the currents reduce to zero or very low values for some time, and this is reflected in the sudden reduction in SSC that occurs at

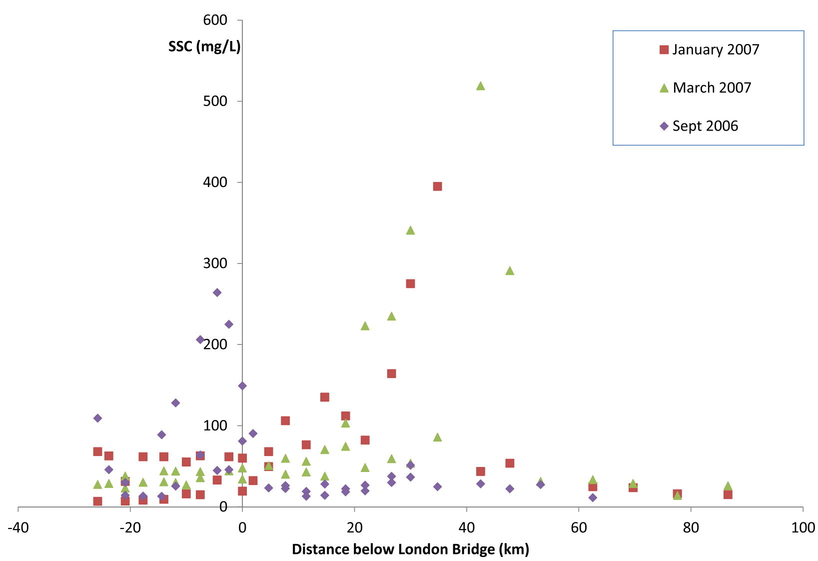

Fig. 2. Near-surface values of suspended sediment concentration (SSC) in 2006–7 obtained by gravimetric analysis of pumped samples.

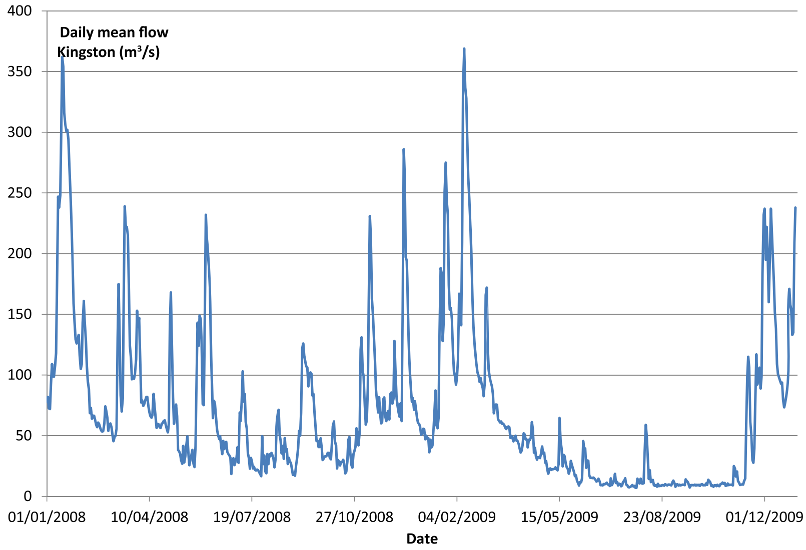

Fig. 3. Freshwater flow into the Thames from the non-tidal Thames during 2008–9.

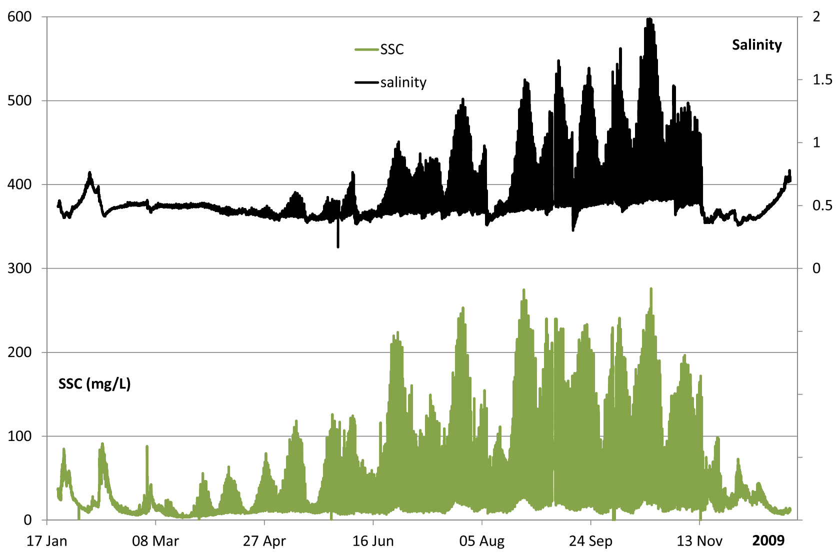

Fig. 4. Fifteen-minute data for salinity and suspended sediment concentration (SSC), Chiswick 2009.

this time due to settling. After that, the current increases again during the ebb tide, causing resuspension of the settled sediment. It must be concluded that the net effect of this pattern of the advection, settling and resuspension of sediment leads to a gradual movement of sediment upstream under these conditions, as it does in other systems (Mitchell *et al*. 1998).

For conditions of high freshwater flow (Fig. 6b), the variation in SSC is rather different. Here, there are still peaks in SSC that correspond to the peaks in velocity during the flood and ebb tide, but in this case, it is noticeable that there is an absence of any significant settling during the slack-water period. The effect is also clearly shown in Fig. 5 for the period November and December 2008, where little, if any, slack-water reduction in SSC is seen. This means that the sediment generally remains in suspension for the whole tidal cycle (or several tidal cycles), and, because the net tidal flux of water in any estuary is always downstream, the net movement of sediment is also downstream under these conditions. It is interesting to note the effectiveness of this downstream 'flushing' of sediment in transporting large quantities of sediment downstream. While the upstream transport of sediment takes several lunar cycles, one significant freshwater flow event re-establishes the conditions before the upstream transport of sediment took place.

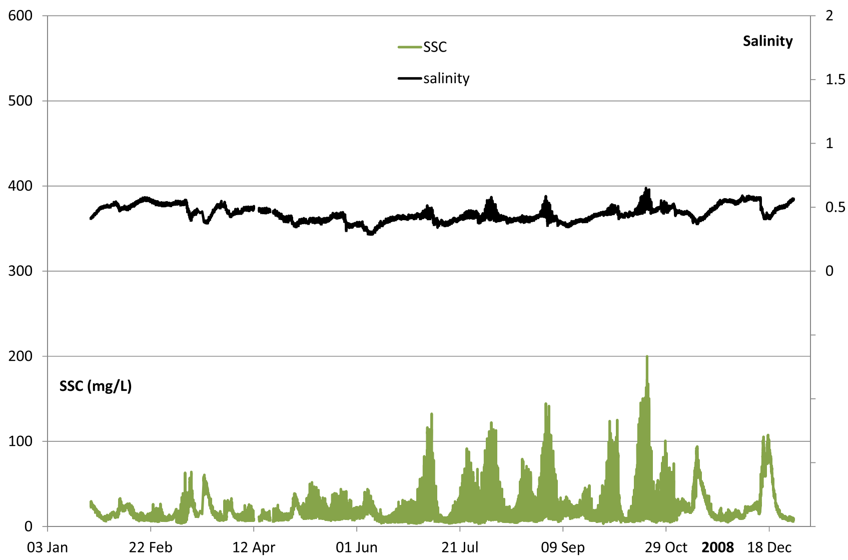

Fig. 5. Fifteen-minute data for salinity and suspended sediment concentration (SSC), Chiswick 2008.

Discussion

The response of the ETM to tidal range and freshwater flow in the Thames is a highly complex and multidimensional problem that must be informed by comprehensive monitoring at a range of depths in a number of locations throughout the estuary. Ideally, it requires the provision of good-quality data collected over many tidal cycles and for a number of years, to ensure that SSC values are obtained for the whole range of possible freshwater flow conditions, and to reduce the effects of outliers. The nature of estuarine fine suspended sediment means that its transport is affected by a wide variety of time lags related to a number of different time scales including tidal, lunar and seasonal. However, due to the financial and practical constraints associated with the collection of data, complete coverage of a large estuary such as the Thames is not possible. The use of continuous monitors, appropriately maintained and managed, is a good means of obtaining the overall picture in this regard (Mitchell *et al*. 2003), although it must be stressed that by their nature, they are generally fixed in space, and thus show SSC and salinity at varying positions within the flow, depending on the state of the tide. For ease of access, they are also located near the bank of the channel, and not in midstream. It should also be stressed that other authors have shown a significant difference between near-bed and near-surface values of SSC in the Thames, with near-bed values of SSC being perhaps at least twice those near the surface (e.g. Baugh *et al*., in press). However, much of the data in this respect is as yet unpublished, and while the estuary is likely to be well mixed with respect to salinity, there are likely to be significant portions of each tide where it is strongly stratified with respect to SSC.

The gradual increase in SSC seen in March–April of both years is clearly linked with the reduction in freshwater flow over the same period. It takes some time for the SSC to build, as a result of the very slow reduction in freshwater flow and of the slow process of upstream movement of sediment brought about by tidal pumping and gravitational circulation. With the sudden increase in freshwater flow (e.g. November 2008, see Fig. 5) the response of the system is much more rapid, with the downstream flushing being a much more effective process at bringing about the net movement of sediment compared with tidal pumping and gravitational circulation. These findings may be summarised in Fig. 7, which shows the relationship between peak daily water level and peak daily SSC. In a system in which the freshwater flow stayed constant and the mobile 'pool' of fine sediment remained stationary, the points could be expected to lie on a straight line or more likely on a curve with some sort of polynomial shape, given the non-linear relationship between velocity and bed shear stress that is the likely driver behind the suspension and transport of sediment. However, it can be seen that there is a great deal of scatter in Fig. 7, due to the lag between changes in freshwater flow and the amount of sediment available for resuspension.

Although it is possible to see a gradual increase in sediment in the months April onwards in both years, the effect is more pronounced at Chiswick in 2009 than it is in 2008. This is due to the difference in hydrological regime, as discussed previously. It is interesting to note the importance of this effect, however, and the fact that there is such a variation in the location of the ETM between successive years.

We have made some attempt to organise the graph of Fig. 7 by categorising the points into 'high', 'normal' and 'low' flow regimes. High and low flow were defined to be the two extremes of flow that occurred on less than 25% of the days used in the analysis (> 87 m^3/s and < 20 m^3/s, respectively), with medium flows lying between these two values. In each

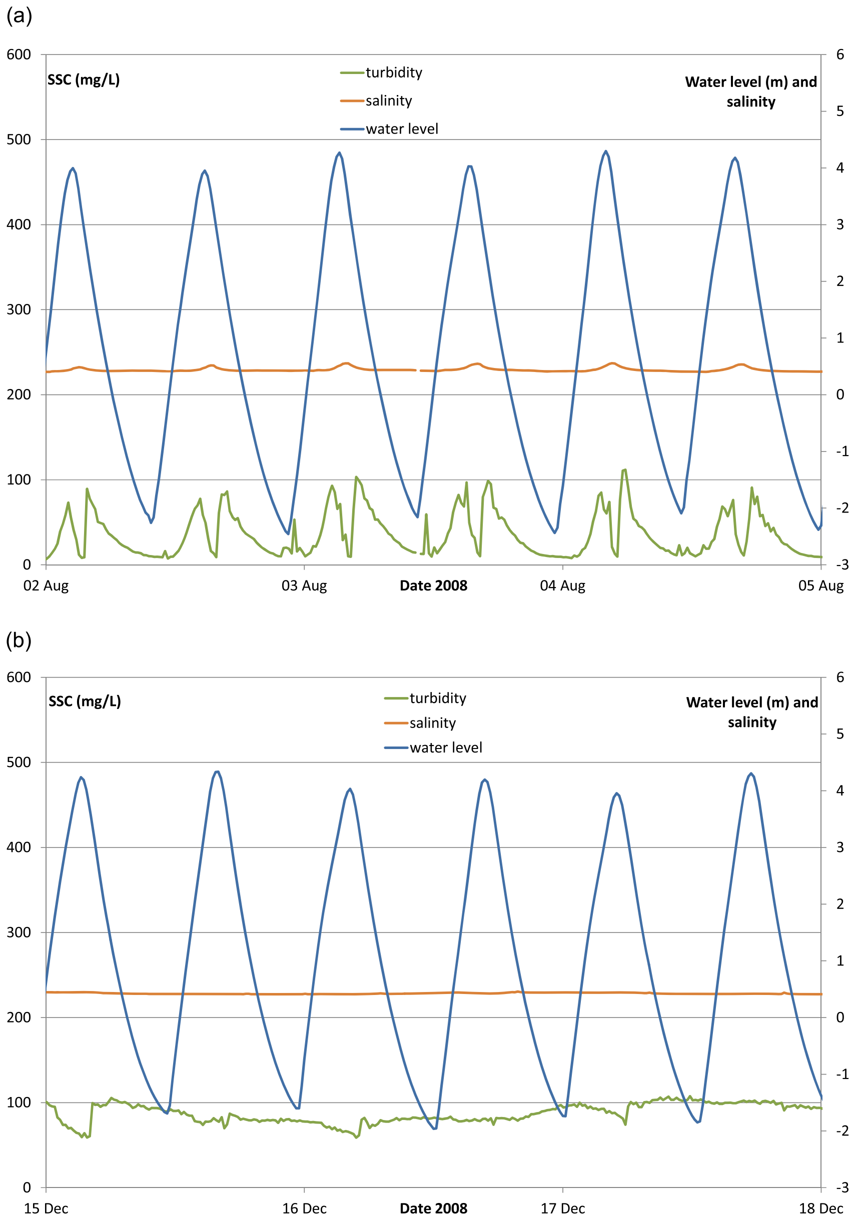

Fig. 6. Fifteen-minute data for salinity and suspended sediment concentration (SSC), Chiswick for 3 day periods for (a) low freshwater flow and (b) high freshwater flow.

case, we show a linear trend line (obtained by regression using a least-squares approach). It is interesting to note that there is a clear difference between the best-fit line that uses the low flow data and that obtained using the normal and high flow data, which are fairly similar. It could be argued that it is really only the low flow (< 20 m^3/s) that causes the high SSC to occur, and that it is in the nature of the Thames catchment that such low freshwater flows are themselves generally only linked with generally longer periods of low flow that allow the upstream transport of the ETM seen here. In the individual tides of Fig. 6, it can be seen that under low freshwater flows (Fig. 6a), there is a landward transport of sediment during the flood tide and a seaward transport during the ebb, with a period of settling over high slack water. The water level rises more quickly during the flood tide than it falls during the ebb tide, thus implying a degree of tidal asymmetry between flood and ebb, which in turn also implies a lag between HW and high slack water, as seen, for example, in the Humber system (Mitchell *et al*. 1998). The slack-water period lasts long enough, under the conditions shown in Fig. 6(a), to allow settling to occur. It is the tidal asymmetry, and the related effects, that lead to the net landward movement of sediment over an individual tidal cycle. The generally lower values of SSC during neap tides imply that less landward movement of sediment occurs during neap tides than during spring tides.

Figure 6(b) shows the same tidal regime, but this time under conditions of high freshwater flow. Two important dif-

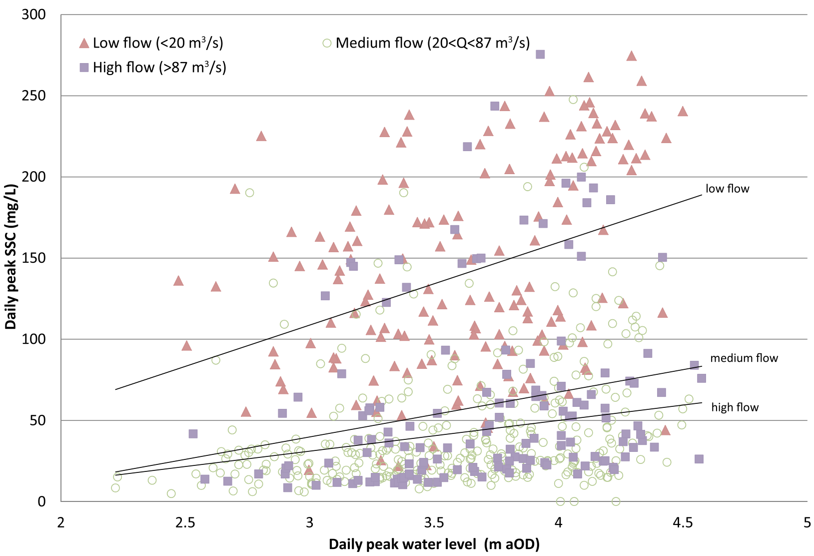

Fig. 7. Peak daily suspended sediment concentration (SSC) at Chiswick plotted against peak daily water level at Chelsea for the whole of 2008. The data are divided into high (> 87 m^3/s), medium (20–87 m^3/s) and low (< 20 m^3/s) freshwater flows, and best-fit lines for each are shown. M aOD, metres above Ordnance Datum (UK).

ferences can be seen between Fig. 6(a) and 6(b). Firstly, despite the similar hydraulic conditions, much less sediment is transported by flood and ebb tides, no doubt due to the lack of available mobile sediment as discussed earlier. Secondly, and most importantly, much less settling occurs during high slack water. The effect of the freshwater flow is to change the hydraulic regime such that the sediment remains in suspension throughout the tidal cycle. Because much less settling occurs, the net effect is for the sediment to be flushed downstream.

It is interesting to compare the results shown here with equivalent results obtained on the Humber estuary system (Mitchell *et al*. 1998; Uncles *et al*. 2006). This work points to the same build-up of sediment as a result of low freshwater flow during dry periods and the same downstream flushing of sediment during wet periods. Additionally, the build-up of the turbidity maximum occurs independently of the location of the freshwater–saltwater interface, a phenomenon that is typical of estuaries where the tidal range is high and the system is therefore well mixed, thereby reducing the effects of saline stratification in this respect. There are important differences, however, and these pertain to the concentrations of sediment, which are far lower in the Thames than in the Humber, even though the tidal range is similar and the body of water at the seaward end (the North Sea) is the same. Other key differences exist however, notably in the vertical resolution in the data on SSC that is not available in the present study. Such resolution is clearly important (Garel *et al*. 2009), in that it is clear that higher concentrations of sediment in the near-bed region will move more slowly than the lower concentrations near the surface, leading to a degree of longitudinal dispersion along the axis of the estuary. If this predominates during the ebb tide, as it appears to in the Humber system, then this represents another mechanism for the landward movement of sediment under low freshwater flows. It also appears that the ETM in the Thames responds rather more slowly than that in the Humber to reductions in freshwater flow, as evidenced by the far greater degree of scatter in Fig. 7 than in the equivalent figure (Fig. 6) in Mitchell *et al*. (1998). It is clear that more information is required on the vertical variation of SSC for different combinations of tidal range and freshwater flow, in order that the reason for these differences can be better understood.

Conclusions

Observations made by continuous monitors in the tidal section of the river Thames, UK, have enabled us to obtain a better understanding of the transport of fine sediment under a range of freshwater flow and tidal conditions. The main findings of the present study are as follows, in relation to the observed SSCs at Chiswick Bridge for the period 1 January 2008–31 December 2009:

(1) Periods of below-average freshwater flow in the non-tidal reaches of the Thames allow the gradual increase in tidal mean SSCs in the tidal section, caused by the landward migration of sediment due to tidal pumping and gravitational circulation. The occurrence of higher freshwater flow results in a rapid flushing of sediment in a downstream direction. This seasonal migration of the ETM is a common feature of estuaries of this type that have a high tidal range and a clear variation in freshwater flow that depends on season.

(2) The inspection of water level and SSC for individual tidal cycles reveals an interesting difference between the amount of settling that occurs during the period of high slack water. It is clear that some settling occurs at high slack water (although not at low slack water) during most tidal cycles; however, rather less settling, if any, takes place during periods of high freshwater flow. This finding enables us to put forward the view that the downstream flushing is related to a lack of settling at high slack water.

(3) Inspection of the general trends of SSC and tidal range shows that there is a relationship between the two, and that higher tides lead to faster tidal currents, which in turn lead to higher values of SSC, giving rise to a spring neap variation in mean tidal SSC. However, it is also clear that the tidal mean SSC depends on the availability of sediment for resuspension, and that where sediment is unavailable (during or after periods of high freshwater flushing), then little or no sediment can be resuspended from the bed.

(4) There is a clear need for more data and models to inform our understanding of the tidal transport mechanisms that occur in the Thames Estuary. In particular there is a need for a better resolution in the variation in SSC with depth. Observations in other macrotidal estuaries suggest that these systems are generally fairly well mixed with respect to salinity, but that there is considerable degree of vertical stratification with respect to SSC. It is this understanding that must be the focus of future efforts, where the acquisition of data is practical and affordable.

Acknowledgements

This study would not have been possible without the help of a number of staff at the Environment Agency who provided data and answered the technical queries of the authors.

To submit a comment on this article please go to http://mc.manuscriptcentral.com/wej. For further information please see the Author Guidelines at wileyonlinelibrary.com

References

Arundale, A.M.W., Darbyshire, E.J., Hunt, S.J., Schmitz, K.G. and West, J.R. (1997) Turbidity Maxima Formation in Four Estuaries. *In* Burt, N., Parker, R. and Watts, J. (eds). *Cohesive Sediments*, pp. 135–146. Wiley, Chichester, UK.

ATT. (2010) Admiralty Tide Tables 2010, Volume 1.

Avoine, J., Allen, G.P., Nichols, M.M., Salomon, J.C. and Larsonneur, C. (1981) Suspended Sediment Transport in the Seine Estuary, France: Effect of Man-Made Modifications on Estuary-Shelf Sedimentology. *Mar. Geol.*, **40**, 119–137.

Baugh, J.V. and Littlewood, M.A. (2005) Development of a Cohesive Sediment Transport Model of the Thames Estuary. *In* Spaulding, M. (ed). *Estuarine and Coastal Modeling*. (Proceedings of the 9th International Conference on Estuarine and Coastal Modeling, Charleston, South Carolina, October 31–September 2, 2005), pp. 824–841. ASCE, 0-7844-0876-9, 2006, 864 pp. American Society of Civil Engineers (ASCE), Reston, VA, USA.

Baugh, J.V., Feates, N., Littlewood, M.A. and Spearman, J. (In press) The Fine Sediment Regime of the Thames Estuary – A Clearer Understanding. *Ocean Coast. Manage.*, Special Issue.

Brenon, I. and Le Hir, P. (1999) Modelling the Turbidity Maximum in the Seine Estuary (France): Identification of Formation Processes. *Estuarine, Coastal Shelf Sci.*, **49** (4), 529–544.

Bunt, J.A.C., Larcombe, P. and Jago, C.F. (1999) Quantifying the Response of Optical Backscatter Devices and Transmissometers to Variations in Suspended Particulate Matter. *Cont. Shelf Res.*, **19**, 1199–1220.

Capo, S., Brenon, I., Sottolichio, A., Castaing, P. and Le Goulven, P. (2009) Tidal Sediment Transport Versus Freshwater Flood Events in the Konkouré Estuary, Republic of Guinea. *J. Afr. Earth Sci.*, **55**, 52–57.

Castaing, P. and Allen, G.P. (1981) Mechanisms Controlling Seaward Escape of Suspended Sediment from the Gironde: A Macrotidal Estuary in France. *Mar. Geol.*, **40**, 101–118.

Chauchat, J., Guillou, S., Barbry, N. and Nguyen, K.D. (2009) Simulation of the Turbidity Maximum in the Seine Estuary with a Two-Phase Flow Model. *C.R. Geoscience*, **341**, 505–512.

Chen, M.S., Wartel, S., Van Eck, B. and Van Maldegem, D. (2005) Suspended Matter in the Scheldt Estuary. *Hydrobiologia*, **540**, 79–104.

Chernetsky, A.S., Schuttelaars, H.M. and Talke, S.A. (2010) The Effect of Tidal Asymmetry and Temporal Settling Lag on Sediment Trapping in Tidal Estuaries. *Ocean Dyn.*, **60**, 1219–1241.

Dobereiner, C. and McManus, J. (1983) Turbidity Maximum Migration and Harbour Siltation in the Tay Estuary. *Can. J. Fish. Aquat. Sci.*, **40** (Suppl. 1), 117–129.

Doxaran, D., Froidefond, J.-M., Castaing, P. and Babin, M. (2009) Dynamics of the Turbidity Maximum Zone in a Macrotidal Estuary (the Gironde, France): Observations from Field and MODIS Satellite Data. *Estuarine, Coastal Shelf Sci.*, **81**, 321–332.

Garel, E., Pinto, L., Santos, A. and Ferreira, O. (2009) Tidal and River Discharge Forcing upon Water and Sediment Circulation at a Rock-Bound Estuary (Guadiana Estuary, Portugal). *Estuarine, Coastal Shelf Sci.*, **84**, 269–281.

Grabemann, I. and Krause, G. (1989) Transport Processes of Suspended Matter Derived from Time Series in a Tidal Estuary. *J. Geophys. Res.*, **94** (C10), 14373–14379.

McManus, J. (2005) Salinity and Suspended Matter Variations in the Tay Estuary. *Cont Shelf Res.*, **25**, 729–747.

Mitchell, S.B. and West, J.R. (2002) Particle Size Distribution in an Estuarine Turbidity Maximum Region. *In* Winterwerp, J.C. and Kranenburg, C. (eds). *Proceedings in Marine Science 5: Fine Sediment Dynamics in the Marine Environment*, pp. 251–263. Elsevier, Amsterdam.

Mitchell, S.B., West, J.R., Arundale, A.M.W., Guymer, I. and Couperthwaite, J.S. (1998) Dynamics of the Turbidity Maxima in the Upper Humber Estuary System. *Mar. Pollut. Bull.*, **37**, 190–205.

Mitchell, S.B., Lawler, D.M., West, J.R. and Couperthwaite, J.S. (2003) Use of Continuous Turbidity Sensor in the Prediction of Fine Sediment Transport in the Turbidity Maximum of the Trent Estuary, UK. *Estuarine, Coastal Shelf Sci.*, **58**, 645–652.

Mitchell, S.B., Burgess, H.M. and Pope, D.J. (2004) Observations of Fine-Sediment Transport in A Semi-Enclosed Sheltered Natural Harbour (Pagham Harbour, UK). *In* Ciavola, P., Collins,

M. and Corbau, C. (eds). *Sediment Transport in European Estuarine Environments*, pp. 141–147. Journal of Coastal Research, special issue no. 41.

Nichols, M.M. (1993) Response of Coastal Plain Estuaries to Episodic Events in the Chesapeake Bay Region. *In* Mehta, A.J. (ed). *Nearshore and Estuarine Cohesive Sediment Transport*, pp. 1–20. Amer. Geophys. Union, Washington, D.C.

Rao, V.P., Shynu, R., Kessarkar, P.M., Sundar, D., Michael, G.S., Narvekar, T., Blossom, V. and Mehra, P. (2011) Suspended Sediment Dynamics on a Seasonal Scale in the Mandovi and Zuari Estuaries, Central West Coast of India. *Estuarine, Coastal Shelf Sci.*, **91**, 78–86.

Uncles, R.J. (2010) Physical Properties and Processes in the Bristol Channel and Severn Estuary. *Mar. Pollut. Bull.*, **61**, 5–20.

Uncles, R.J. and Mitchell, S.B. (2011) Turbidity in the Thames Estuary: How Turbid Do We Expect It to Be? *Hydrobiologia*, **672**, 91–103.

Uncles, R.J. and Stephens, J.A. (1993) Nature of the Turbidity Maximum in the Tamar Estuary. *Estuarine, Coastal Shelf Sci.*, **36**, 413–432.

Uncles, R.J., Barton, M.L. and Stephens, J.A. (1994) Seasonal Variability of Fine-Sediment Concentrations in the Turbidity Maximum Region of the Tamar Estuary. *Estuarine, Coastal Shelf Sci.*, **38**, 19–39.

Uncles, R.J., Barton, M.L. and Stephens, J.A. (1996) Seasonal Variability of Mobile Mud Deposits in the Tamar Estuary. *In* Pattiaratchi, C. (ed). *Mixing in Estuaries and Coastal Seas*, pp. 374–387. Amer. Geophys. Union, Washington, D.C.

Uncles, R.J., Stephens, J.A. and Harris, C. (2006) Runoff and Tidal Influences on the Estuarine Turbidity Maximum of a Highly Turbid System: The Upper Humber and Ouse Estuary, UK. *Mar. Geol.*, **235**, 213–228.

UNESCO. (1983) *Algorithms for computation of fundamental properties of seawater*. UNESCO Technical Papers in Marine Science 44.

Vale, C. and Sundby, B. (1987) Suspended Sediment Fluctuations in the Tagus Estuary on Semi-Diurnal and Fortnightly Time Scales. *Estuarine, Coastal Shelf Sci.*, **25**, 495–508.

Wai, O.W.H., Wang, C.H., Li, Y.S. and Li, X.D. (2004) The Formation Mechanisms of Turbidity Maximum in the Pearl River Estuary, China. *Mar. Pollut. Bull.*, **48**, 441–448.