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Use of continuous turbidity sensor in the prediction of fine sediment transport in the turbidity maximum of the Trent Estuary, UK

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Abstract

Results from field observations using continuous monitors of turbidity and water level at Burringham, R Trent, UK, are presented, for the period 18 May to 3 December 1997. These results, together with measurements of vertical profiles of velocity and suspended solids concentration (SSC) at a nearby location enable some conclusions to be drawn relating to the response of the TM to tidal range (TR) and fresh water flow (Q_f) in the tidal Trent. The temporal variation in vertical profiles of velocity and SSC means that interpretation of results from fixed continuous monitors must be carried out very carefully, owing to the high degree of suspended solids stratification at high slack water and during the first few hours of the ebb tide. SSC is a function of local bed shear stress (related to tidal range) and sediment availability, which is controlled by the antecedent Q_f. A semi-empirical predictive relationship is recommended for predicting flood and ebb tide SSC, based on tidal range, for various different antecedent fresh water flow conditions.

1 Introduction

Understanding the transport processes of fine, cohesive sediment in macrotidal estuaries is important for the effective management of these complex systems. The interaction of tidal activity and fresh water input creates a highly dynamic environment. The resulting temporal and spatial variation in the suspension, transport and deposition of sediment, and the concentration of suspended material in the water, may affect, for example:

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- the fate of pollutants which may be adsorbed to the surface of sediment grains and thus transported with them;
- primary production in the water by reduction in photosynthetis through light attenuation caused by high suspended sediment concentration;
- the diversity and abundance of invertebrates, and thus bird species, through dependence on availability of suitable intertidal sediments;
- passage of migratory fish in estuaries affected by sediment oxygen demand.

The high concentration of suspended sediment often found near the fresh-salt water interface in many estuaries is commonly known as the turbidity maximum (TM). It is generally recognised that the tidal range (TR) and fluvial flow (Q_f) control the maintenance and migration of the TM through a variety of mechanisms (Dyer [1]). However, prediction of the degree to which this occurs, and the design of predictive mathematical models to estimate the transport of fine sediment in macrotidal estuaries, presents a considerable challenge. In particular, many previous studies of TM's in estuaries have focused on individual tidal cycles, and have addressed the detail of variations of SSC within these tidal cycles. Longer-term data gathering campaigns have been less successful, due to the problems of servicing remote sensing equipment in remote areas, among other factors. It is therefore highly desirable to build up a pattern of data from longer-term deployments, in order that lunar and seasonal patterns of sediment transport may be investigated, and incorporated into mathematical models to predict net tidal sediment flux, for example.

In this paper, results will be presented from a continuous monitor of water level and suspended solids concentration (SSC) for a fixed monitor deployed from a culvert platform at Burringham, R Trent, UK for the period 18 May to 2 December 1997. Continuous monitors of this kind may be used to formulate a multivariate, semi-empirical model which may be used to predict sediment flux under high and low TR and Q_f.

2 Turbidity Maxima in Macrotidal Estuaries

There are many descriptions of turbidity maxima in terms of their magnitude and migration in response to Q_f and TR in medium to high TR estuaries. These include the Columbia, U.S.A. (Gelfenbaum [2]) and the Tamar, U.K. (Uncles, *et al.*[3]). Grab samples taken from the bed of the Tamar reveal the dependence of the position of the TM to the location of an area of mobile bed sediment that forms the source of the TM (Uncles *et al.*[4]). 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 fresh water flow conditions after a prolonged heavy rainfall event lead to a 'flushing' effect whereby the residual (tidal-average) transport of sediment is downstream, thus effecting a seaward migration of the turbidity maximum (Nichols [5]). Conversely, low dry-season fresh water flows lead to a relocation of the turbidity maximum zone landward.

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In macrotidal estuaries, the mechanism of 'tidal pumping' has been described, in which a net tidal landward sediment flux is brought about by tidal asymmetry (Dyer [1]). Inhibition of turbulence due to vertical density gradients has also been observed to enhance the landward dispersion of sediment. A non-tidal numerical model devised by Geyer [6] revealed how this stratification can result in a 20-fold reduction in vertical turbulent transport of silt-sized particles. A high degree of stratification leads to a greater proportion of sediment near the bed, where the flow velocity will be lower than the depth mean velocity. For the case of short, intense flood tides and longer ebb tides found near the tidal limits of many macrotidal estuaries, it is common to find such stratification taking place over high slack water and persisting over the early part of the ebb tide (e.g. Mitchell *et al.*, [7]). As the ebb current increases the resulting bed-generated turbulence may be sufficient to break down, or partially break down, any stratification resulting in well-mixed, or at any rate less stratified, conditions, thus increasing the downstream sediment transport. The SSC on any given tide may therefore be related to TR, Q_f and the proximity of the mobile mud reach. Since the availability of the mud reach is itself proportional to the antecedent flow conditions, an approach taking into account mean flows prior to the day itself may be adopted.

3 Study Site and Methods

The tidal Trent (Figure 1) is a long canalised estuary approximately 80 km in length, stretching from Cromwell Weir in the south to the Humber confluence in the north, with its fluvial section rising in the Derbyshire peak district. The two rivers Trent and Ouse have a combined catchment area of 24,240 km^2, and are connected at the downstream end at Trent Falls. Typical values of Q_f measured at North Muskham range from 30 m^3/s to over 400 m^3/s. Mean TR, predicted for Immingham, ranges from 3.2 m (Neaps) to 6.4 m (Springs).

Burringham is located 15 km from the confluence of the Trent and Ouse rivers. At this site, a continuous fixed-point monitor was installed to measure turbidity and water level. Water level was recorded at the site by a Dynamic-Logic Pressure Transducer mounted on a vertical support structure, which was connected to a land drainage culvert platform. This was levelled to Ordnance Datum. Similarly, a Partech IR15C Turbidity meter was mounted on the same support structure. This operated within a range of 0-13 g/l and was calibrated using gravimetric analysis of pumped samples (Mitchell *et al.*[7]). Both the turbidity sensor and pressure transducer were positioned in the main channel flow and were well protected from collisions by debris. They recorded data at one-minute intervals, which were then averaged over 15-minute time periods. Both sensors were exposed approximately 0.5 m above the flow at low water. Measurements of water velocity and SSC were also made on the opposite bank

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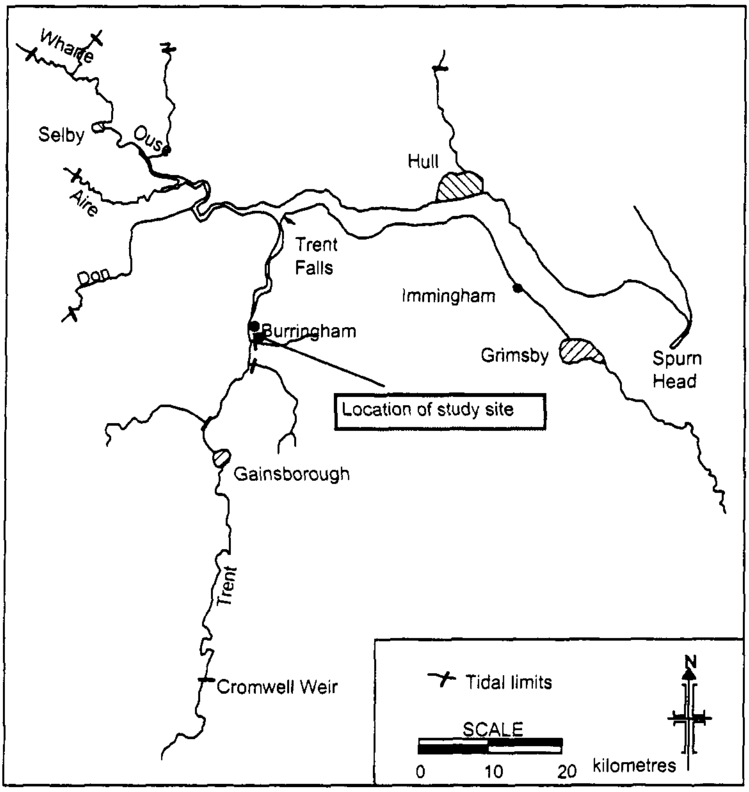

Figure 1 The Humber Estuary System

from the sampling platform at Burringham, near the village of Derrythorpe, during a complete individual tidal cycle on 30-31 July 1996 (for details of experimental procedure see Mitchell *et al.* [7]). Calibration of pressure and turbidity sensors was carried out and the resulting straight-line relationships were incorporated into the analysis. The results of these calibrations may be found in Mitchell *et al.* [7]. In general good correlation was found in both cases, except for SSC for the period around high slack water, which in general occurred around 1 hour after high water, due to momentum effects. This was thought to be due to the effect of preferential settling below the level of the sensor by larger particles, leaving a greater density of finer material at the level of the sensor itself (Mitchell & West [8]).

Daily mean river flow data, at the tidal limit of the Trent at North Muskham, near Cromwell Weir, have been obtained from the UK Environment Agency. Predicted peak tidal height values, relative to local chart datum, have been

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obtained from the Admiralty Tide Tables. The TM in the tidal Trent has previously been described as having a magnitude of approximately 10g/l between Trent Falls and Gainsborough under low summer flows (Mitchell *et al.* [7]).

4 Results

Results from the continuous monitor at Burringham, showing peak tidal water level, Q_f, flood-tide and ebb-tide SSC from 18 May to 2 December 1997, are shown in Figure 2. Flood tide SSC values (Figure 2) have been calculated by taking the mean of the four values from the hour before high water at Burringham. Ebb tide SSC values have been obtained by calculating the mean value for the hour before the sensor dries out. In this way, values for SSC have been obtained which are thought to be as far as possible representative of well-mixed conditions, thus the effects of density stratification on the observed values may be ignored. Values of SSC greater than 13 g/l have in most cases caused the sensor to return an error value, and where this has occurred, a value of 13 g/l has been used. Thus several plateaux corresponding to this value can be seen in Figure 2. Of particular interest in Figure 2 is the dependence of flood-tide SSC on TR under low Q_f conditions. As the TR increases from neap to spring tides, so the flood tide SSC increases dramatically. Under high Q_f conditions, SSC is suppressed due to the migration of the TM region downstream from the study site. It is important to note that this feature depends on the antecedent flow for the period, rather than the flow on the day itself, owing to the lag between changes in hydraulic and sediment transport regimes, as described by Dyer [1].

In order to help interpret the results from the fixed-point turbidity sensor, observations of depth variations in velocity and SSC were made at Derrythorpe, as described previously. Results for the single tidal cycle are shown (Figure 3 a-c). A positive velocity represents a velocity in the downstream (ebb) direction. Each plot represents vertical profiles measured at a time relative to high slack water (HSW). A high degree of vertical stratification, coupled with a relatively slow moving near bed layer, may be noted for the two hours after high slack water (Figures 3 a), after which the SSC stratification is broken down and the water becomes well mixed over the late ebb tide (Figures 3 b-c). This helps explain the mechanism of landward dispersion of sediment under high tidal range, low Q_f conditions, as outlined in Mitchell *et al.* [7].

5 Discussion

The marked difference in flood and ebb SSC depending on antecedent fresh water flow conditions may be explained in terms of the availability of sediment on the bed. The falling Q_f between 1-15 July leads to a marked increase in mean flood tide SSC during the spring tides of mid-July compared with those at the beginning of the month (Figure 2). This is because the spring tide flood currents

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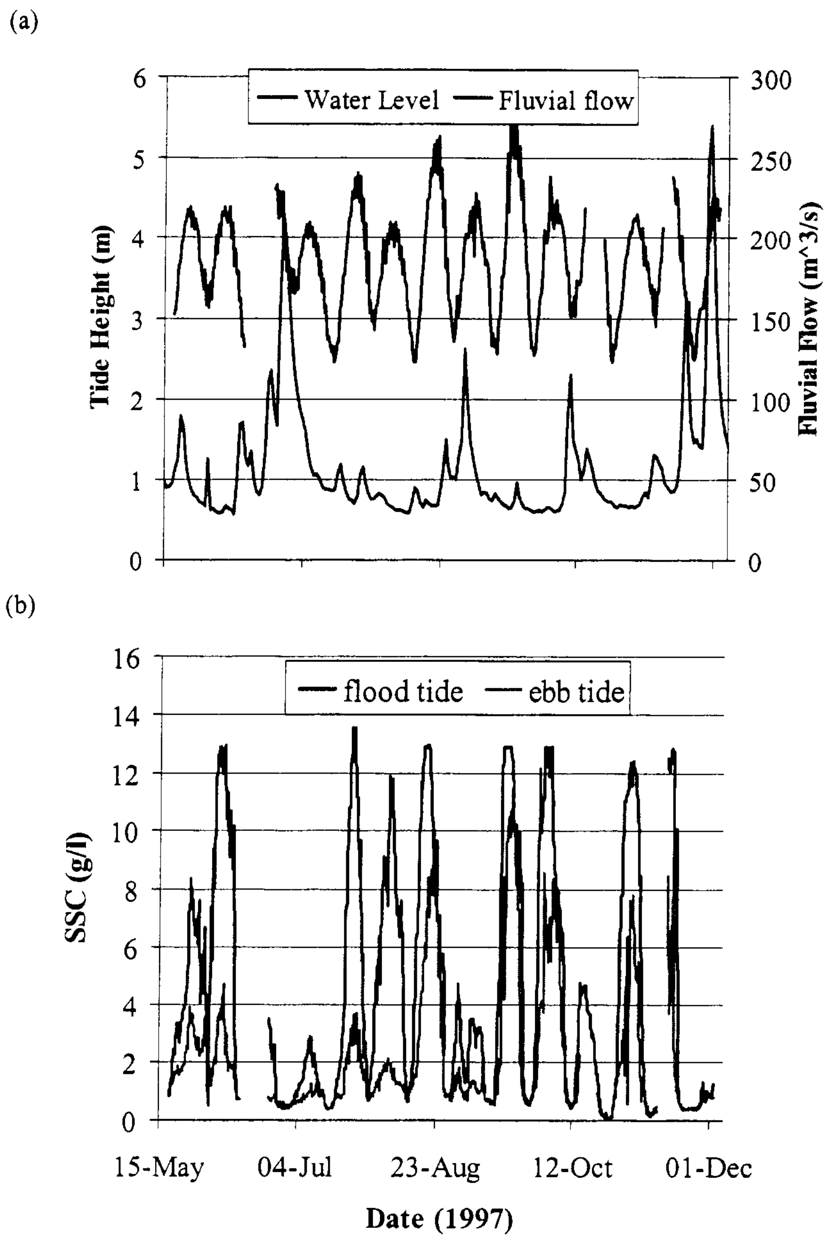

Figure 2 (a) Peak tidal water level (Burringham) and fluvial flow (North Muskham) and (b) Mean flood and ebb tide suspended sediment concentration (SSC), Burringham, 18 May to 2 December, 1997.

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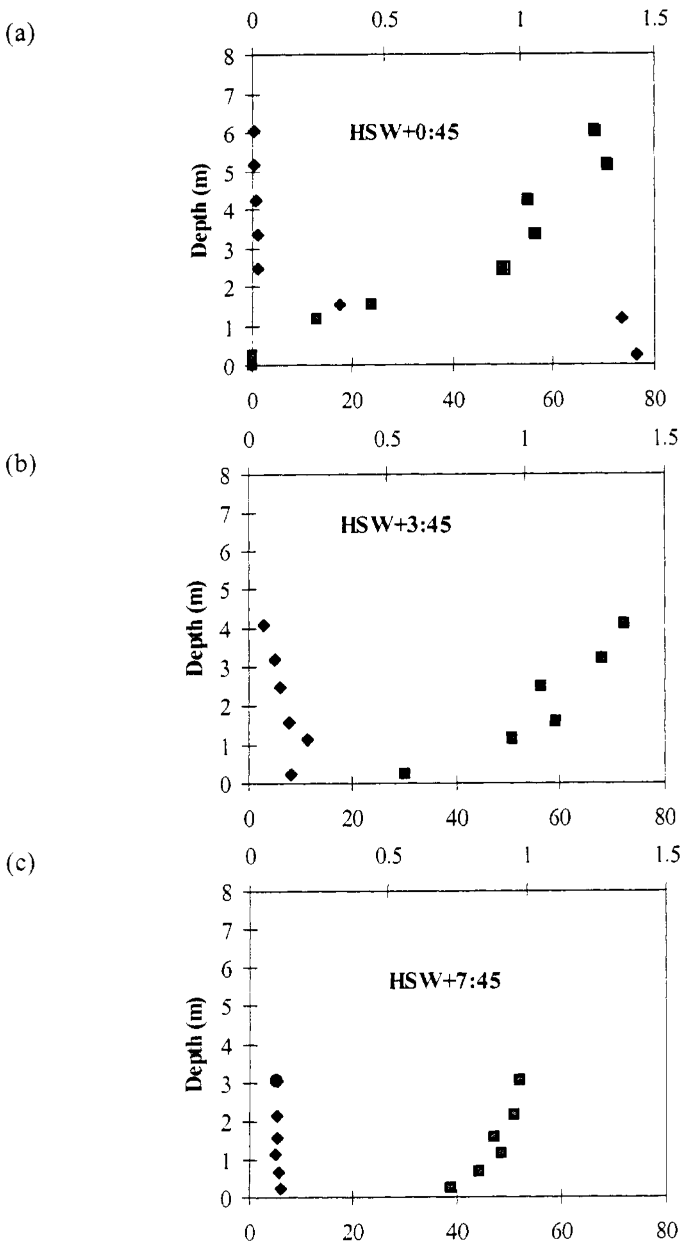

Figure 3 Suspended sediment concentration (diamonds, bottom axis, g/l) and velocity (squares, top axis, m/s) at 3 different stages during the tide, Burringham, 31 July 97

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are more successful in suspending material as there is now more sediment available following the lower antecedent Q_f, leading to upstream tidal pumping of sediment. Mean flood tide SSC's during the spring tides around 20 August are marginally less than those of mid-July, pointing to the possibility of tidal pumping of the mobile sediment pool to a location *upstream* of the observation point.

In general the lower ebb tide currents cause less sediment to be suspended than the higher flood currents. Slack water at the end of the flood tide is marked by a gradual deceleration, followed by a period of relatively stationary flow, then a gradual acceleration into the ebb tide. By contrast, low slack water is characterised by a more rapid change in flow direction. This pattern of activity leads to a more homogeneous distribution of sediment suspended in the water column during the flood tide than during the ebb tide.

The results shown in Figure 3 demonstrate that great care must be taken when interpreting the results from fixed monitors. For example, it is shown that for the early part of the ebb tide, suspended sediment does not reach the upper part of the water column due to stratification. Since the water level falls below the level of the sensor for the latter part of the ebb tide, it is possible that the sensor generally fails to detect ebb tide transport to the same degree as for the flood tide. In any case, for the tides of late August, significantly greater ebb tide transport *is* observed. This suggests that, for some reason, the sediment is re-suspended to a greater extent over the early ebb tide under prolonged low Q_f. This could be due to a greater availability of sediment under these conditions, or more likely, a greater proportion of finer sediment with a lower critical erosion shear stress and lower specific gravity. This reinforces the observations of varying particle size distribution, dependent on location within the TM region, as described by Mitchell & West [8].

The results of Figure 2 enable a simple predictive relationship of flood and ebb tide SSC based on predicted TR and Q_f. Values of mean flood-tide SSC and mean ebb-tide SSC, have been plotted against predicted tidal height (related to TR) at Immingham, for two different 10-day antecedent fresh water flow conditions (Figure 4). For the purposes of the analysis, 'high' and 'low' Q_f are those above and below mean Q_f for the period (60.3 m^3/s). It should be noted that the calculated R^2 values shown in Figure 4 are considerably better for flood tide, indicating a better fit under these conditions. A second order relationship has been assumed in each case, reflecting the dependence of sediment suspension on bed shear stress, which is related to the square of flow velocity.

6 Conclusions

Results from observations of turbidity and water level at Burringham, R Trent have been made for the period 18 May to 2 December 1997. These results, together with measurements of vertical profiles of velocity and suspended solids

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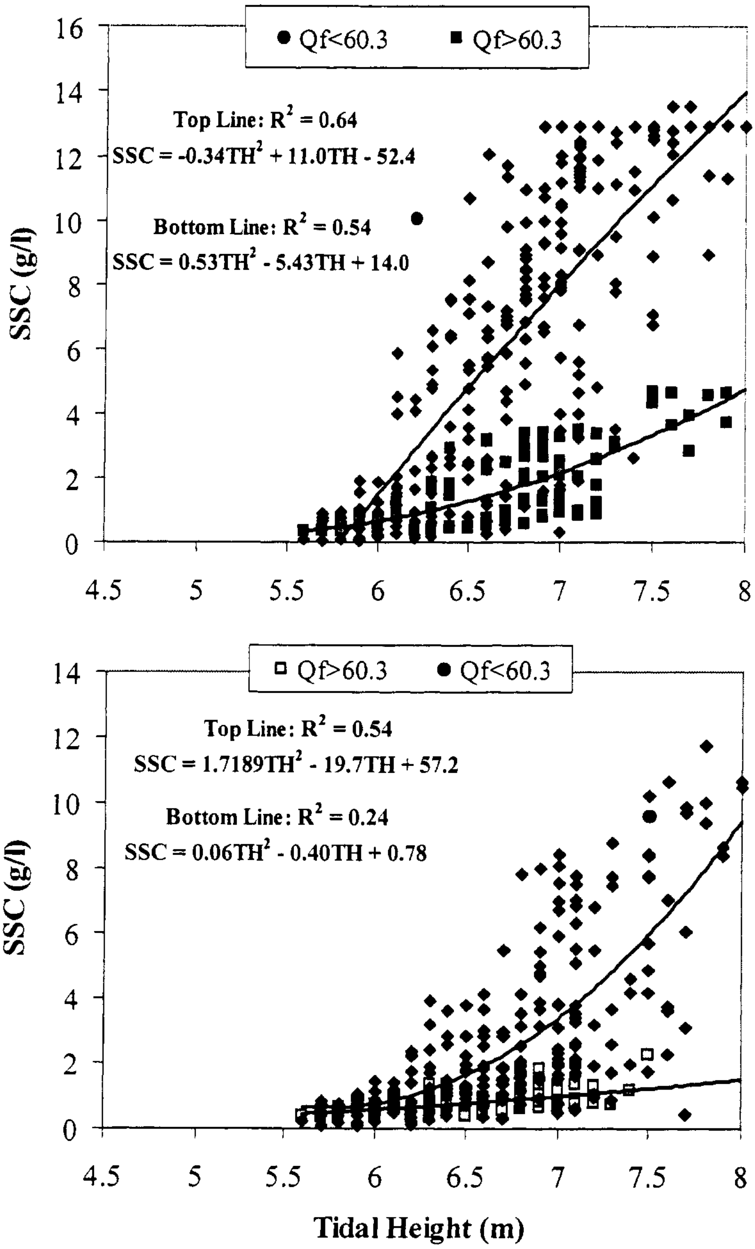

Figure 4 Suspended sediment concentration against predicted tidal height (Immingham) for (a) Flood tide SSC and (b) Ebb tide SSC. Fluvial flow (Q_f) conditions taken as 10-day average antecedent flows, measured at North Muskham, together with best-fit lines and calculated R^2 values

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concentration (SSC) in a nearby location have enabled some conclusions to be drawn relating to the response of the turbidity maximum in the tidal Trent:

1. The use of fixed point, continuous monitors over time periods of several months or more helps to build up a long-term picture of how sediment transport is affected by tidal range and fluvial flow in macrotidal estuaries.
2. The temporal variation in vertical profiles of velocity and SSC means that interpretation of results from continuous monitors must be carried out with caution, owing to the high degree of flow stratification at high slack water and over the early ebb tide.
3. A semi-empirical relationship may be used to predict SSC for flood and ebb phases estimated from maximum predicted tidal height, measured at Immingham and 10-day average antecedent fresh water flow, measured at the tidal limit at North Muskham.

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