Final Report on the Sediments and Hydrography of the Devonshire Avon Estuary

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Technical Summary

This report describes the results of work on the Avon Estuary undertaken by PML Applications Ltd under contract to the Aune Conservation Association as part of their 'Avon Siltation Study'. Field measurements were made during summer 2005 that included the collection and analyses of hydrodynamic and bathymetric data and surficial sediment grain-sizes. These measurements were extended to winter conditions and modelling studies during 2006 and 2007. Field data showed that a considerable reduction in tidal range and wave height occurred between Bantham Beach and the upper estuary. The lower estuary was dominated by sand-sized sediment. The upper part of the estuary had a scoured, river-like channel of very coarse sediment deposits, whereas the central to upper part of the estuary had a high percentage of fine sediment, much of which was muddy, which corresponded to a minimum depth in the longitudinal, main-channel bed profile. Main-channel grain sizes were much greater than those over the intertidal areas. SPM concentrations in the estuary generally were small. In the lower estuary there appeared to be preferential transport of sediment into the estuary on the flood with a compensatory, outward pulse of turbid waters from the upper estuary on the late ebb. Sediment resuspension occurred in the central-to-upper estuary, especially during the flood. Measurements of sandbank levels in the lower estuary over a 1-year period provided no evidence of sand accumulation. Modelled data showed that the influence of the Avon reservoir on water levels and currents generally was small. The model also showed that tides were very important in producing both ebb and flood-directed sediment transport and that the effect of waves was substantial. The differences in modelled sediment transport due to the reservoir generally were very small, but with some exceptions that occurred late in the year. A cross-estuary model of the Aunemouth Sands section showed that the mean sediment transport tended to be out of the estuary in the deepest part of the section and up-estuary on the flanking intertidal shoulders. Sediment transport was very small on the majority of the intertidal areas. The conclusions of the study are presented succinctly in Section 9, which offers the most likely reasons for changes in morphology in the lower estuary and increased siltation in the central-to-upper estuary over recent decades.

Acknowledgement

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1. Introduction

This report describes the results of work on the Avon Estuary undertaken by PML Applications Ltd under contract to the Aune Conservation Association as part of their ‘Avon Siltation Study’. Although the contracted work entailed relatively few working weeks, these were spread over a 3-year period in order to observe seasonal behaviour and to utilise measured and analysed data in the subsequent modelling work.

Emphasis in Year #1 (April 2005 to March 2006) was on summer, low-flow behaviour and the collection and analyses of surficial sediment grain-size. We used the Atkins topographic data to identify transects throughout the Avon and undertook the field sampling of bed sediments jointly with University of Plymouth staff to ensure that sediment samples were taken from same sampling points and to maximise the efficient use of staff. Measurements of currents were undertaken for a spring tide and a neap tide (or portions thereof) and suspended solids and other physical variables, such as waves, water levels, salinity and temperature were measured at a site near North Efford (near the head of the estuary), at a site between the Harbourmaster’s office and Ham Cottage (close to the narrow entrance to the beach area) and at a site at Bantham Beach. Topographic data supplied by Atkins were utilised to commence the process of developing a 1-D estuary model in order to (eventually) estimate (a), tidal flows through the estuary and how these might result in sediment movement and (b), the influence of freshwater flow on the tidal currents and how this influence might impinge on the sediment transport.

Emphasis in Year #2 (April 2006 to March 2007) was on early spring, higher freshwater flows and on measuring the siltation (or erosion) at four locations on a sandy intertidal area in the lower Avon. This work was not initially contracted and replaced the planned work to re-sample the bed-sediment distributions during a winter period; the change in planned work was felt to be necessary because of the increasing stress laid on the siltation ‘problem’ in the absence, at that time, of any quantitative data on the issue. Measurements of physical variables were undertaken for a spring tide and a neap tide (or portions thereof) at the same sites as for Year #1. The sediments data, analysed from Year #1 sampling, were used to continue the development of a 1-D estuary model.

Emphasis in Year #3 (April 2007 to September 2007) was on producing a final report and seminar as well as completion of the model and its applications to: (1) the effects of tides and waves on sediment transport; (2) the possible effects of changed freshwater flows (due to the construction of the Avon reservoir) on tides and sediment movements; and (3) the influence of cross-estuary variations in bathymetry and sediment grain-sizes on tides and sediment movements.

2. Environmental factors

2.1. Freshwater Flows

Freshwater discharge into the Avon Estuary from the River Avon is measured by an automatic gauging station at Loddiswell. These data were obtained from Environment Agency (EA) archives. The data-set runs from 1971 until 1981, where there is a break in the monitoring, and resumes during 1990 until the present time (our acquisition runs to 2006).

The extremes of freshwater runoff during this period ranged from a low summer flow of 0.16 $m^3 s^{-1}$ (i.e. cumecs) to 62.2 $m^3 s^{-1}$ during winter. A pronounced seasonal cycle is evident in all annual plots that show higher winter and autumn flows and lower spring and summer flows.

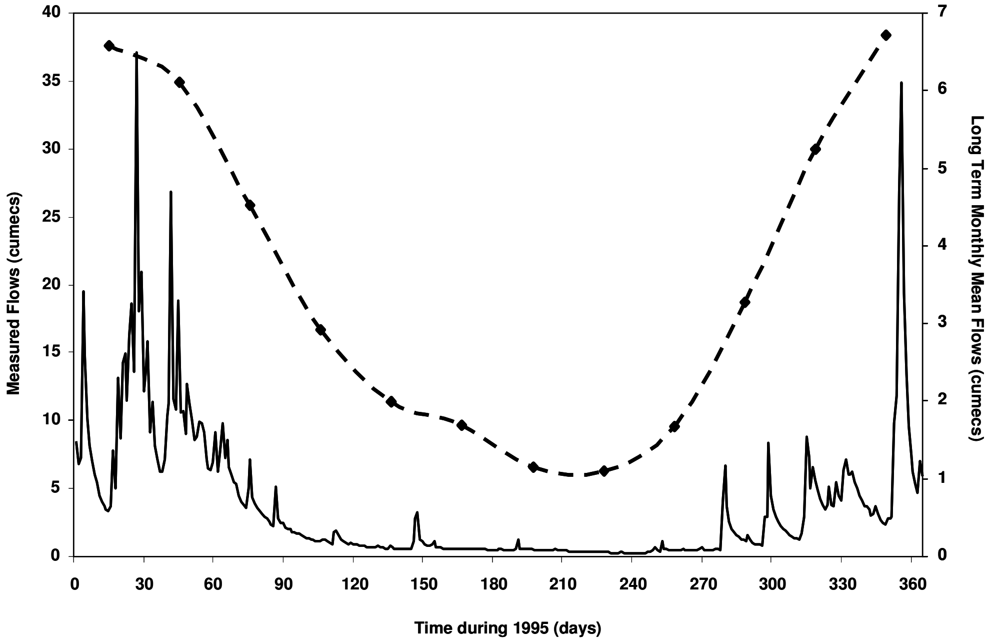

Figure 2.1: This figure shows the daily mean measured flows during 1995 at Loddiswell (continuous line) and the long term monthly mean flows calculated from the data available (1971-2006, dashed line).

Figure 2.1 is a data-set of daily-mean flows for 1995 that shows a similar seasonal cycle to the long term monthly mean (LTMM) trend, although the daily-mean flows display the high runoff spikes associated with high precipitation and spate conditions, particularly in the autumn and winter months. The LTMM maximum flows are just under 7 $m^3 s^{-1}$ in winter with minimum flows of just over 1 $m^3 s^{-1}$ in summer.

Changes in weather patterns due to climate change may also increase storm events, increasing flood risk. In the south west it is predicted that there will be an annual average increase in precipitation, although this will be from increased autumn and winter rainfall dominating the effects of dryer summers (www.mendip.gov.uk/ Documents/). In the light of climate change and the increased probability of dryer summers in the southwest, progressively dryer summers in the Bantham region are likely to result in enhanced siltation of very fine sediments in the central and upper reaches of the Avon Estuary if they are not compensated by erosion due to greater freshwater flow rates in winter.

2.2. Tides and sea levels

Tides at Bantham Beach are very similar to those at Devonport (see later, e.g. Figure 5.2C). Tides are semidiurnal, i.e. high-water (HW) and low-water (LW) occur approximately twice per day, and they exhibit a pronounced spring-neap cycle (largest and smallest tidal ranges tend to occur with a periodicity of approximately 15 days) with the largest of the spring tides and the smallest of the neap tides occurring during spring and autumn (e.g. Figure 5.2C). At Devonport, mean spring tidal range is 4.7 m and mean neap tidal range is 2.2 m. Bantham tidal ranges are somewhat smaller than this, typically 92% of Devonport ranges, and tidal phases (e.g. HW, LW) are somewhat later, typically 10 minutes later.

These semidiurnal tides increase and decrease in range over an 18.6 year period because of changes in the lunar declination cycle. When the declinations are small the semidiurnal tides are bigger. The most recent maximum in semidiurnal tides was in 1997, with a subsequent fall to 2006. The theoretical modulations are 3.7% about the mean but shallow-water effects around the UK can alter this value (www.oceannet.org/ medag/ reports/ IACMST_reports/ MCP_report/ ch_sealev/ MCPreport_sealev.htm). Although relatively small, these tidal modulations will lead to corresponding cycles in sediment transport and estuary morphology over an 18.6 year period.

Sea level records from Liverpool, Newlyn, Portsmouth and Dover show local short-term variations in amplitude and phase of tidal constituents but no long-term trends (www.oceannet.org/ medag/ reports/ IACMST_reports/ MCP_report/ ch_sealev/ MCPreport_sealev.htm). There is no evidence of a trend in sea level surges at Liverpool since 1768, Newlyn since the 1920s, or Portsmouth and Dover since the 1960s. Global mean sea level (MSL) has risen by about 120 meters since the last ice age around 20,000 years ago and by 1.0 to 2.0 mm per year during the 20th twentieth century. After adjusting for land movements, ‘absolute’ sea level around the UK coast has increased by about 1mm per year during the 20th Century. ‘Relative’ MSL, due to the combined effect of absolute MSL changes and land movements, is increasing around most of the UK coast but remains constant or is even decreasing along some northern coasts. UK MSL showed an increase in the rate of rise towards the second half of the 19th Century. However, sea level is now rising on average less fast than over a base period of 1921-1990; i.e. there has been a decrease in the rate of rise in the 20th Century. It is unlikely, therefore, that the perceived increased rate of siltation of the Avon over the last few decades can be related to sea level rise, storm-surge levels or changes in tidal characteristics. However, it is likely that observable changes in estuary morphology have occurred due to the 18.6 year cycle of tidal modulations.

2.3. Winds and extreme waves

An illustration of monthly wind data for January over the region during 1962 to 1976 (MAFF, 1981) is shown in Figure 2.3(A). Each wind rose plot shows wind speed data as ‘arms’ for the eight primary direction-sectors. The sum of the eight wind rose arms equals 100% and the length of each arm is the percentage of winds in that direction-sector. The length along each arm is divided into four segments of differing thickness that represent the percentage of winds within that direction-sector having Beaufort scales 1 - 3, 4, 5 - 6, and 7 – 12. In the Bantham region the winds are predominantly from the southwest or west.

Some care must be taken in the interpretation of these published data in the light of climate change, however, because they are now rather old. Recent work by the Hadley Centre (2003) has shown that the average number of storms in October to March (as detected by 3-hourly pressure changes) at UK stations has increased significantly over the past 50 years or so (www.oceannet.org/ medag/ reports/ IACMST_reports/ MCP_report/ ch_weath/ MCPreport_weath.htm; pressure changes were used instead of winds because the results are less sensitive to site moves and instrumentation changes). There is also some evidence that storm frequency has increased over the UK. Regional analysis shows that the largest increases occur over the southern UK. However, evidence of storm frequency from daily indices suggests that although it has increased in recent times, the magnitude of storminess at the end of the 20th century was similar to that at the start. This could mean that natural variations in the magnitude of storminess on timescales of several decades or more are responsible for all or part of the trends seen in these new results and that data covering a longer period is needed in order to distinguish a climate change trend from the natural variability (Hadley Centre, 2003). Therefore, based on these results, it is probable that the frequency of storms in the Bantham region, from whatever cause, has been increasing over a substantial time-period (in terms of an individual's life-span).

The predicted heights of the highest individual waves that are likely to occur in the worst storm in any 50-year interval and also the period of the wave at that time are shown in Figure 2.3(B). Data are based on predicted 50-year extreme winds and assume that the storm responsible for the waves will last in its fully-developed state for 12 hours (MAFF, 1981). The effects of wave breaking, bottom friction, shallow water topography or tidal currents on waves are not taken into account. Wave height decreases from approximately 35 m close to the southwest boundary of the Celtic Sea to less than 20 m near the St. George's Channel and the Bristol Channel, and to less than 13 m in the eastern English Channel (Figure 2.3(B)). The wave period decreases from greater than approximately 16 s close to the southwest boundary of the Celtic Sea to approximately 14 s near the St. George's

Channel and the Bristol Channel, and decreases to less than 10 s in the eastern English Channel.

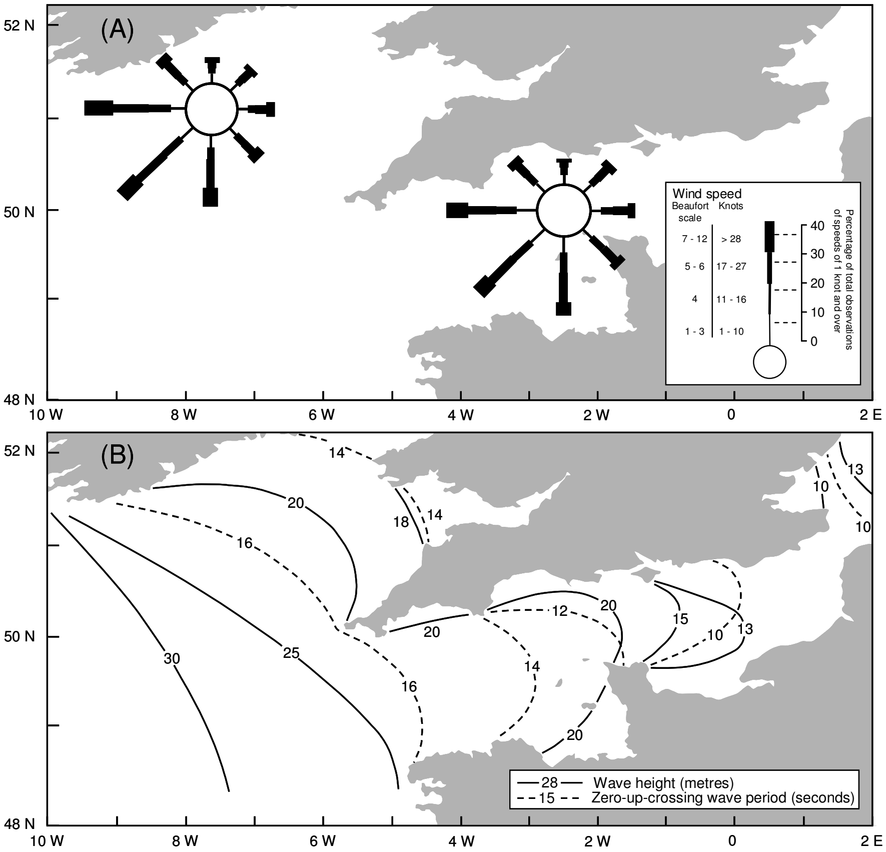

Figure 2.3: (A), Monthly wind data for January over the English Channel, Celtic Sea region during 1962 to 1976; (B), Predicted heights of the highest individual waves that are likely to occur in the worst storm in any 50-year interval and the mean zero-up-crossing period of the wave at that time (Redrawn with modifications from MAFF, 1981).

2.4. *Annual waves*

The ‘significant’ wave height contoured here corresponds approximately to the value estimated by an experienced mariner from visual observations of the sea’s surface. Figure 2.4(A) shows the significant wave heights that are predicted to be exceeded for 10% of the year. These waves are an order of magnitude smaller than the extreme waves contoured on Figure 2.3(B). Heights decrease from greater than 4 m at the southwest limit of the Celtic Sea to less than 2 m in the eastern English Channel, inner Bristol Channel and Severn Estuary, while remaining greater than 3 m in the St. George's Channel.

Figure 2.4(B) shows the significant wave heights that are predicted to be exceeded for 75% of the year. Heights decrease from greater than 1.5 m at the southwest limit of the Celtic Sea to less than 0.5 m in the eastern English Channel, inner Bristol Channel and Severn Estuary, while remaining greater than 1 m in the St. George's Channel. Annual wave periods are greater than 6 s and less than 8 s at the southwest limit of the Celtic Sea and reduce to less than 4 s in the eastern English Channel and inner Bristol Channel (Figure 2.4(B)). Seasonal variations in wave period are small.

In the Bantham region one would therefore expect waves in excess of 1.5 – 2 m to occur for 10% of the year (Figure 2.4(A)), whereas waves in excess of 0.5 m are likely to occur for 75% of the year (Figure 2.4(B)). Typical wave periods in the region are 4 seconds. Some care must again be taken in the interpretation of these published data in the light of climate change, however, because they are now rather old. For example, wave data from ships and buoys indicate that the mean winter wave height in the northeast Atlantic increased significantly between the 1960s and 1980s and satellite data confirmed that this increase continued into the early 1990s (www.oceannet.org/ medag/ reports/ IACMST_reports/ MCP_report/ ch_waves/ MCPreport_waves). In the northern North Sea there was an upward trend of about 5 - 10% (0.2 - 0.3 m) in mean significant wave height for January–March for the period 1973 - 1995, but a decrease thereafter. In the central North Sea the trend for January – March was upwards until 1993/94, with a decrease thereafter; the mean significant wave height for October – December peaked around 1982/83 and 1983/84, with a similarly high value in 1999/2000. In the southern North Sea, there was no discernible trend in mean significant wave height for January – March and only a slight indication of a downward trend in mean significant wave height for October – December from 1980/81. At Sevenstones Light Vessel, off land's End, the accepted value is an increase of 0.02 m per year in mean wave height over a period of about 25 years. This trend seems to have persisted into the early 1990s at least, although recent winters have suggested a levelling off. Therefore, based on the northeast Atlantic and Sevenstones findings, it is probable that waves in the Bantham region have been increasing over a substantial time-period (in terms of an individual's life-span).

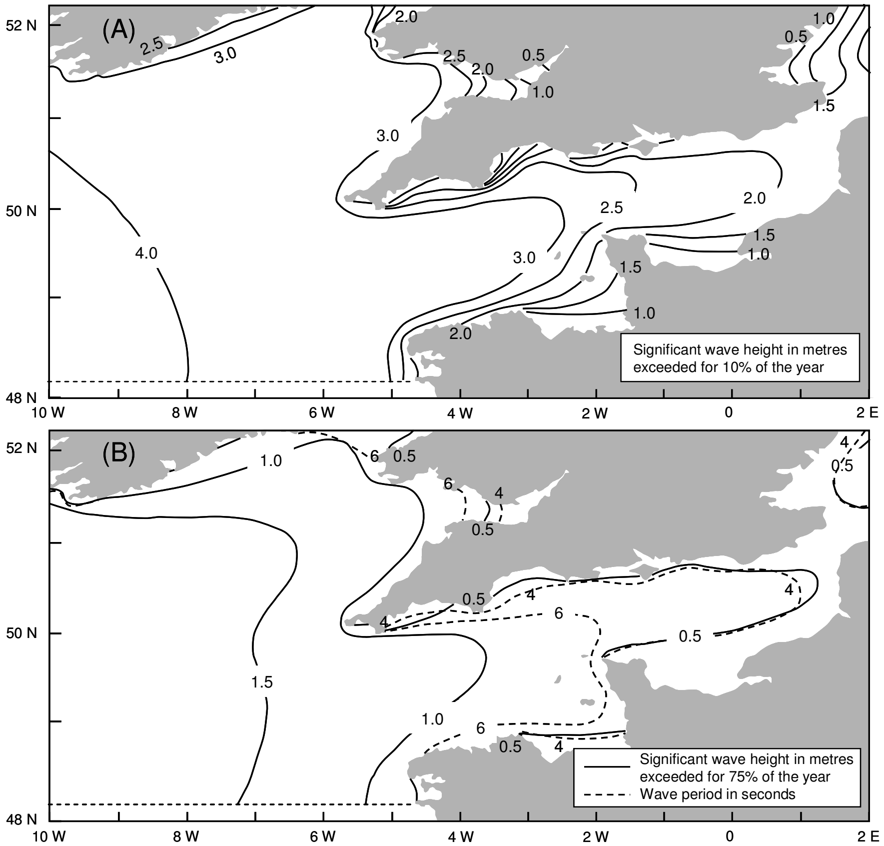

Figure 2.4 (A), Significant wave height (m) exceeded for 10% of the year; (B), Significant wave height (m) exceeded for 75% of the year and the zero-up-crossing wave period in seconds, shown as the dashed line (Redrawn with modifications from Draper, 1991).

3. Avon Bathymetry

3.1. Estuary sections

Thirty-one cross-sections, drawn perpendicular to the main channel, were specified along the longitudinal axis of the Avon Estuary at approximately 250 m spacing (Fig. 3.1). These sections comprised the basic bathymetry for modelling studies and defined the estuary's geometry. The longitudinal (or axial) distance of each cross-section from both head and mouth of the estuary was determined in kilometres (Table 3.1). A comprehensive survey of the central part of the Avon Estuary, undertaken by Atkins plc, supplied the major contribution of depth soundings to the bathymetric data-base (20 cross-sections). A further series of surveys by the PML provided data for the seaward and the freshwater boundaries (11 cross-sections). The PML cross-sections were determined using an inflatable boat and an echo-sounder. Each cross-section was constructed from the mean of data derived from forward and return passes over the section and corrections for tidal state were made using data from an *in-situ* tide gauge.

3.2. Section bathymetry

The 31 cross-sections were defined in terms of width and cross-sectional area relative to ODN (ordnance datum, Newlyn, Figure 3.2(A, B)). Width and cross-sectional area also were determined for tidal elevations of -3m, -2m -1m, +1m, +2m and +3m relative to ODN. The nominal seaward boundary of the Avon Estuary, where the Avon discharges into Bigbury Bay, cross-section 1, is a line drawn between Bigbury lifeguard station and the rocks below the cliffs on Bantham beach. This cross-section is 900 m long and has a maximum depth of 2.5 m at ODN (Figure 3.2A). Within a kilometre the estuary narrows to just over 100 m at cross-section 3, and shallows slightly to 2.4 m at ODN. Section 3A, between sections 3 and 4, corresponds approximately to Cockleridge Narrows (Figure 3.1).

After Cockleridge Narrows the estuary widens bank-to-bank to 200 – 290 m between cross-sections 4 and 11, a distance of approximately 4.5 km. The channel width at ODN also widens after the Narrows, but reduces from 180 m at cross-section 4 to 100 m at cross-sections 5 and 6, and further to 50 m at cross-sections 7, 8, and 9. By cross-section 11 (5.3 km), the channel width at ODN is reduced to 30 m and the depth has steadily reduced from 1.5 m at cross-section 4 to 0.2 m at cross-section 11 (Figures 3.2(A, B) and 3.1).

At cross-section 6 there is a shoal at ODN in the main channel and this feature is still evident 500 m upstream at cross-section 7 (Figure 3.2(A)). A further ODN mid-channel shoal is evident at cross-section 8, but is not part of the previous formation.

Cross-sections 12 and 13 show a bank-to-bank width of 80 m and 110 m, respectively, and at ODN there is virtually no channel due to the increased bed slope (Figure 3.2(B)). The upper three cross-sections (14, 15 and 16) display significantly reduced bank-to-bank widths of 20 m reducing to 14 m at the tidal limit - the weir at Aveton Gifford. The deep channel at ODN is only a few metres wide and displays varying depths to 1.2 m, suggesting river scour in the narrow channel (Figure 3.2B).

The position of the deep channel follows the outside of bends and meanders along the axis of the estuary. However, a bed-profile ‘hump’ of very shallow depths occurs in the estuary’s bed, as reflected in the deep-channel depth between sections 10 to 13 (Figures 3.1, 3.2B).

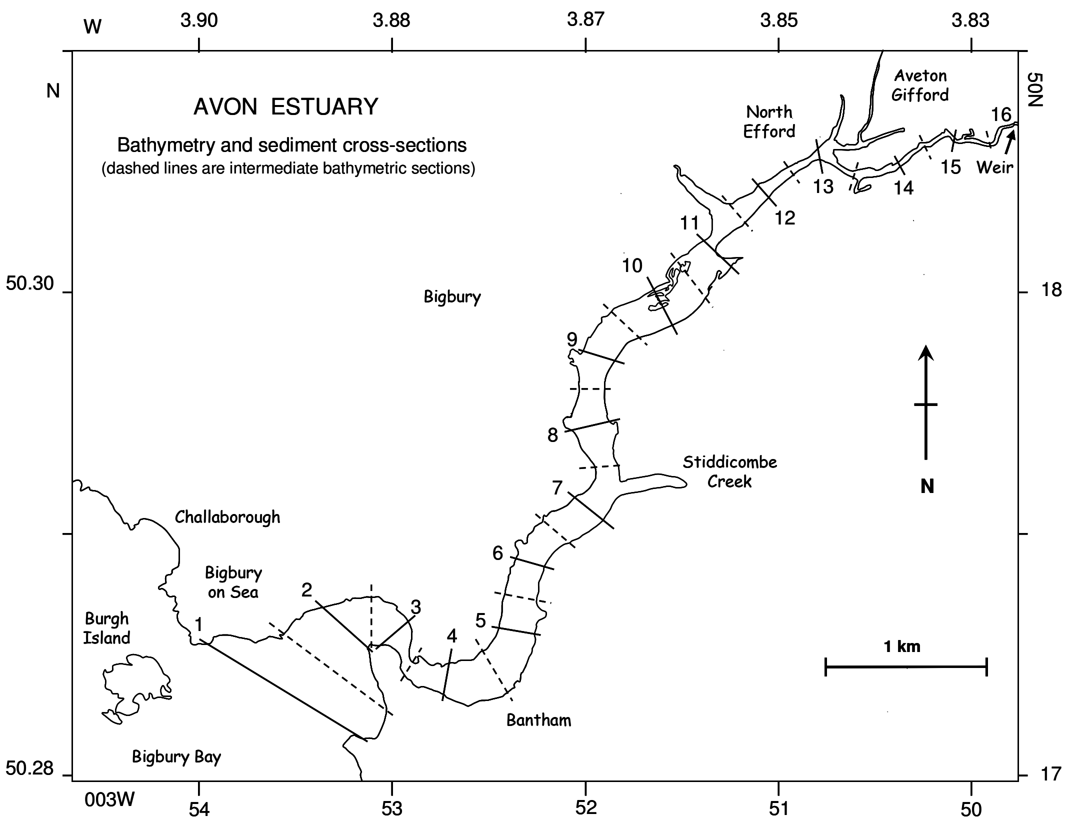

Figure 3.1: Map of the Avon Estuary bathymetric and sediment profile cross-section locations (solid lines) and intermediate bathymetric cross-sections (dashed lines).

Cross-section	Distance from mouth (km)	Distance from head (km)		Cross-section	Distance from mouth (km)	Distance from head (km)
1	0.000	7.473		9	4.137	3.336
1A	0.258	7.215		9A	4.431	3.043
2	0.516	6.957		10	4.724	2.749
2A	0.738	6.735		10A	5.013	2.460
3	0.961	6.512		11	5.302	2.171
3A	1.228	6.246		11A	5.525	1.948
4	1.495	5.979		12	5.747	1.726
4A	1.802	5.672		12A	5.939	1.535
5	2.109	5.356		13	6.130	1.343
5A	2.327	5.147		13A	6.401	1.072
6	2.544	4.929		14	6.673	0.801
6A	2.802	4.671		14A	6.882	0.592
7	3.060	4.413		15	7.091	0.383
7A	3.376	4.097		15A	7.282	0.191
8	3.692	3.781		16	7.473	0.000
8A	3.915	3.559				

Table 3.1: Cross-section distances along the axis of Avon Estuary.

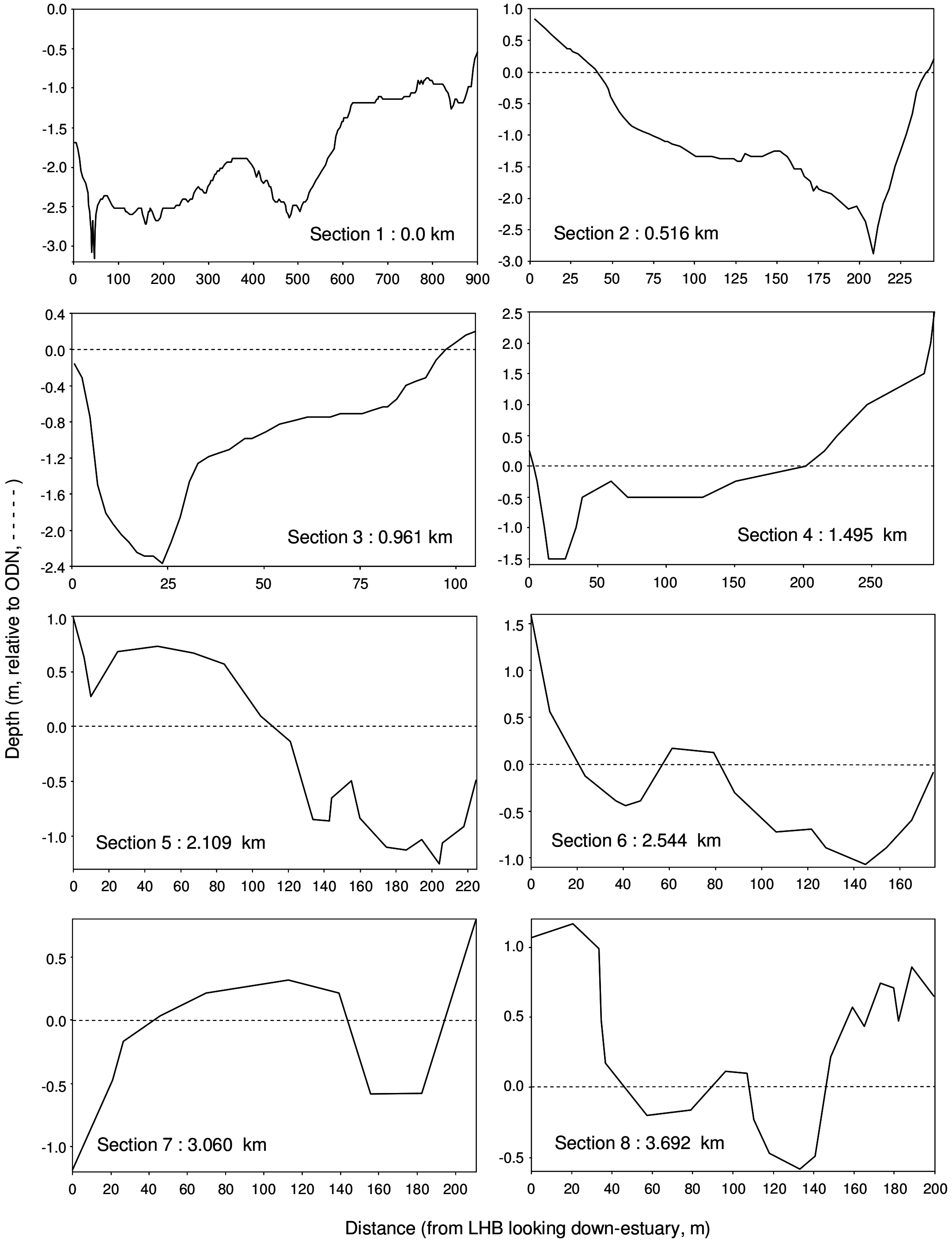

Figure 3.2A: Bathymetric cross-sections 1-8 for the Avon Estuary. All depths are relative to ODN (ordnance datum, Newlyn, - - - -). Section 1 is the nominal seaward boundary.

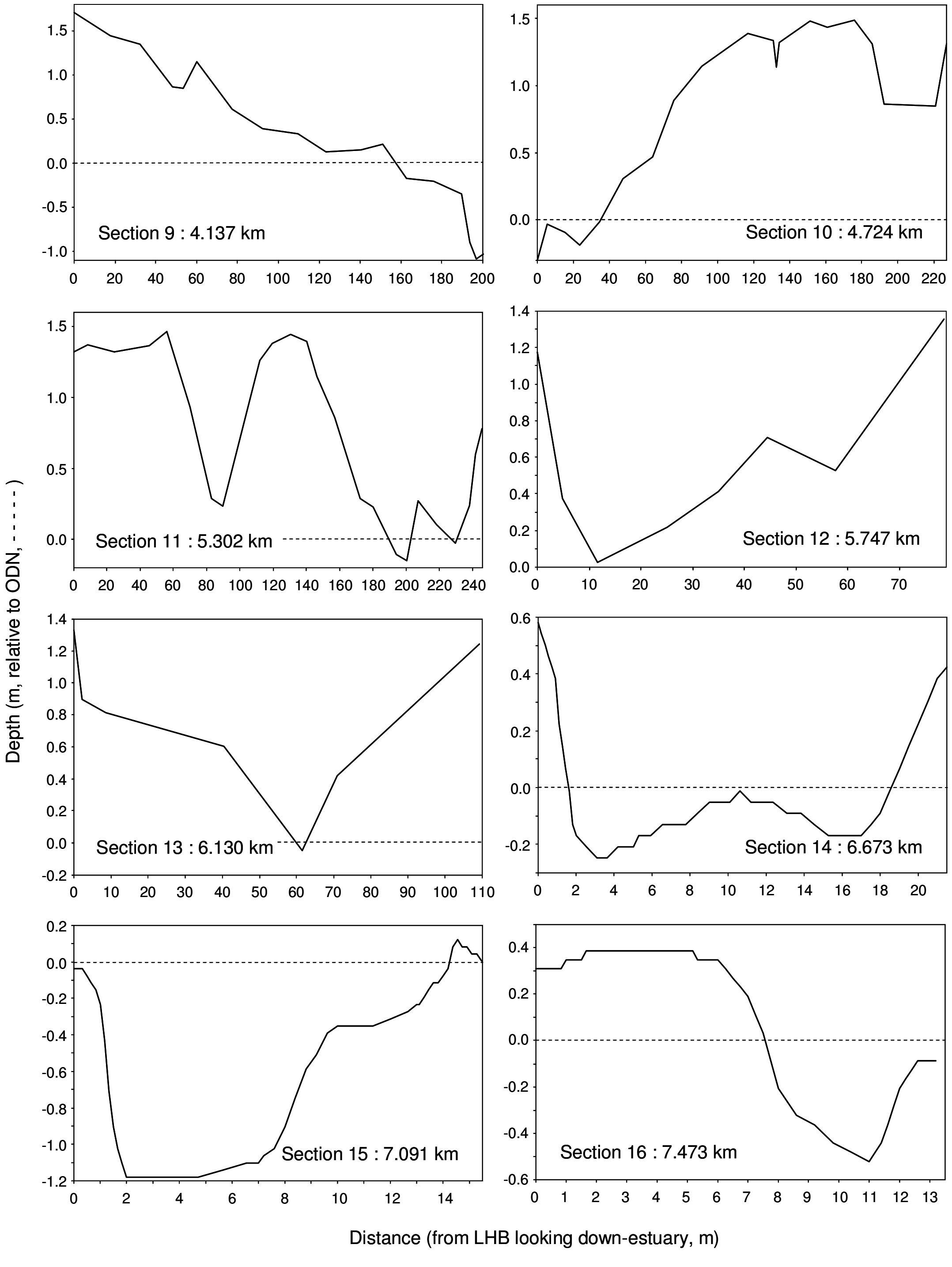

Figure 3.2B: Bathymetric cross-sections 9-16 for the Avon Estuary. All depths are relative to ODN (ordnance datum, Newlyn, - - - -). Section 16 is the limit of tidal intrusion, the weir.

4. Avon Sediments

A number of cross-sections, perpendicular to the main channel and spaced at approximately 500-m intervals, were worked along the longitudinal axis of the Avon Estuary during 5th and 6th June 2005. Sediment samples were collected at regular intervals across each section at low water (LW), sampling the top 10 mm of bed substrate. Where the sampling site was in the main channel and therefore covered by water, a Van-Veen grab, deployed from an inflatable boat, was used to obtain the sample. Each sampling site was fixed with a GPS position. Additional samples were taken along the axis of the estuary at the same cross-sections during winter, February and March 2007. These were single, representative samples taken at LW springs, just above the LW line.

Analysis of the sediment size composition was undertaken by laser diffraction using automated University of Plymouth instrumentation, which gave a size-category breakdown into 40 ‘channels’ ranging from 0.086 to 64000 μm (millionth of a metre). The percentage volume of each size fraction was computed and from this determination the sediment composition was quantified into universally-accepted classification categories. Further statistics determined the mean, median and modal size distributions.

4.1. Cumulative percentages

The resulting cumulative percentage-volume data for the summer sampling during June 2005 were cross-sectional-averaged and plotted against distance along the longitudinal axis of the estuary (Fig. 4.1A). The distributions show that the upper (500 m) section of the estuary has a scoured, river-like profile with virtually all the substrate grain-sizes being above 2300 μm (2.3 mm) – i.e. coarse gravel and cobbles. As the estuary widens, progressing down-estuary, the fine-sediment (silt and clay) contribution to the bed substrate increases dramatically and exceeds 50%. At about 2.5 km from the weir (section 10A, Table 3.1) the silt and clay fraction (< 63 μm) peaks at about 52% and combined with the very fine sand (< 125 μm) and fine sand (< 250 μm) fractions constitutes the majority (> 87%) of bed sediments in the estuary at this location. This percentage contribution of fine sand and smaller sediment then falls steadily to about 30% at 7 km from the head, with the bulk of the difference made up with medium sand (< 500 μm) and coarse sand (< 1000 μm) in increasing proportions. The sediment coarsening is co-incident with the narrowing of the estuary prior to its ebb-tide discharge into Bigbury Bay. The very coarse sand (< 2000 μm) and gravel (< 4000 μm) contribute a fairly small but constant percentage to the overall substrate mix and larger materials such as pebbles, cobbles and rocks are more in evidence at the extreme ends of the estuary. Once the estuary crosses the beach and discharges into Bigbury Bay, the fine-sand fraction contribution increases once again and the coarser materials reduce.

The longitudinal distribution of cross-sectional-averaged D50 (median diameter) grain sizes for the estuary (Fig 4.1B) shows that the river-like upper 1 km of the estuary has a median-size distribution between 1000 μm and 10000 μm that rapidly falls to just below 100 μm at cross-section 11 and then gradually increases to give a range lying between 100 μm and 1000 μm for the central part of the estuary down to cross-section 3. At cross-section 3, where the estuary narrows before the mouth, the D50 value rises to between 1000 μm and 10000 μm before falling again to between 100 μm -1000 μm as the estuary discharges into Bigbury Bay.

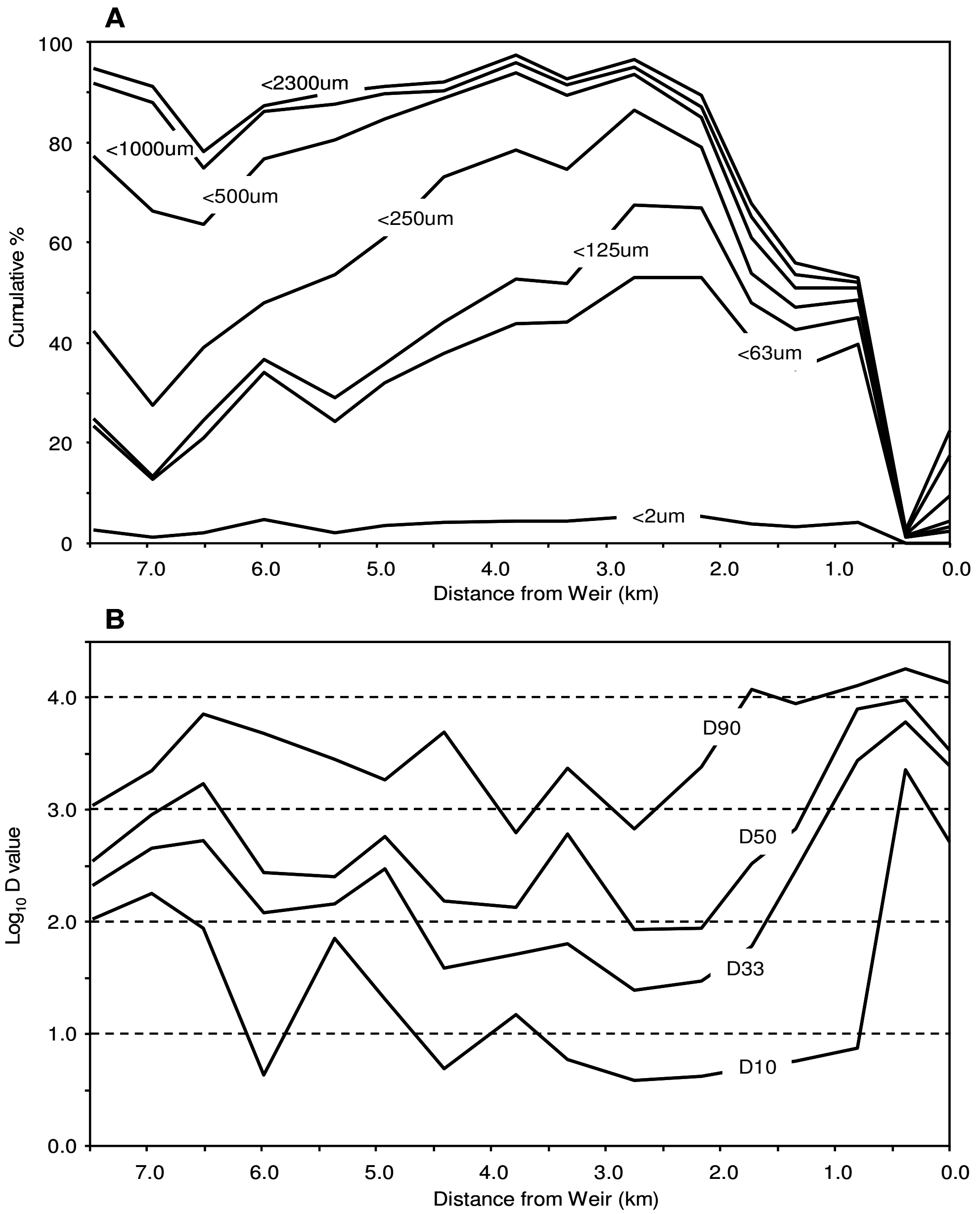

Figure 4.1: (A) This shows the axial distribution of cross-sectional-averaged, cumulative percentage-volume distribution of sediment in the Avon Estuary during June 2005. (B) Axial distribution of the cross-sectional-averaged log10 D value.

4.2. Distribution of grain sizes along the estuary

Median diameter (D50) grain-size data for the LW, deep-channel shoulder sediment samples collected during summer (June 2005) and the summer deep-channel D50 bed-sediment data are shown on Fig. 4.2.

The summer deep-channel D50 values are higher than those on the channel shoulder, confirming that the material on the inter-tidal part of the estuary bed is of a smaller size composition than that in the deep channel. This is particularly noticeable at the extreme ends of the estuary, where the channel is river-like at the higher end and constricted at the lower end, resulting in more concentrated flows at LW and a greater likelihood of fine sediments being winnowed out of the deep channel.

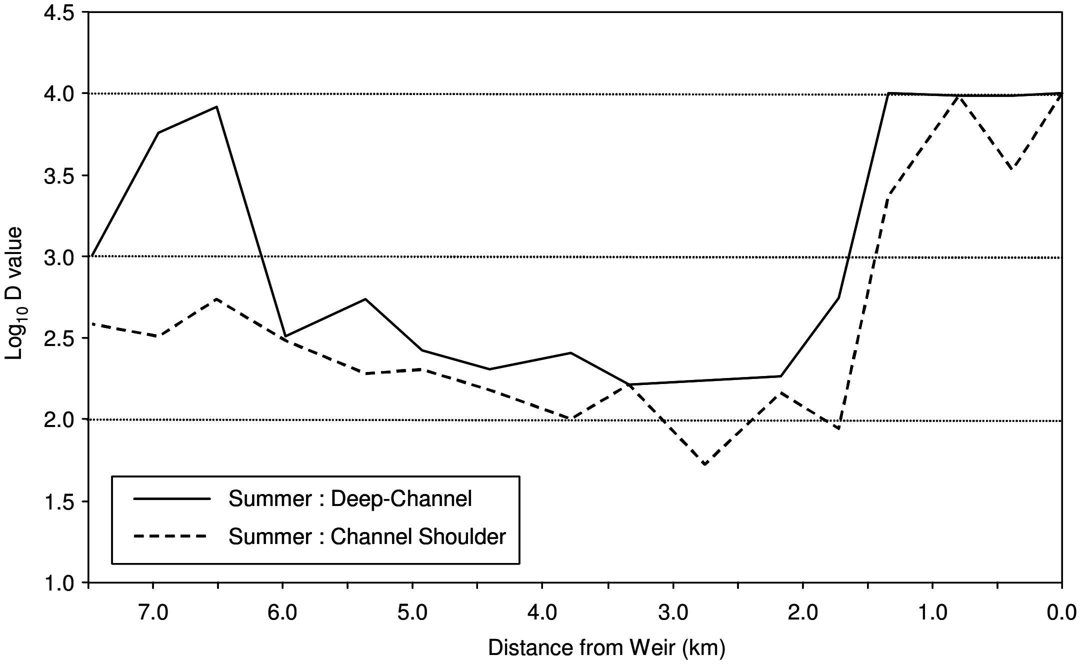

Figure 4.2: This shows the axial distribution of (log to the base 10) D50 grain sizes during summer for the deep channel (continuous line) and the channel shoulder at low water (dashed line) along the Avon Estuary.

4.3. Distribution of grain sizes across the estuary

Cross-sectional profiles of the cumulative-percentage composition of bed sediment, together with the median grain-size distribution and bathymetry, were plotted for selected sites (Fig. 4.3). Because the two (sediment and bathymetry) sampling surveys were undertaken on different days, the sediment cross-section was matched with the nearest bathymetric profile. While this is not an ideal comparison, it does indicate important features of the bed topography relative to the sediment distribution. Four sets of data are shown in Figure 4.3 (A-D), one each for cross-sections 1, 5, 8 and 12. Each data-set consists of two plots; the upper panel of each pair shows the cumulative-percentage composition of the bed sediment substrate by size category (1 - 7) and the median size distribution (μm, dashed line). The lower panel of each pair shows the bathymetry of the nearest cross-section, drawn relative to ODN. The size categories are (1) clays (< 2 μm), (2) silt and clay (< 63 μm), (3) very fine sand (63 - 125 μm), (4) fine sand (125 - 250 μm), (5) medium sand (250 - 500 μm), (6) coarse sand (500 - 1000 μm) and (7) very coarse sand (1000 - 2000 μm) and gravel (2000 - 4000 μm).

In all cases the median grain-size distribution (μm) shows a predominance of finer sediments at the channel margins leading to a dramatic increase in size that is coincident with the deep channel, as exemplified by the bathymetry. For cross-section 8 (up-estuary of Stiddicombe Creek) there are two median grain-size peaks because the channel runs either side of a mid-channel shoal (Fig. 4.3C). The median size peaks at about 1000 μm in the deep channel at the mouth of the Avon (Bantham Beach, cross-section 1, Fig. 4.3A), reducing to about 550 μm at cross-section 5 (Aunemouth Sands, Fig. 4.3B) and reducing further to 280 μm at cross-section 8 (up-estuary of Stiddicombe Creek, Fig. 4.3C). The deep channel median size reduces further still at cross-sections 10 and 11 (Stadbury Plantation, not shown) reaching less than 200 μm and then begins to increase again to about 560 μm progressing up-estuary to cross-section 12 (down-estuary of North Efford, Fig. 4.3D), thereafter increasing to 2300 μm at cross-section 13 (North Efford, not shown) and in excess of 9000 μm at cross-sections further up-estuary.

This distribution of bed sediment in the deep channel shows that the upper estuary displays a scoured bed in which the larger, less mobile sediments are left *in-situ* and that the majority of fine material is deposited in the mid-estuary region. The physical reasons for this accumulation of finer sediments are explored later, although this region clearly is less affected by winter spates than that nearer the weir and is sheltered from strong wave activity that affects the coastal zone. The deep-channel median grain-size in the lower estuary is consistent with coarse sand, which probably can be attributed to the continual winnowing of finer sediments during the ebb.

The percentage-compositions of the inter-tidal areas from lower-estuary cross-sections 1 and 5 (Fig. 4.3A, B) show an almost uniform 40% fraction of silts and clays (< 63 μm, labelled (2)) on the banks of the deep channel and this 'fining' also is evident at cross-section 8 (Fig. 4.3C) although the percentage increases dramatically to about 80% near the HW margins of the section. This HW margin 'effect' is still present at cross-section 12 (Fig. 4.3D) although it is somewhat reduced.

The bulk of the rest of the cross-sectional sediment in the lower estuary is made up of fine sand (4) and medium sand (5) and it is this material together with the silt and clay fraction that dominates the substrate composition at cross-section 10 (not shown). At cross-section 12 (Fig. 4.3D) the composition of the substrate is fairly uniform across much of the width except on one bank, which shows a much higher silt and clay component. The substrate begins to show a significant reduction in the finer sand fractions and a pronounced increase in material that is greater than 2000 μm. This trend of increasingly larger material continues into the upper estuary and dominates the river-like section between cross-section 13 and the weir.

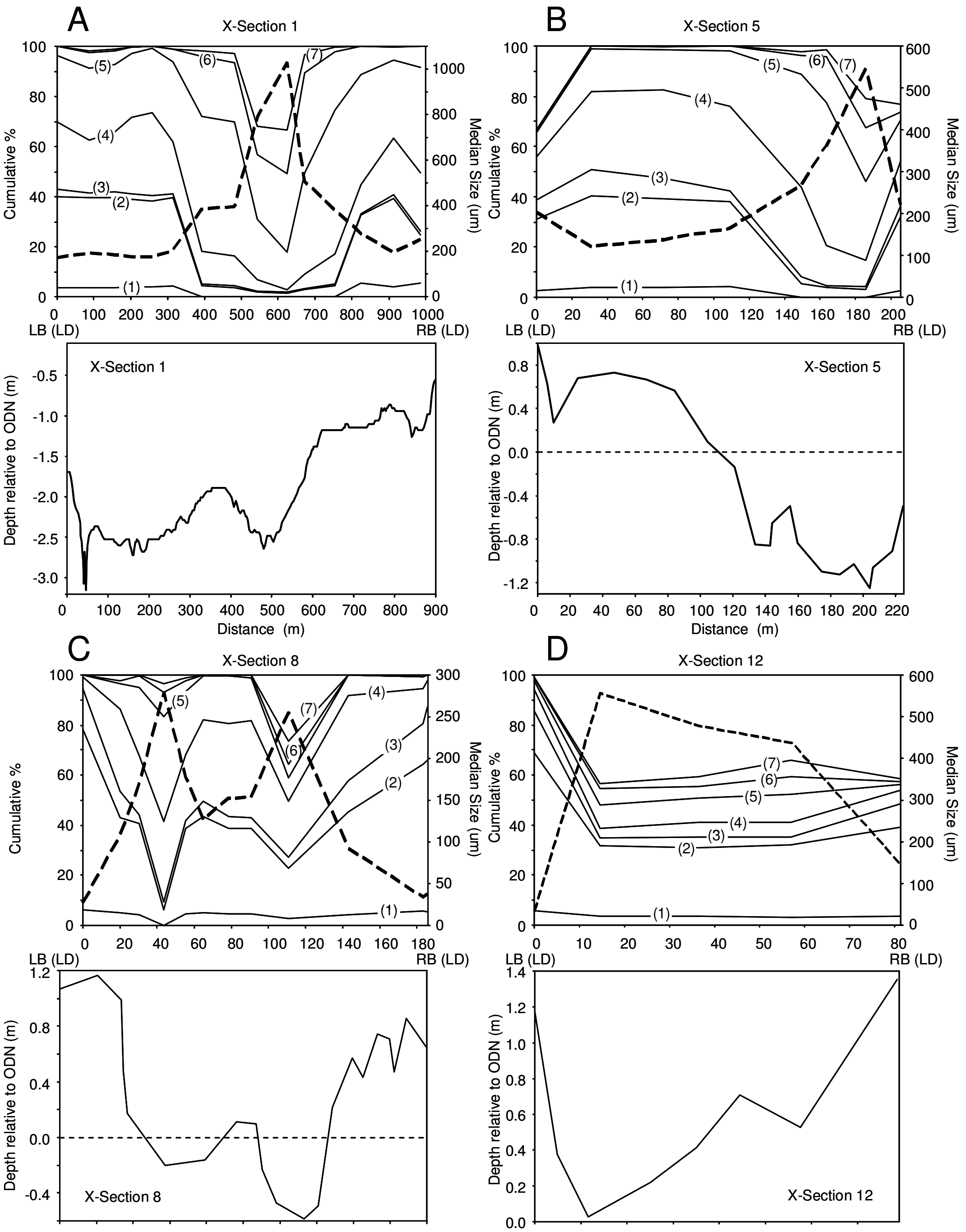

Figure 4.3: This figure shows four pairs of plots (A-D) for cross-sections 1, 5, 8 and 12. The upper panel of each pair shows the cumulative percentage composition of the bed substrate by size category (1)-(7), and the median size distribution (dashed line). The lower panel of each pair shows the bathymetry of the nearest cross-section relative to ODN. The size categories are (1) clays, (2) silt and clay, (3) very fine sand, (4) fine sand, (5) medium sand, (6) coarse sand and (7) very coarse sand and gravel.

5. Sand accumulation/erosion posts

5.1. Deployments

Four posts (25 mm x 25 mm x 1.5 m long) were driven (1 m) into the bed sediment of the shoal directly opposite the harbourmaster's office at Bantham on 15th March 2006 (Fig.5.1). During the succeeding months posts 1 and 4 were subsequently lost and had to be replaced. The posts were located as follows:

Down-stream end of the shoal:

Post 1: GPS: 50 16.753N, 003 52.296W;
Post 7: GPS: 50 16.757N, 003 52.288W (replacement for Post 1)
Harbourmaster's Office side of the shoal (south):

Post 2: GPS: 50 16.756N, 003 52.252W

Upstream end of the shoal:

Post 3: GPS: 50 16.793N, 003 52.221W

Bigbury side of shoal (north):

Post 4: GPS: 50 16.773N, 003 52.264W
Post 5: GPS: 50 16.773N, 003 52.250W (replacement for Post 4)
Post 6: GPS: 50 16.771N, 003 52.253W (replacement for Post 5)

One end of a radial arm was placed over the post and a pole was driven into the substrate at the other end until the arm was level (spirit level). Vertical readings (mm) of the radial arm clearance from the bed substrate were taken in sequence at defined distances from the centre of the post (32, 57, 82, 107, 132, 157 and 182 cm) at the four main points of the compass (N, S, E, W). The circular area delimited by the radius of the arm is 10.406 m^2. The posts were read at approximately monthly intervals for 13 months.

5.2. Time-series data

A mean data point was calculated for each post (28 readings, 7 for each compass point), each month to give a broad estimate of net erosion or accretion for the vicinity of the post. When each point is plotted against time, the substrate net loss or gain (mm) can be compared for each of the four posts (Fig.5.2A).

Figure 5.1: Location of the four posts on the shoal opposite the Harbourmaster's (HM) Office, Bantham.

The data from the posts do not all show a uniform or consistent pattern of erosion (loss) or accretion (deposition). Post 3, located at the upstream end of the shoal, showed a gentle accretion of sediment for the first few months of the survey (early summer 2006) but then a progressive pattern of erosion of bed material occurred, with the exception of September 2006, until the post was washed away during February 2007. The bed material had eroded by over 0.35 m and undermined the post stability in the estuary bed. The edge of the shoal had migrated downstream and the site of the post was thus located in the main ebb flow at LW for the latter few months of the survey. Conversely, Post 1, located at the downstream end of the shoal, started off with an erosion profile until June 2006 when there was an accretion signal. Unfortunately the post was lost during late July/early August 2006 and a replacement showed continuing erosion during

September/October 2006 when the trend stopped and the shoal at this post began an accretion phase until the record ended. This accretion was evident from field observations; the post was initially located on the southerly edge of the secondary channel, whereas during the accretion phase the lower edge of the shoal extended downstream several tens of metres beyond the post.

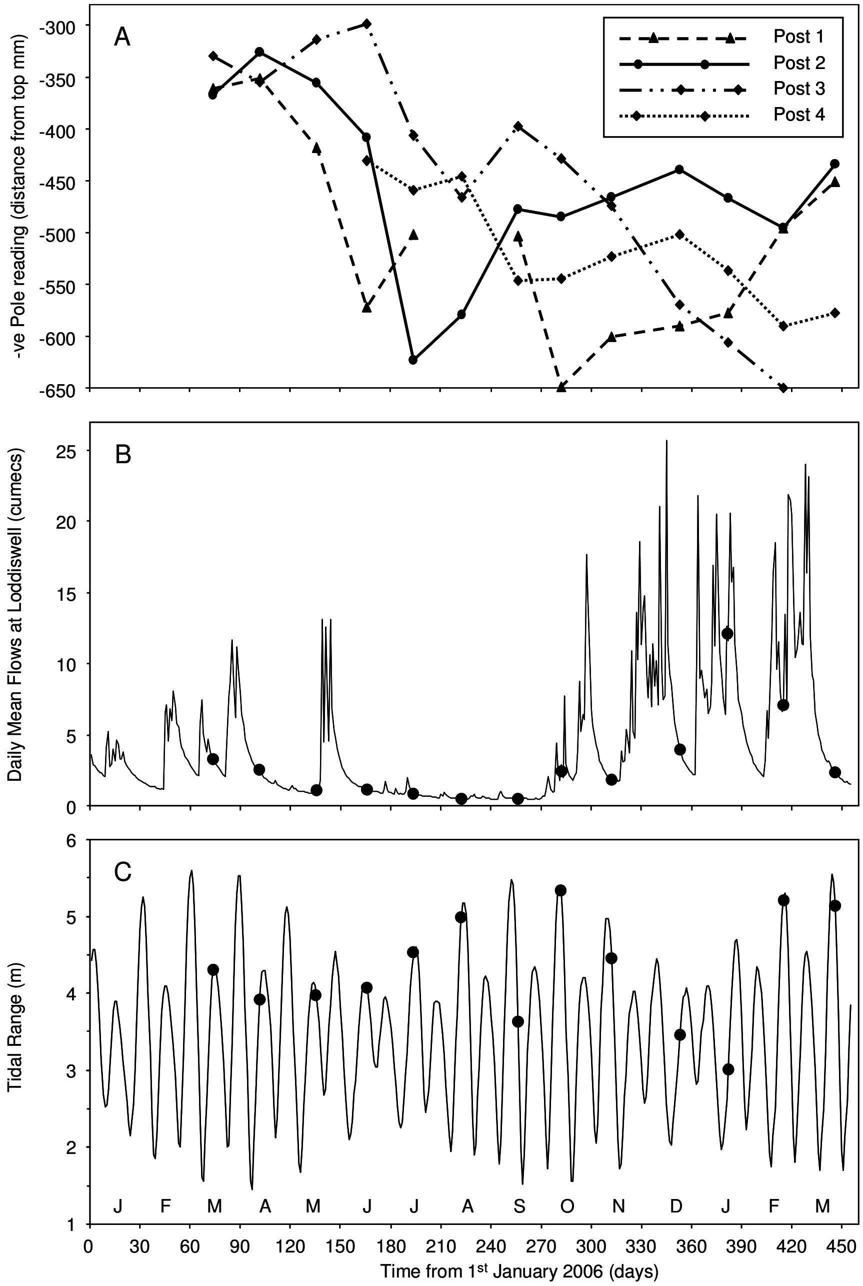

Figure 5.2: This figure shows A.) Post readings (mm, from the top of the pole to the bed substrate) for the monitoring period. B.) Daily mean flows at Loddiswell gauging station ($m^3 s^{-1}$), C.) The tidal range (m) is shown for Devonport). The symbols and black dots on the graphs denote pole-reading days.

The posts located on the north and south banks at the mid-point of the shoal (Posts 2 and 4) showed an initial erosion profile with a particularly large loss (0.22 m) for Post 2 during June/July 2006. The two posts then began to mirror similar patterns of erosion and accretion for the remainder of the record. Overall, the pattern of erosion and accretion of each post was very different from that of its neighbours during the monitoring period; however, it is apparent that the middle of the shoal, as delimited by the two posts, had a tendency to behave in a relatively straightforward way. Also, the upstream end of the shoal had eroded when the downstream end of the shoal had accreted. The implication is that the up-estuary and down-estuary limits of the shoal shifted up-estuary and down-estuary about the middle mass and that this appeared to occur with a seasonal cycle. Subsequent sediment levels across the shoal may vary between years, depending on the environmental forcing, and a repeating annual redistribution of sediment may not always occur.

5.3. Environmental forcing

Freshwater flows measured by the automatic gauging station at Loddiswell (15 minute intervals) were obtained for the Avon Catchment from the Environment Agency. Meteorological data (5 minute intervals) was obtained from the PML automatic weather station located on the Hoe in Plymouth. Tidal range at Devonport also was calculated for the monitoring period (Fig.5.3 A-D).

The freshwater flow data show winter and autumn maxima and a late spring to summer minimum. The early part of 2006 shows five peak runoff periods (Fig.5.3.A) where the flows exceed 5 $m^3 s^{-1}$ and reach up to 15 $m^3 s^{-1}$ towards the end of May. During the summer months the flows drop below 1 $m^3 s^{-1}$ and then increase dramatically during October 2006, showing four peak runoff periods over the ensuing winter months to March 2007, where flows exceed 15 $m^3 s^{-1}$ and often reach in excess of 20 m^3 s^{-1}. The westerly wind vector is far more dominant than the easterly-component over the period plotted (Figs. 5.3 B, D). These high runoff periods are coincident with a strong westerly wind vector but also an equally important strong southerly wind vector showing that south-westerly winds are associated with the high runoff. The summer period of low runoff maintains a significant westerly wind vector but the southerly wind vector is much smaller than that during the winter periods and is almost equally matched by the northerly summer wind vector.

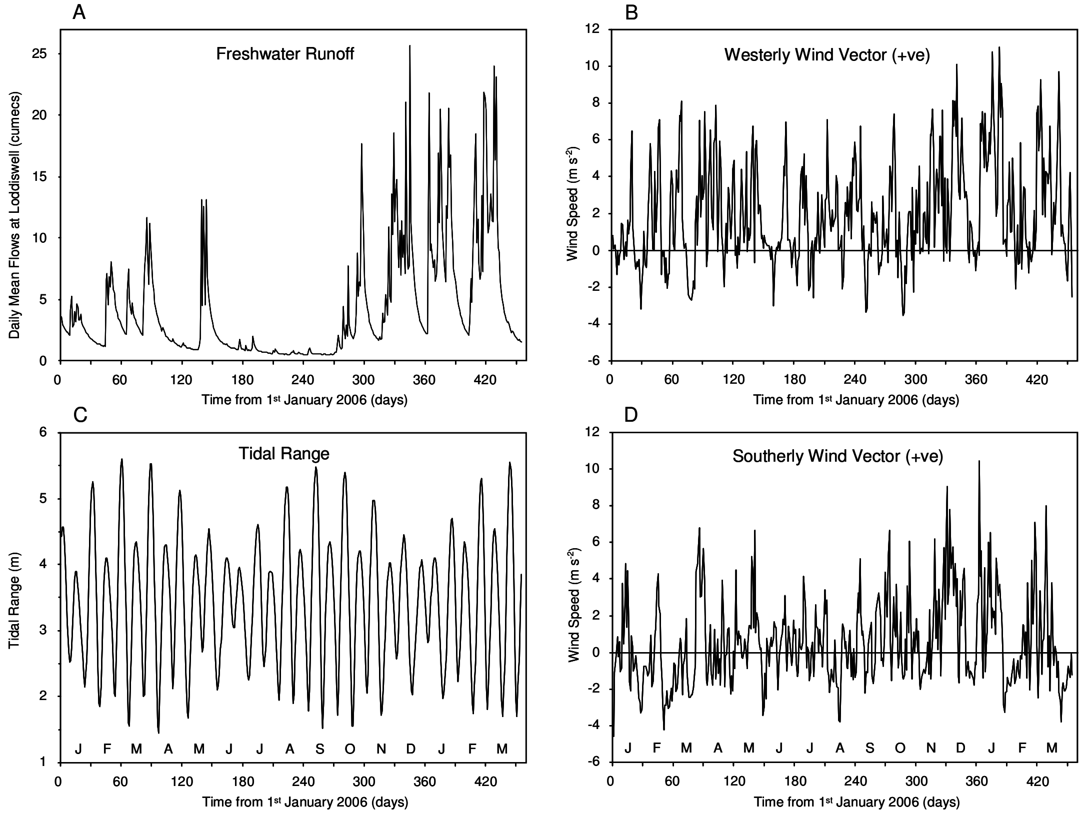

Figure 5.3: This figure shows four of the main variables that can influence sediment erosion/accretion in estuaries; (A), Freshwater input (m^3 s^{-1}); (B), Westerly winds (m s^{-1}); (C) The tidal range at Devonport (m) and; (D), Southerly winds (m s^{-1}).

5.4. Visual changes

The topography of the shoal changed dramatically during the sampling period and even between tides. Figure 5.4A shows two photographs of the surface bed form for Post 2 on the 8th November 2006 and again a similar view on the 19th December 2006.

Figure 5.4A: This figure shows two photographs of Post 2 and the surrounding bed form for 8th Nov. 2006 (left hand panel) and the 19th Dec. 2006 (right hand panel).

Figure 5.4B: Summer (left hand panel) and winter (right hand panel) conditions at Post 5, showing that an algal growth was able to establish itself on the northern side of the shoal during the summer months but that it was gone by the middle of winter.

The northern edge of the shoal was stable enough to support a significant algal growth during the summer months and this coverage began to establish itself during May 2006 but was gone by October 2006. Figure 5.4B shows the contrast at Post 5 at LW springs between the stable summer conditions and those displayed in winter where the northern edge of the shoal appears to have eroded significantly. This is an illustration of the interaction between physical and biological processes that can influence the stability and morphology of intertidal regions and can confound sediment-transport predictions that are based on purely physical arguments.

6. Field Deployments

6.1. Summer (July) 2005

6.1.1. Instrumentation and deployment

To obtain physical data for summer conditions two Valeport 730D Wave Recorders were deployed for the period 4th – 9th July 2005, measuring current speed and direction, depth, temperature and suspended particulate matter (SPM). The wave recorders measured in tide-burst mode of 20 seconds at 4 Hz and wave-burst mode of 128 seconds at 4Hz every 10 minutes. Attached to each wave recorder was a multi-parameter sonde (YSI 6600) with a 5-minute sampling resolution, measuring depth, salinity, temperature and SPM. The wave recorder sensors were located 0.45 m above the bed and the YSI sensors were located at 0.1 m above the bed.

The first pair of instruments was deployed in the deep-channel of the upper estuary at North Efford, (GPS: 50 18.505N, 003 50.640W). A second pair of instruments was deployed at Bantham, just below the harbourmaster's office, in the deep-channel (GPS: 50 16.731N, 003 52.295W). The instruments were carried into the water and placed in position on the bed of the estuary and buoyed off; a weighted safety-line was attached to the shore.

While the bed mounted equipment was deployed we undertook a tidal-cycle, vertical-profiling station at each site; Bantham on 6th – 7th July 2005 and North Efford on 8th July 2005. At each station data were collected using a YSI 6600 multi-parameter sonde and a Valeport direct reading current meter (DRCM) deployed from a boat anchored in the deep channel of the estuary. Discrete readings were obtained through the water column for current speed and direction, depth, temperature, salinity and SPM, profiling at 30-minute intervals. During periods of maximum flood and ebb some profiling was undertaken at 20-minute intervals. The current speed and direction returned by the DRCM was a mean of 3 readings obtained using a 30-second sampling period with 10-second sampling. At Bantham the ebb tide was measured on 6th July and the flood tide on the 7th July during two days of sampling, whereas at North Efford a full tidal cycle was obtained on 8th July during one day of sampling.

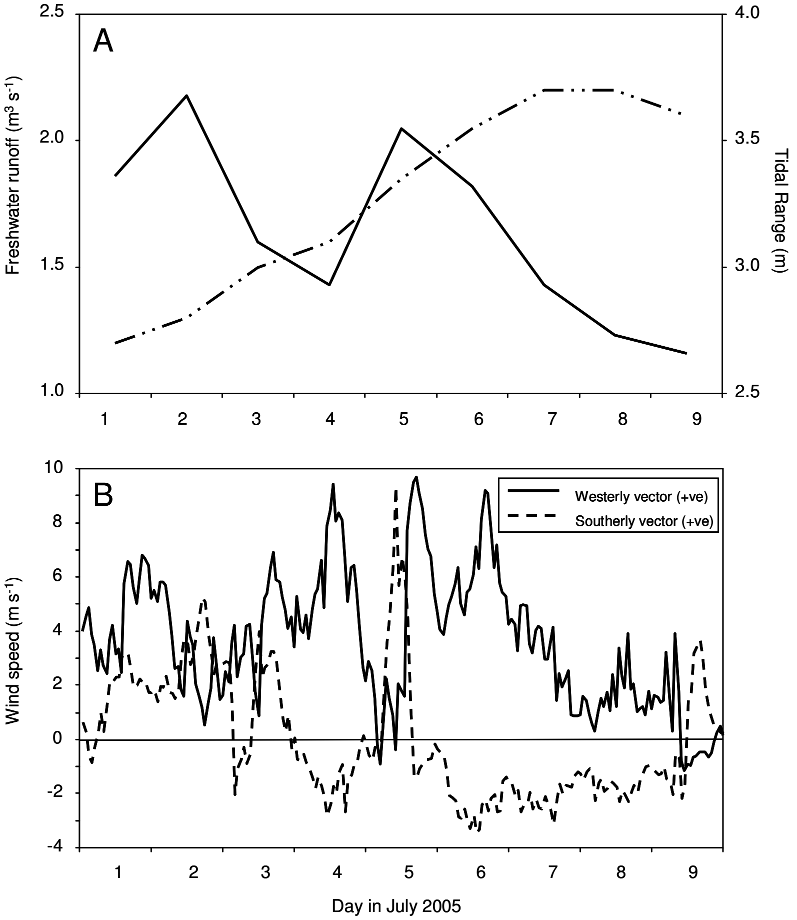

Figure 6.1.2 A.) Freshwater runoff (continuous line) and mean tidal range (broken line) for the deployment period, B.) Daily mean westerly (continuous line) and southerly (broken line) wind vectors for the deployment period.

6.1.2. Environmental conditions

The prevailing physical conditions leading up to and pertaining during the deployment period were of low and decreasing runoff and neap tides rising to spring tides (Fig. 6.1.2A). The wind vectors (Fig. 6.1.2B) showed a predominantly north-westerly direction for the deployment period with a short period of stronger southerly winds on 5th July that were followed by a small increase in runoff.

6.1.3. Vertical Profiling

6.1.3.1. Bantham station, surface and bed data

SPM concentrations were small at the Bantham station, generally less than 15 mg l^{-1}, and concentrations were greater on the flood and not related to current speed, but were greatest at low salinity (Fig. 6.1.3.1A). This indicates preferential transport of sediment into the estuary on the flood with a compensatory, outward pulse of turbid waters from the upper estuary on the late ebb. Currents were fast and reached 1 m s^{-1} on the ebb and 0.8 m s^{-1} on the flood. Surface currents were consistently faster than near-bed currents. Salinity was well-mixed between surface and bed (Fig. 6.1.3.1B).

6.1.3.2. Bantham station, contoured data

Vertical-profile data for the YSI at the Bantham station can be represented by contour plots on a depth – time diagram (Figure 6.1.3.2). The salinity plot (Figure 6.1.3.2A) and the temperature plot (Figure 6.1.3.2B) show vertical homogeneity as the tide ebbed and flooded with a maximum concentration of SPM (mg l^{-1}) that occurred over the LW period, when the water column was very shallow (less than 1-m deep, Figure 6.1.3.2C).

Vertical homogeneity in salinity and temperature indicates strong vertical mixing associated with fast tidal currents, shallow depths and low freshwater runoff, and therefore buoyancy, into the estuary at that time (Figure 6.1.2A). Peak flood current speeds at the surface and near-bed were essentially the same, whereas peak ebb current speeds at the surface exceeded those near the bed, which indicates the influence of friction at the bed, the enhanced mixing that occurred during the flood, and the possible occurrence of a small component of density-driven (buoyancy) current.

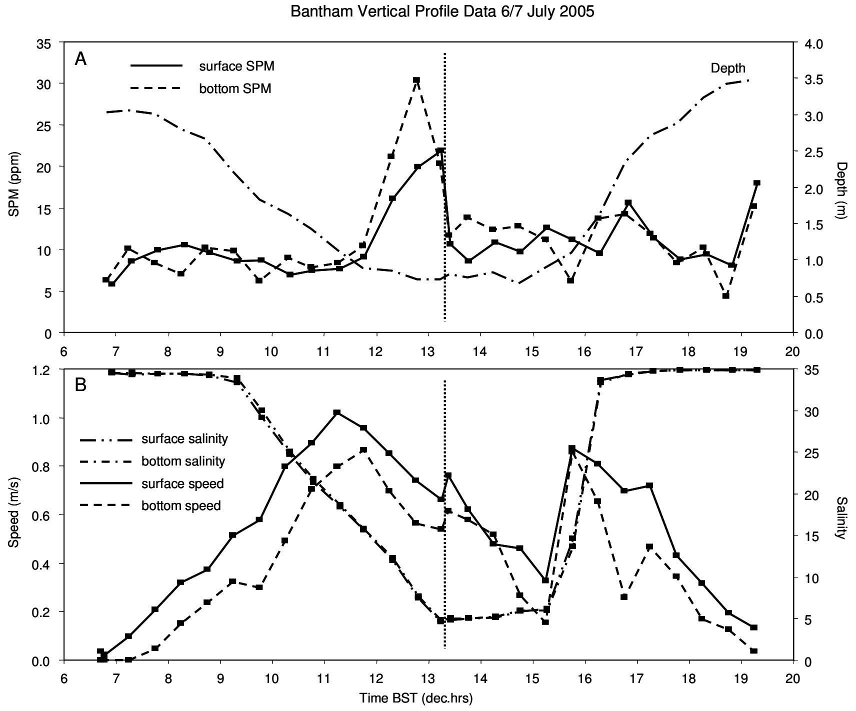

Figure 6.1.3.1: Bantham vertical profile data obtained on 6th and 7th July 2005, with separate days delimited by vertical dotted line. A) Surface and bed suspended particulate matter (SPM, mg l^{-1}) and depth profile (m). B) Surface and bottom salinity and surface and bottom current speed (m s^{-1}).

6.1.3.3. North Efford station, surface and bed data

SPM concentrations were small at the North Efford station (Fig. 6.1.3.3A) and generally less than 10 mg l^{-1}, but were greater on the flood (up to 60 mg l^{-1}) due to suspension of bed sediments by the flood currents (Fig. 6.1.3.3B). Current speeds at the surface reached 0.5 m s^{-1} on the ebb and 0.7 m s^{-1} on the flood and a layered flow developed over HW and the early ebb in which salinity was strongly stratified (Fig. 6.1.3.3B). This indicates preferential transport of sediment into the estuary on the flood.

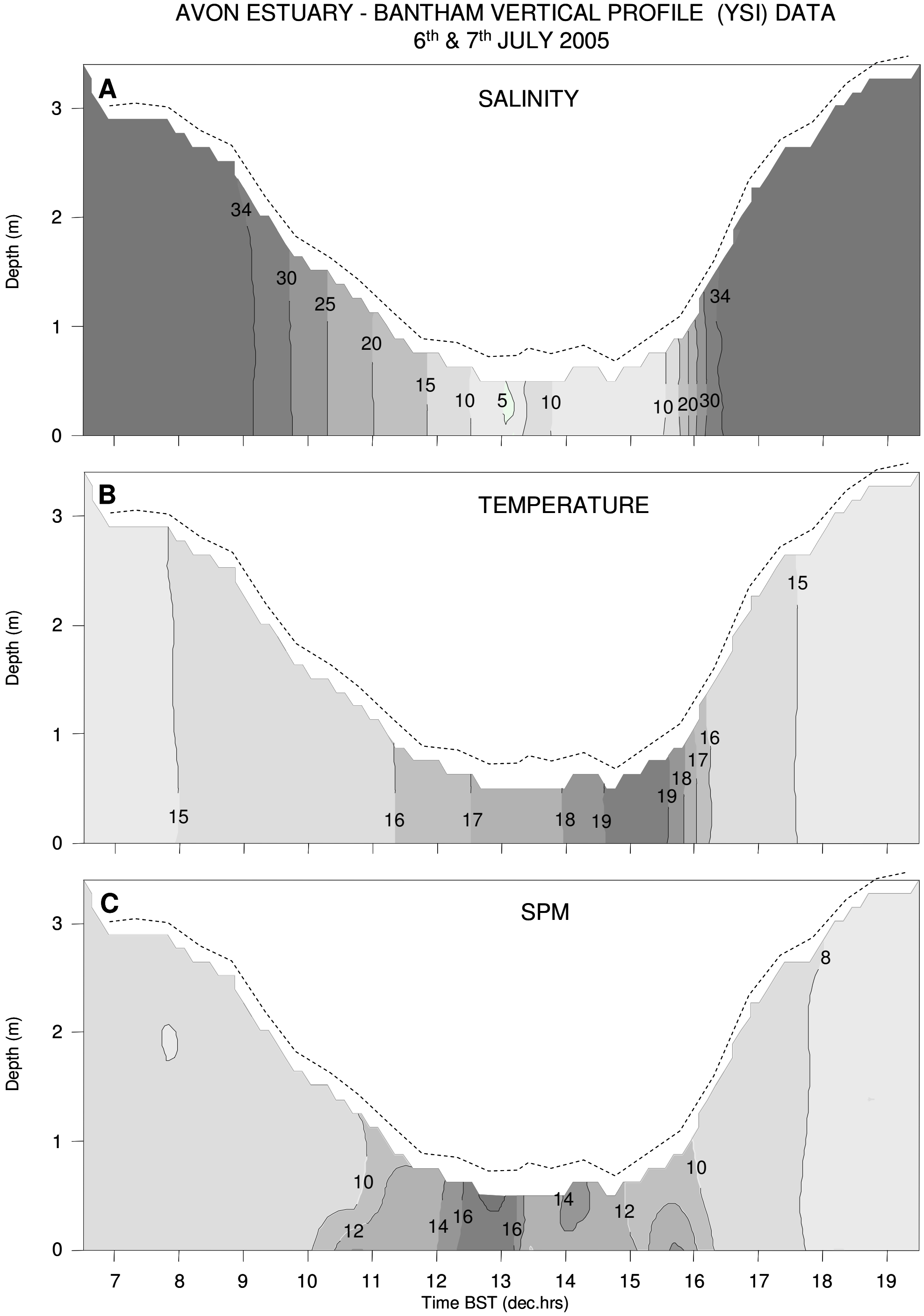

Figure 6.1.3.2: Contoured vertical profile data at Bantham (YSI) for the 6th and 7th July 2005. A) Salinity. B) Temperature and C) SPM (mg l^{-1}).

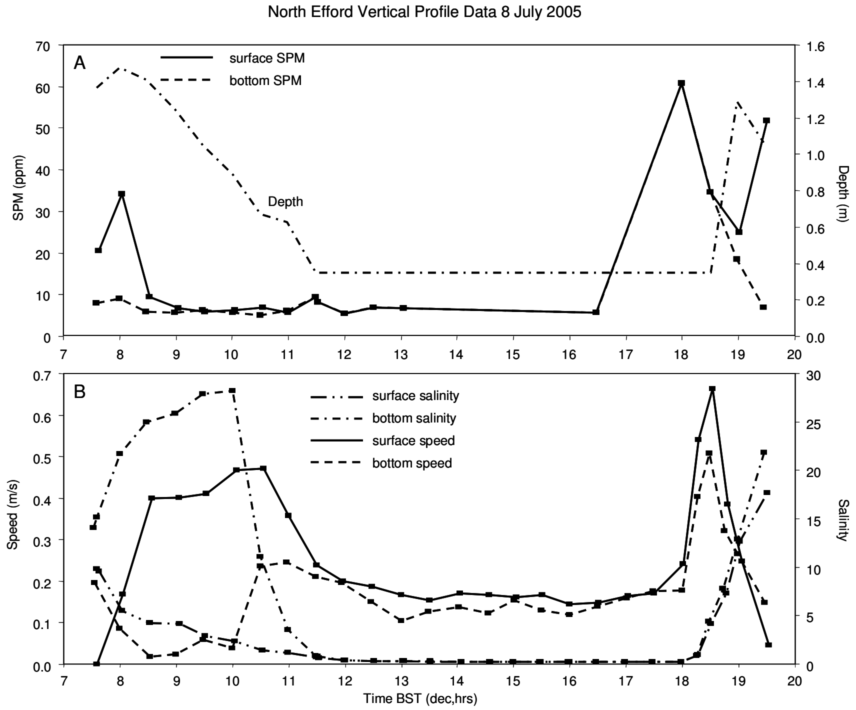

Figure 6.1.3.3: North Efford vertical profile data obtained on 8^{th} July 2005. A) Surface and bed suspended particulate matter (SPM, mg l^{-1}) and depth (m); B) Surface and bottom salinity and surface and bottom current speed (m s^{-1}).

6.1.3.4. North Efford station, contoured data

Vertical-profile data at the North Efford station can be represented as contour plots for the YSI instrument (Figure 6.1.3.4). The salinity plot (Figure 6.1.3.4A) shows strong stratification on the ebb whereas the flooding tide shows vertical homogeneity. The temperature plot (Figure 6.1.3.4B) shows vertical homogeneity as the tide ebbed and flooded with strong solar heating during the day. The SPM (mg l^{-1}) increased during the early flood with a maximum that occurred during the middle of the flood tide (Figure 6.1.3.4C) close to peak speeds.

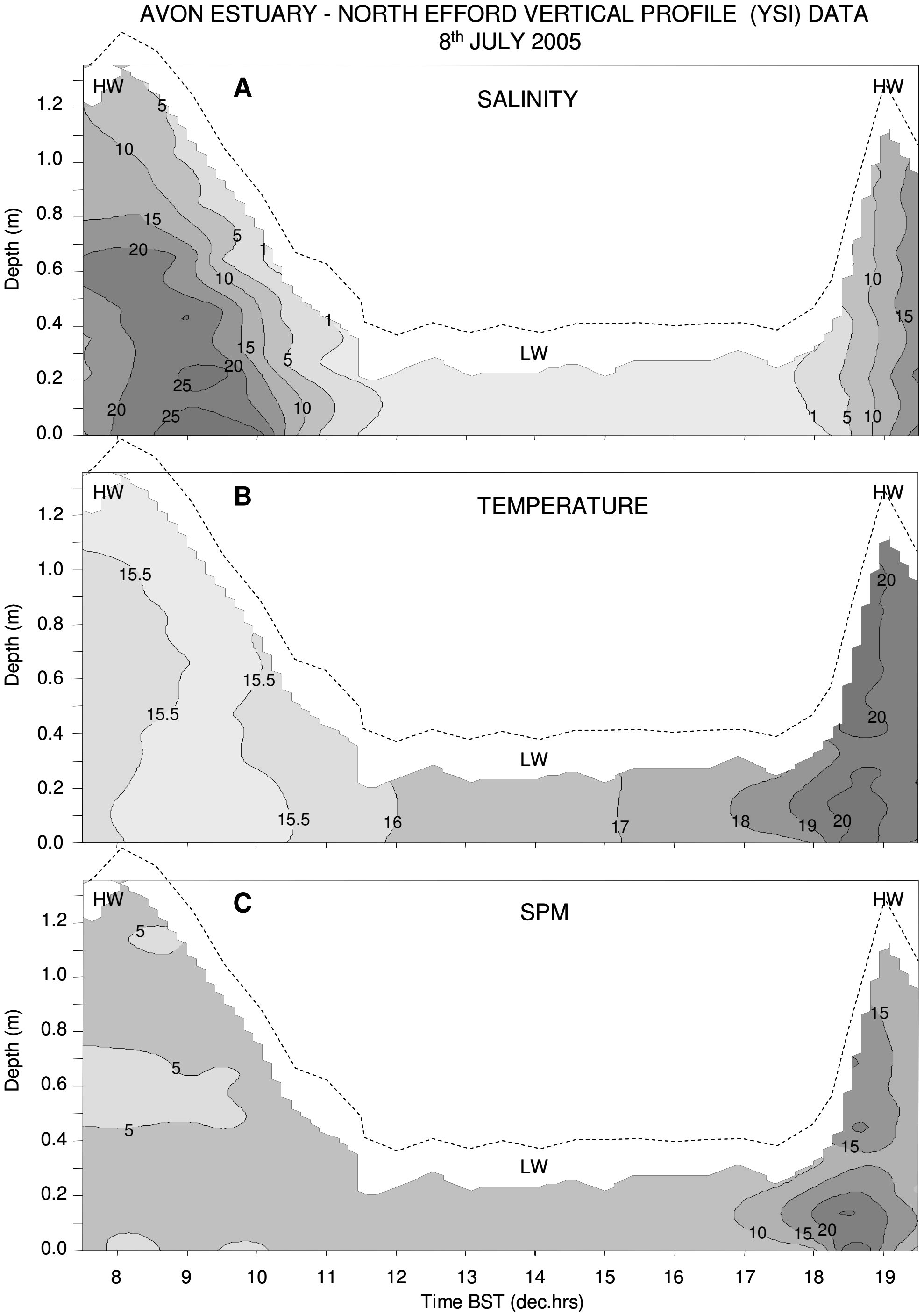

Figure 6.1.3.4: Contoured vertical profile data at North Efford (YSI) for 8th July 2005. A) Salinity. B) Temperature; and C) SPM (mg l^{-1}).

6.1.4. Bed Mounted Instrumentation

6.1.4.1. Bantham station

Longitudinal (axial, U-component) currents at 0.45 m above the bed returned from the wave recorder at the Bantham station are plotted against time for the deployment period (Figure 6.1.4.1, upper panel). The flood currents peaked at between 0.4 m s^{-1} and 0.5 m s^{-1} and occurred for only 3 - 4 hrs of the 12.5 hr tidal cycle. An ebb flow occurred for the remainder of the cycle and reached speeds of between 0.5 m s^{-1} and 0.6 m s^{-1}. LW-slack at this station was very short-lived because currents reversed quickly when the tide turned from ebb to flood (Figure 6.1.4.1, upper panel).

The wave-recorder turbidity sensor became fouled after about 72 hrs of deployment time, leading to the short observed record (Figure 6.1.4.1, central panel). The units of SPM on Figure 6.1.4.1 are instrument volts, which equate to roughly 0 - 10 mg l^{-1} for a voltage range of 0 - 0.04 V. Peak turbidity occurred over the LW period, which is indicative of turbid water from further up-estuary having been carried down-stream on the ebb and up-stream at the beginning of the following flood, carrying resuspended sediment upstream (Figure 6.1.4.1, lower panel). It is unlikely that the SPM maximum is a localised resuspension event at North Efford because flood current speeds maximised after peak turbidity had occurred, although it is likely that resuspension occurred from further down-estuary, in the vicinity of maximum silt and clay accumulation. Significant wave heights for the same period were very small and ranged from 0.01 m at LW to 0.08 m at HW (Fig. 6.1.4.1, lower panel).

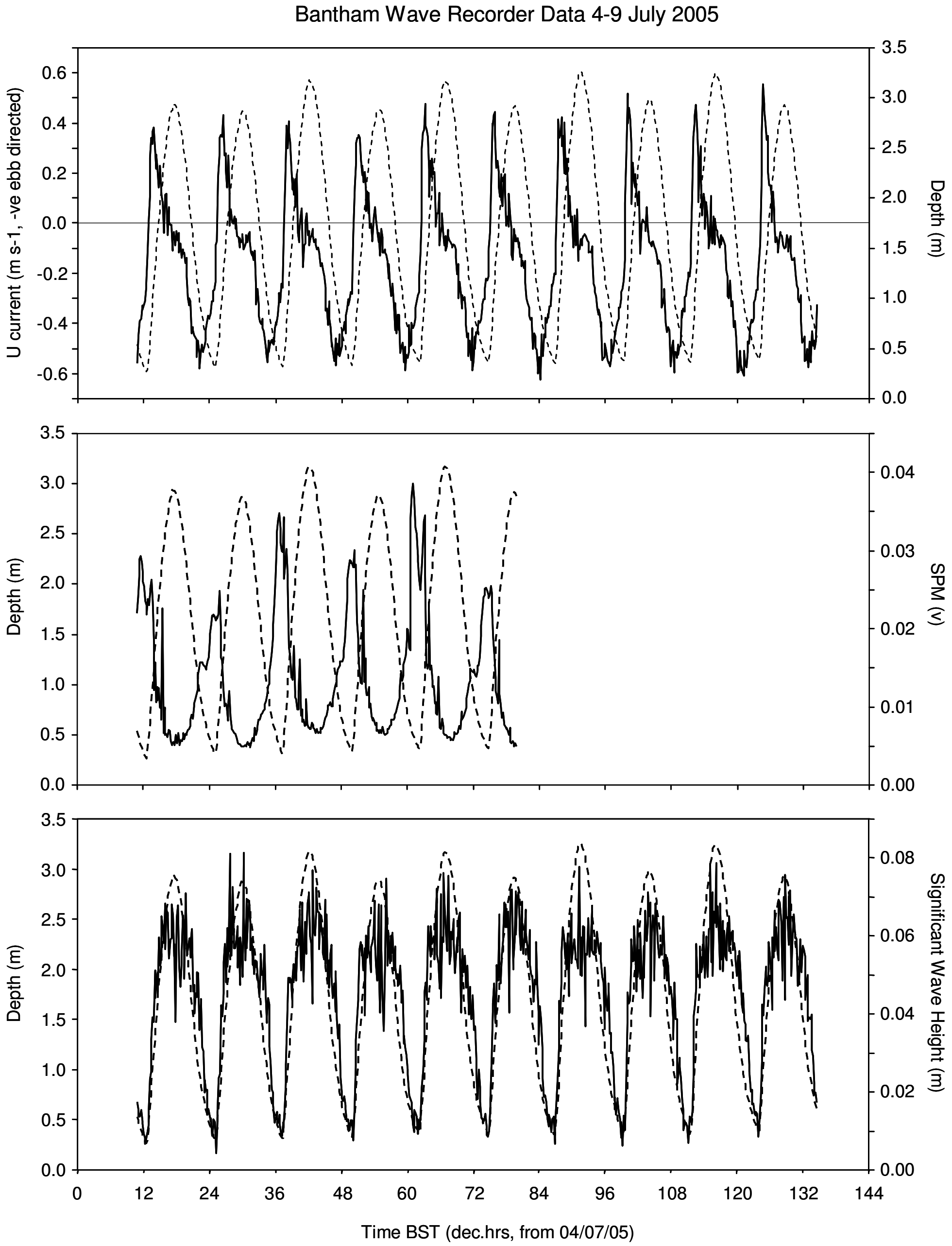

Figure 6.1.4.1: Bantham wave recorder data for 4th – 9th July 2005. The upper panel shows current speed (U component, m s^{-1}); the central panel SPM (instrument volts) and the lower panel the significant wave height (m).

6.1.4.2. North Efford station

The North Efford longitudinal (axial, U component) currents measured by the wave recorder at 0.45m above the bed were plotted against time for the deployment period (Figure 6.1.4.2A). The flood currents maximised at between 0.5 m s^{-1} and 0.6 m s^{-1} and flowed for up to 4 hrs of the 12.5 hr tidal cycle. The ebb flowed for the remainder of the tidal cycle and reached maximum speeds of between 0.3 m s^{-1} and 0.4 m s^{-1}. LW was reached quite quickly once the ebb began and the period of LW-slack often exceeded 5 hrs.

SPM and depth at the North Efford station were taken from the YSI 6600, which was located slightly deeper in the water column than the wave recorder (Figure 6.1.4.2B). SPM showed a dual peak for each tide, a larger peak on the flood tide and a slightly smaller peak on the ebb. These peaks of SPM concentration were coincident with the maximum flood and ebb current speeds and suggest tidal resuspension on the flood and some settling or deposition at HW-slack, followed by down–estuary advection of the remainder on the ebb tide with some resuspension as the ebb maximised. SPM concentration at LW and HW was consistently low when compared with periods of maximum current speed.

Significant wave height for the same period was very small, ranging from 0.01 m at LW to 0.06 m at HW (Fig. 6.1.4.2C). This depth-dependence reflects the greater ‘fetch’ of water surface experienced by the local winds at HW compared with that at LW. At LW the channel widths are narrow and cross-estuary winds are less effective at generating local wave activity.

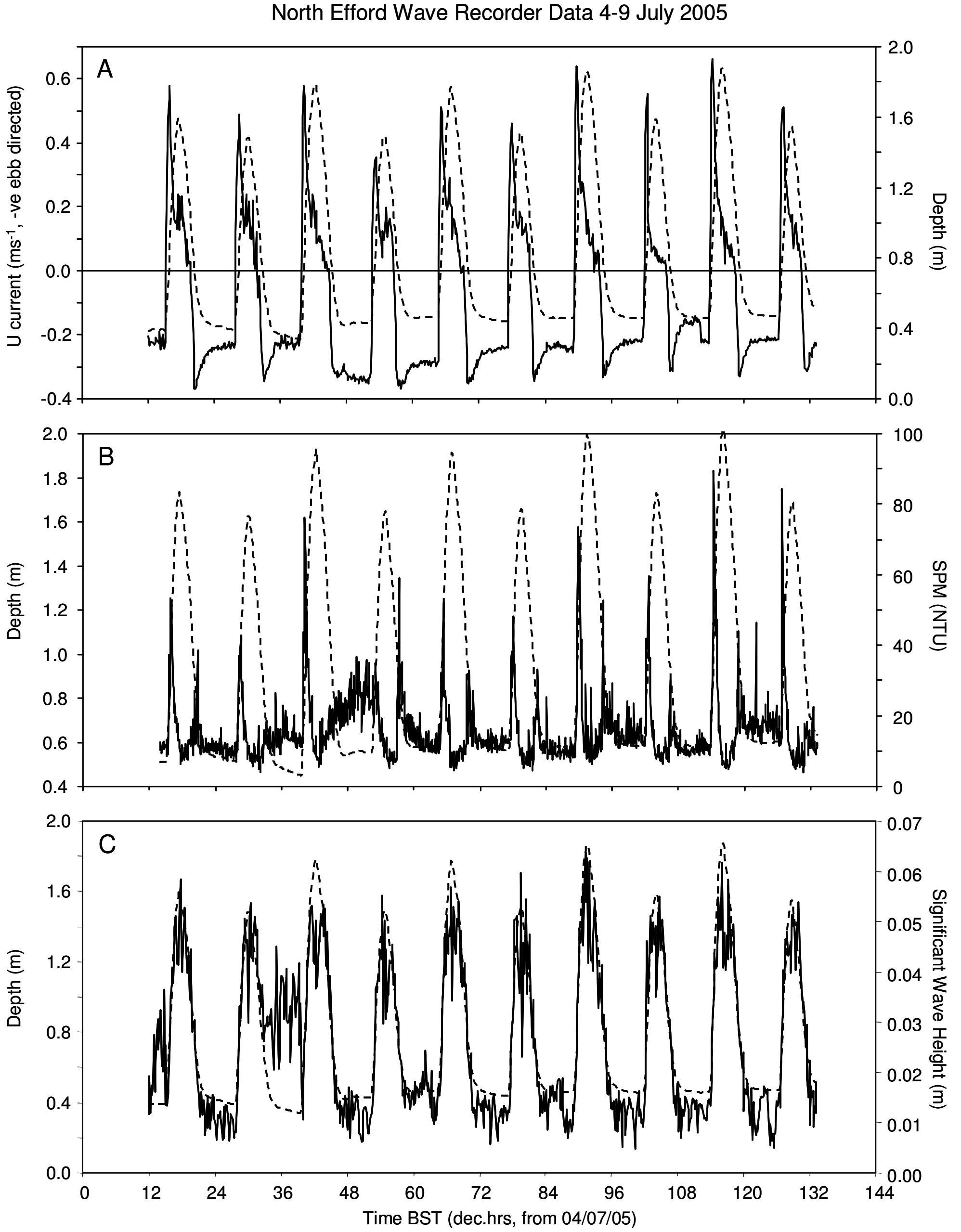

Figure 6.1.4.2: North Efford wave recorder and YSI 6600 data for 4th – 9th July 2005. A) The longitudinal component of current speed (U component, m s^{-1}). B) SPM (NTU) and C) Significant wave height (m).

6.1.5. Tidal Elevation and Wave Damping

6.1.5.1. Tide damping in the estuary

Wave recorders and YSI 6600 multi-parameter sondes were deployed at the Bantham estuary site close to the Harbour Master's Office (GPS: 50 16.731N, 003 52.295W) and just seaward of Bantham Beach, close to the rocks at the eastern side of the beach (GPS: 50 16.674N, 003 52.945W), in order to determine the differences in tidal elevation between the two sites during 4th August 2005. YSI 6600 data from the field program of 5th July 2005 were used to determine differences in tidal elevation between the Bantham and North Efford sites (Figure 6.1.5.1). The tides chosen were as close as possible, in terms of tidal range, as could be achieved within the fieldwork timetable. For August 4th, tidal range (TR) was 3.7 m and HW level was 5.1 m; for July 5th, TR was 3.6 m and the HW level was 5.0 m.

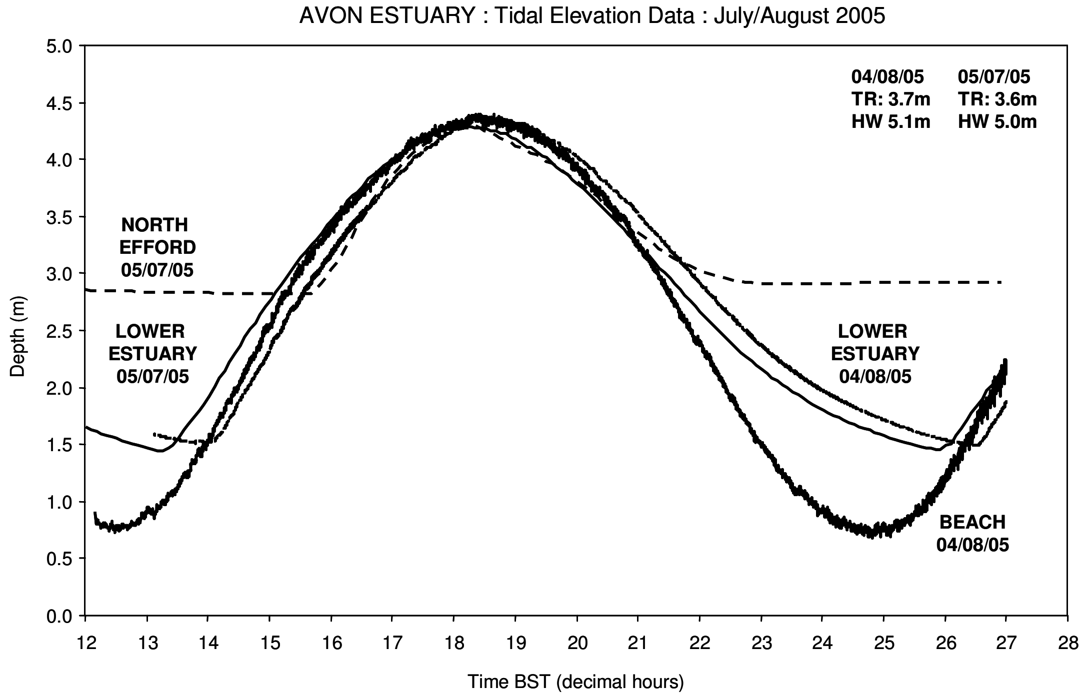

Figure 6.1.5.1: Tidal elevation data for Bantham Beach, Bantham (lower estuary) and North Efford sites during 5th July and 4th August, 2005.

The two lower-estuary water-level plots are in broad agreement and enable a comparison to be made for all three sites despite the measurements being made at different times. The graphs show that there was a considerable reduction in tidal range between the beach and the North Efford site. At Bantham Beach there was a tidal range of 3.7 m, reducing to 3.0 m at Bantham (Harbourmaster's office) and reducing further to 1.5 m at North Efford on the same tide.

6.1.5.2. Wave damping in the estuary

During the evening of 4th August the prevailing winds changed from south-westerly Beaufort 3 (gentle breeze) to south-westerly Beaufort 6/7 (strong breeze to moderate gale). The wave recorder at Bantham Beach, located in the LW surf zone, recorded the resulting increase in significant wave height (Fig. 6.1.5.2A). The wave height increased from 0.5 m over the HW of 4th August to 1.4 m over the following HW during the morning of 5th August.

The wave recorder located in the lower Avon estuary near the Harbourmaster's office showed a significant wave height of 0.07 m on the evening HW of the 4th August and it didn't significantly change by the following HW during the morning of 5th August (Fig. 6.1.5.2B). Both panels of Figure 6.1.5.2 are plotted on the same scale to emphasise the damping effect of the estuary topography on a flooding tide with significant wave activity at the mouth.

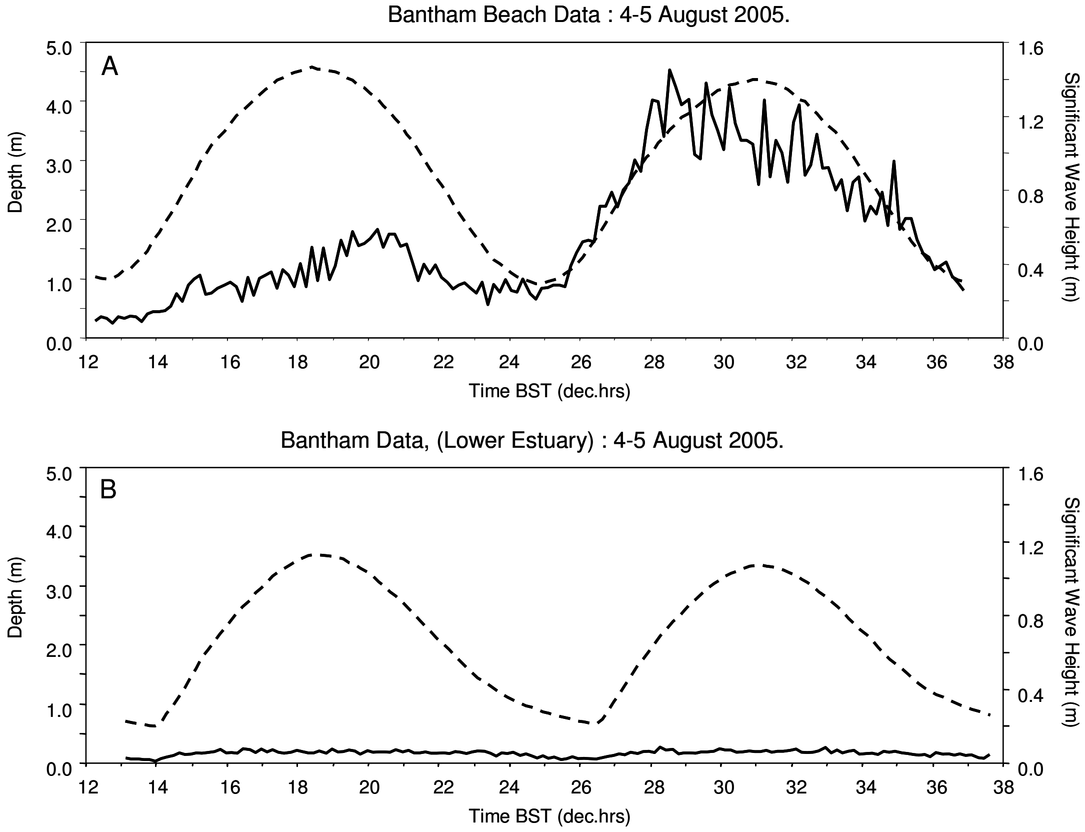

Figure 6.1.5.2: Significant wave height data and water level data (dashed lines, m). A), The Bantham Beach surf zone. B), The Bantham Harbour Master's Office site in the lower estuary.

6.2. Winter (March) 2007

6.2.1. Instrumentation and deployment

To obtain physical data for winter conditions two Valeport 730D Wave Recorders were deployed for the period 9th – 22nd March 2007. The instruments measured current speed and direction, depth, temperature and SPM. The wave recorders measured in a tide-burst mode of 20 seconds at 4 Hz, and a wave-burst mode of 128 seconds at 4Hz every 10 minutes. Attached to each wave recorder was a YSI 6600 multi-parameter sonde with a 5-minute sampling resolution, measuring depth, salinity, temperature and SPM. The wave recorder sensors were located 0.45 m above the bed and the YSI sensors were located at 0.1 m above the bed.

The first pair of instruments was deployed in the deep-channel of the upper estuary at North Efford (GPS: 50 18.505N, 003 50.640W). A second pair of instruments was deployed at Bantham, just below the Harbourmaster's Office in the deep-channel (GPS: 50 16.731N, 003 52.295W). The instruments were carried into the water and placed in position on the bed of the estuary, buoyed off, and a weighted safety line was attached to the shore.

The wave recording instrument at Bantham suffered impact-damage during the period of deployment and the record is subsequently 3 days shorter than that for the instrument at North Efford.

6.2.2. Environmental conditions

Freshwater runoff for the deployment (Fig. 6.2.2A) showed a steady decline in volume from about 14 m^3 s^{-1} at the start of the monitoring period to just over 2 m^3 s^{-1} at the end of the period. The mean tidal range over the monitoring period covered a significant part of a spring - neap cycle (Fig. 6.2.2A).

Prevailing weather conditions are represented by daily-mean westerly and southerly wind vectors (Fig. 6.2.2B). These show that the first 7 days of the deployment were dominated by westerly and south-westerly winds of up to 7 m s^{-1} which then increased in strength and shifted to north-westerly for the next 7 days before calming down to a gentle breeze at the end of the sampling period (Fig. 6.2.2B).

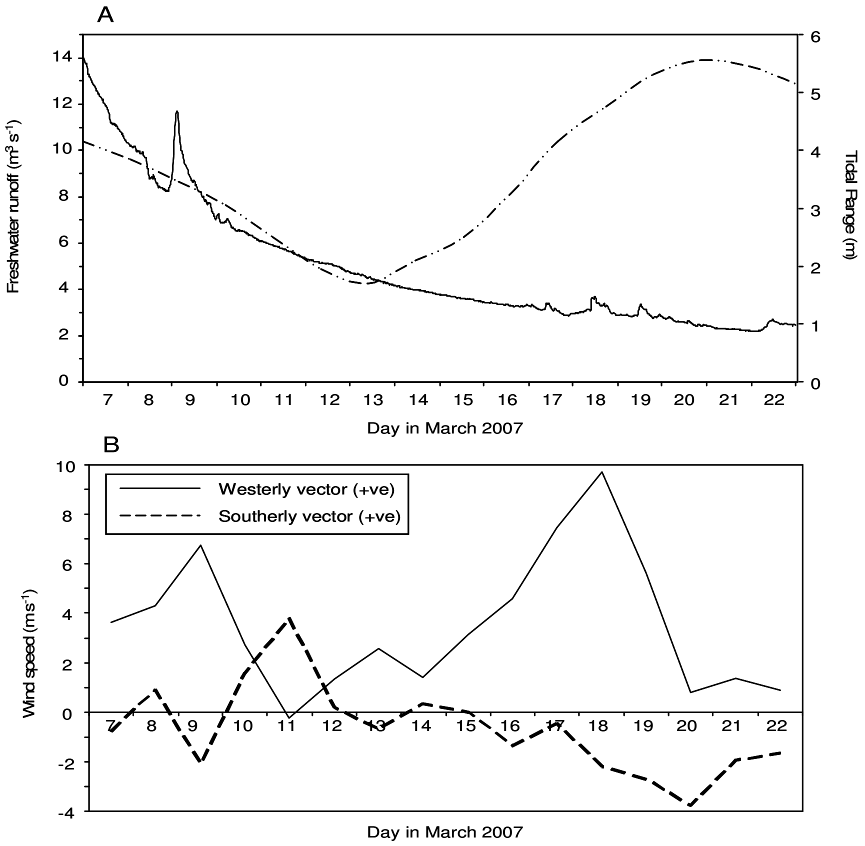

Figure 6.2.2: A.) Freshwater runoff (continuous line) and mean tidal range (broken line) for the deployment period, B.) Daily mean westerly (continuous line) and southerly (broken line) wind vectors for the deployment period.

6.2.3. Bed Mounted Instrumentation

6.2.3.1. North Efford station currents

The wave-recorder data obtained at the North Efford location show the ebb-directed (down-estuary) dominance of currents during the deployment (Figure 6.2.3.1). The time-series of axially directed flows (m s^{-1}, solid line) for the deployment period, when superimposed on the water depth (m, broken line), illustrates the ‘competition’ between tidal forcing and freshwater forcing (Figure 6.2.3.1). Flood tides at North Efford were relatively short-lived events, but could reach current speeds in excess of 0.6 m s^{-1}. Ebb directed currents were dominant and the LW periods of water level were accompanied by a series of current 'plateaus' at about -0.5 m s^{-1}, depending on freshwater flow and tidal range.

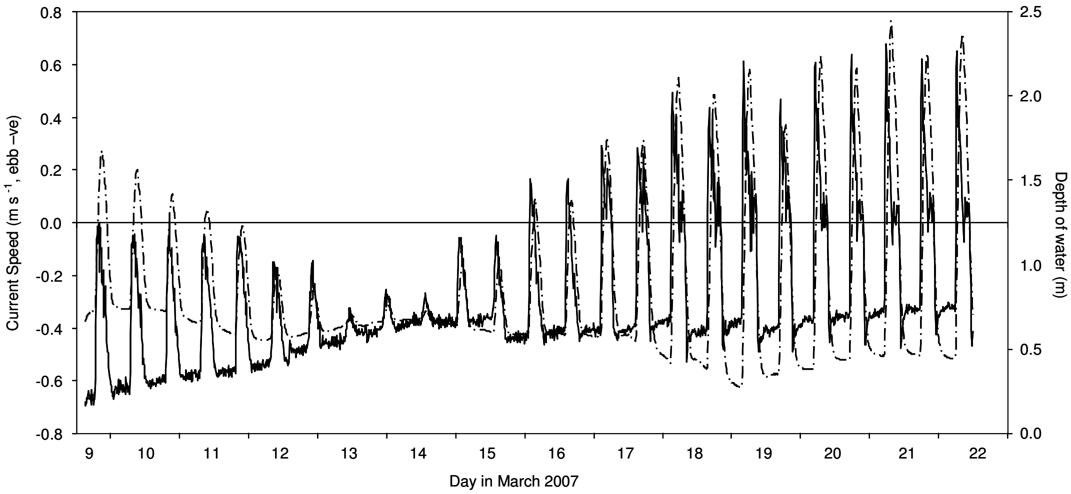

Figure 6.2.3.1: Axial (longitudinal), U, current component (ebb -ve, solid line, m s^{-1}) and water depth (broken line, m) for the North Efford wave recorder deployment.

For the first 6 days of the deployment the wave-recorder data show that all current flows at North Efford were ebb directed, even though the tidal range on 9th March was similar to that on 17th March, when a flood-directed flow occurred on the rising tide. The high runoff of about 14 m^3 s^{-1} on the 9th March was opposing the tide during rising water levels so that ebb-directed flows occurred throughout the tide, although these slowed to minimum speeds at HW. Ebb directed LW currents reached speeds up to 0.7 m s^{-1}. By the time similar tidal ranges were experienced on 17th March, the freshwater flows had reduced and current speeds were between 0.3 - 0.4 m^3 s^{-1} and flood-directed currents occurred on the rising tide.

Tidal range had an important influence on water levels at this site even though currents could be ebb-directed throughout the tide. Spring-tide variations in water level remained strong, whereas the weaker neap tides, in the presence of strong freshwater flows, could have an almost negligible effect on water levels (as observed on 13th and 14th March, when the currents and water levels barely differed from those experienced over LW periods).

6.2.3.2. North Efford station depths, salinity and SPM

The freshwater flow and spring-neap cycle had an important influence on the movement of saline water into the upper part of the Avon Estuary. Increased flows and smaller tides acted together to limit saline intrusion into the estuary, as recorded during 9th – 16th March (Fig. 6.2.3.2A). Saline water was observed only when the runoff had reduced and the tide was large enough to force saline water into the upper estuary, during 17th -22nd March.

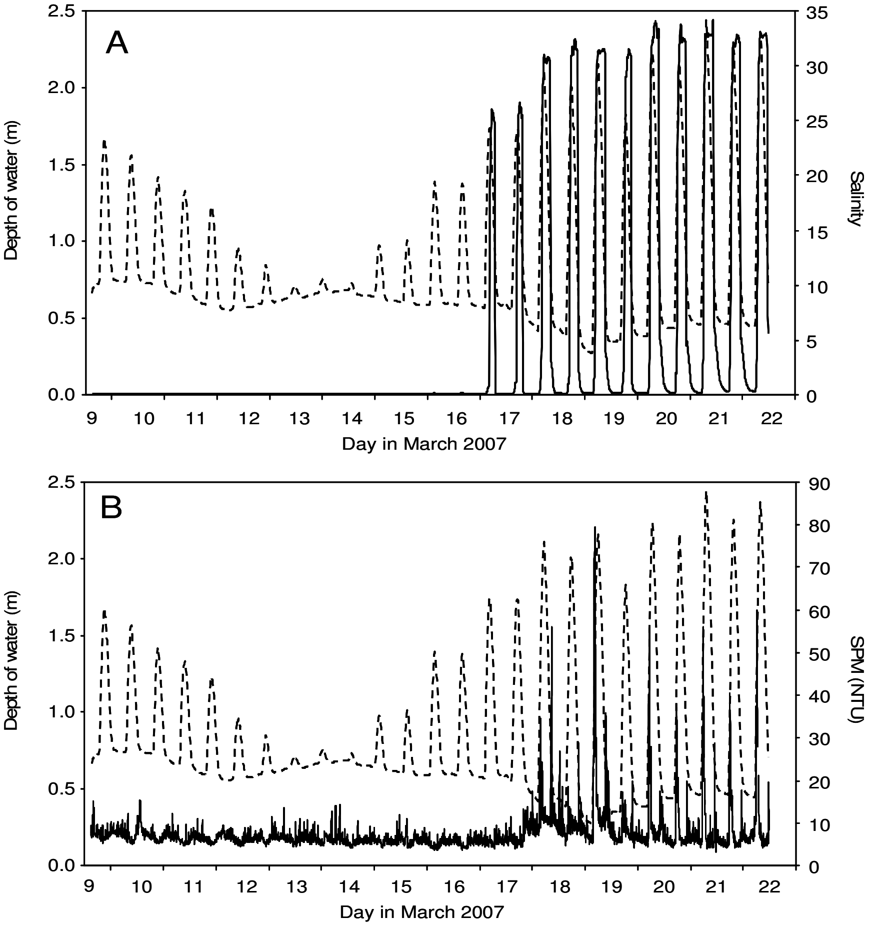

Figure 6.2.3.2: A.) The observed salinity (continuous line) and water depth (broken line) at the North Efford location. B.) The suspended particulate matter concentration (SPM, continuous line) and water depth (broken line) at the North Efford location.

The amount of suspended particulate matter (SPM) in the estuary at the North Efford location (Fig. 6.2.3.2B) generally was relatively low <90 NTU (nephelometric turbidity units) which very roughly equated to 45 ppm (mg l^{-1}). For the first 8 days of the deployment the SPM was fairly constant and represented a fluvial input of SPM with concentrations <10 NTU. When the rising tides eventually led to up-estuary-directed flood-tide currents (Fig. 6.2.3.1) there was an increase in the amount of SPM at both maximum flood (up to 80 NTU) and, to a lesser extent, at maximum ebb (up to 30 NTU). The probable source of this SPM may have been resuspended bed-sediment from the region of maximum accumulated fine sediment, located slightly further down-estuary.

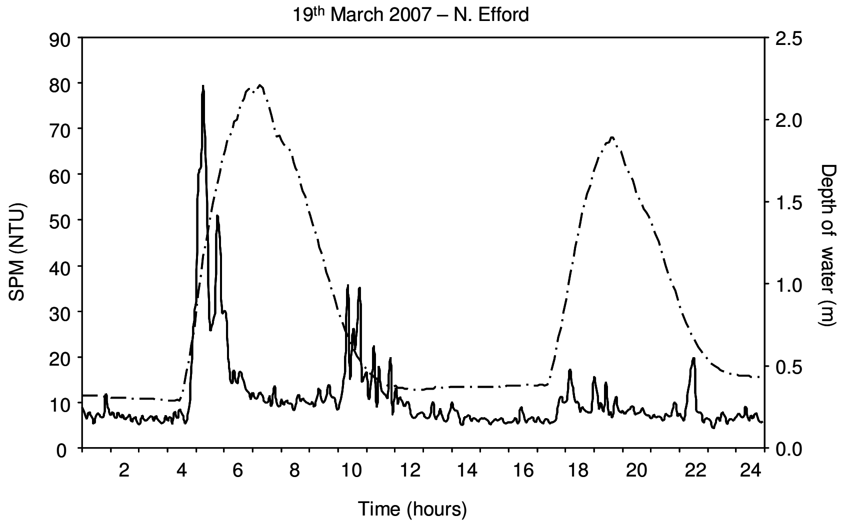

Figure 6.2.3.3: Suspended particulate matter (SPM, continuous line) and water depth (broken line) for the North Efford location for 19th March 2007.

6.2.3.3. North Efford station - intratidal depths and SPM

An expanded view of the SPM data is valuable and for this purpose SPM (solid line) and water depth (broken line) data at North Efford are shown for 19th March 2007 (Figure 6.2.3.3). SPM maximised on the mid-flood toward the end of the ebb for the first and largest tide of the day but was only just discernable on the 0.4 m smaller tide approximately 12 hrs later, suggesting that for similar meteorological forcing and runoff, tidal amplitude could have a significant effect on bed resuspension in the upper estuary.

6.2.3.4. North Efford station – wave effects on SPM

Wave action as a contributory factor to bed resuspension in the main channel of the upper estuary during the monitoring period seems to be unlikely; the significant wave height was less than 0.08m in a 2.5-m water column. At LW the significant wave height was frequently less than 0.04m (Fig. 6.2.3.4). The direct effect of these small waves on resuspension was most likely restricted to the finest sediment on the upper parts of the intertidal areas.

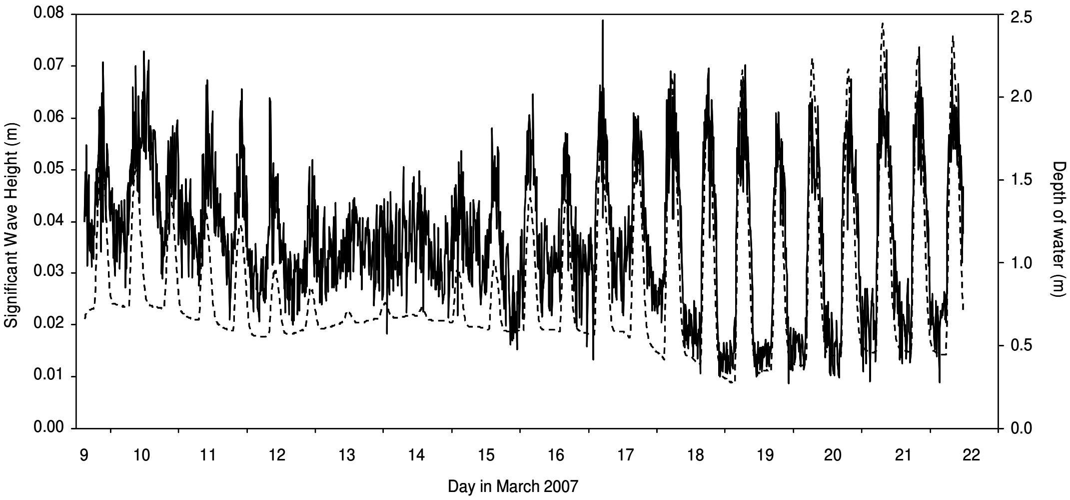

Figure 6.2.3.4: Significant wave height (solid line) and water depth (broken line) for the North Efford wave recorder deployment.

6.2.3.5. Bantham station currents

The second pair of instruments was deployed at Bantham (Fig. 6.2.3.5). The flood-tide current component U (axial, m s^{-1}, solid line) during rising water levels (water depth in m, broken line) ranged from 0.22 m s^{-1} to 0.50 m s^{-1} during the period of observations. The high-runoff and neap-tide part of the record (9th – 15th

March) had flood currents of up to 0.3 m s^{-1} increasing to 0.5 m s^{-1} as the spring tides increase in range between 16th – 18th March.

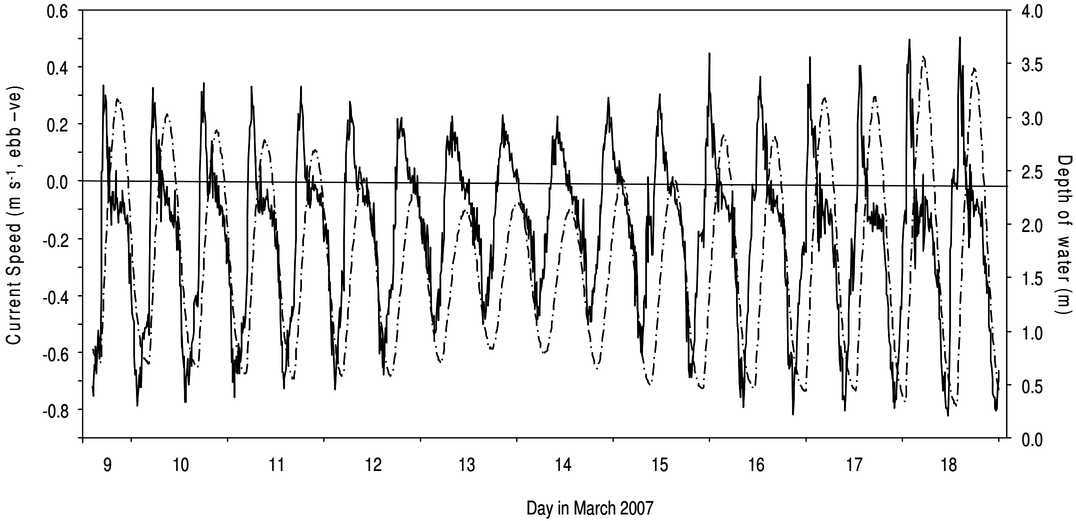

Figure 6.2.3.5: Longitudinal current component (U, ebb -ve, solid line) and water depth (broken line) for the Bantham wave recorder deployment.

Flood-directed currents were relatively short lived in this estuary, even near the mouth (Figure 6.2.3.5). Ebb currents reached speeds of up to 0.8 m s^{-1} during high runoff and spring tides and 0.5 m s^{-1} during neap tides. Ebb current speeds maximised toward the end of the falling tide, but before LW.

6.2.3.6. Bantham station depths, salinity and SPM

The lower estuary experienced a full range of salinity during most tides, ranging from less than 1 at LW, due to freshwater discharge, to >33 at HW, due to coastal seawater (Fig. 6.2.3.6A). As spring tides increased and freshwater runoff fell the maximum salinity at observed over each tide at Bantham became increasingly plateau-like (during 18th – 22nd March) as coastal waters 'spent' more time at the site. A LW presence of saline water (< 7) was recorded when the tide was large enough to force saline water into the upper estuary and the runoff was too low to completely flush saline waters from the estuary during the ebb.

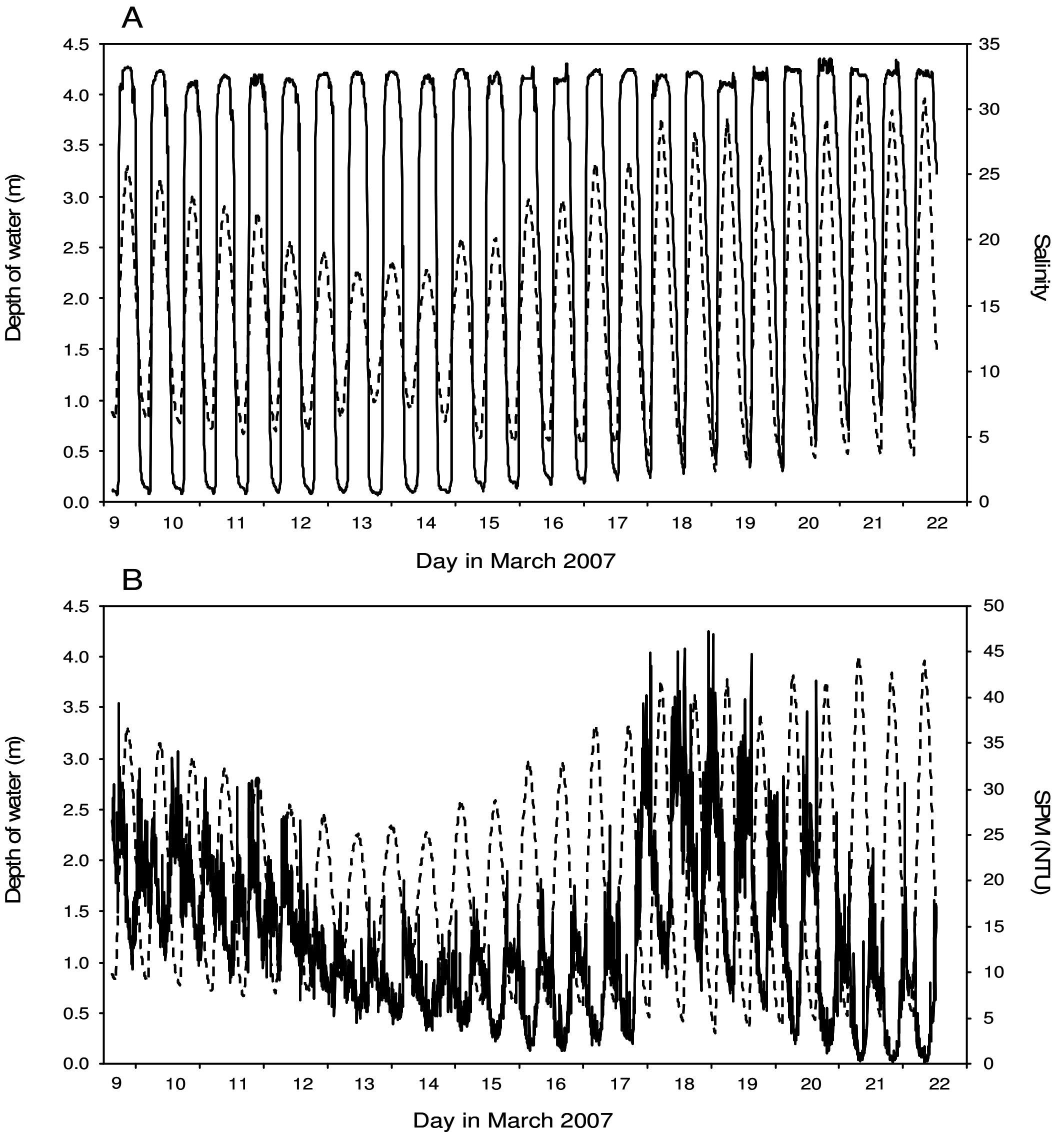

Figure 6.2.3.6: A.) This shows salinity (continuous line) and water depth (broken line) for the Bantham location. B.) Suspended particulate matter (SPM, continuous line) and water depth (broken line) at Bantham.

The trend in the SPM loading tended to reflect the reduction in tidal amplitude and freshwater runoff for the period 9th – 15th March and stayed fairly low until 17th March (Fig. 6.2.3.6B). SPM loading in the lower estuary was less than 50 NTU for the whole deployment period but peaked as low as 20 NTU during weak tides and low runoff. As the tidal amplitude increased during the period 18th -20th March there was a significant rise in the level of SPM which was not sustained with the continuing spring tides, which suggests that another influence contributed to bed-sediment resuspension over this period.

6.2.3.7. Bantham station - depths and waves

Significant wave height for the deployment period (Fig. 6.2.3.7) was fairly consistent for the whole period of deployment and ranged from 0.01 m during LW periods to 0.07 m at around HW.

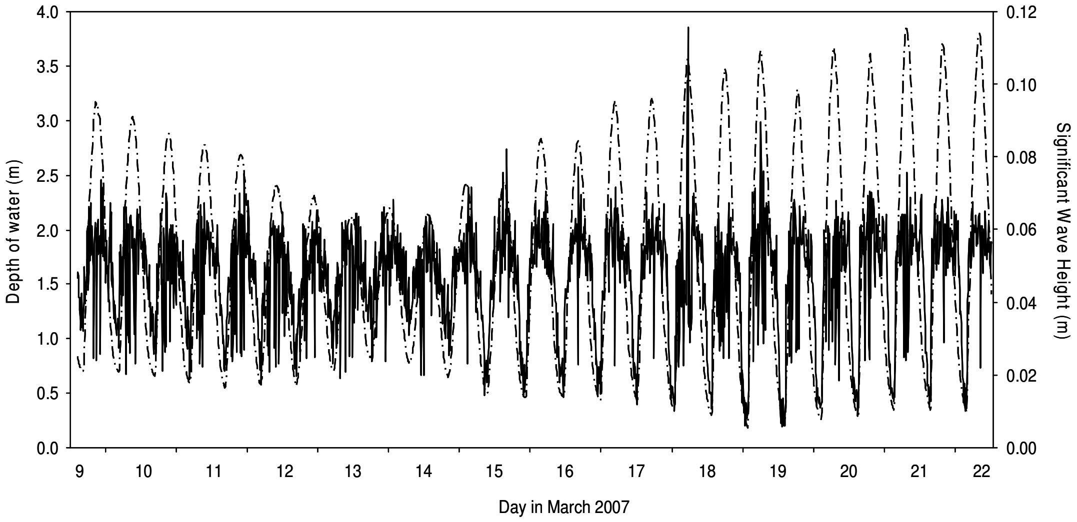

Figure 6.2.3.7: Significant wave height (solid line) and water depth (broken line) for the North Efford wave recorder deployment.

6.2.3.8. Bantham station - waves and SPM

Raised SPM levels at the Bantham station were coincident with LW periods and with peak flood and ebb currents, whereas they were much lower over the HW period, especially up to 17th March (Figure 6.2.3.8). The highest levels of SPM were reached on the 17th – 19th March, coincident with LW, and occurred on days when the prevailing north-westerly winds were at their strongest and freshwater runoff was low and decreasing (Figures 6.2.3.8 and 6.2.2).

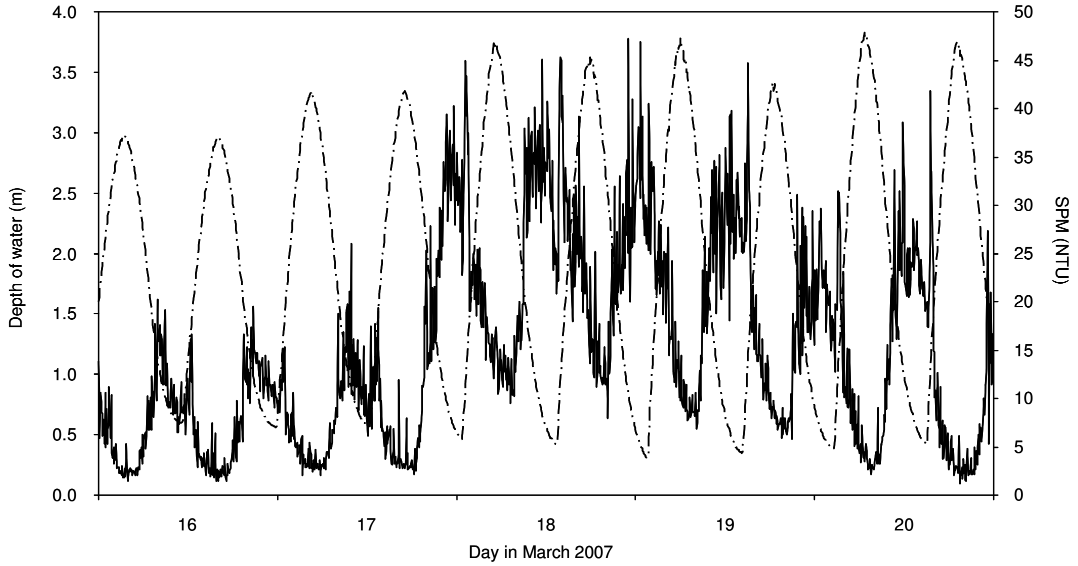

Figure 6.2.3.8: Suspended particulate matter (SPM, continuous line) and water depth (broken line) for the Bantham location during 16th – 20th March 2007.

7. Modelling

7.1. Water transport solution

The one-dimensional, cross-sectional-averaged hydrodynamic equations for water levels and currents were solved as a function of distance along the Avon Estuary from the estuary's head (the Weir near Aveton Gifford) to its mouth (at Bantham Beach) utilising the observed bathymetric data provided by the Atkins and PML surveys on widths, areas and depths as functions of water level. Data on freshwater runoff into the estuary was supplied by the EA and comprised 'actual', daily-averaged flow, as measured in the river Avon at Loddiswell, and 'naturalised' flow, which is the daily-averaged flow that is estimated to have occurred in the absence of the Avon Reservoir (Tim Shipton, personal communication). The difference between these flows generally (but not always) is small and a comparison of the modelled estuarine hydrodynamics with and without the reservoir gives an indication of the effects of the reservoir on the estuary. Modelled water levels at the mouth of the model Avon (Bantham Beach) were computed using a tidal forecast/hind-cast program. The model was run for the period May 1990 to December 2004.

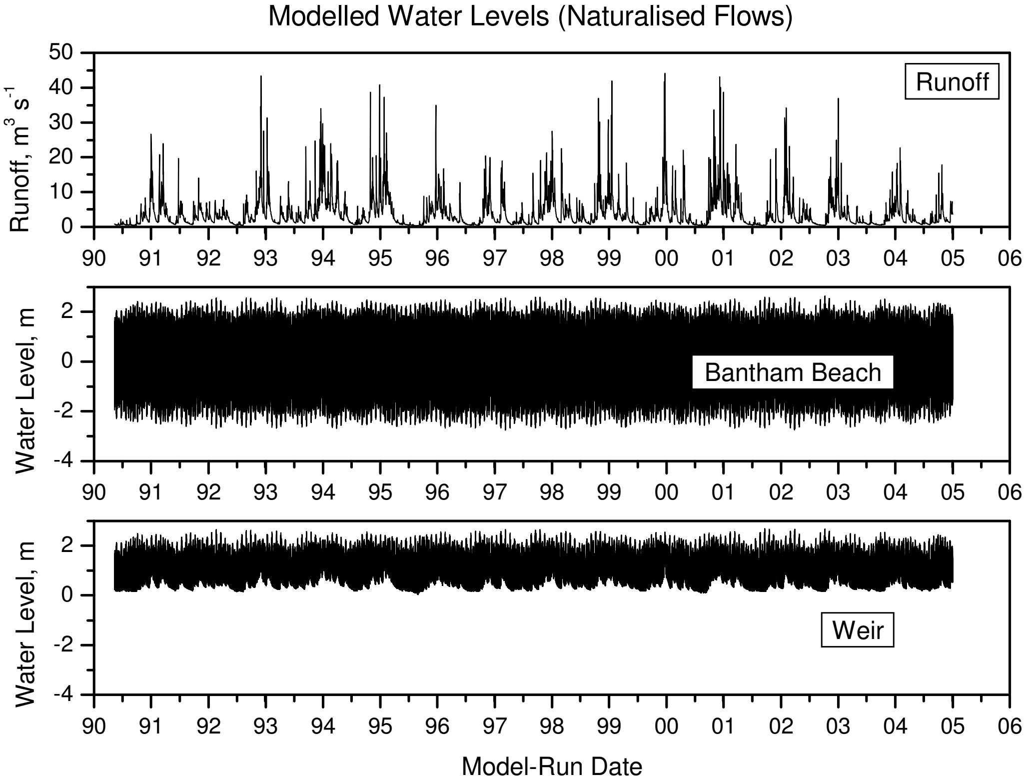

Figure 7.1.1: Time-series of modelled data for the period May 1990 to December 2004. The upper panel shows the estimated freshwater flow into the estuary at the weir in the absence of the Avon reservoir (the 'naturalised' flow, courtesy of the EA); the central panel shows the 'forced' water levels (relative to ODN) at the mouth of the estuary; and the lower panel the computed water levels (relative to ODN) at the weir, subject to 'naturalised' freshwater flow.

7.1.1. Modelled water levels

The daily-averaged naturalised freshwater flow into the estuary at Aveton Gifford during the period May 1990 to December 2004 is shown on Figure 7.1.1(upper panel). At the scale plotted the naturalised freshwater flow is indistinguishable from the actual freshwater flow. A strong seasonal signal is present with a winter flow that can occasionally exceed 40 $m^3 s^{-1}$ and a summer flow that can be less than 0.5 $m^3 s^{-1}$.

An example is given of the modelled water levels computed by the model by showing those at Bantham Beach and those at the weir (Figure 7.1.1(central and lower panels)). The water levels at Bantham Beach have a mean of 0.13 m above ODN (ordnance datum Newlyn) and vary from +2.6 to -2.7 m over the period, relative to ODN (Figure 7.1.1(central panel)). The spring-neap cycle is evident as closely-spaced large and small alternate peaks, as are the seasonal spring and autumn tidal maxima.

Similar water levels occur at the weir over HW but the LW portion of the water level variations is truncated by the shallow water depths and the attenuation of the tide as it propagates into the estuary from Bantham Beach (Figure 7.1.1(lower panel)). The water levels at the weir have a mean of 0.87 m above ODN (ordnance datum Newlyn) and vary from +2.7 to 0.04 m over the period, relative to ODN. The spring-neap cycle is again evident as closely-spaced large and small alternate peaks, as are the seasonal spring and autumn tidal maxima.

7.1.2. Effects of 'naturalised' as opposed to actual flow on water level

The effects of freshwater flow and the influence of the Avon reservoir are illustrated for a sub-sample between June 2001 and December 2004 of output data from the whole modelled period, in order to show greater temporal detail. The influence of freshwater flow on LW water levels is very pronounced, with LW levels strongly correlating with the flow (Figure 7.1.2 (upper and central panels)). LW levels increase by as much as approximately 1 m in response to the highest freshwater flows that occurred during the reduced period illustrated in Figure 7.1.2.

The influence of the Avon reservoir is illustrated for a sub-sample of output data from the whole modelled period, again between June 2001 and December 2004, by subtracting the water levels at the weir computed using naturalised freshwater flow (i.e. without the Avon reservoir) from water levels at the weir computed using actual freshwater flow (i.e. with the Avon reservoir, Figure 7.1.2 (lower panel)). It is seen that the difference generally is small (less than a couple of centimetres, with the reservoir acting to reduce estuary water levels at the weir) although on occasions the effect can be as great as 0.1 – 0.2 m. Over the whole period (1990 to 2004) the greatest water-level difference was 0.3 m and the mean was 0.01 m. Therefore, the effect of the Avon reservoir on estuary water levels near the weir is relatively slight.

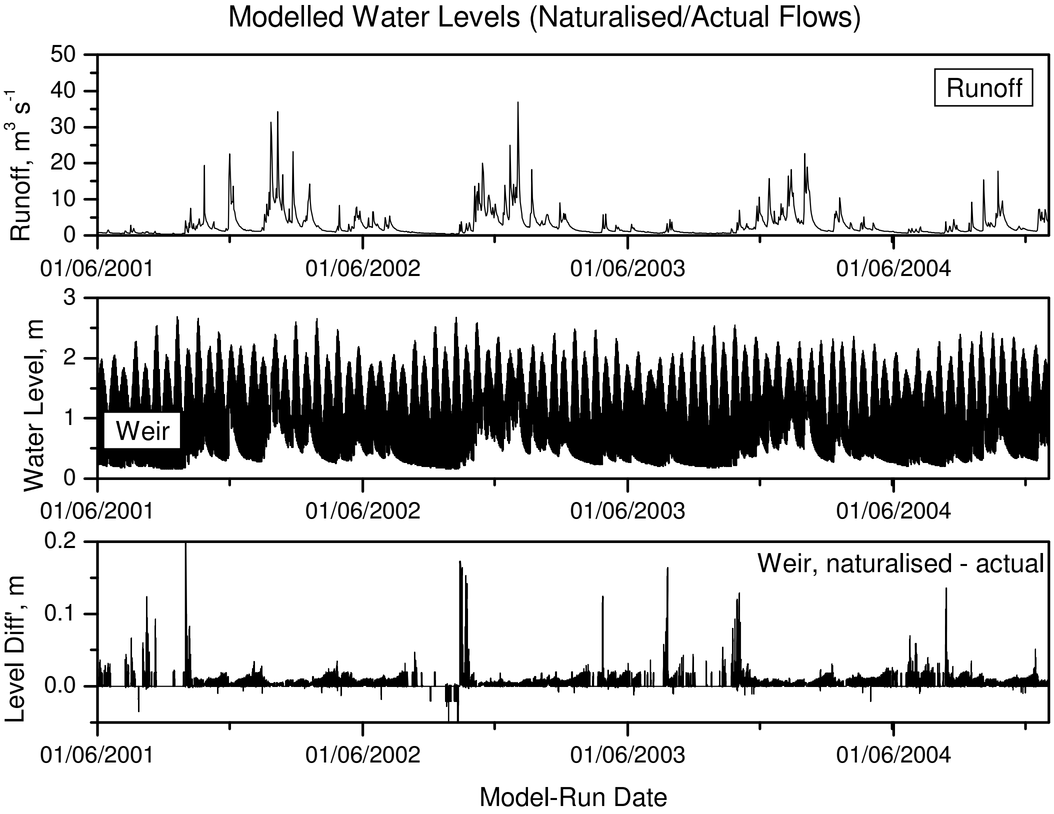

Figure 7.1.2: Time-series of modelled data for the period June 2001 to December 2004. The upper panel shows the estimated freshwater flow into the estuary at the weir in the absence of the Avon reservoir (the 'naturalised' flow, courtesy of the EA); the central panel shows the computed water levels (relative to ODN) at the weir, subject to 'naturalised' freshwater flow; and the lower panel the difference between 'naturalised'-flow water levels at the weir and actual-flow water levels there.

7.1.3. Effects of 'naturalised' as opposed to actual flow on current speeds

The effects of freshwater flow and the influence of the Avon reservoir on estuary current speeds are again illustrated for a sub-sample between June 2001 and December 2004 of output data from the whole modelled period, in order to show greater temporal detail. The influence of freshwater flow on currents is very pronounced, with maximum ebb current speeds strongly correlating with the flow (Figure 7.1.2. (upper and central panels)). These currents exceeded 1 m s^{-1} in response to the highest freshwater flows that occurred during the reduced period illustrated in Figure 7.1.3 (central panel). The effect of tides on currents just down-estuary of the weir is to reduce the ebb-directed current during the rising tide.

The influence of the Avon reservoir is illustrated for a sub-sample of output data from the whole modelled period, again between June 2001 and December 2004, by subtracting the currents at the weir computed using naturalised freshwater flow (i.e. without the Avon reservoir) from currents at the weir computed using actual freshwater flow (i.e. with the Avon reservoir, Figure 7.1.2 (lower panel)). It is seen that the difference generally is small (less than a couple of cm s^{-1}, with the reservoir acting to reduce ebb-directed estuary currents at the weir) although on occasions the effect can be as great as 0.1 m s^{-1}. Over the whole period (1990 to 2004) the greatest speed difference was 0.2 m s^{-1} and the mean was less than 0.01 m s^{-1}. Therefore, the effect of the Avon reservoir on estuary current speeds near the weir is relatively slight.

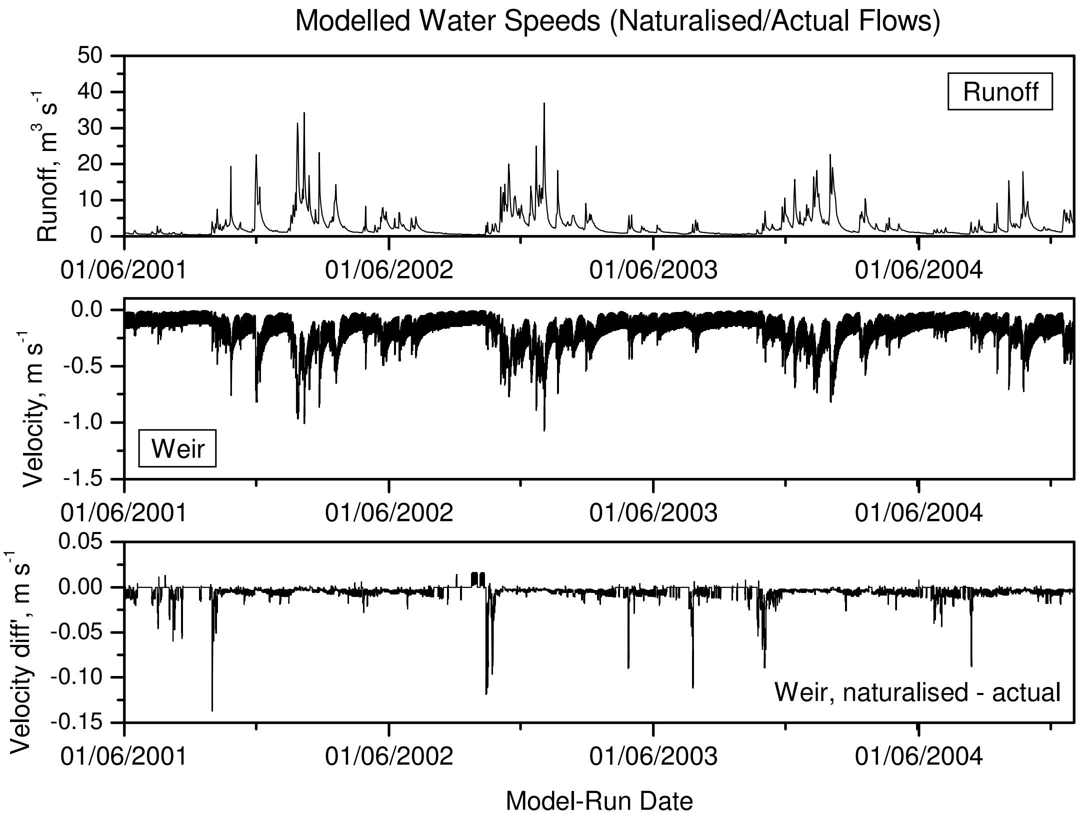

Figure 7.1.3: Time-series of modelled data for the period June 2001 to December 2004. The upper panel shows the estimated freshwater flow into the estuary at the weir in the absence of the Avon reservoir (the 'naturalised' flow, courtesy of the EA); the central panel shows the computed current velocities (flood positive, ebb negative) at the weir, subject to 'naturalised' freshwater flow; and the lower panel the difference between 'naturalised'-flow velocities at the weir and actual-flow velocities there.

7.2. Sediment transport solution along the Avon

The one-dimensional, cross-sectional-averaged water levels and currents that were computed as a function of distance along the Avon Estuary from the Weir near Aveton Gifford to its mouth at Bantham Beach using the hydrodynamic model were used to compute the local sediment transport at each section of the estuary. To do this, cross-sectional-averaged sediment grain sizes were used in the various sediment transport relationships and sediment cohesion was ignored (section-averaged median sizes are never less than the equivalent of very fine sand). Calculations are made with and without the effects of waves, although these are small within the estuary itself, and for naturalised and actual freshwater flows, in order to give an indication of the effects of the reservoir on the estuary. The model was run for the period May 1990 to December 2004.

7.2.1. Modelled sediment transport – effect of tides

Although freshwater flow is always present, its main influence on sediment transport is felt during the late ebb, especially in the upper reaches, near the weir; at other times the tidal currents are very important in moving sediment, if they are sufficiently fast. Sediment is moved both as suspended load, i.e. conveyed in suspension by the currents and as bed-load (the movement of bed-form features by currents that cause drag at the seabed).

As an illustration of tidal influences, the modelled, instantaneous sediment transport rates due to the tides (with naturalised freshwater flow entering at the weir) across three sections of the estuary are shown on Figure 7.2.1 (upper, central and lower panels). The transport relates to each specific section with its own particular currents and grain-size distribution. At Cockleridge narrows (the very narrow section of estuary close to Ham Cottage) there is ebb and flood transport that increases at spring tides due to the faster current speeds then (Figure 7.2.1 (upper panel)). Therefore, the fastest flood currents will transport sediment into the estuary, which is an effect that will be enhanced if storms occur during the flooding tide, although the long-term tendency (the mean transport over several years) in the absence of waves and storms is for material to be transported out of the estuary, especially during winter months, due to the dominance of ebb-directed currents from tides and freshwater runoff. At Stadbury Plantation, in the central reaches of the estuary, the flood-directed sediment transport due to tidal currents is much more pronounced (Figure 7.2.1 (central panel)), which corresponds to the accumulation of large amounts of finer sediment in this region of the estuary (Figure 4.1). Again, the effect of larger freshwater flow during winter is to enhance the ebb-directed tidal currents and reduce the flood-directed tidal currents such that sediment transport is directed down-estuary. Accumulation therefore occurs during the low freshwater runoff months. Close to the weir (200 m down-estuary) the sediment transport is very small and occurs only during the strongest freshwater flow (Figure 7.2.1 (lower panel)). This is a consequence of the very coarse material there and the absence of a flood-directed tidal current.

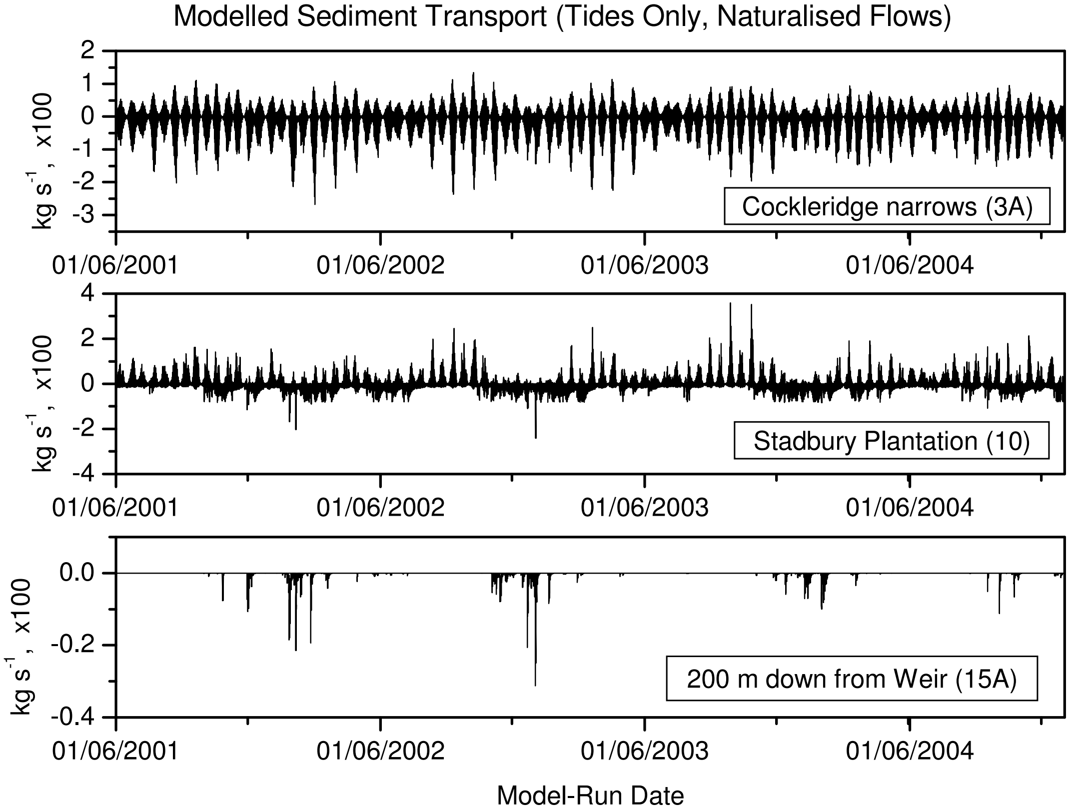

Figure 7.2.1: Time-series of modelled data for the period June 2001 to December 2004. The upper panel shows the computed sediment transport due to tides at Cockleridge narrows, using the 'naturalised' freshwater flow into the estuary at the weir (flood positive, ebb negative); the central panel shows the same for Stadbury Plantation; and the lower panel the same for just down-estuary (200 m) of the weir.

7.2.2. Modelled transport – effect of 'naturalised' as opposed to actual flow

As an illustration of the effects of 'naturalised' as opposed to actual freshwater flow on the sediment transport due to tides, the modelled, instantaneous sediment transport rates due to the tides were computed with both naturalised and actual freshwater flow entering at the weir and the solutions subtracted to derive differences. These differences in sediment transport across three sections of the estuary are shown on Figure 7.2.2 (upper, central and lower panels).

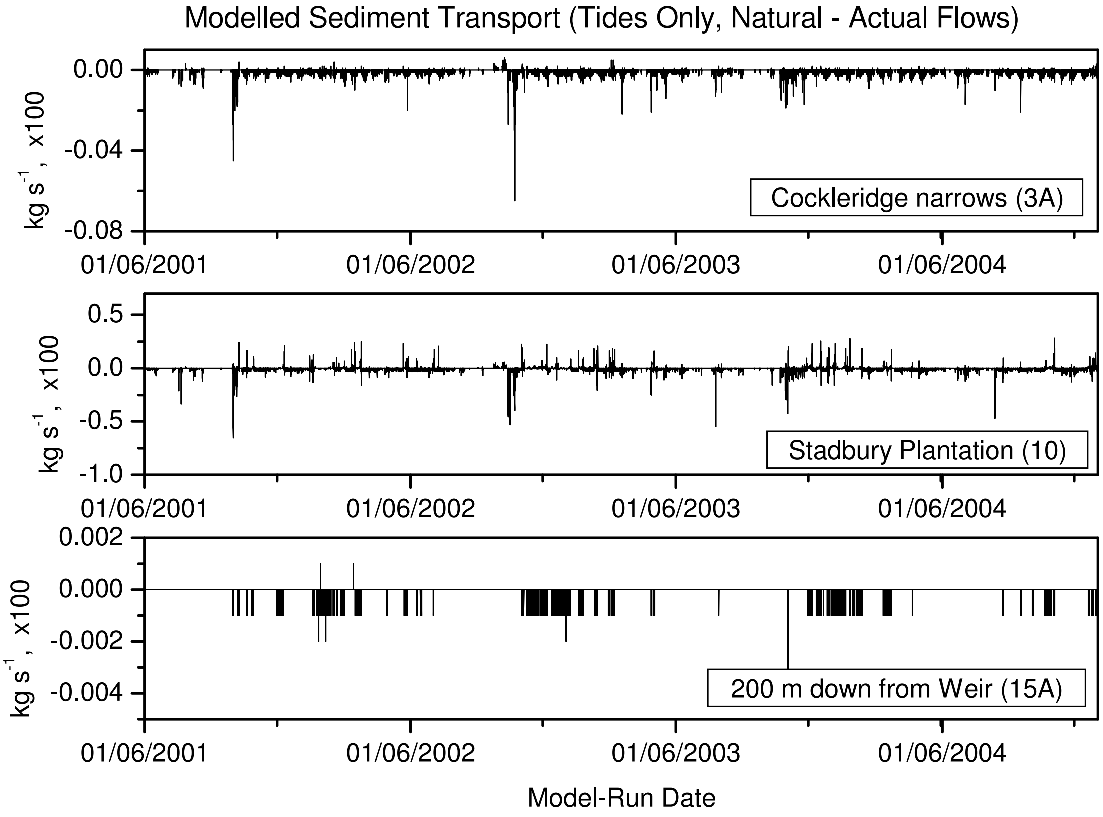

Figure 7.2.2: Time-series of modelled data for the period June 2001 to December 2004. The upper panel shows the computed difference in tidal sediment transport at Cockleridge narrows (flood positive, ebb negative) caused by the difference between naturalised and actual freshwater flow; the central panel shows the same for Stadbury Plantation; and the lower panel the same for just down-estuary (200 m) of the weir.

The differences in sediment transport generally are very small, but with some exceptions that occur late in the year. They are also generally ebb-directed, so that the effect of the reservoir is to reduce ebb-directed transport and thus enhance any tendency for siltation, although the effect is slight. In the case of Cockleridge narrows (Figure 7.2.2 (upper panel)) the reservoir reduces seaward transport of sediment by about 1% over the period 1990 to 2004. At Stadbury Plantation (Figure 7.2.2 (central panel)) the reservoir reduces seaward transport of sediment by about 5% over the same period and close to the weir (200 m down-estuary, Figure 7.2.2 (lower panel)) the reservoir reduces seaward transport of sediment by about 2%.

7.2.3. Modelled sediment transport – effect of waves

The effect of waves is investigated by computing the sediment transport both with and without waves. The 'control' solution is that for sediment transport with tidal flow and naturalised freshwater flow (Figure 7.2.1) whereas the 'wave' solution is the sediment transport throughout the estuary with tidal flow, naturalised freshwater flow as well as waves. The difference between the solutions is the computed wave effect (Figure 7.2.3). The applied wave conditions seaward of Cockleridge Narrows correspond to significant wave heights of 1 m (a maximum value, which is decreased if water depths become very small) and peak wave periods of 6 seconds; significant wave heights and periods within the estuary are 0.1 m and 1.5 seconds.

The effect due to waves is substantial. The long-term seaward transport of sediment at Cockleridge Narrows is increased by 25% and the flood-ebb fluctuations are increased by 33% on average over the whole record (Figure 7.2.3 (upper panel)). At Stadbury Plantation the long-term seaward transport of sediment is increased by 5% and the flood-ebb fluctuations are increased by 6%

on average over the whole record (Figure 7.2.3 (central panel)). Just down-estuary from the weir, the long-term seaward transport of sediment is increased by 26% and the flood-ebb fluctuations are decreased by 10% on average over the whole record (Figure 7.2.3 (lower panel)). This latter decrease is a consequence of the extremely complicated sediment transport time-series that occur in this region.

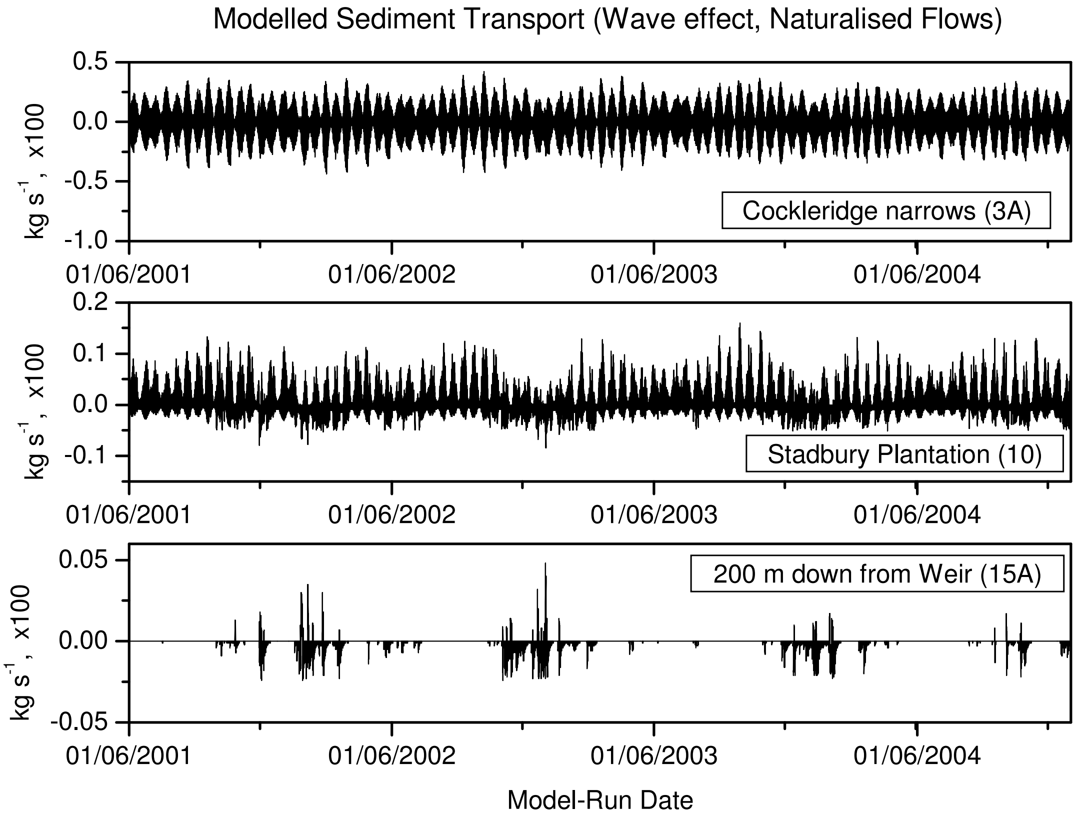

Figure 7.2.3: Time-series of modelled data for the period June 2001 to December 2004. The upper panel shows the computed difference in tidal sediment transport at Cockleridge narrows due to waves (flood positive, ebb negative) using naturalised freshwater flow; the central panel shows the same for Stadbury Plantation; and the lower panel the same for just down-estuary (200 m) of the weir.

7.3. Sediment transport solution across the Avon

The sediment transport model discussed in the previous sections assumes average conditions of tidal flow and sediment grain properties over each section of the estuary. A hydrodynamic model of the flow across (perpendicular to) an estuarine section was written and applied to the sediment transport computation using observed grain sizes over the section. Section 5 (Aunemouth Sands) was used as an illustration. The calculations were made for both average and low freshwater flow at the head of the estuary and with and without waves.

7.3.1. Modelled sediment transport – cross-estuary effects, average flow

For average freshwater flow at mean spring tides the mean sand transport (averaged over several tides) is ebb-directed and largely confined to the main channel.

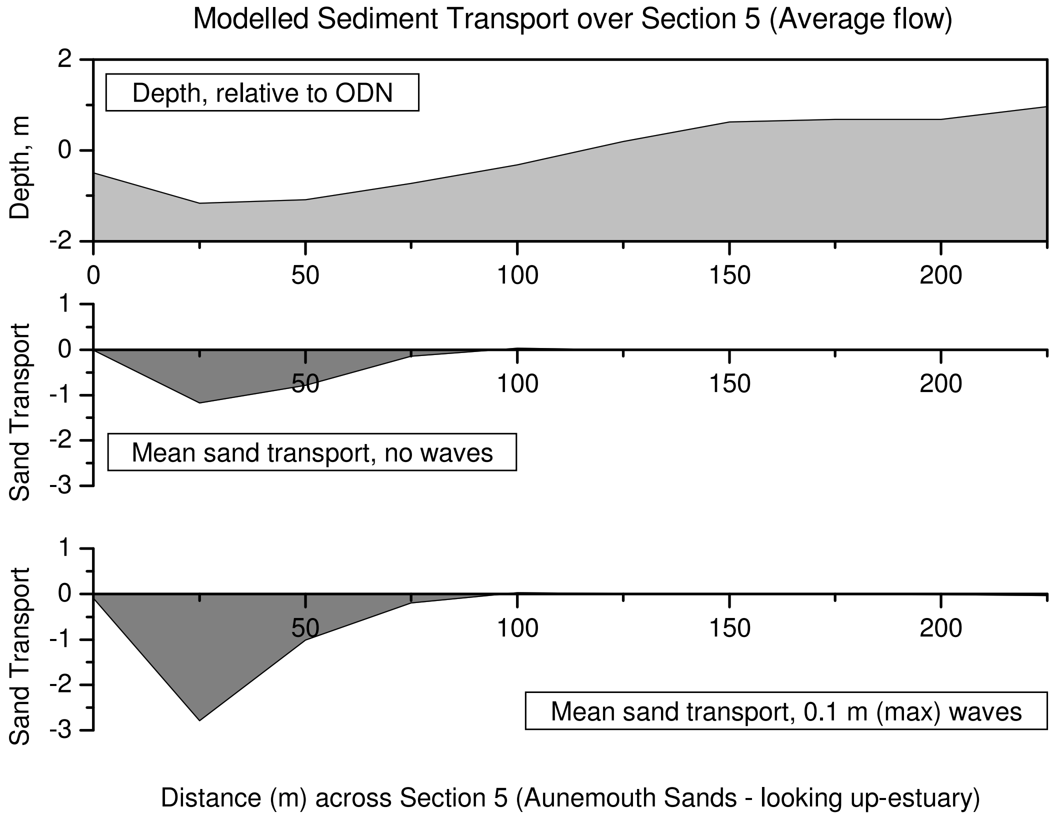

Figure 7.3.1: Cross-estuary profile of modelled data for average freshwater flow and spring tides. The upper panel shows the schematic cross-section, based on Aunemouth. The central panel shows computed mean sediment transport (arbitrary units) with no waves and the lower panel the same with waves incorporated.

The effect of waves is to substantially increase the mean transport of sediment.

7.3.2. Modelled sediment transport – cross-estuary effects, low flow

For low freshwater flow at mean spring tides the mean sand transport (averaged over several tides) is again largely confined to the main channel but, in the case of no waves, is now ebb-directed in the deepest part of the section with a return, flood-directed up-estuary transport in the flanking regions (Figure 7.3.2 (central panel)). Sand transport is still very small on the majority of the intertidal areas.

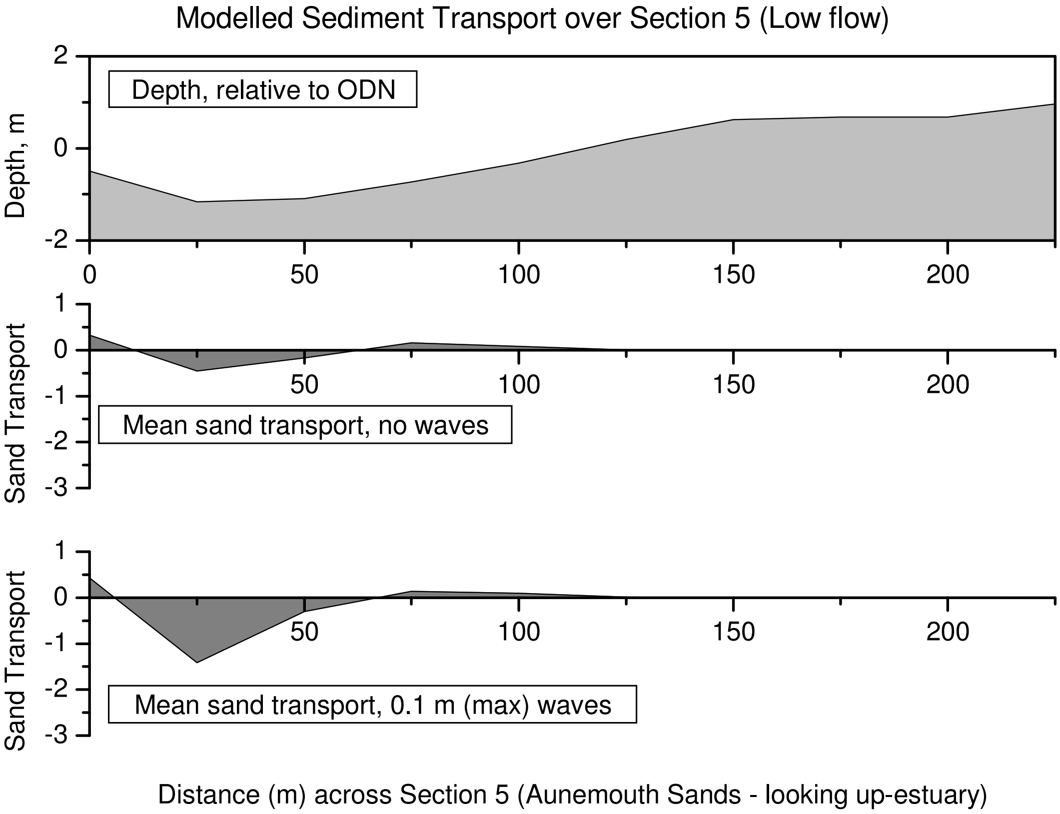

Figure 7.3.2: Cross-estuary profile of modelled data for low freshwater flow and spring tides. The upper panel shows the schematic cross-section, based on Aunemouth. The central panel shows computed mean sediment transport (arbitrary units) with no waves and the lower panel the same with waves incorporated.

With the inclusion of waves (0.1 m significant wave height and 1.5 second periodicity) there is a substantial increase the mean transport of sediment both out of the estuary in the deepest part of the section and up-estuary on the flanking shoulders.

8. Summary

The Avon has a pronounced seasonal cycle of freshwater flow with higher winter and autumn flows and lower spring and summer flows. The extremes of freshwater runoff measured during 1971 to 2006 ranged from a low summer flow of 0.16 $m^3 s^{-1}$ to 62 $m^3 s^{-1}$ during winter. Tides at Bantham Beach are very similar to those at Devonport. Tides are semidiurnal and they exhibit a pronounced spring-neap cycle. At Devonport, mean spring tidal range is 4.7 m and mean neap tidal range is 2.2 m. Bantham tidal ranges are somewhat smaller than this, typically 92% of Devonport ranges, and tidal phases (e.g. HW, LW) are somewhat later, typically 10 minutes later. These semidiurnal tides increase and decrease in range over an 18.6 year period, which will lead to corresponding cycles in sediment transport and estuary morphology. In the Bantham region the winds are predominantly from the southwest or west. Typical wave periods in the region are 4 seconds and waves larger than 1.5 – 2 m are expected to occur for 10% of the year. It is probable that wave heights in the Bantham region have tended to increase over a substantial time-period (in terms of a person’s life-span).

Thirty-one cross-sections, perpendicular to the main channel, were specified along the longitudinal axis of the Avon Estuary with approximately 250-m spacing. These sections comprised the basic bathymetry for modelling studies and defined the estuary’s geometry; they highlighted a bed-profile ‘hump’ of very shallow main-channel depths in the estuary’s bed between approximately Stadbury Plantation and North Efford. The sections also were used to define sites for bed-sediment sampling, which was undertaken during summer conditions. The resulting data for the sediment-sample size distributions showed that the upper

(500 m) section of the estuary had a scoured, river-like profile with coarse gravel and cobbles. As the estuary widened, progressing down-estuary, the silt and clay contribution to the bed sediment increased dramatically (averaging over sections) and exceeded 50%. At about 2.5 km from the weir the silt and clay fraction peaked at about 52% and, combined with the very fine sand and fine sand fractions, constituted the majority (> 87%) of bed sediments at this location. The percentage contribution of fine sand and smaller sediments then fell steadily progressing toward the sea. In all cases the grain-size distribution over an individual section showed a predominance of finer sediments at the channel margins and over intertidal areas with a dramatic increase in size within the deep channel.

Four posts were driven into the bed sediment of the sandy shoal directly opposite the harbourmaster's office at Bantham on 15th March 2006 and monitored for 1 year. The two posts in the middle of the shoal had a tendency to behave in a similar pattern whereas the upstream end of the shoal eroded whilst the downstream end accreted. The implication is that the up-estuary and down-estuary limits of the shoal shifted up-estuary and down-estuary and that this appeared to occur with a seasonal cycle. Although there was evidence of seasonal channel shifting and other morphology changes there was no evidence of long-term accretion (siltation) of sediment. The northern edge of the shoal was stable enough to support a significant algal growth during the summer months; this coverage began to establish itself during May 2006 but was gone by October 2006.

To obtain physical data for summer conditions, the first of two pairs of instruments was deployed in the deep-channel of the upper estuary at North Efford and a second pair of instruments was deployed in the deep-channel at

Bantham, just below the harbourmaster's office. While the bed mounted equipment was deployed we undertook tidal-cycle, vertical-profiling stations at both sites. SPM concentrations were small at the Bantham station, generally less than 15 mg l^{-1}, and concentrations were greater on the flood and not related to current speed, but were greatest at low salinity. Currents were fast and reached 1 m s^{-1} on the ebb and 0.8 m s^{-1} on the flood, and salinity was well-mixed between surface and bed. This indicates preferential transport of sediment into the estuary on the flood with a compensatory, outward pulse of turbid waters from the upper estuary on the late ebb. Longitudinal currents at 0.45 m above the bed at the Bantham station were slower and had flood currents that peaked at between 0.4 m s^{-1} and 0.5 m s^{-1} and occurred for only 3 - 4 hrs of the 12.5 hr tidal cycle. An ebb flow occurred for the remainder of the cycle and reached speeds of between 0.5 m s^{-1} and 0.6 m s^{-1}. LW-slack at this station was very short-lived because currents reversed quickly when the tide turned from ebb to flood. Peak turbidity near the bed occurred over the LW period, which was again indicative of turbid water from further up-estuary having been carried down-stream on the ebb and up-stream at the beginning of the following flood, carrying resuspended sediment upstream.

SPM concentrations also were small at the North Efford station and generally less than 10 mg l^{-1}, but were greater on the flood (up to 60 mg l^{-1}) due to resuspension of bed sediments by the flood currents. This indicates preferential transport of sediment into the estuary on the flood. Current speeds at the surface reached 0.5 m s^{-1} on the ebb and 0.7 m s^{-1} on the flood and a layered flow developed over HW and the early ebb in which salinity was strongly stratified. The flooding tide showed vertical homogeneity for salinity and the SPM increased during the early flood with a maximum that occurred during the middle of the flood tide, close to peak speeds. It is unlikely that the SPM maximum is a localised resuspension event at North Efford because flood current speeds maximised after peak turbidity had occurred, although it is likely that resuspension occurred from further down-estuary, in the vicinity of the maximum silt and clay accumulation. Significant wave heights for the same period were very small and ranged from 0.01 m at LW to 0.08 m at HW.

Instruments were deployed within the estuary and just seaward of Bantham Beach in order to determine the differences in tidal range and wave height between the coastal zone and inner estuary. The data showed that there was a considerable reduction in tidal range between the beach and the North Efford site. At Bantham Beach there was a tidal range of 3.7 m, reducing to 3.0 m at Bantham (Harbourmaster's office) and reducing further to 1.5 m at North Efford. Waves also were reduced. The wave recorder at Bantham Beach, located in the LW surf zone, recorded a maximum significant wave height of 1.4 m over HW compared with 0.07 m within the estuary, demonstrating a strong wave damping.

To obtain physical data for winter conditions, two pairs of instruments were deployed in the deep-channel of the estuary. The first pair was deployed at North Efford and the second at Bantham, just below the Harbourmaster's Office. Larger freshwater flow at North Efford caused all current flows to be ebb directed whereas lesser (but still winter) freshwater flow ensured that flood-directed currents were relatively short-lived events. The significant wave height was less than 0.08m. Tidal range had an important influence on water levels at this site, even though currents could be ebb-directed throughout the tide. Spring-tide variations in water level remained strong, whereas the weaker neap tides could have an almost negligible effect on water levels in the presence of strong freshwater flows. The freshwater flow and spring-neap cycle also had an important influence on the movement of saline water into the upper part of the Avon Estuary. Increased flows and smaller tides acted together to limit saline intrusion into the estuary. The amount of SPM in the estuary at North Efford generally was relatively low during the winter deployment (<90 NTU). When rising tides and decreasing freshwater flows eventually led to up-estuary-directed flood-tide currents there was an increase in the amount of SPM at both maximum flood (up to 80 NTU) and, to a lesser extent, at maximum ebb (up to 30 NTU). The source of this SPM may have been resuspended bed-sediment from the region of maximum accumulated fine sediment, located slightly further down-estuary.

The second pair of instruments was deployed at Bantham. The flood-tide current for rising water levels ranged from 0.22 m s^{-1} to 0.50 m s^{-1} during the period of observations. The high-runoff and neap-tide part of the record had flood currents of up to 0.3 m s^{-1} increasing to 0.5 m s^{-1} as the spring tides increased in range. Flood-directed currents were relatively short-lived, even near the mouth. Ebb currents reached speeds of up to 0.8 m s^{-1} during high runoff and spring tides and 0.5 m s^{-1} during neap tides. Ebb current speeds maximised toward the end of the falling tide, but before LW. The lower estuary experienced a full range of salinity during most tides, ranging from less than 1 at LW, due to freshwater discharge, to > 33 at HW, due to coastal seawater. A LW presence of saline water (< 7) was recorded when the tide was large enough to force saline water into the upper estuary and the runoff was too low to completely flush saline waters from the whole estuary during the ebb. SPM loading in the lower estuary was less than 50 NTU for the whole deployment period but peaked as low as 20 NTU during weak tides and low runoff. Raised SPM levels were coincident with LW periods and with peak flood and ebb currents, whereas they were much lower over the HW period. The highest levels of SPM were coincident with LW and occurred on days when the prevailing north-westerly winds were at their strongest and freshwater runoff was low and decreasing. Significant wave height for the deployment period was less than 0.07 m.

A 1D (one-dimensional) cross-sectional-averaged model was written to solve water levels and currents for the Avon Estuary from the estuary's head (the Weir near Aveton Gifford) to its mouth (at Bantham Beach). Data on freshwater runoff into the estuary comprised 'actual' daily-averaged flow, as measured in the non-tidal River Avon and 'naturalised' flow, the name given to the daily-averaged flow that was estimated to have occurred in the absence of the Avon Reservoir. The difference between these flows generally (but not always) was small and a comparison of the modelled estuarine hydrodynamics with and without the reservoir gave an indication of the effects of the reservoir on the estuary. The model was run for the period May 1990 to December 2004.

The modelled water levels at Bantham Beach had a mean of 0.13 m above ODN (Ordnance Datum Newlyn) and varied from +2.6 to -2.7 m over the period, whereas water levels at the weir had a mean of 0.87 m and varied from +2.7 to 0.04 m over the period. Therefore, similar water levels occurred at the weir over HW whereas the LW portion of the water-level variations was truncated by the shallow water depths and the attenuation of the tide as it propagated into the estuary from Bantham Beach. The influence of freshwater flow on LW levels was very pronounced close to the weir and levels increased by approximately 1 m in response to the highest freshwater flows. The effect on currents also was very pronounced near the weir. Currents exceeded 1 m s^{-1} in response to the highest freshwater flows; the effect of tides on currents just down-estuary of the weir was to reduce the ebb-directed current during the rising tide. The influence of the Avon reservoir on modelled water levels generally was small (less than a couple of centimetres, with the reservoir acting to reduce estuary water levels at the weir) although on occasions it could be as great as 0.1 – 0.2 m. Over the whole period (1990 to 2004) the greatest difference in water-level was 0.3 m and the mean was 0.01 m. Therefore, the effect of the Avon reservoir on estuary water levels near the weir generally was relatively slight. The influence of the Avon reservoir on estuarine currents near the weir generally also was small (less than a couple of cm s^{-1}, with the reservoir acting to reduce ebb-directed estuary currents at the weir) although on occasions the effect was 0.1 m s^{-1}. Over the whole period, 1990 to 2004, the greatest speed difference (with and without the reservoir) was 0.2 m s^{-1} and the mean was less than 0.01 m s^{-1}. Therefore, the effect of the Avon reservoir on estuarine current speeds near the weir generally was relatively slight.

The hydrodynamic model was used to compute the local sediment transport at each section of the estuary. To do this, cross-sectional-averaged sediment grain sizes were used in the various sediment transport relationships and sediment cohesion was ignored (section-averaged median sizes were never less than the equivalent of very fine sand). Calculations were made with and without the effects of waves, although these were small within the estuary itself, and for naturalised and actual freshwater flows, in order to give an indication of the effects of the reservoir on the estuary. The model was run for the period May 1990 to December 2004. The calculations did not take into account advection (e.g. there was no flood-tide input of sand from the coastal zone that may have resulted from storm-wave activity) but computed only the transport of sediment that was currently located at the bed over a section.

Although freshwater flow was always present, its main influence on sediment transport was felt during the late ebb, especially in the upper reaches near the weir; at other times the tidal currents were very important in moving sediment. The modelled, instantaneous sediment transport rates due to the tides across three sections of the estuary were computed. At Cockleridge narrows (the very narrow section of estuary close to Ham Cottage) there was ebb and flood sediment transport that increased at spring tides due to the faster current speeds at that time. Therefore, the fastest flood currents transported sediment into the estuary. However, the long-term tendency (the mean transport over several years) in the absence of waves and storms was for sediment to be transported out of the estuary, especially during winter months, due to the dominance of ebb-directed currents from tides and freshwater runoff. At Stadbury Plantation, in the central reaches of the estuary, the flood-directed sediment transport due to tidal currents was much more pronounced, consistent with the accumulation of large amounts of finer sediment in this region of the estuary. Again, the effect of larger freshwater flow during winter was to enhance the ebb-directed tidal currents and reduce the flood-directed tidal currents, such that sediment transport was directed down-estuary. Sediment accumulation therefore occurred during the months of low freshwater runoff. Close to the weir (200 m down-estuary) the sediment transport was very small and occurred only during the strongest freshwater flow, which were consequences of the very coarse material there and the absence of flood-directed tidal currents.

The differences in sediment transport due to the reservoir generally were very small, but with some exceptions that occurred late in the year. The effect of the reservoir was to reduce ebb-directed transport and thus enhance any tendency for siltation, although the effect was slight. In the case of Cockleridge narrows the reservoir reduced seaward transport of sediment by about 1% over the period 1990 to 2004. At Stadbury Plantation the reservoir reduced seaward transport of sediment by about 5% over the same period and close to the weir (200 m down-estuary) the reservoir reduced seaward transport of sediment by about 2%.

The effect of waves was substantial. The applied wave conditions seaward of Cockleridge Narrows corresponded to maximum significant wave heights of 1 m and peak wave periods of 6 seconds; corresponding values within the estuary were 0.1 m and 1.5 seconds. With waves, the long-term seaward transport of sediment at Cockleridge Narrows was increased by 25% and the flood-ebb fluctuations were increased by 33% as an average over the whole simulation. At Stadbury Plantation the long-term seaward transport of sediment was increased by 5% and the flood-ebb fluctuations were increased by 6% on average over the whole record. Just down-estuary from the weir, the long-term seaward transport of sediment was increased by 26%.

A hydrodynamic model of the flow across (perpendicular to) an estuarine section was written and applied to the sediment transport computed using the observed bed-sediment grain-sizes over the section. The Aunemouth Sands section was used as an illustration. The calculations were made both for average and low freshwater flow at the head of the estuary and both with and without waves. For average freshwater flow at mean spring tides the mean sand transport (averaged over several tides) was ebb-directed and largely confined to the main channel. The effect of waves was to substantially increase the mean transport of sediment. For low freshwater flow at mean spring tides the mean sand transport was again largely confined to the main channel but, in the case of no waves, was ebb-directed in the deepest part of the section with a return, flood-directed up-estuary transport over the flanking regions. Sand transport was still very small on the majority of the intertidal areas. With the inclusion of waves (0.1 m significant wave height and 1.5 second periodicity) there was a substantial increase in the mean transport of sediment both out of the estuary in the deepest part of the section and up-estuary on the flanking intertidal shoulders.

9. Conclusions

Field data showed that:

- A considerable reduction in tidal range and wave height occurred between Bantham Beach and the upper estuary. In the upper estuary a layered flow could develop over HW and the early ebb, in which salinity was strongly stratified, although greater freshwater flows during winter caused all currents there to be ebb directed and at those times weaker neap tides had an almost negligible effect on water levels.
- The lower estuary was dominated by sand-sized sediment. The upper part of the estuary had a scoured, river-like channel of very coarse sediment deposits associated with fast ebb current speeds due to tides and freshwater flow across the weir, whereas the central to upper part of the estuary had a high percentage of fine sediment, much of which was muddy, that corresponded to a minimum depth in the longitudinal, main-channel bed profile. Main-channel grain sizes were much greater than those over the intertidal areas.
- SPM concentrations in the estuary generally were small. In the lower estuary there appeared to be preferential transport of sediment into the estuary on the flood with a compensatory, outward pulse of turbid waters from the upper estuary on the late ebb. Sediment resuspension occurred in the upper estuary, especially during the flood.
- Measurements of sandbank levels in the lower estuary over a 1-year period provided no evidence of sand accumulation. Seasonal changes in sediment levels of more than 0.3 m occurred, as did movements of the sandbank

boundaries and main channel, but annual sediment levels did not increase overall.

Modelled data showed that:

- Modelled tides showed that similar water levels occurred throughout the estuary over HW, whereas the LW portion of the water-level variations was truncated by the shallow water depths and the attenuation of the tide as it propagated into the estuary. The influence of freshwater flow on water levels (especially LW levels) and currents was very pronounced in the upper estuary.
- The influence of the Avon reservoir on modelled water levels and currents generally was small, with the reservoir acting to reduce estuary water levels and ebb-directed currents in the upper estuary.
- The modelled, instantaneous sediment transport rates showed that tides were very important in producing both ebb and flood-directed sediment transport and that the effect of waves was substantial.
- The differences in sediment transport due to the reservoir generally were very small, but with some exceptions that occurred late in the year. The effect of the reservoir was to reduce ebb-directed transport and thus enhance any tendency for siltation, although the effect was slight.
- A cross-estuary model of the Aunemouth Sands section showed that the mean sediment transport tended to be out of the estuary in the deepest part of the section and up-estuary on the flanking intertidal shoulders. Transport was very small on the majority of the intertidal areas.

More speculatively:

- Because the tides at Bantham increase and decrease in range with an 18.6-year cycle, and because the model shows that tides are very important for sediment movement, this cycle will lead to corresponding cycles in sediment transport and estuary morphology.

- It is probable that wave heights in the Bantham region have tended to increase over a substantial time-period (in terms of a person's life-span). Because the model shows that waves are an important cause of resuspension, especially in the outer Avon, this may be associated with enhanced suspended sediment levels in the Bantham coastal zone that are then conveyed to the estuary during the flood portion of the tides.
- It is likely that winds and storminess In the Bantham region have increased in recent decades. Winds are predominantly from the southwest or west, so that wind-blown sand derived both from Bantham beach and the Bantham sand dunes may be contributing to the sandy sediment load within the estuary. Another source of wind-driven sand to the inner part of the estuary is the estuarine intertidal sandy shore itself, at times when strong up-estuary-directed winds coincide with LW periods.
- The accumulation of muddy sediment in the 'minimum depth' part of the estuary can be understood in terms of hydrodynamic processes and the much greater inputs of muddy sediments into the upper estuary, produced as a result of the changing agricultural practices in the 1970s onwards, may have exacerbated this accumulation.

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