AVON ESTUARY SILTATION RESEARCH PROJECT (AESRP)

FINAL SUMMARY REPORT ON UNIVERSITY OF PLYMOUTH CONTRACT

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Preface

This final report document represents an executive summary of the research findings from the suite of AESRP MSc, MRes and BSc projects undertaken by students at the University of Plymouth under our academic supervision.

The student theses provide a detailed account of the work undertaken and the primary data generated plus the student's interpretations. Here we present our selected key findings from the work.

For information, we are currently undertaking sister projects in the region sponsored by the Seale Hayne Educational Trust and also have a PhD student, sponsored by the University of Plymouth and Westcountry Rivers Trust, assessing soil conservation techniques in collaboration with Avon and Dart Valley farmers. The wealth of data and knowledge generated by the AESRP will no doubt attract future undergraduate and masters students to undertake their research projects in the catchment and estuary. We will endeavour to keep the Aune Conservation Association up-to-date on the outcome of future research.

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November 2007

1. ESTUARINE GEOMORPHOLOGY

At its mouth, the Avon estuary experiences a spring and neap tidal range of 4.4 and 1.9 m, respectively. The amplitude of the main tidal constituent M2 is 1.5 m. The mouth of the estuary is partly sheltered from westerly waves by Burgh Island, but is relatively exposed to easterly waves. According to Davidson *et al.* (1991), who conducted a comprehensive review of all estuaries in Great Britain, the Avon estuary has a total surface area of 213.5 ha, of which 146.2 ha are intertidal. The estuarine shoreline is 19.8 km long and the tidal channel is 7.8 km long. The Atkins survey data further demonstrate that the average depth of the tidal channel near the mouth is *c.* 2 m. The surface of the intertidal shoals in the estuary is 0.5–1 m ODN and the salt marsh surface is c.1.5 m ODN.

Based on the overall estuarine outline, the Avon estuary can be considered a *ria* (drowned river) estuary. However, it could equally be termed a *bar-build* estuary, because it has two sand barriers at its mouth: Bantham beach and Cockleridge. It should be pointed out, however, that Bantham beach is not entirely depositional, but represents a raised interglacial shore platform capped with coastal dunes, fronted by a relatively thin beach deposit.

Estuaries are often classified on the basis of the dominant sediment transporting process operating in the lower and central part of the estuary into wave- or tide-dominated (Figure 1.1). The upper part of the estuary is always dominated by fluvial processes. This classification is only partly useful for the Avon estuary, because the estuary has features that are characteristic of both estuarine types. For example, a distinct wave-dominated barrier-inlet system with tidal deltas is present at the mouth of the estuary, whereas tide-dominated salt marshes and a meandering tidal channel are present in the central estuary. At the same time, several other distinctive features are not present at all, such as a muddy central basin (*i.e.*, wave-dominated feature) and tidal sand bars (*i.e.*, tide-dominated features). Due to the combination of moderately large tides and wave energy conditions, the Avon estuary is best described as a mixed wave/tide-dominated estuary.

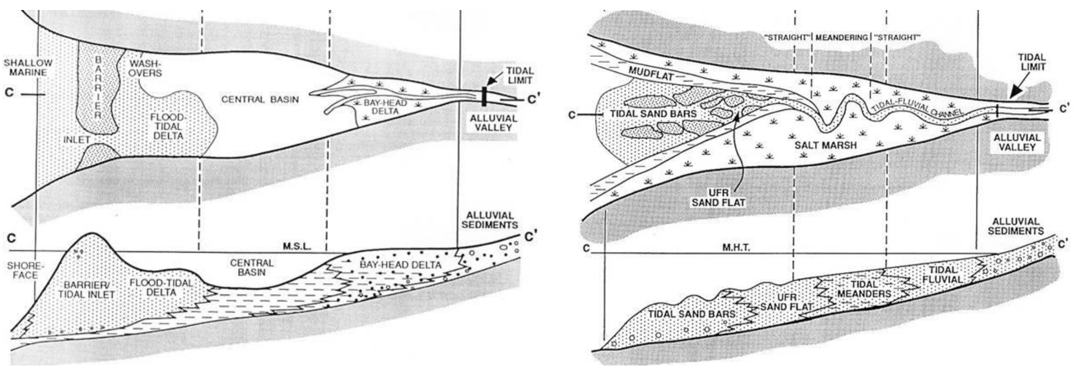

Figure 1.1: Schematic showing wave-dominated (left panels) and tide-dominated estuary (right panels) (Dalrymple *et al.*, 1992).

The morphology of the estuarine mouth shows plenty of evidence of a net influx of sediment by flood-tidal currents (Figure 1.2). These include onshore migrating intertidal bars on the ebb tidal delta, the recurved spit terminus at Cockleridge and landward-migrating tidal bedforms at several locations (especially prominent on Aunemouth Sand, just up from Bantham). On the other hand, there are also clear indications of net export of sediment by ebb-tidal currents in the form of seaward-migrating bedforms located in the channel.

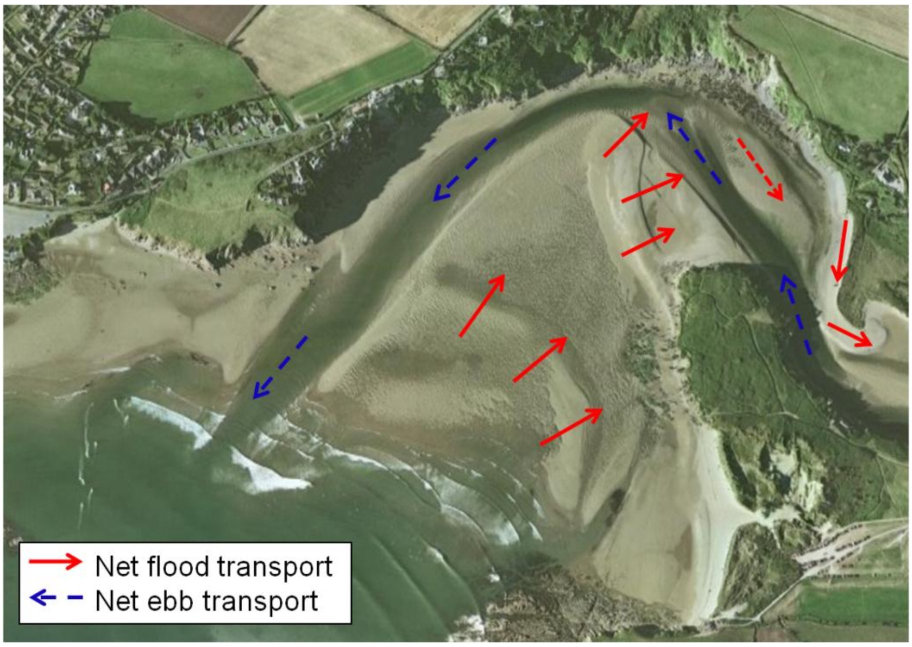

Figure 1.2: Aerial photograph of the mouth of the estuary showing sediment pathways interpreted from the morphology (aerial photo from Google Earth).

To determine the net sediment transport in the estuarine mouth, *i.e.*, the difference between landward (up-estuary) transport by the flooding current and seaward (down-estuary) transport by the ebbing current, requires extensive measurements of tidal hydrodynamics and sediment transport processes. However, the conceptual model of Friedrichs and Aubrey (1988) can be used to provide some insight into whether the mouth of the Avon estuary is flood- or ebb-dominant. According to this model, ebb/flood-dominance is strongly dependent on the ratio between the amplitude of the M2 tidal constituent (1.5 m) and the average depth of the tidal channel at mid-tide (2 m). When this ratio is larger than 0.4, the estuary is relatively shallow and flood-dominant; when the ratio is smaller than 0.3, the estuary is relatively deep and ebb-dominant. The ratio between the amplitude of the M2 tidal constituent and the mean channel depth at mid-tide is 0.75 for the Avon estuary. This suggests that the estuary is flood-dominant and should be characterised by a net influx of marine sediment. The morphological evidence supports this suggestion.

2. SEA-LEVEL CHANGE [1]

Chronological and microfossil analyses on the monolith collected in the Main marsh were used to reconstruct the changes in tide level (Figure 2.1). Between 1600 and 1900, the rate of sea-level rise was ~1 mm/yr. The sea-level reconstruction for the past century has doubled compared to preceding centuries and shows a good agreement with the tide-gauge measurements at Newlyn (~2 mm/yr).

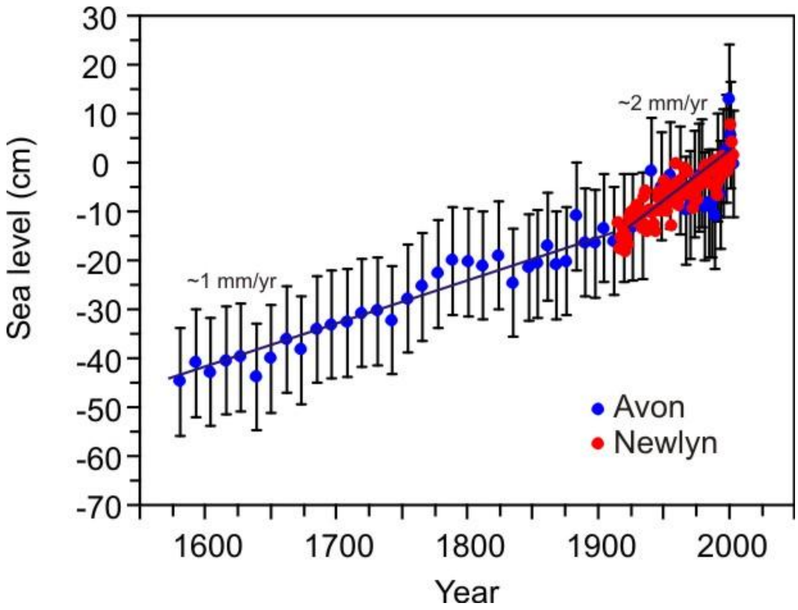

Figure 2.1: Changes in sea level during the past four centuries. Black dots are reconstructed sea-level positions in the Avon. Error is ~11 cm. Red dots are sea-level measurements at Newlyn since 1916.

3. HISTORICAL CHANGES IN THE POSITION OF THE TIDAL CHANNEL[2]

Three series of OS maps from 1890, 1954 and 2000 were used to investigate historical changes in the position of the tidal channel (Figure 3.1). The most noticeable changes have been: (1) the increased importance of the eastern channel 1 km up from the mouth near Villa Crusoe (Millin, 2006); (2) the almost-abandonment of the eastern channel near Aunemouth Sand; and (3) the progressive westward migration of the channel in the mouth of the estuary. These channel changes are driven by internal estuarine dynamics and are not associated with progressive changes in the estuary due to the influx of fluvial and marine sediments.

[1] Based on MRes thesis of Bugler (2006)
[2] Based on BSc thesis of Millin (2006)

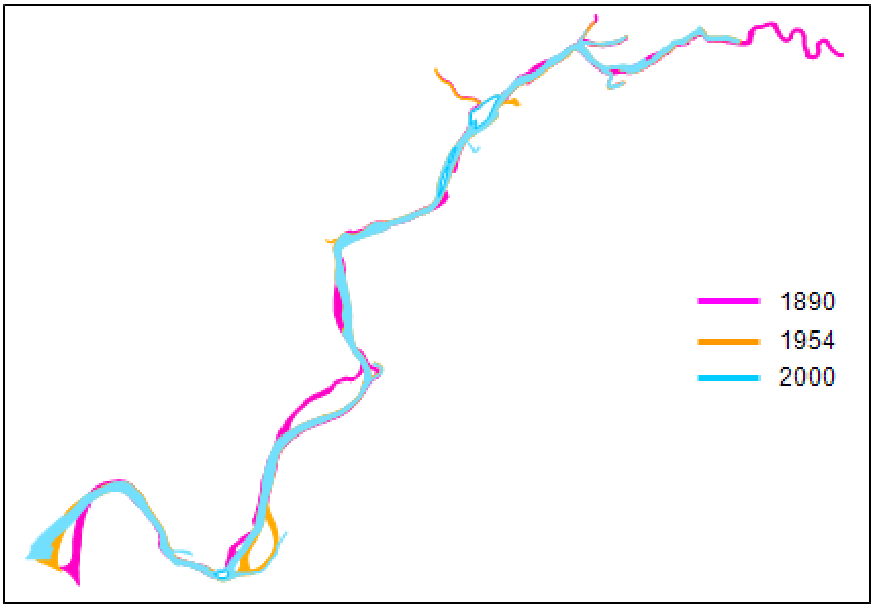

Figure 3.1: Changes in the position of the tidal channel derived from OS maps.

4. MEASUREMENTS OF TIDAL CURRENTS AND SEDIMENT TRANSPORT[3]

Detailed measurements of tidal currents and tidal bedform dynamics were conducted on Aunemouth Sand from July to September 2007 (near Atkins Transect 5 – see Figure 8.1). At this location, large tidal bedforms, referred to as *sand waves*, with a crest-to-trough height of 0.1–0.15 m and a spacing of 5–10 m are ubiquitous (Figure 4.1). The sand waves are most pronounced at the seaward end of Aunemouth Sand, but become increasingly subdued in the landward direction. The asymmetric cross-shore profile of the sand waves indicates that they are migrating up the estuary.

Figure 4.1: Ground photo and aerial photo of the sand wave field at Aunemouth Sand (aerial photo from Google Earth). The dashed red line in the right panel indicates the location of the survey transect shown in Figure 3.2.

[3] Based on MSc thesis of Cointre (2008)

Figure 4.2 shows the evolution of the morphology of the sand waves over the 3-month monitoring period. The sand waves clearly move up the estuary with average migration rates of *c.* 0.25 m day^{-1} at the seaward end of the shoal, decreasing to 0.1 m day^{-1} at the landward end. The sand waves only migrate during spring tides and are remain virtually unmodified during neap tides. Taking into account the heights and migration rates of the sand waves, and the width and length of Aunemouth Sand, the amount of sediment transported onto the shoal by flood-tidal currents can be computed. It is estimated that the landward migrating sand waves represent an influx of sediment of 1 m^3 day. This represents an average vertical accretion rate of the shoal of 0.05 mm per day or 2 cm per year. This estimate is tentative and probably represents the upper-limit; accretion rates during winter are likely to be smaller due to river outflows weakening flood currents and strengthening ebb currents.

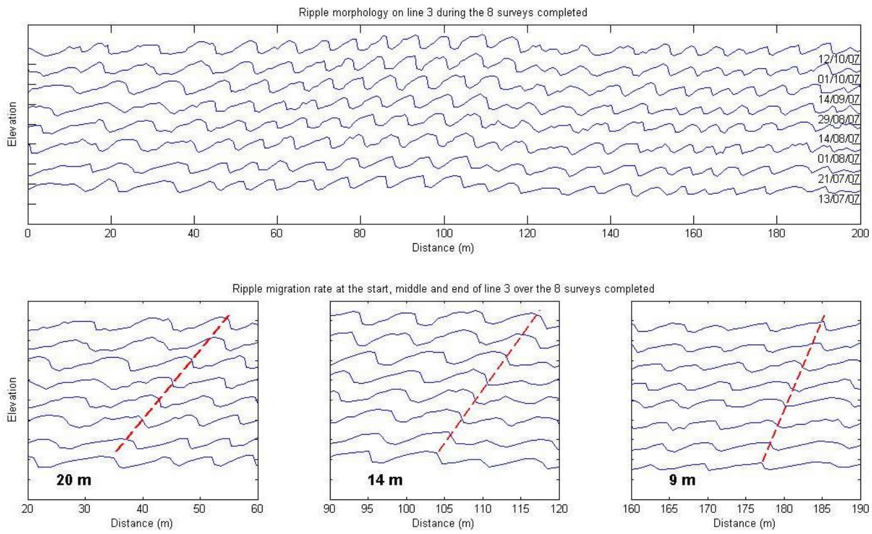

Figure 4.2: Results of sand wave monitoring on Aunemouth Sand from July to September 2007. The upper panel shows 8 consecutive surveys, vertically offset, taken at approximately fortnightly intervals. The lower three panels show zoomed-in versions of the data and clearly demonstrate that the sand waves migrate up-estuary. The bold numbers in the lower panels represents the estimated migration rate over the 3-month survey period.

To complement the sand wave monitoring, tidal currents and water levels were measured on Aunemouth Sand over a spring-to-spring tidal cycle using a Valeport electromagnetic current meter (Figure 4.3). The water depth over the shoal ranges from 2 m during spring high tides to 0.5 m during neap high tides. Likewise, the tidal currents also display a distinct spring-neap modulation with currents during spring tides significantly stronger than during neap tides. During neap tides, maximum flood and ebb currents are comparable and do not exceed 0.25 m s^{-1}. However, maximum flood currents during spring tides are significantly stronger than maximum ebb currents (0.4–0.5 m s^{-1} during spring compared to 0.3 m s^{-1} during ebb). The flood-dominance of the tidal current regime during spring tides is responsible for the onshore migration of the sand waves. It is of interest to point out that similar measurement carried out in the tidal channel near Bantham by PML shows that the channel is ebb-dominant (Uncles *et al.*, 2007).

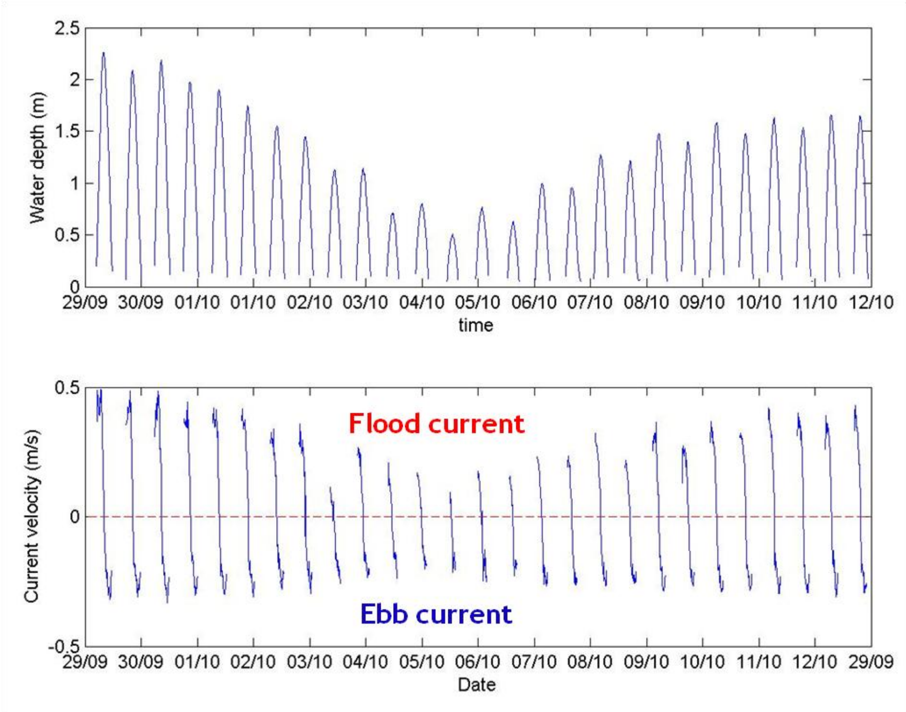

Figure 4.3: Water depth and current velocity measured over a spring-to-spring tidal cycle on Aunemouth Sands. The data were collected using a Valeport electromagnetic current meter and were collected at 4 Hz for 1 minute every 10 minutes. Positive current velocities denote flood currents and negative velocities represent ebb currents.

Research on the sediment transport processes on Aunemouth Sand is ongoing and future work will involve using the tidal current measurements to compute sediment transport rates and compare these with sand wave migration rates. The results of this research should be available in March 2008.

5. SALT-MARSH SEDIMENTATION [4]

Based on ~50 cores we established the stratigraphy of the salt marshes in the upper estuary. Salt marsh sediments here are up to ~1 m thick and are underlain by intertidal sands. Depth to bedrock is generally less than 2 m. Sedimentation rates in the upper estuary were investigated through analyses of three monoliths collected from pits dug in the marsh at Stadbury Wood ("Stadbury Marsh"), the marsh in the main channel south of Milburn Orchard ("Main marsh") and the marsh northwest of the tidal road ("Milburn marsh"). A radiocarbon measurement at the base of the salt-marsh sediments in the Main marsh produced an age of 380±40 ^{14}C yr BP (AD 1440-1630 in calendar years), indicating that the marshes have been in existence for

[4] Based on MRes thesis of Bugler (2006)

at least 500 years. A Pb spike, related to mining activities at the Loddiswell mine, was found at ~30 cm depth and dates to the late 1840s (Figure 5.1).

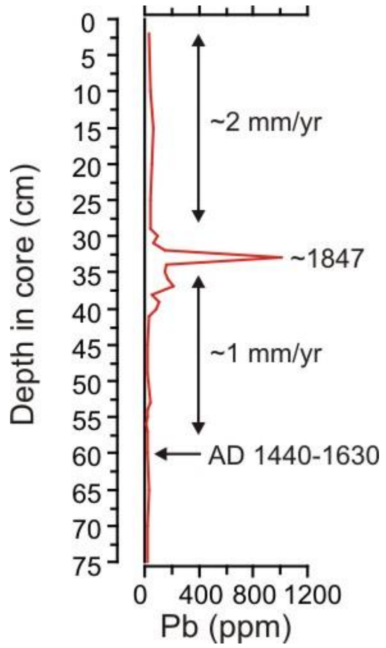

Figure 5.1: Estimated long-term sedimentation rates in the Main marsh, calculated from a radiocarbon date (380±40 ^{14}C yr BP, AD 1440-1630) and a Pb maximum which relates to the peak of mining activity at the Loddiswell mine in the middle 1800s.

Based on the chronological analyses the following sedimentation rates were calculated:

- From ~AD 1500 to 1850: ~1 mm/yr
- From 1850 to ~1960: ~2 mm/yr.
- Since 1960s: ~3-7 mm/yr

Analyses of ^{137}Cs and ^{210}Pb clearly show increased sedimentation rates since the 1960s (Figure 5.2a). The most significant recent change was found in the Stadbury marsh. When expressed in mass units (to account for compaction) the sedimentation rate here increased threefold around 1970 (Figure 5.2b). In the Main Marsh, mass accumulation has increased since ~1960 and reached a maximum around 2000. There was an earlier maximum around ~1950. In the Milburn marsh, mass accumulation rates since the 1960s have been consistently been above the pre-1960 rates (Figure 5.2b).

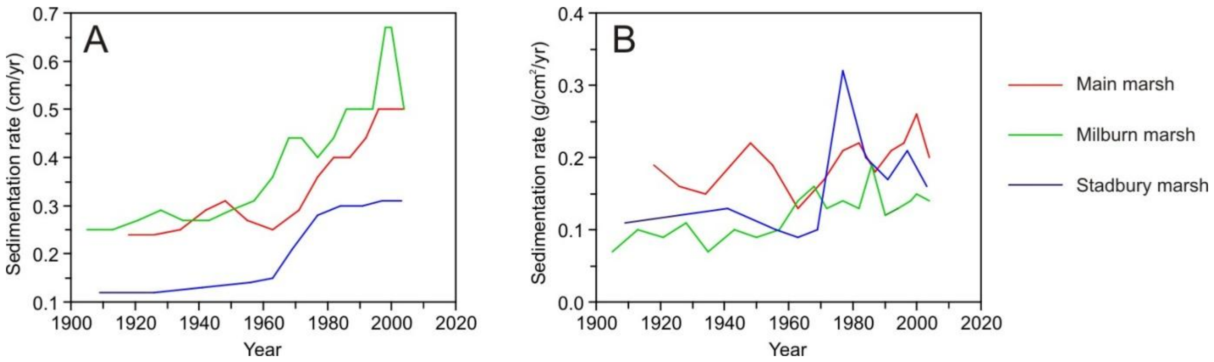

Figure 5.2: Sedimentation rates determined in three salt-marsh cores. A. Expressed as vertical accretion in cm/yr. B. Expressed as mass accumulation in g/cm^2/yr.

6. FINE SEDIMENT STORAGE IN THE MAINSTEM RIVER CHANNEL[5]

A survey of fine (<63 µm) sediment storage within the gravel matrix of the main river channel was undertaken during winter to assess siltation of the freshwater channel network. Sediment samples were also analysed for total phosphorus content as an indicator of sediment quality (against agricultural and urban pressures).

Channel storage of fine sediment was observed to increase downstream of Diptford (Figure 6.1) but declined downstream of Topsham Bridge, towards Loddiswell. Maximum siltation levels are at the lower range of similar agriculture-dominated rivers in the UK (range 166-777 g m^{-2}) (Owens and Walling, 2002; Lambert and Walling, 1988). The middle-to-lower reaches of the main Avon channel are important fine-sediment storage areas. While silt levels are not thought to be of major environmental concern, further research is planned for targeted assessment of siltation within sensitive salmon spawning gravel habitats.

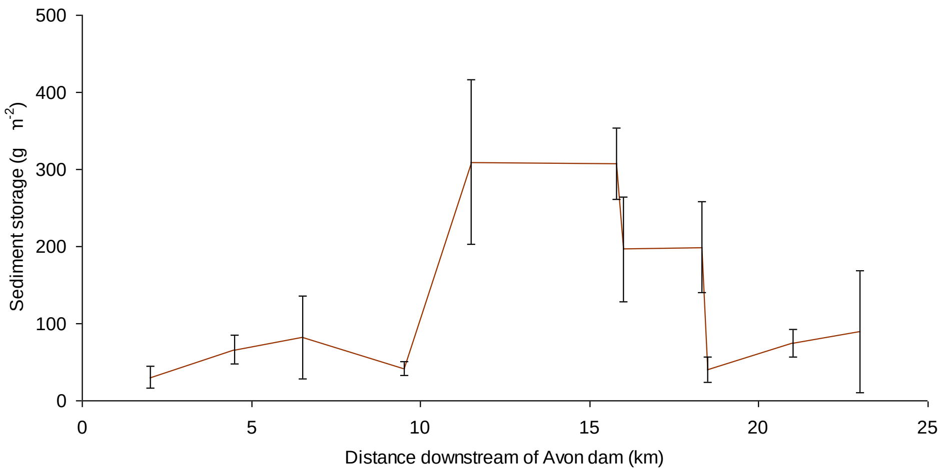

Figure 6.1: Fine sediment storage within the gravel matrix of the Avon mainstem channel bed (where error bars = 1 SE of mean, n=5 at each site).

[5] from MSc project of Pillidge (2005)

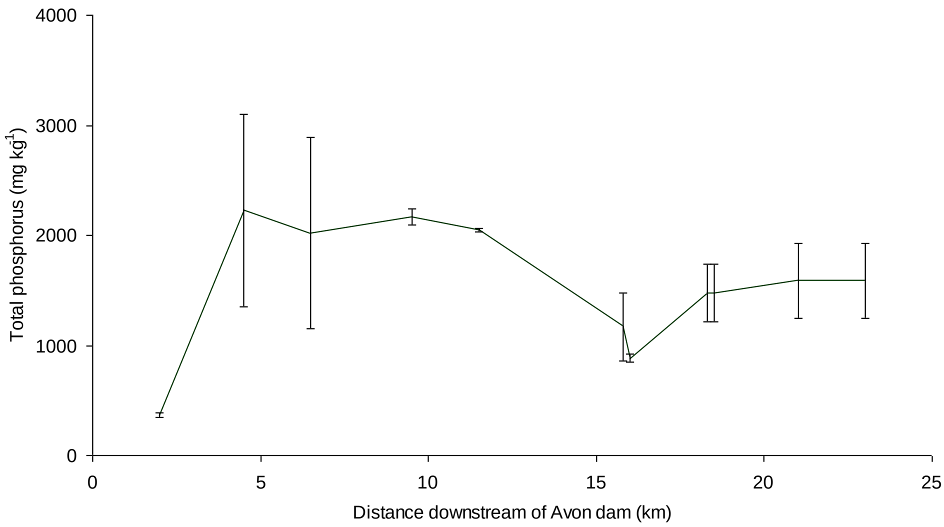

Figure 6.2: Total phosphorus concentrations in channel-stored fine sediment

Total phosphorus levels within the stored fine sediment (Figure 6.2) tend to follow a pattern more linked to urban waste water from sewage treatment works than agricultural sources. In the mid-to-lower reaches, increased sediment storage dilutes the total phosphorus concentration in channel stored sediment. Overall, the total sediment-associated phosphorus concentrations in Avon fine sediment are within the general range of rural UK rivers (950 – 2000 mg kg^{-1}) and well below those of industrialised areas (Owens and Walling, 2002).

7. CURRENT AND PAST SOURCES OF FINE SEDIMENT DELIVERED TO THE ESTUARY[6]

Tracer approaches that aim to quantify the role of specific sediment source areas are often termed 'sediment fingerprinting' approaches. These can provide important information on both the spatial source of suspended sediment within the river basin (i.e. specific zones or subcatchments) and the vertical depth in the soil profile from where material has been derived (i.e. surface *versus* subsurface material or channel bank erosion) (Van der Perk et al., 2007; Walling, 2005).

Mineral magnetic properties of soil in the South Hams River Avon catchment are closely related to changes in underlying geology. Since geological zones within the catchment approximate to zones of contrasting agricultural practice (i.e. increasing intensity towards the lower catchment), mineral magnetic properties of river suspended sediment can be compared to source material to determine the dominant spatial sources of sediment within the system.

[6] Based on MSc project of Stocker (2006) and UoP report Blake et al. (2007)

Tracer data, used to compare river suspended sediment at Loddiswell to catchment sediment source areas (Table 7.1), indicate that a large proportion (up to 66 %) of suspended sediment transported into the upper Avon estuary (by the main freshwater channel) is derived from surface soil erosion in the lower catchment zone underlain by Dartmouth Slates. In more pastorally-dominated areas of the system, natural channel bank erosion is more important than surface soil erosion, in reaches of considerably lower sediment load. This is likely to be representative of catchment processes prior to intensification of agriculture in the lower catchment.

Analysis of sediment fingerprints in sedimentary core material from the saltmarshes (section 5), suggests that recent periods of enhanced sedimentation in the saltmarshes (Figure 5.2) coincide with increased delivery of sediment from cultivated land. In pre-war years, natural channel bank erosion was the dominant sediment source. Targeted soil conservation is required in the identified area to reduce erosion rates and, more importantly, reduce sediment delivery ratios (the proportion of eroded material that reaches the stream) by breaking slope-channel connectivity using measures such as reinstatement of hedgerows and riparian vegetation and wetlands.

8. PHYSICAL AND CHEMICAL ESTUARINE SEDIMENT CHARACTERISTICS[7]

In collaboration with PML, a large number (N = 121) of sediment samples were taken from various locations (salt marsh, sand shoals, tidal channel) along 16 cross-channel transects, from the mouth to the head of the estuary (Figure 8.1). These samples were analysed using a combination of laser-sizing and sieving, and grain-size statistics were computed (mean, sorting and skewness). A further 38 sediment samples from the upper half of the estuary (T8–T11 and T14) were selected for nutrient analysis (nitrogen, carbon, hydrogen and phosphorus). All analysis was carried out in laboratories in the School of Geography.

[7] Based on MSc thesis of Mingins (2005)

Table 7.1: Apportionment of suspended sediment material to surface soil and channel bank erosion within the main upstream geological zones. Proportions represented as a percentage where uncertainty indicates 95% confidence limits around mean output of multiple unmixing model runs (i.e. indication of confidence in source signature definition and model performance, cf. Franks and Rowan, 2000). (n/a = source not applicable)

	Dartmouth Slates *surface soil* (%)	Staddon Grits *surface soil* (%)	Upper Slates *surface soil* (%)	Dartmouth Slates *channel bank* (%)	Staddon Grits *channel bank* (%)	Upper Slates *Channel bank* (%)
Loddiswell (January to March 2006) – JSSS1	58 ± 2	5 ± 2	5 ± 2	16 ± 5	9 ± 3	7 ± 2
Loddiswell (March to April 2006) – JSSS5	66 ± 3	13 ± 4	4 ± 1	5 ± 2	5 ± 1	7 ± 3
Topsham Bridge (January to March 2006) – JSSS4	n/a	16 ± 4	18 ± 3	n/a	29 ± 17	39 ± 18
Penson (January to March 2006) – JSSS3	n/a	n/a	19 ± 1	n/a	n/a	81 ± 1
Penson (March to April 2006) – JSSS6	n/a	n/a	21 ± 1	n/a	n/a	79 ± 1

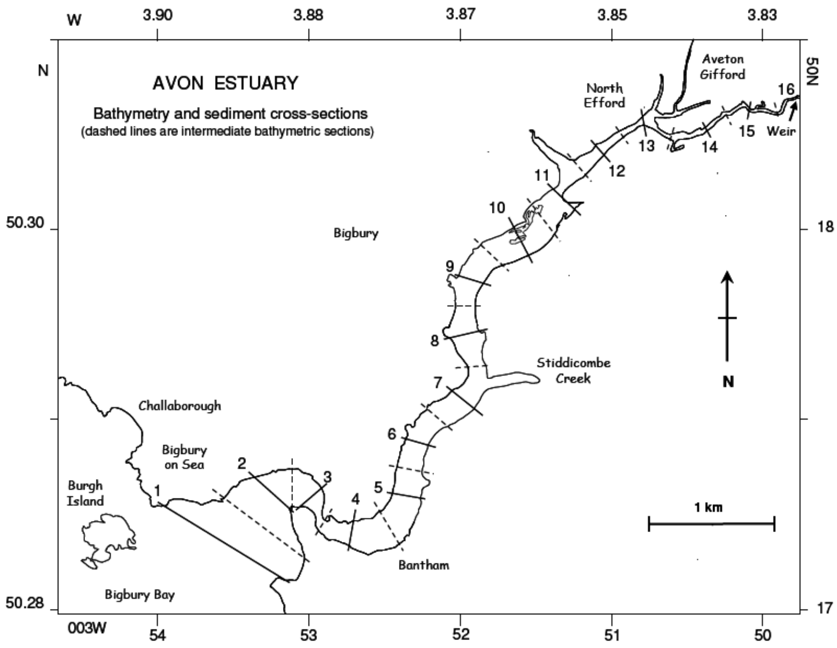

Figure 8.1: Location of cross-shore transects used for sediment sampling (Uncles *et al.*, 2007).

The sediment size results are summarised in Figure 8.2 and show: (1) a coarse, scoured channel at the mouth and the head of the estuary (T2, T3, T9, T15, T16); (2) predominantly coarse and fine sand in the lower estuary (T1–T7); and (3) a mixture of fine sand (channel and intertidal shoals) and silt (salt marsh and tidal flat) in the upper estuary (T8–T14). Sediment sorting generally increases from the head to the mouth of the estuary.

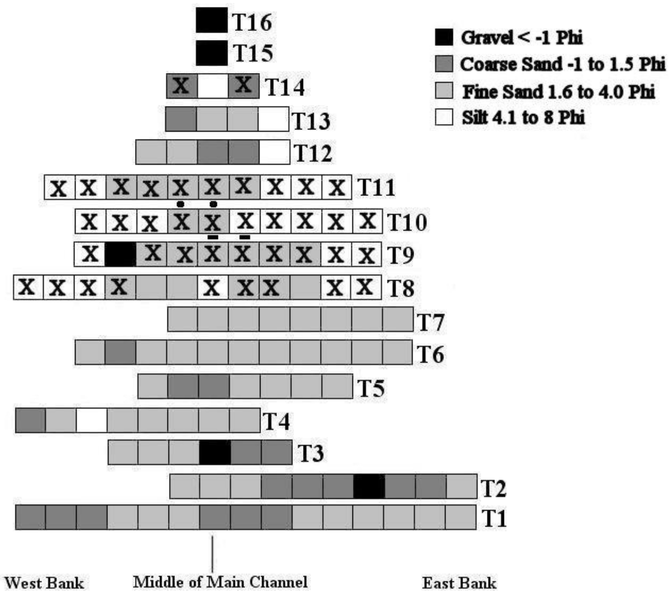

Figure 8.2: Grid showing the spatial distribution of the mean sediment size in the Avon estuary. Each square represents a sample and the central squares represent the middle of the main channel. Squares marked with an X were analysed for nitrogen, carbon, hydrogen and phosphorus.

The results of the chemical analysis are summarised in Table 8.1 and indicate elevated, but modest nutrient concentrations when compared to other rural estuaries. It was further found that the nutrient concentrations exhibited a significant decrease in the seaward direction, and that the sediments collected from the head of the estuary (T14) had the highest nutrient concentrations in line with evidence for the dominance of lower catchment sediment sources. The nutrient concentrations were strongly interrelated.

Table 8.1: Minimum, mean and maximum nutrient concentrations (in g kg^{-1}) of sediments from the Avon estuary.

Concentration	**Minimum**	**Mean**	**Maximum**
nitrogen	0.4	1.82	5.2
carbon	19.9	33.12	63.8
hydrogen	1.4	4.55	14.7
phosphorus	0.35	0.67	1.05

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