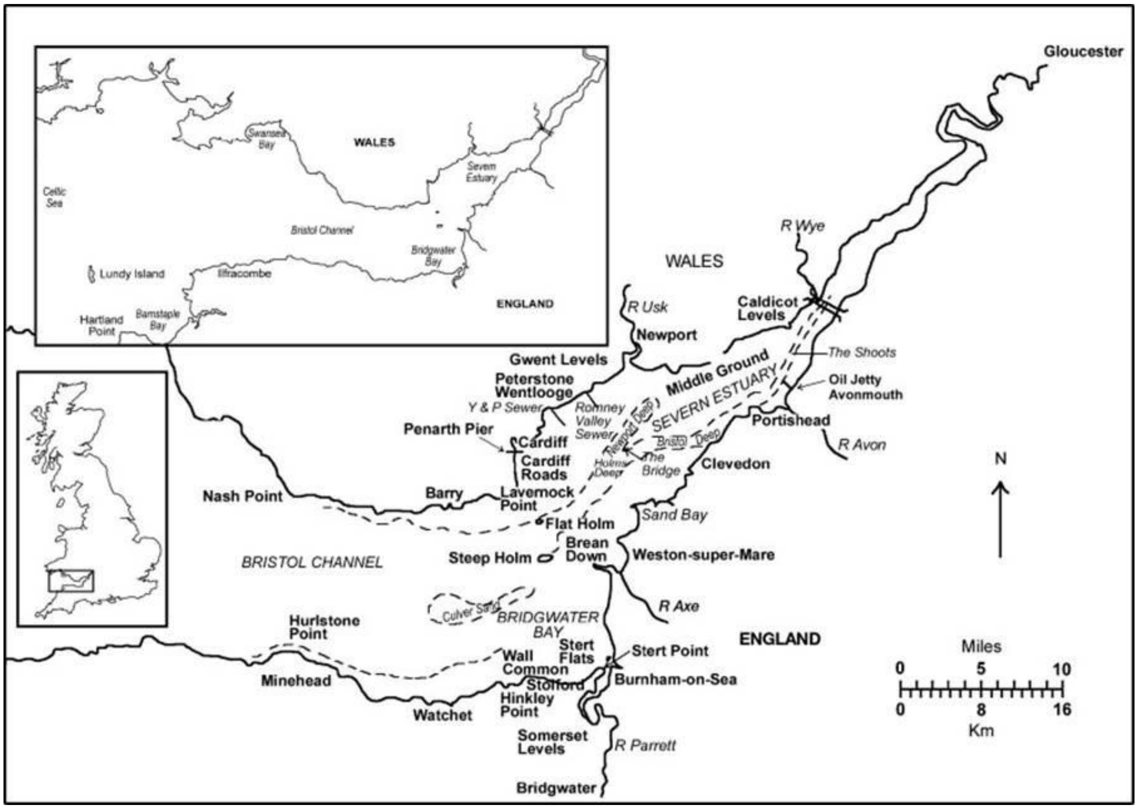


1. Download: Download full-size image

Fig. 1. Inset maps of UK, Bristol Channel and Severn Estuary with locality map showing sites mentioned in the text. Y = Ystradyfodwg; P = Pontypridd.

The essence of the fine cohesive sediment regime in the Severn, the topic of this paper, is tied up in an apparent contradiction. The estuary is, at the same time, both a “super-starved sedimentary system” (Fig. 2) and one renowned for the super-abundance of its population of suspended particulate matter (SPM). This apparent conflict is resolved by explaining that a much higher proportion of the unconsolidated sediment in the system is mobile at one place and time than in less energetic muddy estuaries. Compared to the previous phase of studies for a Severn barrage (HMSO, 1989), in intervening years a much greater understanding has emerged. This is especially of the inter-tidal zone which was formerly both poorly-accessible and poorly-investigated due to its width and the rapid rise and fall of the tide. An outline is provided herein of the transport of fine cohesive sediment on various timescales and the exchanges between the inter-tidal and sub-tidal sources and sinks. Whereas the previous phase of study produced a snapshot of the estuary as it was then, since then a number of large, intensively-measured data sets have been gathered and analysed, permitting a more sophisticated understanding of trends of evolution of the estuary.

1. Download: Download full-size image

Fig. 2. Distribution of rock outcrops (toned zone) at the sea bed in the Bristol Channel and Severn Estuary from BGS Lundy and Bristol Channel sheets (1986).

These include approaching a 17 y intensively monitored sequence of tidal flat elevation change, yearly shorebird counts from British Trust for Ornithology extending over almost 40 y (Burton et al., 2010), approaching 30 y of water temperature and salinity measurements off power station cooling water intakes and their fish screens (Henderson and Bird, 2010), and Environment Agency helicopter surface water quality measurements in 1970 and from 1977 to 1997 and more recently (Jonas and Millward, 2010). Whereas this presentation focuses on the environmentally deterministic fine sediment regime, the three truly environmental time series (above) make predictions of barrage consequences more rigorous.

2. Inter-tidal zone

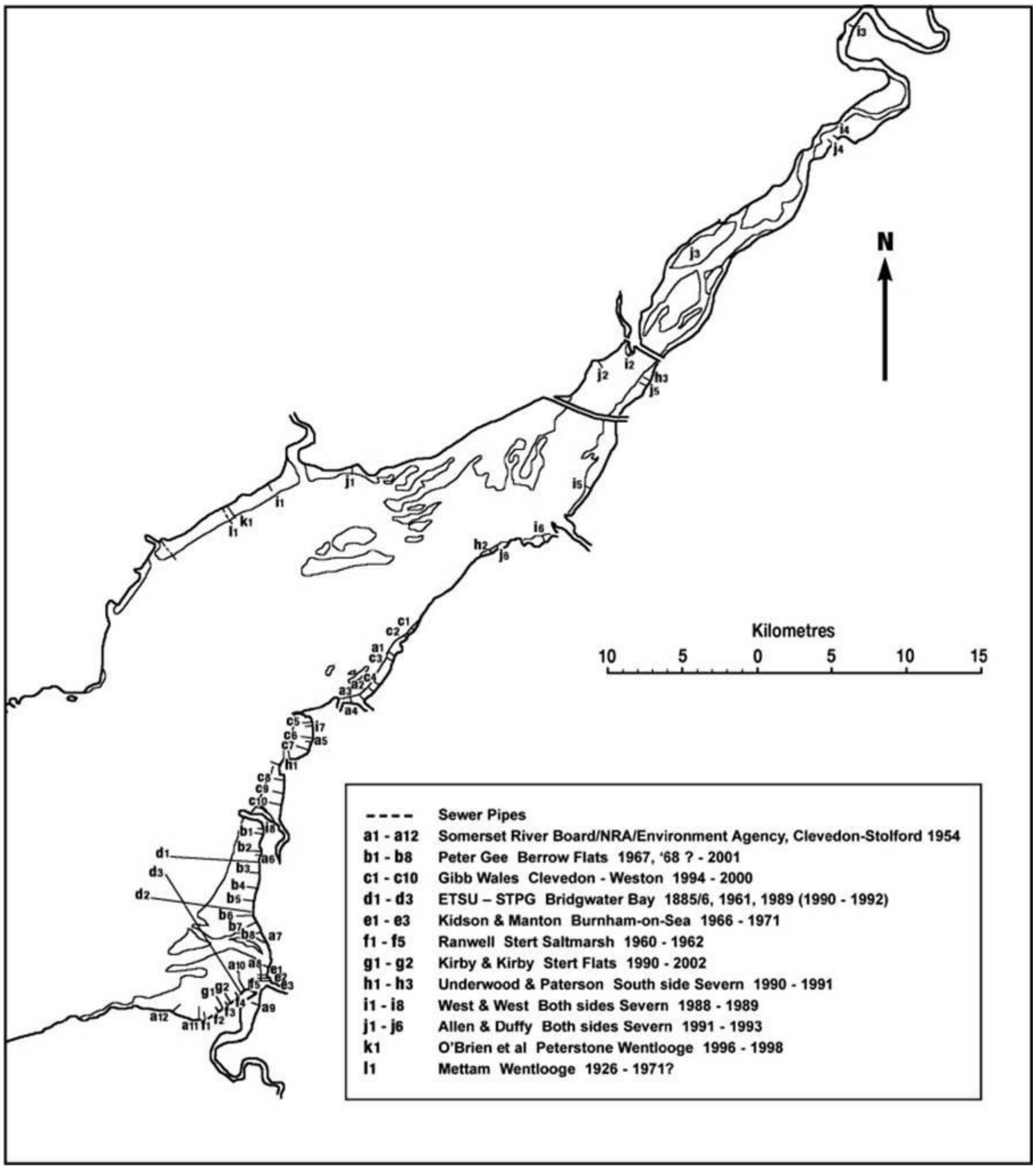
The Severn is a part coastal plain, part high cliffed estuary. Its main alluvial coasts are the Gwent and Somerset Levels on the Welsh and English coasts respectively. The Welsh shoreline has earth and stone-faced banks, in a few local areas fronted by polders and groynes which trap sediment and have formed salt marshes. On the Bridgwater Bay coast, fossil pebble ridges and aeolian sand dunes limit incursion by the tide, with occasional man-made defences at, for example, Burnham-on-Sea and Brean. **The fronting inter-tidal zone is highly susceptible to erosion. In places a narrow salt marsh ribbon survives, but this is almost always marked along its seaward edge by an erosional cliff**. Contemporary photographs taken in 1890 during the installation of the Ystradyfodwg and Pontypridd sewer pipe show that the coast at Rumney (Fig. 1) at that time had a narrow, cliffed salt marsh which has since eroded back to the sea wall. **Much of the salt marsh at Stert Flats is "engineered", being planted out as a cheap coast protection measure by the then Somerset River Authority in 1928–29. This was initially successful, accreting and reaching its maximum seaward and along-coast extent in the 1960s (Ranwell, 1964), since which time it has reverted to an erosional trend and retreated laterally.**

The inter-tidal area of the Severn is large, 22,500 ha according to the Coastal Habitat Management Plan (CHaMP) (ABPmer et al., 2006) **and the mudshore reaches 3 km wide in places**. Other than at Burnham–Brean and Sand Bay, where a precarious, narrow and thin perched sand beach occurs, **this zone consists of mud flats**. The substrate comprises of over-consolidated Holocene peat and clay deposits of Wentlooge Formation Age (Allen and Rae, 1987). During neap tides these flats are often veneered by inhospitable fluid mud. **Tidal mudflats in the Severn have particular attributes, such that their long term erosional nature is proven by exposure of the ancient deposits, from occurrence at the tidal flat surface on the Welsh coast of formerly buried sewer pipes, and from repeat theodolite surveys 20 y apart on the English coast. An important attribute of the tidal mud flats of the main estuary is that they have low and concave cross-sectional profile. Such profiles are "challenging" on both engineering and environmental grounds, in that they imply larger waves reach close to high water, coupled with offering restricted feeding opportunities for birds**. This latter is on the basis that the main biomass of invertebrate prey species for birds is focussed in the zone between mid and high tide, which is intrinsically narrow in such cases (Green, 1968, Anderson, 1972, Burton et al., 2010).

From studies initiated during the previous phase of barrage investigation, and subsequently, it is known that low and concave cross-sectional shapes are characteristic all round the world of eroding mudshores (Kirby, 1989, Kirby, 1992, Friedrichs and Aubrey, 1996, Mehta, 2002). Separate from the cross-sectional shape, Carr (1965) showed that the inter-tidal zone at Stert Flats is inclined along the coast, being lowest in the west. His observations over 28 days show that waves reached the top of the shore for 220 h out of a possible 672 near Stolford, falling to 27 h out of 672 in an up-estuary direction at Wall Common. In about 1960 the top of the mudflat lay at +2.7 m OD near Stolford, but rose steadily to +5.5 m OD in the east near Stert Point, almost a 3.0 m difference. It is not known whether such an up-estuary rise in tidal flat elevation extends beyond Bridgwater Bay into the Severn. Clearly, both cross-sectional profile and alongshore elevation have deterministic implications for bird and fish feeding opportunities.

A further and final attribute of the inter-tidal zone, and one harking back to the extraordinarily low biogenic carbonate content of Severn Estuary sands reported by British Geological Survey (1986), is that **eroding mudflats throughout the world manifest a particular sedimentary feature, namely winnowed, wave-driven shell banks, called "chenier ridges"**. Tidal flats in the Severn occasionally exhibit living but small sized examples of the polychaete *Nereis diversicolor* and the crustacean *Corophium volutator*, which never reach adulthood. Filter feeders are absent and the elsewhere-common bivalves and gastropods with a calcarious exoskeleton *Cardium* (*Cerastoderma*), *Mytilus*, *Ostrea*, *Venus*, *Buccinum*, etc., never occur. Consistent with the long term paucity of burrowing shelly invertebrates, compared to lower tidal range, less turbid eroding foreshores such as the Thames and Medway (Greensmith and Tucker, 1965, Kirby, 1990), the erosional Severn tidal flats are devoid of loose shelly accumulations. Very occasional disarticulated valves of juvenile *Macoma balthica* are seen. This further testifies to the macrofaunal impoverishment of the foreshore.

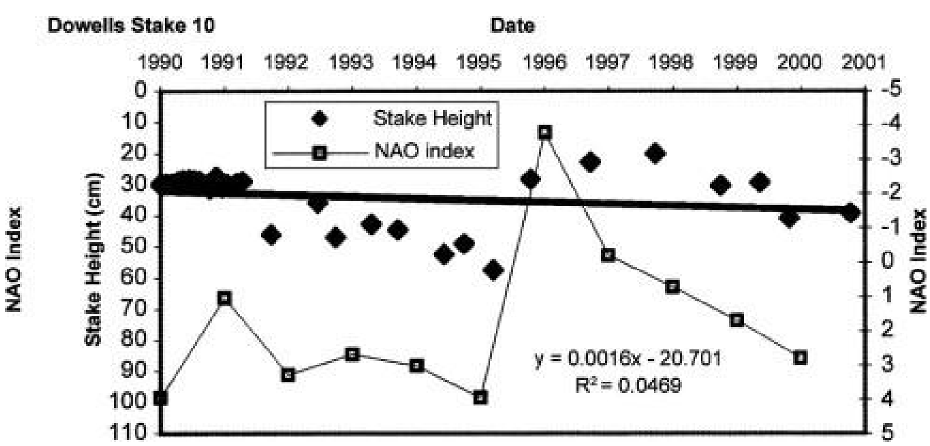
This general evidence establishes the long term trend of the inter-tidal zone and thus its relationship to the estuarine sediment budget. Clearly it is a source. There is also evidence for tidal flat dynamics sufficient to establish exchanges with the water body on various timescales. Partly prior to, but in large measure subsequent to the previous phase of barrage feasibility study, many repeat elevation change studies have been carried out on the tidal flats of the estuary (Fig. 3). The figure shows the extent of measurements, indicating that few zones remain un-surveyed. These mainly involve relatively short time periods of observation and tend to indicate erosion. However, the short term variability prevents an accurate budgetary calculation.



1. Download: Download full-size image

Fig. 3. Sites at which repeat tidal flat cross-sections of elevation change have been measured in the Severn Estuary and Inner Bristol Channel.

In one of the most intensive studies ever carried out over a period of a few years, O'Brien et al. (2000) showed how the tidal flats at Wentlooge wax and wane in height, tending counterintuitively to be higher over the semi-lunar period on springs, as well as on a seasonal basis being higher in summer than winter. This latter effect is well-established and arises from a combination of enhanced algal binding in summer coupled with greater storminess in winter. **Tidal flat elevation measurements show a coincidence between windy spells and erosion**. In spite of its intensity this study, similarly, was too short to establish a long term trend. In the most prolonged study of its type ever carried out, Kirby and Kirby (2008) have intensively measured tidal flat elevations along 2 lines of stakes over a 17 y period at Stert Flats. Twenty-one stakes have been re-measured 35×, extending to almost 1000 individual measurements. In spite of strong signals from two attributes interfering with each other (the formation, episodic submergence in soft mud and easterly migration of ridge and runnel topography, coupled with the long term evolutionary trend) a strong and unambiguous signal emerges (Fig. 4). Associated scrutiny of the data from the recently installed tide gauge at Hinkley Point nuclear power station shows a mean rate of sea level rise of about 4 mm y^{-1}, whereas the net vertical erosion rate using all the data from Kirby and Kirby (2008) is about 16 mm y^{-1}, and higher still at the top of the shore. Short term trends mirror those found by O'Brien et al. (2000). However, the most important conclusion to emerge, distinguishable from the "noise" induced by the topographic complication, is that the long term decreasing trend in the 35 repeat measurements at each stake is not random but instead closely allied to the yearly variation in the Index of the North Atlantic Oscillation (Fig. 4). This factor determines the "winter windiness" of the NW European weather. **Were this long-term erosion rate to apply to the entire mudshores of the Severn, net annual fine sediment loss would lie in the region 5 Mm^3 y^{-1}. The entire fine sediment input to the estuary from rivers, cliff, salt marsh, mudflat and sub-tidal erosion is estimated in CHaMP (ABPmer et al., 2006) to be 3.4–4.0 Mt y^{-1}.**



1. Download: Download full-size image

Fig. 4. Representative example of 21 stakes along 2 lines on Stert Flats (g_1 and g_2 Fig. 3), at which tidal flat elevation change was measured at various intervals from March 1990–January 2001 (35 visits). Tidal flat erosion dominates when the Index of the NAO is positive (stormy winters in UK), whereas accretion dominates when Index is negative.

The Kirby and Kirby (2008) measurement represents 7 Mt y^{-1} using a mean mud density of 1.4 t m^{-3}. In a recent study comparing datums from the installation drawings for the Ystradyfodwg and Pontypridd and Rumney Valley Sewers (installed in 1890 and 1920 respectively) with modern low water Environment Agency LIDAR surveys of the Peterstone–Wentlooge area, a long-term erosion rate for the entire Severn and Bridgwater

Bay very similar to this figure is likely to result (HR Wallingford, pers. comm.). This 100 y, whole cross-section mean will be the most reliable of the inter-tidal fine sediment budget estimates. Evidence from O'Brien et al. (2000) and Kirby and Kirby (2008), plus the compiled short term survey summary plot in Fig. 3 confirm the estuary-wide nature of this calculated trend. This is the first reliable measurement of the whole mudshore fine sediment budget. The recently published CHaMP (ABPmer et al., 2006) shows a predicted loss of inter-tidal "habitat", in the form of the mud flats, using sea level rise data alone of 10–20% in 100 y. Clearly, when shore cross-sectional shape and vertical erosion rate are added to this the loss rate of the outer mudflats (Coastal Squeeze) would be more severe. The tidal flat gradient in the Severn varies between 1:200 and 1:500. Summing sea level rise and the long-term erosion rate, 20 mm y^{-1}, leads to an up-shore retreat rate ranging from 4 to 10 m y^{-1}.

Over the years a number of long term recording siltmeter deployments have been carried out (HR Wallingford, 1981 [Avonmouth Oil Jerry, Flat Holm], and Severn Tidal Power Group, 1993 [**Clevedon Pier,** Penarth Pier, Hinkley Point Cooling Water intake dolphin]). **Records from those deployments adjacent to mud flats show the close association between windy weather inducing wave attack and episodic high suspended sediment concentrations. There is consequently a close agreement between tidal flat dynamics on all timescales and enhancement in coastal boundary suspended sediment concentration due to gales.**

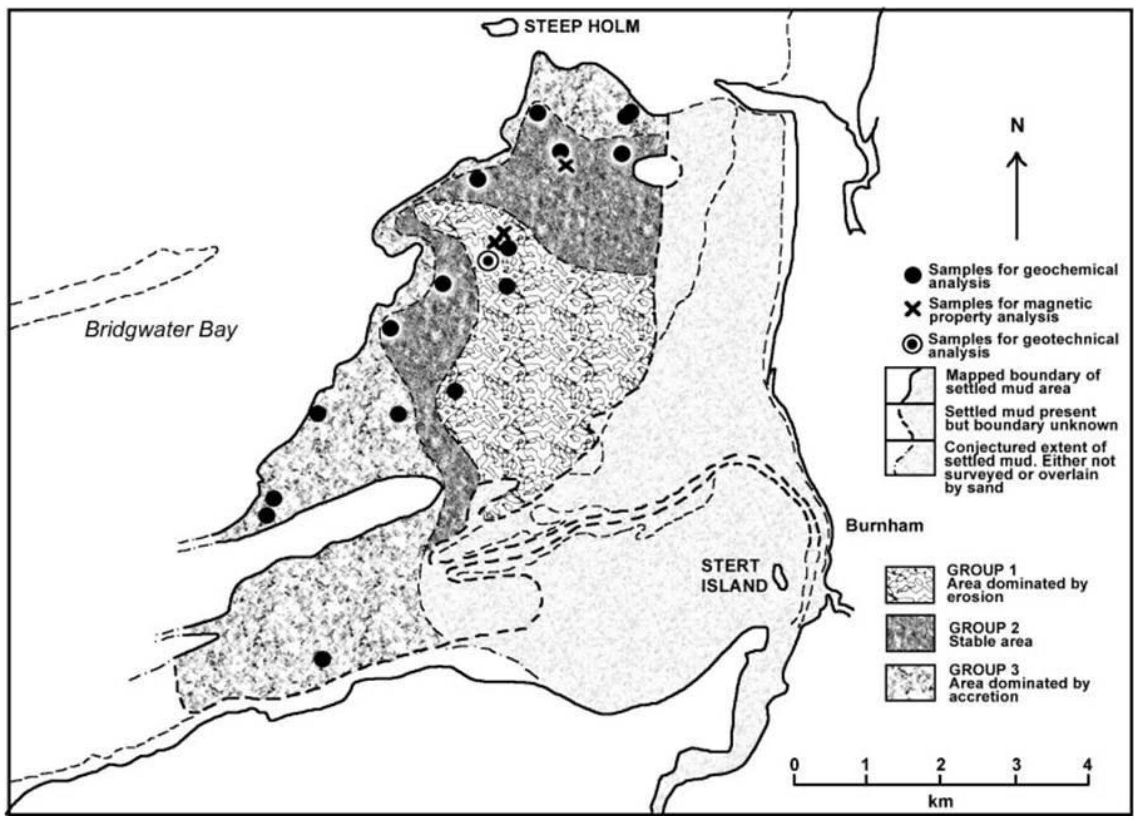
3. Sub-tidal zone

The Severn Estuary and Bridgwater Bay have a number of sub-tidal mud patches which exchange fine cohesive sediment with the erosional foreshore and dynamic water body on various timescales. These are disposed in areas having a degree of shelter from the fiercest currents, Bridgwater Bay, Newport Deep and "at times and in places" Bristol Deep. These differ in degree, the largest, Bridgwater Bay, is both a source and a sink, Newport Deep, appears to be a simple sink, whereas Bristol Deep is in a state of delicate balance, minor short term topographic perturbations such as bar and subsidiary bank formation creating sufficient shelter, even in The Shoots Channel, for settled mud to accumulate on the bed with a stability dictated by that of the sheltering element. It has further been suggested that an additional long term sink is present in the sub-tidal apron fronting the Wentlooge Levels and in Cardiff Roads (British Geological Survey, 1986). The former is difficult to access from a research vessel due to its extreme shallowness, which may partly explain its poorly understood status. The bed sediment map in Parker and Kirby (1982) indicates this is not a significant mud patch. This same shallowness precludes it from making a large contribution to the fine sediment exchanges in the system. Cardiff Roads has not been subject to such detailed inquiry as other sub-tidal mud patches. The fact that it engenders high rates of mud maintenance dredging, 60,400 t dry weight in 2007 with a rapidly reducing trend, makes it likely that it is a sink similar in many ways to the adjacent Newport Deep. (23,400 t dry weight in the port approach channel in 2007, about 15× smaller than Avonmouth). The maintenance dredging need for all ports combined is minor and undetectable in the large scale fine sediment budget (see below).

Newport Deep is a rapidly atrophying blind-ending flood-dominant channel which is both a natural fine cohesive sediment sink, receiving mud from foreshore erosion and reworked dredge material disposal at Cardiff Grounds. It is also a mud maintenance dredge placement area for the port of Newport. Something of its mud dynamics is known from a radioactive tracer test on a barge load of mud carried out in 1966 (Atomic Energy Research

Establishment, 1967). It is, further, the site of regular occurrence of dense stationary fluid mud suspensions which stabilise on the bed for brief periods every neap tide. These can be very extensive, completely filling the Deep on neaps following equinoctial spring tides (Kirby, 1986).

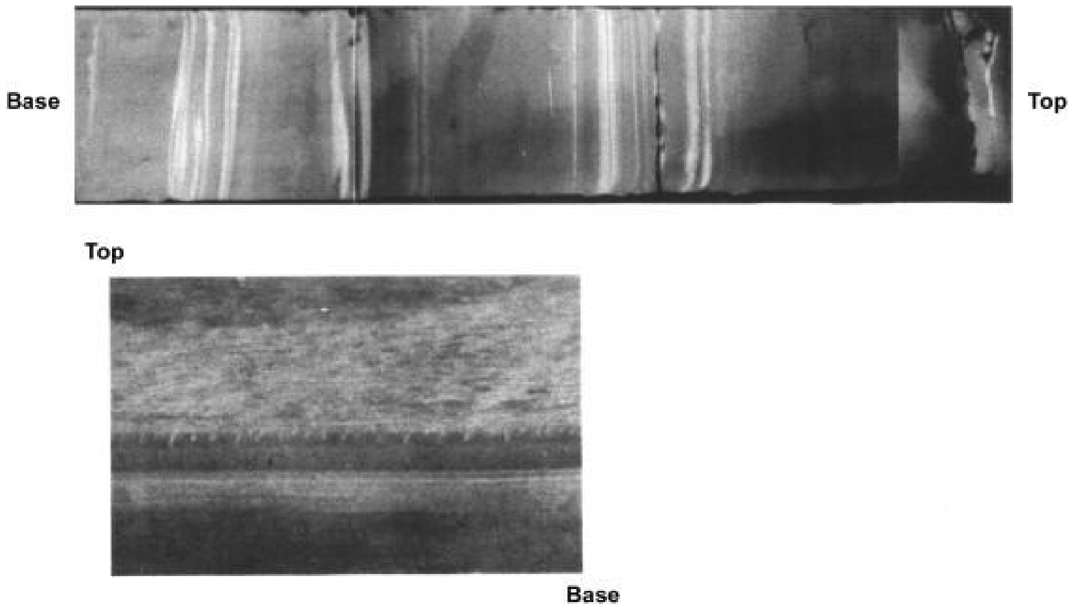
The sub-tidal settled mud patch in Bridgwater Bay is co-extensive with the broad swathe of the inter-tidal zone. It was mapped with high resolution shallow seismic equipment in 1972, 1974 and 1976 (Kirby and Parker, 1980), its boundary being stable within the survey accuracy of the period (±100 m). Interpretation of these records, coupled with analysis of cores for heavy metals from Industrial Revolution discharges, from natural and anthropogenic radio-nuclides plus magnetic fabric and remnant magnetism show (Fig. 5) an erosional central zone co-extensive with the erosional foreshore, surrounded by a stable zone of no net change and with an outer region of accretion.



1. Download: Download full-size image

Fig. 5. Core sample localities and distribution of erosional, stable and depositional zones in the sub-tidal mud patch in Bridgwater Bay. Since making the map, the entire muddy inter-tidal zone is also recognised to be eroding (see Fig. 3, Fig. 4).

Subsequent to these studies and consistent with contours of “deposition potential”, Kirby (1986) and Long et al. (2002) have shown that rapid deposition in the sub-tidal mud patch is progressing westwards in the approaches to the Parrett Estuary and the Port of Bridgwater to beyond Hinkley Point. The mud patch contains about 600 Mt of fine cohesive sediment (Parker and Kirby, 1982). A suite of large diameter (55 mm) cores were sectioned into slices of 3 mm and were X-rayed. Without exception the cores showed a primary (depositional) fabric lacking any evidence of secondary biogenic bioturbated zones. Some of these cores have been dated back 1900 y (Long et al., 2002) testifying to the long term barrenness of this regime. Inter-bedded "tidal lamination" and dewatered fluid mud layers can be distinguished. The combined physical and chemical properties preclude colonisation by burrowing organisms (Fig. 6), (Kirby, 1991).



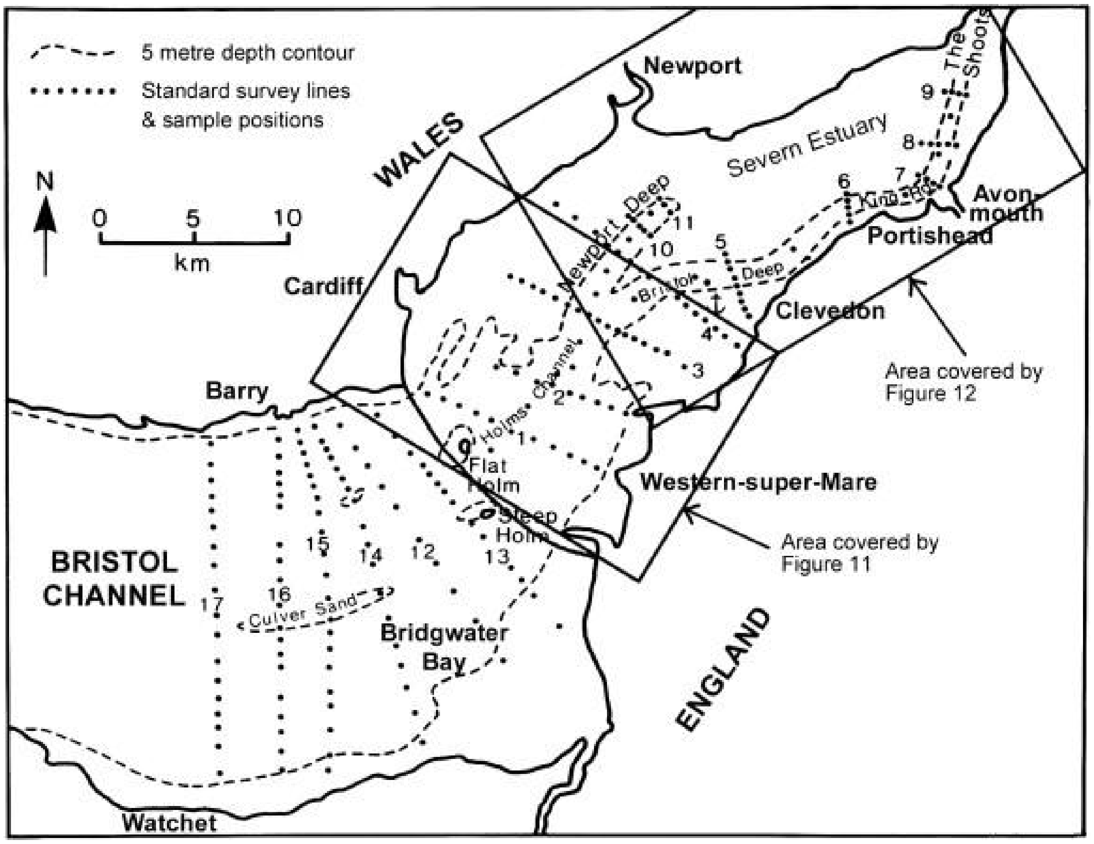
1. Download: Download full-size image

Fig. 6. A primary sedimentary fabric. Thick (3 mm) axial section X-radiographs of gravity cores of muds from Bridgwater Bay showing what are interpreted as massive, "felty-textured" dewatered fluid mud deposits inter-bedded with sub-millimetre "tidal lamination". The lower, magnified image shows a dewatered fluid mud deposit with crushed macroflocs making up the "felty-texture" overlying an earlier clay-rich layer showing 1–2 mm deep creep cracks. There is no sign here, or in any of the 30 + other cores, of secondary sedimentary fabric due to bioturbation.

4. Suspended fine cohesive sediment

Further to undertaking 22 extended shipboard research surveys in the 1970s, the 3D structure of the main estuary turbidity maximum of the Severn and its cycling on various tidal timescales is better understood than any other in the world (Kirby, 1986). There appears to be a threshold in the depth-averaged concentration of SPM, initially calculated from data used in Kirby (1986), to be ~500 mg l^{-1}, separating what might be called "low turbidity phase" from "high turbidity phase" suspension behaviour (see discussion below). The phenomena described herein fall well within the latter phase. Indeed, directly from this body of research, the Severn has become the "Type-Locality" around the world for processes and mechanisms first discovered here.

Arising from the overwhelming tidal control exerted on the system, the "pseudo-synoptic" sampling method adopted at the time, and the resulting description, the data and its interpretation remain just as valid today as when obtained in the 1970s. A pattern of 17 "standard lines" involving 210 "standard stations" was set up between Watchet and The Shoots (Fig. 7). These were monitored intensively "in dynamic mode" using a roving vessel which steamed to and fro along a selected line throughout a semi-diurnal cycle, heaving-to at each station to measure a high speed continuous vertical profile of SPM concentration versus depth. By visiting adjacent lines at comparable times in the semi-lunar cycle but at different dates, and by covering the entire falling spring to neap and rising neap to spring range, close to 2500 profiles spanning all tidal conditions were obtained and digitised into a data bank and analysed.



1. Download: Download full-size image

Fig. 7. Distribution of Standard Lines (1–17) and Standard Stations (210) between Watchet and The Shoots used in pseudo-synoptic surveys of suspended solids distribution. Results shown in Fig. 8, Fig. 11 arose from SPM versus depth profiling. Boundaries of areas in Fig. 11, Fig. 12 are indicated.

The essence of the fine suspended sediment regime can be summed up in two phrases. The system is notable for the regionally high turbidities encountered and for the cycling of this material on semi-diurnal and semi-lunar timescales between the water body and bed (Kirby, 1986). **In the reaches investigated, the estuary contains more than 30 Mt in suspension on high spring tides, reducing two weeks later to about 2 Mt on low neap tides, the difference being made up in extensive fluid mud pools sited mainly in channels.** This large data set has been manipulated to describe the regime in a number of ways, for example, semi-diurnal hourly plan views of surface and bed turbidity on a mean spring or neap tide, hourly cross-sectional plots, mean flood and ebb cross-sectional plots on spring and neap tides, longitudinal plots, as well as being analysed to study fine cohesive sediment phenomena and processes. Commonly at neap tides, suspensions dewater to a hindered settling, fluid mud condition way beyond the range of optical siltmeters. Thus, specially designed gamma-ray densimeters and a modified survey echo sounder were used to track and measure their internal structure. These various presentations are set out in Kirby (1986). The strong tendency for the suspended load to discretise itself in vertical, lateral and longitudinal planes is outlined briefly here.

4.1. Vertical structure

The suspended sediment population shows a strong tendency to form steps or layers in the vertical. In view of the well-mixed salinity and temperature structure of this highly-dynamic estuary this was initially a counter-intuitive phenomenon. Smooth, “Rousian” exponential profiles were expected. By analogy with oceanographic nomenclature (halocline and thermocline), the layers were termed “lutoclines” (Kirby and Parker, 1983). The explanation for these contrasts is the conservative behaviour of salt and heat compared to the non-conservative behaviour of fine sediment, i.e. it both mixes and “un-mixes” during settling. On springs, the lutoclines retain a spatial coherence measured in many minutes to a few hours, whereas in the run up to neaps settling and mixing remain in balance, or nearly so, for a few days at a time (Fig. 8, Fig. 9). On the succeeding neap back to spring stage the stationary fluid mud pools experience a sudden and large scale re-entrainment at shear stresses significantly higher than those at which the layered suspensions ceased flowing. They are mixed into the water body as turbulent eddies without any intervening period involving stable layered structures. Such phenomena, which intrinsically involve repeated large scale cycling between aerobic and anaerobic chemical phases, have a range of important implications for reducing pollutant dispersal, contaminant stripping and for short term large scale dissolved oxygen suppression (Kirby et al., 2004, Kirby et al., 2008). The mechanism of formation, stabilisation and dissipation of lutoclines is well-established (Smith and Kirby, 1989).

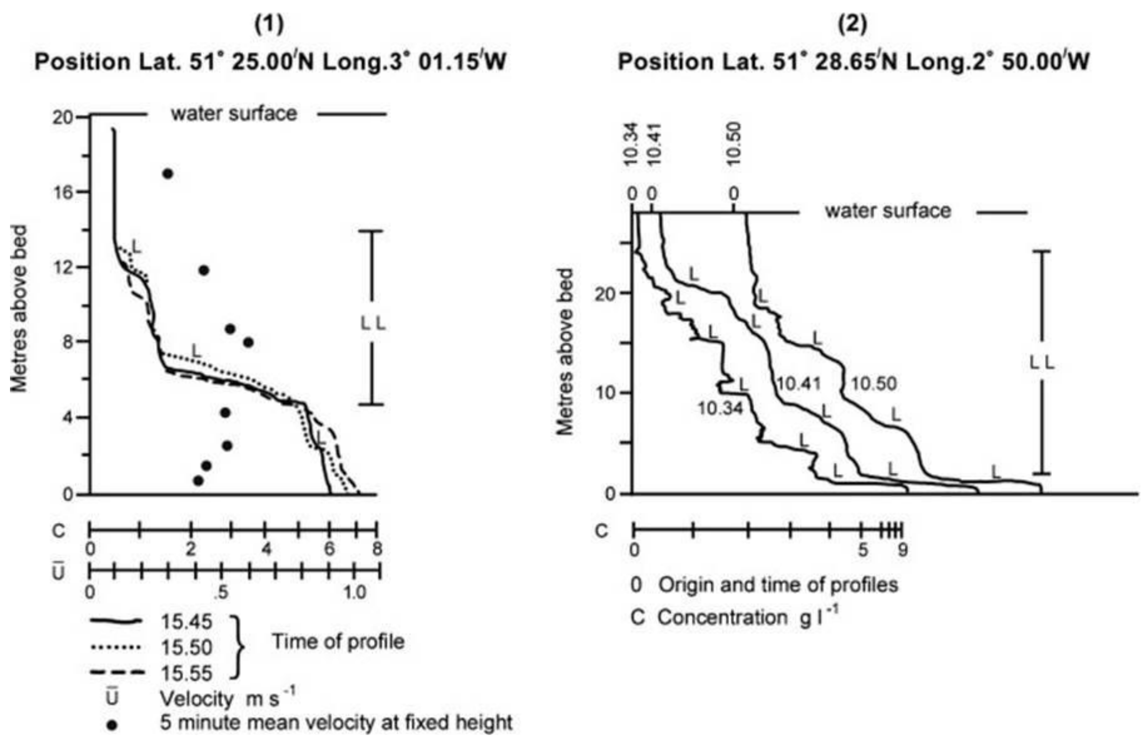
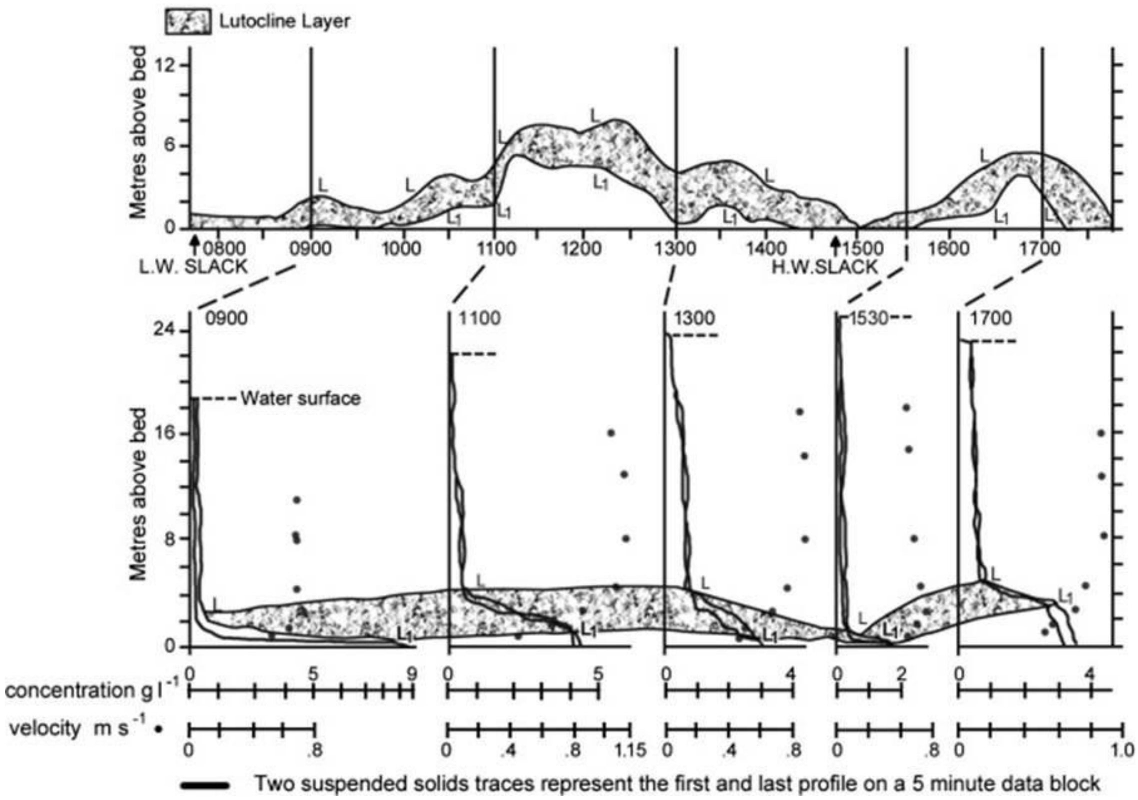


Fig. 8. Typical depth profiles of SPM concentrations showing layers and their stability over 10 and 16 min periods in the Bristol and Holms Deeps. L = Lutocline, LL = Lutocline Layer.

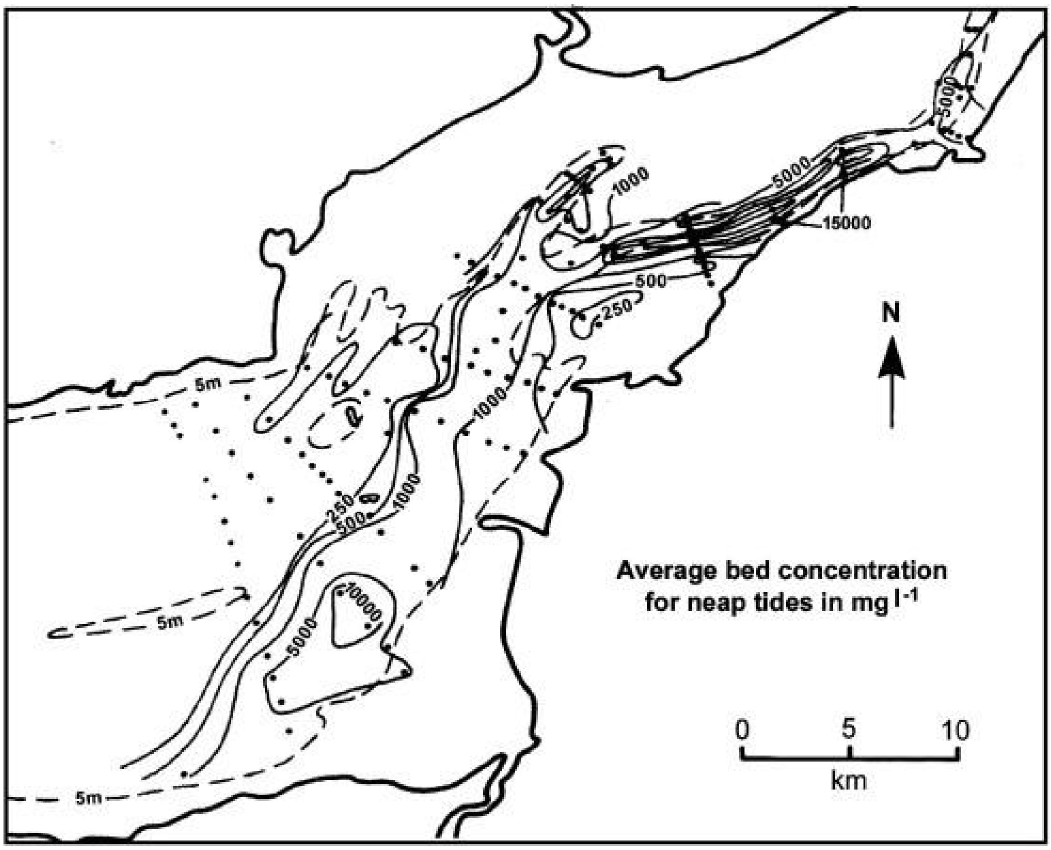


1. Download: Download full-size image

Fig. 9. SPM concentrations in the Bristol Deep off Clevedon. Top:- variation in the thickness of the Lutocline Layer ($L-L_1$) during 10 h of an intermediate-neap range tide and Bottom:- accompanying depth profiles of SPM concentrations and velocity fields.

4.2. Lateral structure

The main estuary turbidity maximum is laterally partitioned on a regional scale being asymmetrically disposed, with a high turbidity zone on the southern, English side (Fig. 10). Its positioning is presumed to relate to a combination of the orientation of The Shoots Channel, which directs high turbidity water from the Inner Severn onto the English coast, plus the interaction between the water body and its largest source and sink in Bridgwater Bay, also on the English side. Frontal dynamics are known and understood. Frontal stability is determined by interaction of the mixing and settling behaviour of the suspended load coupled with ebb/flood alternation in the cross-estuary water surface slope (Kirby, 1986). The conclusion, this is a genuine suspended solids front, the dynamics of which contrasts with buoyant fresh water or thermal plumes.

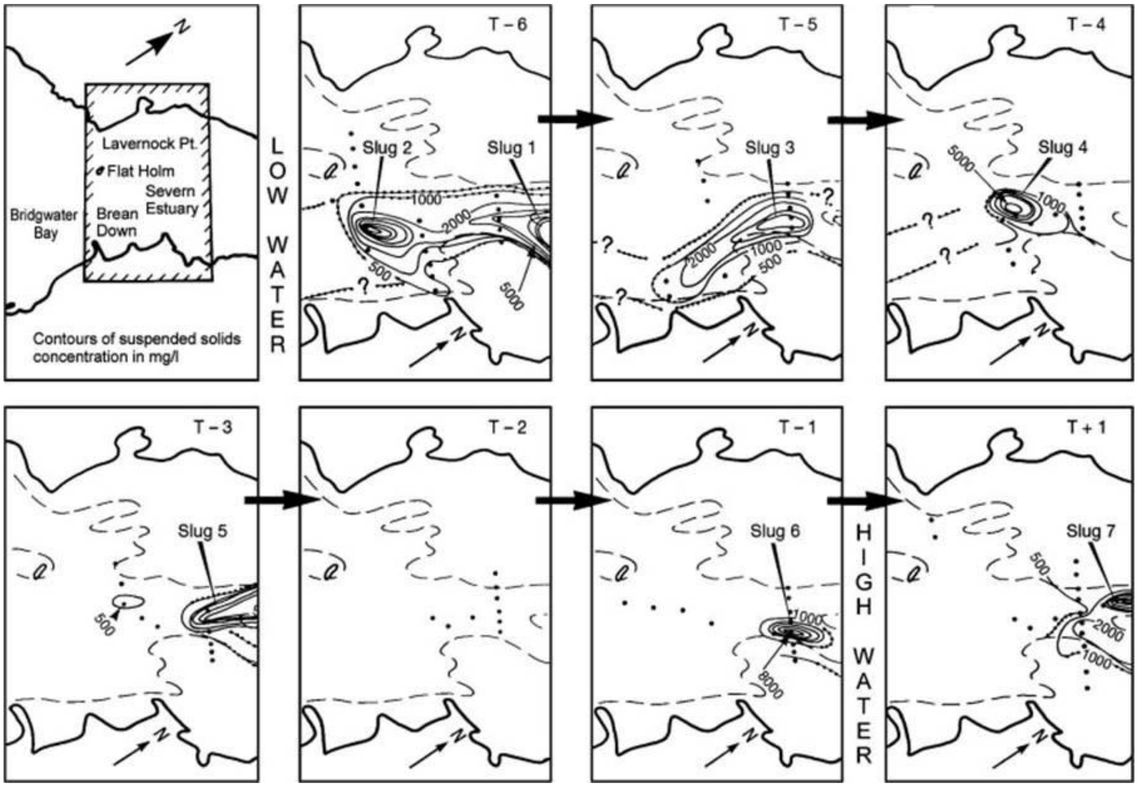


1. Download: Download full-size image

Fig. 10. Plan view of average bed SPM concentrations for neap flood tides between Watchet and The Shoots in mg l^{-1}. Dots are standard stations for which data is available. Concentrations routinely reach 10,000–15,000 mg l^{-1} on the turbid English side. The strong lateral concentration gradient indicates a suspended sediment front.

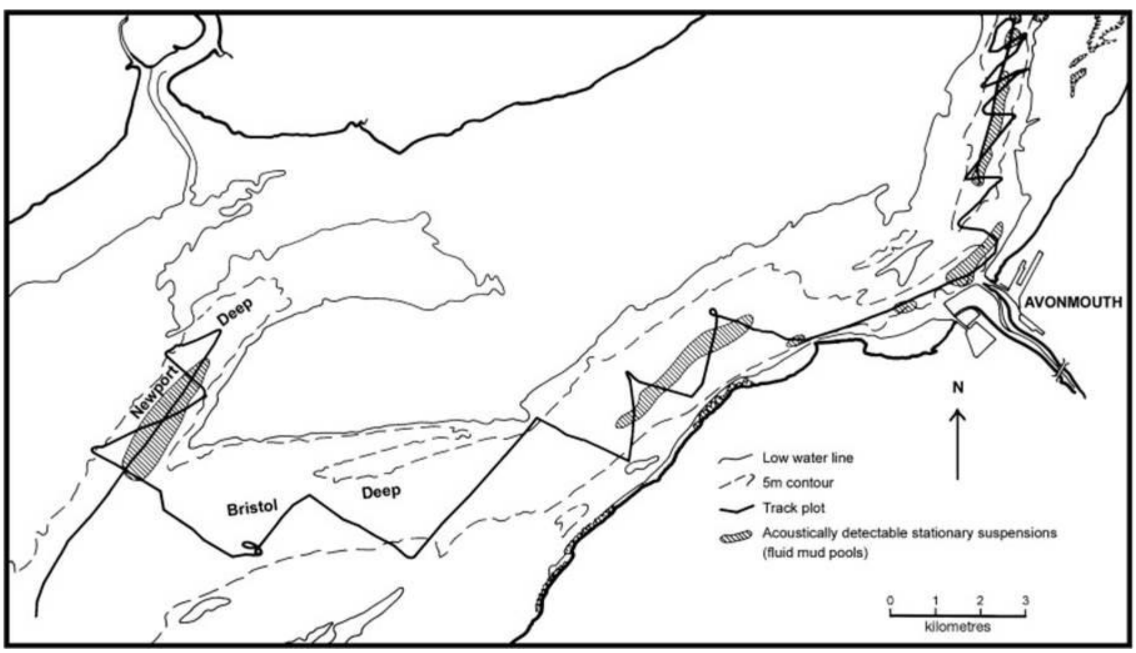
4.3. Longitudinal structure

Plan view plots on decreasing tidal energy phases towards neaps show that the main estuary turbidity maximum discretises itself into slow-moving, near-bed "slugs" of dense mobile suspensions beneath faster flowing tidal waters. Fig. 11 shows a plan view of three standard lines in the zone Lavernock Point-Wentlooge (Wales) and Brean Down-Clevedon (England). The hourly flood tide plots show 7 slow-moving slugs creeping up Holms Deep between Steep Holm/Flat Holm and passing "The Bridge", the channel divergence where Bristol and Newport Deeps separate. The slugs are thought to be individual slack water settlement events inherited from previous semi-diurnal tidal minima and not homogenised on subsequent re-entrainment phases. In contrast to the vertical and lateral planes, these appear not to have sharp turbidity discontinuities marking their boundaries. Across neap phase tides these slugs stagnate for a few days forming the "environmentally-constraining" fluid mud pools (their combined fluid and anaerobic nature prevent colonisation by macroscopic organisms), which have been mapped using survey echo sounders (Fig. 12). Their location across any particular neap tide is preferentially in deep channels but otherwise seemingly random, though with a bias favouring Newport Deep and the Avonmouth area.



1. Download: Download full-size image

Fig. 11. Plan view of three Standard Lines in the zone Lavernock Point-Clevedon (inset top left and Fig. 7 for location) showing in the near-bed zone on an intermediate, descending-energy, spring-neap flood phase tide, seven slow-moving, high turbidity slugs migrating into Newport and Bristol Deeps.



1. Download: Download full-size image