Fig. 12. Distribution of fluid mud pools detected with a high resolution echo sounder on the bed in inner deep water channel areas on a low neap tide (29.3.1973). These are inherited from the slug flows shown in Fig. 11.

4.4. Summary

Clearly, the Severn is a "high turbidity phase behavioural system". It is dominated by its high turbidity and the large scale cycling of fine sediment between water body and bed on daily and fortnightly tidal intervals. Meteorological effects, especially heavy rain on emerged tidal flats or wind waves, perturb the semi-diurnal and semi-lunar mixing and settling but are never large enough to destroy the cyclicity in behaviour described. These episodic storm events qualitatively and quantitatively part-mask the sediment cycling induced by the tidal rhythms. **On stormy days surficial internal turbulence in the water body inhibits the process of settlement, which is usually initiated at shallow depth. Similarly, large scale erosion of tidal flats is induced (Severn Tidal Power Group, 1993, Kirby and Kirby, 2008). The largest amounts of fluid mud on neaps, including formation in Bridgwater Bay, occurs after equinoctial spring tides coincident with gales.** (In contrast, "low turbidity phase behavioural systems" are dominated by episodic river spate and storm wave induced input). In these ways and on these various timescales the fine sediment in the main estuary turbidity maximum interacts with long term sources in the inter-tidal zone and centre of the Bridgwater Bay sub-tidal mud patch. Fortnightly fluid mud increments are almost always re-eroded on the next spring tide phase. Dewatering and consolidation to form new bed deposits in the long term sinks in Bridgwater Bay, Newport and Bristol Deeps and perhaps Cardiff Roads is presumed to occur subsequent to these largest scale inputs (low neaps following severe gales) especially when these are succeeded by calm weather spells (Kirby, 1986).

5. Other aspects of sediment suspensions

5.1. Self-cleansing muds

The issue of natural and induced "self-cleansing" of fine cohesive sediment suspensions in which anthropogenic contaminants are released or decomposed in situ is beginning to emerge. For example, Periáñez et al. (2005) propose the estuarine self-cleansing of sediment contaminated with radium due to a discharge from a fertilizer plant located on the Odiel river near Huelva in Spain. Natural self-cleansing has been hypothesised arising from storm-wave entrainment of contaminated anaerobic bed deposits in low turbidity systems or due to burrow irrigation by organisms living in anaerobic substrates. These are mechanisms too ephemeral and small scale to investigate readily in the field, whereas controlling physical, chemical and microbiological conditions in a laboratory mesocosm for prolonged periods remains a challenge. Induced self-cleansing has been linked to mud maintenance dredging operations in which contaminated anaerobic fine sediment is brought into suspension in aerobic water bodies, leading to desorption of sediment-bound chemicals. In contrast, the scale and frequency of natural cycling of fines between aerobic and anaerobic phases in the main estuary turbidity maximum of the Severn is such that release of sediment-bound contaminants could be a large scale process (Kirby et al., 2008). For example in the Severn the release of dissolved cadmium and zinc (Langston et al., 2003) and dissolved copper (Jonas and Millward, 2010).

In mainland Europe there is now close to 20 y of experience with "induced self-cleansing". The concept called "Active Nautical Depth" has been pioneered in Emden as a means of managing fluid mud in the harbour (Wurpts and Torn, 2005, Kirby et al., 2008). By this means mud maintenance dredging need has fallen from 4 Mt y^{-1} to zero and maintained at that level. The technology is spreading to other ports, as well as being applied to whole estuary management. The point here is to emphasize another incidental benefit in terms of pollution levels. "Active Nautical Depth" involves occasional manipulation of the physical, chemical and microbiological attributes of the sediment with a view to creating and sustaining an aerobic micro-climate in the fluid mud cloud in order to sustain vessel passage in such media. By this means it has been found that as an incidental by-product the active component of the now-banned anti-fouling paint, tri-butyl tin (TBT), has been decomposed in situ (Kirby et al., 2008). Similar decomposition of TBT has been accomplished by oxygenation of maintenance dredged muds placed in storage fields in the Port of Bremen and regularly turned over to expose the material to air (PIANC, 2008). "Self-cleansing" for the Severn may have progressed to the extent that, coupled with natural dispersion, previously high contaminant levels have reduced to ranges in which environmental hazard is no longer a concern. Were a Cardiff-Weston barrage to be built, self-cleansing would greatly reduce as the fluid mud phase would disappear.

5.2. High and low turbidity phase behavioural systems

What might be termed high and low turbidity phases separate at a depth mean concentration somewhere in the region 500 mg l^{-1} (Kirby, 1986). Above this threshold lutoclines, slug flow and fluid mud formation on neaps occur. None is present below this. In the ambient high turbidity phase the following chemical and biological consequences can be recognised:

- i.

Absence of sunlight penetration limits primary production (Joint, 1984, Williams, 1984; Underwood, this volume).

- ii.

Dissolved oxygen concentration levels in the water body may be suppressed by the presence of organic-rich fines. As found in other high turbidity systems (Dong et al., 2000), dissolved oxygen levels throughout the estuary from the tidal limit to at least Hurlstone Point west of Minehead are lower on spring tides than on neaps (Kirby et al., 2004**). The estuary bed, especially in the channels and at times in summer the entire water body up-estuary of The Shoots Channel, is de-oxygenated by neap tide fluid mud or re-entrainment of this on the neap-spring cycle (Kirby et al., 2004). This de-oxygenation serves to suppress colonisation of the bed in these zones, as well as to intensify the inhibition due to absence of sunlight penetration.**

- iii.

A combination of salt water and UV radiation may reduce the concentrations of sewage-derived bacteria, pathogens and alien exotic micro-organisms. In the Severn, UV radiation is unable to penetrate the water body, which diminishes the rate of destruction of such organisms.

- iv.

Whereas the strong currents of the estuary are regarded as highly dispersive for contaminants, the presence of suspended sediment fronts and lutoclines, the latter being especially persistent on the spring to neap cycle (days), constrain the dispersion rate of any sediment-adsorbed chemicals. This is relevant to both industrial and domestic discharges. With (iii) (above), this implies that assumptions of high diffusion rates or destruction for such materials may be erroneous.

- v.

Salt and heat are conservative, whereas fine cohesive sediment is non-conservative. Waterborne contaminants can only disperse along the mixing gradient whereas, due to the scale of energy fluctuations and sediment cycling, chemically and microbiologically reactive fines involved in the sediment phase are continually "sweeping" the water body between surface and bed, with a number of consequences.

- vi.

On low neap tides more than 28 Mt of fluid mud located in extensive pools dewaters progressively, expelling anaerobic, potentially contaminant-enriched pore waters into the overlying water body (Hamilton et al., 1979), which advect, initially, in a non-mixing near-bed zone with potential consequences for benthic invertebrates and fish.

- vii.

The overwhelming tidal domination of the turbidity maximum under the existing regime would possibly shift very largely to an episodic, storm and river spate dominated system if a Cardiff-Weston barrage were built.

Items ii and vi, reductions in dissolved oxygen, are an inhibiting factor for invertebrates but especially for benthic feeding vertebrate fish, which are absent from the faunal community (Centre for the Environment, Fisheries and Aquatic Sciences, 1999, Centre for the Environment, Fisheries and Aquatic Sciences, 2000, Kirby et al., 2004, Henderson and Bird, 2010). At times this severe oxygen depletion is being exacerbated by long term rise in estuary water temperature (see below). Water temperature elevation is directly linked with progressive impairment in ability to carry dissolved oxygen.

Building a Cardiff-Weston barrage would shift the fine sediment behavioural system into a low phase. Daylight penetration would increase, dissolved oxygen levels would rise in both the water column and at the bed. Primary production would be jump-started. Saline waters and UV radiation would begin acting in unison and the suspended sediment front, lutoclines, slug flow and the fluid mud phase would all disappear. Ability to destroy micro-organisms would increase and constraints on dispersion would be eliminated. On the other hand large scale cycling of fine sediment between aerobic and anaerobic chemical climates, thought to engender natural self-cleansing would cease, as would prolonged periods with anaerobic pore waters in the near-bed zone. In this way ability to flush or destroy in situ various contaminants would diminish. As above, domination of the suspended load would shift in favour of episodic high energy events.

5.3. Fines mineralogy and turbine operations

Long term deployment of propeller current meters to determine flow velocities proved impractical in cases where movement was detected by opening and closing of a reed switch on an impeller. These employ a magnet which segregated finely divided "magnetite flour" from the suspensions causing seizure after as little as 45 min. It is not known whether Severn suspensions contain an unusually high proportion of magnetite. Mobile suspension concentrations reach 30,000 mg l^{-1} and the tidal excursion off Clevedon on a high spring tide reaches 53 km. This implies that perhaps 10 Mt of mud will pass any cross-estuary barrage line every spring tide. Tidal turbines contain electro-magnets, which are used in the nuclear industry to remove magnetic scale from inside cooling water pipes. This suggests the need to consider whether tidal turbines will segregate magnetite flour out of the suspensions and, if so, whether this might impair operation in any way. Concentration values in the water body will continue almost unchanged up to the "instant of closure" with a Cardiff-Weston barrage but diminish by an order magnitude subsequently. Whilst it seems unlikely such machines could stall, the material might, conceptually, get into the bearings. Enquiries have revealed no operational problems with magnetite have been encountered at the Rance and Annapolis Royal barrages, but these had comparatively low turbidities before barrage installation. It has recently emerged that Yangtze River fine suspensions passing turbines in the Three Gorges Dam are magnetite-rich, so this issue might be pursued with Chinese engineers.

6. Tidal power schemes in the Severn

6.1. Existing ecosystems

The fine cohesive sediment regime dominates both engineering and environmental issues in the Severn, especially with respect to a barrage. This has been reviewed by the author in 10 papers since 1975, plus the latest by Kirby and Retière (2009), which also draws upon complementary "before" and "after" evidence from the Rance tidal power barrage. This latter has recently become available in English. All the evidence cannot be repeated here but, in summary, the water body (Williams, 1984) and sub-tidal mud patches in the Severn (Fig. 5 herein) are barren, with sub-tidal sand (Mettam, 1998) and rock substrates almost so. The inter-tidal sand banks, most notably the biggest, Middle Ground, are barren or verging on barrenness (Centre for the Environment, Fisheries and Aquatic Sciences, 1999, Centre for the Environment, Fisheries and Aquatic Sciences, 2000). **The inter-tidal mudflats had (1987–91) the lowest carrying capacity for shorebirds, and probably for fish, of any in the UK (Kirby et al., 2004).** Since the last study phase (1987–91) a number of long ecological time series have emerged. As mentioned in the Introduction, since the early 1970s, due to combined climate change and reduced organic inputs, shorebird numbers have collapsed to a third or less of their former abundance. Seven species are involved (Fig. 13; British Trust for Ornithology "WEBS" to 2007, 2008). This reduction in abundance has not been made up by new incoming species.

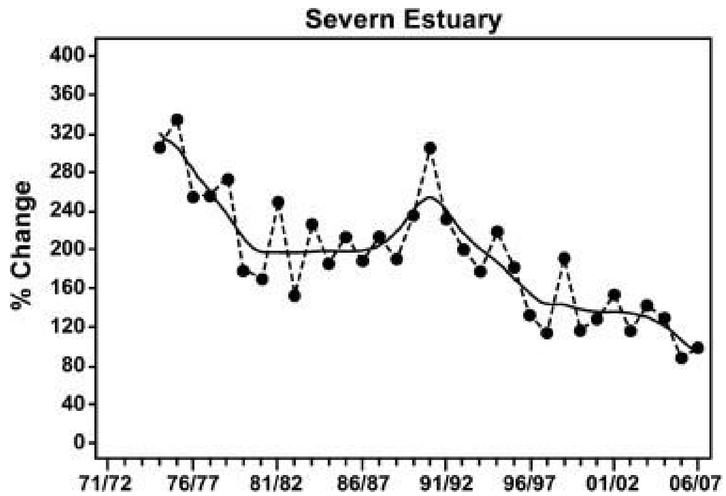

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Fig. 13. Average winter (Dec.-Feb.) numbers of dunlin on the Severn Estuary Special Protection Area 1971/2 to 2006/7 (as %, with last count = 100%; Data from British Trust for Ornithology).

In association with monthly counts of vertebrate fish on the cooling water intake screens of power stations, more than 25 y of seawater temperature and salinity measurements have been assembled. Fig. 14 shows a rising trend in water temperature for Hinkley Point (data from Pisces Conservation Ltd.; Henderson and Bird, 2010). Data for other power stations in the estuary is comparable. Mean temperature has risen slightly but a 6–7 °C shift in the winter minima has arisen. **On the one hand, vertebrate fish species abundance is rising at 0.83 y^{-1} (i.e. 1 every 15 months) but on the other our indigenous fish are highly adapted to life in waters fully saturated in dissolved oxygen**. There is an inverse relationship between water temperature and ability to carry dissolved oxygen. Water temperature rise is attributed mainly to recent absence of high altitude winter snowfields in the Welsh uplands. **The sediment-induced sags in dissolved oxygen levels were already a severe problem to indigenous and migratory fish (the fish fauna lacks any exclusively benthic feeding species). Rising water temperature adds two further effects, first the diminution in dissolved oxygen carrying capacity, and second the increased rate of microbial metabolism, which further enhances oxygen consumption. These three attributes together are already influencing fish behaviour by way of summer withdrawals from shallow zones with diminished oxygen levels. With further inevitable water temperature rises, whole water body de-oxygenation could be in prospect. Predicting the timescale and circumstances inducing this is difficult. This unambiguous evidence of coupled natural and anthropogenic environmental degradation may cause a reappraisal of the environmental consequences of a Cardiff-Weston barrage.**

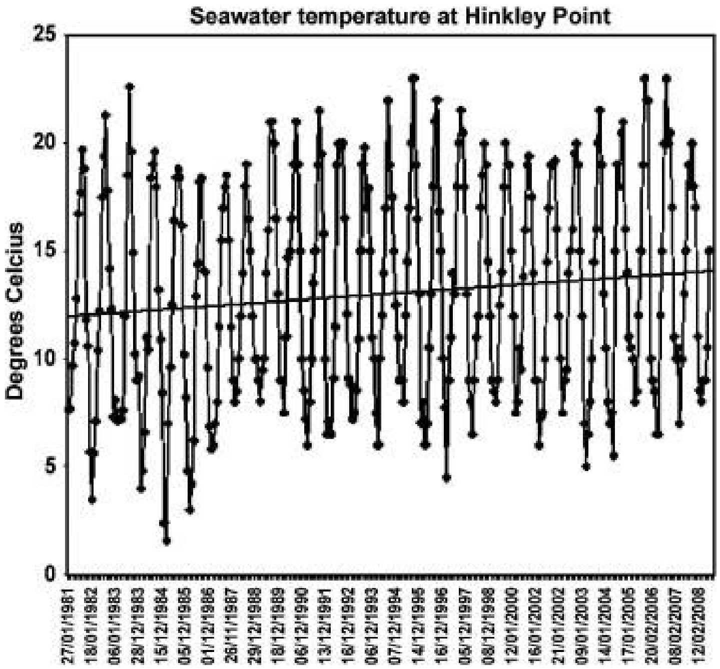

Fig. 14. Monthly sea water temperature off Hinkley Point nuclear power station Jan. 1981-Feb. 2008. Mean has risen 2 °C, winter minima by up to 7.5 °C. Data for other power stations around the estuary is comparable (Pisces Conservation Ltd).

In respect of the water body, past "improvements" due to closing down industrial discharges, implementation of the Urban Waste Water Treatment Directive from 1989, and construction of new sewage works such as Netheridge near Gloucester (1998–2004), whilst influencing underlying water quality, have had no impact on primary productivity on grounds that this is determined by the "all pervasive" suspended fine sediment.

6.2. Tidal power options

Tidal lagoons such as those proposed at the Welsh Grounds and Bridgwater Bay are not viable in economic or engineering terms. Their length and cost of the perimeter wall renders these impractical, **the enclosures they provide are relatively small and unacceptable siltation rates are unavoidable**. Even their proposed outlet points in Newport Deep or between Brean Down and Steep Holm are impractical. Newport Deep is a rapidly atrophying, blind-ending flood-dominant channel, the closure of which, due to siltation, is unavoidable. Were a Bridgwater Bay lagoon to be provided with an outlet along its NW margin, its discharge would be directed at almost 180° to the ebbing tide, offering severe stability problems for the enclosure. The Beachley barrage would silt up quickly and provide negligible electrical power. Nominally the cheapest option, the Shoots barrage (£109 MW h^{-1}), would create a convergence zone in the cohesive sediment circulation and be overwhelmed by fine sediment. It would be approached by about 0.75 Mt y^{-1} from the Severn river, by 7 Mt y^{-1} from mudshore erosion to seawards, where the tidal excursion would remain almost unchanged compared to today. It would encounter the same fortnightly fluctuation between more than 30 Mt on a high spring tide reducing rapidly to 2 Mt on a low neap tide a few days later. Advecting "slugs" of dense suspensions would penetrate the barrage line and stagnate within and in front of it. This represents an intractable sediment problem.

A Cardiff-Weston barrage has come to be traditionally regarded as the optimum location. Optimally, too, it would be an ebb-only scheme, as at the Rance. It's energy cost would be about £127 MW h^{-1}. This is the zone where the highest electrical output arises for the smallest construction cost. The "optimum" location arises on grounds of the naturally deep water in the Lavernock Point–Brean Down narrows. To seawards of this zone the tidal range decreases progressively, the Bristol Channel widens and, in fact, shallows. To landward the estuary immediately becomes too shallow. Thus, only Cardiff-Weston is commented on further. Were this to be built, the well known physical attributes of the fine sediment regime would be forfeit. The present high degree of hydraulic fractionation of bed deposits typifying the area would be lost due to diminished currents and bioturbation. Similarly, the very unusual exclusively primary sedimentary fabric shown in the cores (Fig. 6) would rapidly be lost due to invasion by burrowing organisms of all kinds. Some doubt remains as to the hypertidal mud deposits remaining seaward of such a barrage, which may remain barren. In respect of the suspended sediment, reductions in carrying capacity of the currents will diminish SPM concentrations. The Severn is the "Type-Locality" in the world for lutoclines, suspended sediment fronts and for slug flow. Similarly, on grounds that the scale of spring/neap velocity fluctuations will diminish by a large amount, the important fluid mud phase, with all its chemical and biological implications, will very largely or entirely disappear. Up to 2.5 m of fluid mud will be deposited in channels on the assumption of a sudden and initial neap tide closure of the barrage. This will progressively dewater to a settled mud bed layer about 0.3 m thick. Mean sea level will rise by about 3 m in the enclosed basin.

In the post-barrage regime two major changes will alter the water body. Firstly, permanent settlement of a large proportion of the suspended load will remove the constraint on daylight penetration and dissolved oxygen levels. Water quality will instantly improve. Primary production will be jump-started for the first time in several millennia. The second change will be that the degree of oxygenation will escalate both from the removal of lutoclines, fronts and the neap tide fluid mud component but will be enhanced further by the additional high degree of mixing from the flood tide entering the enclosed basin through the barrage sluices and the ebb tide discharge through the 216 × 9 m diameter turbines. These two factors together will improve water quality by a large amount, possibly being the saviour of the threatened vertebrate fish population. Similarly, most scientists consider it perfectly possible to design low pressure bulb turbines, as at the Rance, which will not damage fish. Severn and Bristol Channel fish faunas involve no species, with the possible exception of the flexible-bodied conger eel, which are large at adulthood. Study will establish whether fish passes are necessary. The currently absent, exclusively benthic feeding fish species would colonise the basin.

A number of concerns have been expressed with respect to the post-barrage environment inside the basin provided by a Cardiff-Weston barrage. One is whether an increase in biodiversity and faunal abundance will occur. Firstly, basins at the Rance, Annapolis Royal and Kislogubskija all experienced such a change. It is an unavoidable generic effect. Secondly, water, fine sediment and spat of all estuarine species which typify the Bristol Channel fauna are advected into the Severn on the flood tide. This will remain the case with a

Cardiff-Weston barrage in place. There is no known mechanism whereby these faunas would be prevented from colonising the area. In particular, the currently virtually absent filter feeding group of invertebrates (only *Sabellaria* in the present faunal assemblage is a filter feeder) would rapidly establish themselves (Kirby and Retière, 2009). This seems to be the generally accepted consensus, for example Langston et al. (2003).

In public statements the Environment Agency, Natural England, and the Countryside Council for Wales have insisted that the post-closure basin water body would become hypernutrified, leading to eutrophication (their Press Statement issued May 2006). It is easy to demonstrate that this could not possibly be the case. Cole et al. (1999) produced a comparison of the nutrient status of 33 selected English estuaries using General Quality Assessment based on Total Inorganic Nitrogen (TIN) and Total Reactive Phosphate (TRP). The Severn rates B on a scale A–D for TIN, being lower than the mean (C), and C for TRP, being much lower than the mean (D) for the 33. Taking the large English systems, the Severn is better than the Thames and Wash, and is comparable with the Humber and Mersey. Thus, there is no reason to anticipate a nutrification problem.

The impounded dock systems of Barry, Cardiff, Newport, Avonmouth and Sharpness presently take in a mixture of ambient estuary water, suspended fine sediment and spat in the course of ship locking operations. Once in the quiescent dock systems, the sediment settles out. The spat are then able to develop into mature colonies of adults. For example, Purchon (1937) found extensive mussel colonies in the now in-filled Portishead Dock. These docks are a good analog for what the water body in the basin formed by Cardiff-Weston would be like. In reality, absence of circulation plus tendency to develop thermal stratification in summer will render dock water more susceptible to eutrophication than could be the case in the basin waters of the estuary. Dock waters in the Severn do not become eutrophic.

Similarly, concern has been expressed that basin waters would not flush adequately, with the consequence that nutrients would build up and salinity would diminish. Modelling at the last phase of study demonstrated that the salinity would actually rise (Water Research Centre, 1989). This is axiomatic from the large rise in mean water level implicit in the scheme. Good flushing is essential to the effective operation of a tidal power scheme. Unusually for a large temperate estuary, and of relevance to these concerns, the main carbon sources in the Severn are allochthanous (mainly from rivers) rather than the normal autochthanous dominance (Mantoura and Woodward, 1983). This must have become even more extreme since the implementation of various EU Directives (Ballinger and Stojanovic, this volume), including the Water Framework Directive (Borja, 2005). Aside from comparison with other systems and with existing dock systems, a school of thought suggests it is inevitable that the large scale proliferation of organisms in the basin waters and bed will uptake nutrients from the river catchment.

Construction of a Cardiff-Weston barrage would shelter significant zones of the shores of the enclosed basins from the worst effects of wind waves. About 60% of the existing mudflats would become permanently sub-tidal, benefiting fish. The CHaMP (APBmer et al., 2006), amplified by evidence presented here, shows that without a barrage low elevation and concave outer shores will be quickly forfeit due to sea level rise, exacerbated by erosion. New sea level curves to 2100 show a rise of 1 m or more by this date (Church et al., 2008, Woodworth et al., 2008). The CHaMP (ABPmer et al., 2006) and Kirby and Kirby (2008) publications indicate mean mudshore loss rates of 3.5–4.0 and 7 Mt y^{-1}, respectively. Various evidence from the sediment regime and organism response to it, shows that some entire inter-tidal zones and the outer zones of others have minimal ecological value today. The 40% remaining will experience a rapid shift (a single season) to a more habitable (normally-consolidated) substrate and a slower shape-change to a high and convex profile with space for salt marsh at the coastal periphery (Kirby, 1989, Kirby, 1992, Friedrichs and Aubrey, 1996, Mehta, 2002). Kirby (1989) predicted a tendency for new tidal flats with a high and convex shape to develop over a range of timescales of the order of "tens of years".

Cross-sectional shapes such as this exhibit a broad zone focussed at mid-high tide level offering enhanced invertebrate colonisation prospects (Green, 1968, Dörjes, 1970, Anderson, 1972, Ferns, 1984). Fig. 15 modified from Dörjes (1970) shows this. Opportunities for shorebird utilization will increase, possibly favouring UK west coast-type Icelandic and Canadian migrants. Whether shorebirds, whose habitat elsewhere along their flyways is degraded, can take advantage of these improved conditions remains unclear. Clearly though, this is an "elsewhere" not a "Severn Barrage" issue. Careful "study-in-anticipation" of fish passage to and fro through the barrage is required. The Rance has no fish passes and a fish fauna comparable with the Severn has little or no problem routinely traversing it. Even delicate species such as jellyfish and cuttlefish make regular unimpeded passage. At the Rance there is record of a yachtsman falling overboard and emerging unharmed after being drawn through a rotating turbine (Kirby and Retière, 2009). Study must include evidence from Annapolis Royal in Nova Scotia, though here a different machine (rim as opposed to bulb turbine) and contrasted, larger migratory fish species were involved. Annual fish migration into the basin formed by the Annapolis Royal barrage remains a tourist attraction. Contrasted operating modes also need to be considered - for example, rotation speed. At the Rance the rotation speed is 93 rpm, and at Annapolis Royal 50 rpm, whereas at Cardiff-Weston the same 50 rpm is envisaged.

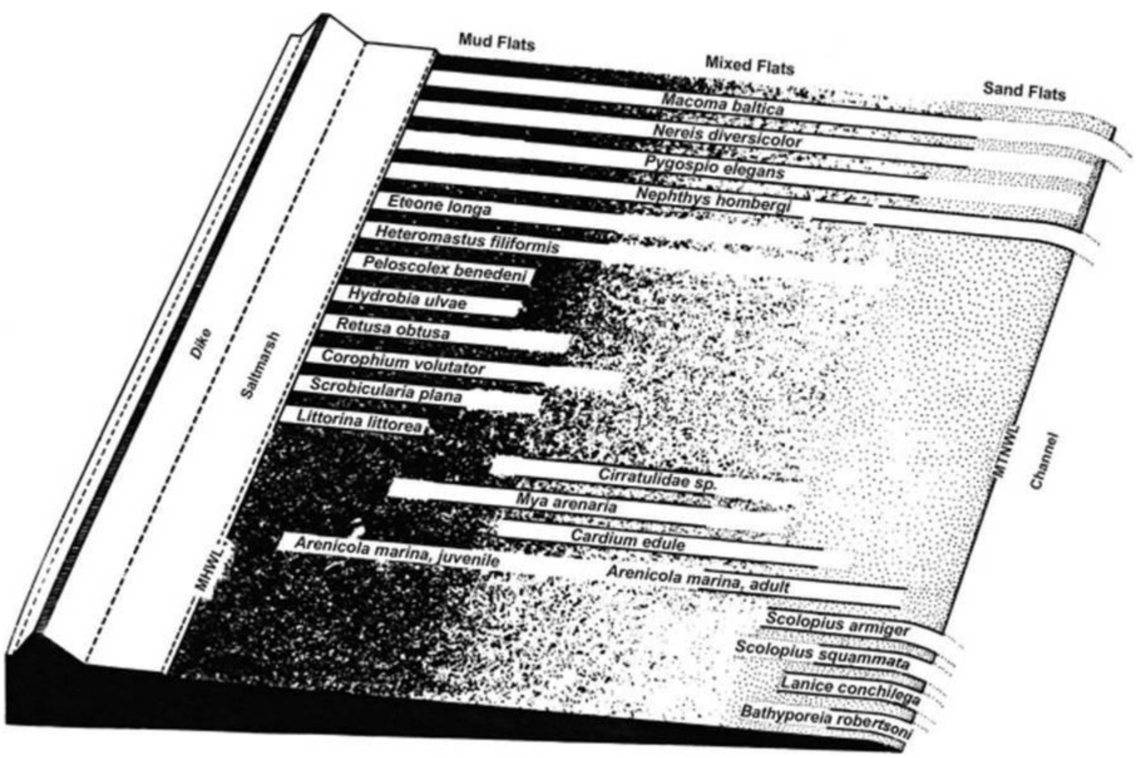

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Fig. 15. Population zones and biomass distribution of important macrobenthic animals on a tidal flat in Jade Bay, Germany. Major occurrences are shown by darker zone between mid and high tide. Scanty population and sporadic occurrences are shown by paler zones (from Dörjes, 1970). A shift favouring high and convex tidal mud flats in a post-barrage regime will lead to expansion of the mid-high water zone.

Understanding of the alteration to fine cohesive sediments in the main estuary turbidity maximum is vital. The most sensitive time period is the construction phase (not pursued further here), followed by the more straightforward post-closure regime. The sub-tidal bed at the Rance became "more muddy" post-closure due to siltation during its prolonged separation from the sea during construction, coupled with subsequent input from seaward and a more extended stillstand at high water which encouraged settlement and rendered the substrate more readily colonised (Kirby and Retière, 2009). However, it was a low turbidity regime prior to closure and has changed little. A Cardiff-Weston barrage would be constructed "Mulberry Harbour"-style by towing in and sinking in line floating caissons built at remote sites. All sluices and turbine bays would remain open until the "instant of closure" in order to maintain the fine sediment circulation.

7. Conclusion

This account is slightly biased towards reviewing the inter-tidal zone, on grounds that the main progress since the last phase of tidal power investigation has been increased understanding of this**. In the Severn salt marshes have a limited areal extent, being limited to a narrow, mostly contracting fringe. In contrast, the fronting bare mud flats are especially wide (up to 3 km) and especially vulnerable to effects of sea level rise, being a net erosional zone with a low and concave profile and an elevation which rises up-estuary. This replicates geomorphology of other eroding muddy estuaries, for example, the Medway**. **The recently published CHaMP predicted rapid inter-tidal "habitat" loss due to sea level rise (10–20% in 100 y) without, it seems, including a component for vertical erosion, which is proceeding 3–5× more rapidly.** The net short term rate of sea level rise for the Hinkley Point tide gauge is about 4 mm y^{-1}, whereas mean vertical tidal flat degradation rate at Stert Flats is 16 mm y^{-1}. Recent predictions of sea level rise are running about 3× faster than the CHaMP predictions. The mud flat "regime" is established from studies of dynamic evolution on a number of timescales. There is a strong relationship between intensively measured long term level change and the Index of the NAO, which determines the degree of windiness of the NW European winter. **Similarly, and linked to this, long term siltmeter deployments clearly reveal the dominant effect of wind waves on the foreshore through time. A mean foreshore erosion rate which is ~7 Mt y^{-1} is now in progress**. This is around 10× the rate of fresh river input. Archived data sets, mainly of the inner shore and too short to calculate a long term trend, indicate erosion to be estuary-wide. In the sub-tidal zone, the Bridgwater Bay mud patch acts as both a long term source and a sink, the locus of deposition migrating westwards, as shown by siltation rate measurements on cores in the 1970s and 2000s. Newport Deep is also a long term sink, as (perhaps) is Cardiff Roads. Bristol Deep is acutely sensitive to settlement and dewatering of material from fluid mud suspensions, requiring only minor changes of ambient conditions.

The three-dimensional structure of the main estuary turbidity maximum and its semi-diurnal and semi-lunar fluctuation is well documented, though only aspects of its physics are presented here. It is the world's classical "high turbidity phase behaviour system", exhibiting lutoclines, suspended sediment fronts and slug flow phenomena in the three principal axes. It is a tide-dominated system in which the fine sediment load in the region between Watchet and The Shoots cycles fortnightly between more than 30 Mt on high springs and 2 Mt on low neaps. Arising from the fine sediment regime, the water body and sub-tidal mud patches are barren, and sub-tidal sands, gravels and rock nearly so. **Inter-tidal sand banks are demonstrably barren and the muddy inter-tidal zone formerly had the lowest carrying capacity for higher organisms of any in the UK, but in recent decades, and especially in the case of birds, this has crashed to vestigial levels. The fish population is threatened by diminution in dissolved oxygen levels.** The barrenness/impoverishment is clearly not natural but enhanced by anthropogenic impacts. This must have implications for the nature conservation designation of the estuary. **The foreshore is narrowing and lowering, barren sub-tidal mud patches are expanding and smothering other almost barren substrates. Tidal range and storminess are increasing, nominally raising the mobile fine sediment load. Each has an engineering and environmental impact.**

A Cardiff-Weston barrage would render the system more benign. The lower and outer inter-tidal foreshore, inevitably lost by barrage alterations to water level, currently has negligible environmental value, but would become so once sub-tidal. Presently barren sub-tidal mud patches showing only primary sedimentary fabrics would become colonised and mixed by extensive bioturbation. The "high turbidity phase behavioural system" which currently prevents photosynthesis would be shifted wholly or largely to a "low turbidity phase behavioural system", raising water quality and kick-starting primary production. As at the Rance, the sub-tidal barrenness would be forfeit and a more abundant and biodiverse fauna would colonise the area.

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