Environmental consequences of tidal power in a hypertidal muddy regime : the Severn estuary (UK)

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I ■ INTRODUCTION

The pre-barrage Rance estuary had a tidal range not dissimilar to the Severn, both being categorised as hypertidal (Mean Tidal Range > 6.0 m). The Mean Tidal Range of the Severn is actually 8.55 m. Although their tidal ranges were comparable, in other respects they were physically dissimilar, notably in the fact that the Rance was and remains a sandy dominated system, whereas the Severn, especially along its coast, is predominantly muddy. The combination of the hypertidal regime and the muddiness of the system, coupled to a degree with its exposure to westerly waves, lead to the sedimentary regime controlling and dominating almost all aspects of the ecosystems of the Severn. Indeed, there can be few sites in the world quite so dominated by their sedimentary system as the Severn.

Should a tidal power barrage ever be constructed in the estuary, as has been investigated over a 20 year period from 1973-1993 to pre-feasibility level, it would reduce the tidal range within its basin to macrotidal (4.0-6.0 m) as well as reducing the wave climate in much of the estuary. The ecosystem would change in a major way as a result, the extreme degree of physical control would diminish and within the basin the water, subtidal and intertidal environments would become more closely comparable with "normal" macrotidal muddy faunal and floral ecosystems. Outside the barrage a hypertidal sediment-dominated ecosystem would persist in Bridgwater Bay. The paper concentrates on describing the essential character of the present physical and biological systems and uses these as a platform to anticipate physical and biological changes arising from a Cardiff-Weston barrage.

Conséquences environnementales de l'énergie marémotrice en régime de grandes marées boueuses : l'estuaire de la Severn

Les régimes à marées de grande amplitude, comme dans l'estuaire de la Severn, posent des difficultés à la faune et à la flore en raison des fluctuations énergétiques semi-diurnes et semi-lunaires. En particulier au printemps, la forte concentration en sédiments empêche la photosynthèse et les niveaux de phytoplanctons sont au plus bas. En marée de morte eau, les sédiments se déposent et une faune de lit composée d'individus immatures se développe.

Les conditions de vie dans la zone intercotidale sont également difficiles en raison de l'érosion pendant les tempêtes. On y trouve des dépôts de coquillages qui s'attardent.

L'installation d'un barrage entraînerait une baisse de la turbidité et un accroissement de la photosynthèse et du phytoplancton, stimulant la chaîne alimentaire. L'écosystème estuarien devrait se développer. Des études ont montré que la Severn possède actuellement un régime atypique en ce qui concerne les sédiments. La fermeture de l'estuaire permettrait aux oiseaux de trouver de la nourriture et les attirerait. Même si ça paraît bizarre, en l'absence de barrage, si l'on épure les eaux usées, on ne trouvera plus d'oiseaux.

II ■ SEDIMENTARY REGIME OF THE ESTUARY

The sedimentary regime has a number of features specific to an exposed, hypertidal estuary. During the last 10,000 years, the recovery phase from the latest glacial advance, the Severn and Bristol Channel has been supplied with gravel, sand and mud from its hinterland, from glaciers and their associated products. Visually and superficially the estuary gives the impression of being superabundantly supplied, especially with fine- grained sediment. Examination of maps of unconsolidated sediment distribution and thickness in fact confirms the contrary, much of the bed of the Bristol Channel and Severn Estuary is bare rock or has only limited veneers of unconsolidated sediment (*fig. 1*). The best way of explaining this apparent contradiction is by saying that the Severn, in relative terms, has much less unconsolidated sediment contained within it than any other UK estuary, but that a disproportionately high fraction of this is mobile at any one place and time.

Another manifestation of the high energy of the system is that the various grain sizes of sediment are fractionated one from the other to an unusual and extreme degree. Thus, although interbedded pure sands, pure silts and pure clays occur in some places, many areas are characterised by very well sorted sediments of a single and narrow grain- size spectrum. Sand size decreases systematically from the outer to the inner estuary [1] testifying to a net up-estuary sand transport arising from ebb-flood asymmetry and sea level rise. Mixed substrates, almost universally to be found in micro, meso and macrotidal systems, are rarely encountered in the Severn. This extreme fractionation into individual grain-size components is perpetuated and exaggerated by the almost total absence of colonising organisms. As a result the primary sedimentary fabric of deposits in core samples, representing many decades of deposition, is preserved without the bioturbation and the secondary fabric generation caused by animals, which is so universal almost everywhere else [2]. This fractionation and sparsity of organisms feeds back to the flora and fauna, with the consequence that impoverished muddy and sandy faunas occur but mixed muddy sand and sandy mud faunas tend to be absent.

The fauna and flora is very largely dominated by the mobility and instability of all grades of sediment, although it is the fine cohesive component which is especially problematical. The intertidal and subtidal bed, as well as the water column itself, is involved. Taking these in turn :

2.1 Intertidal zone

Arising from the combined effects of sea defence construction commencing 1000 years ago and compounded by sea level rise, the intertidal mudflats have a low and concave cross-sectional profile [3] and are experiencing steady erosion [4]. Where long-term rate of change can be estimated, any remaining salt marshes are retreating laterally at rates reaching several metres/year and at the same time the mud flats are eroding vertically, preserving their concave equilibrium shape. The rate of vertical erosion lies in the region 3.0 m/70 years [4]. Many tidal flats have extensive areas of overconsolidated Holocene clays and peats, although they are veneered at times and in places by unconsolidated mud layers, which are largely the product of the self-destruction of the intertidal zone. Erosion-dominated mudshores with these general characteristics are well known from around the world. What is notably different in the Severn is that elsewere, winnowing of tidal flat muds by waves leads to the accumulation and up-shore migration of large banks of intertidally-derived shell deposits called *Cheniers*. Despite eroding rapidly, and certainly for the last several hundred years, there are no cheniers either out on the tidal flat or banked up at high water mark. This testifies to the long term natural inability of this hypertidal regime to provide a host for "normal" estuarine shelly intertidal faunas. A further constraining influence on intertidal zone colonisation is the presence

1. Distribution of rock outcrops (toned zone) at the seabed in the Severn Estuary and Bristol Channel. Note tendancy for sediment starvation to be greatest along the lower (English) coast. (Data from BGS).

twice a month of extensive neaptide fluid mud layers [5]. Finally, the exposed intertidal zone is unusually susceptible to the effects of wave attack during gales. Storm waves strip the unconsolidated host sediment which provides the ephemeral habitat for intertidal invertebrate faunas *(fig. 2)* [6, 7] generating elevated zones of suspended solids concentrations along the coast [8]. All these sedimentary factors lead to the intertidal zone being an acutely difficult one for organisms to colonise.

2.2 Subtidal zone

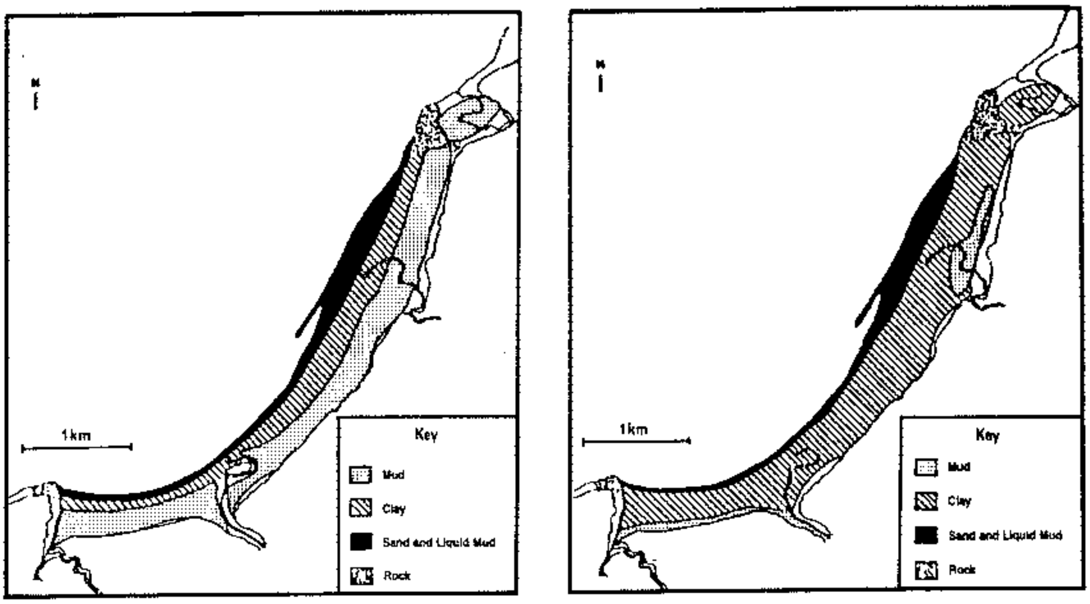
Although a less stressful regime in so much as it is not susceptible to the effects of breaking waves, the subtidal zone has the drawback that it is never, or virtually never, able to receive direct sunlight due to the masking effect of the overlying high turbidity water column. There are three major types of substrate, rock exposures which provide a stable holdfast for colonies of the reef-building worm *Sabellaria* and also sandy and muddy deposits. Both of these are somewhat unstable, especially at the bed/water surface, and also regularly swept by bed load materials which may be abrasive. Instability, coupled with large scale oscillation in bed elevation, make these deposits extremely difficult to colonise, other than for the briefest period. In respect of muddy grounds and to a lesser extent sandy areas, in addition to instability of the bed, there is a further factor. On spring tides the concentration of near-bed suspended sediment may be high (often 5-10,000 mg^{-1}) but on neaps large quantities of sediment settle rapidly onto the bed to form neap tide fluid muds [5]. These are both extensive and frequently occupy at least the 1.0 m zone of the water column immediately on top of the bed. Two features make them and the beds they veneer especially problematical for colonising organisms. Firstly, their concentration, often 20,000 — 100,000 mg^{-1} is such that they have no strength and organisms cannot keep a burrow open, secondly they are anaerobic. For perhaps 2-5 days a fortnight such deposits form veneers over muddy and sandy subtidal bed sediments. The instability, coupled with frequent smothering by anaerobic suspensions, is in combination especially stressful for organisms [9].

2.3 Water column

The very strong currents, coupled with fortnightly cycling of fine sediment between the water column and bed, are somewhat extreme [5]. On spring tides the total fine sediment load between Avonmouth and Watchet exceeds 30 million tonnes by an unknown amount. By the neap tide phase only 14 days later most of this load has settled onto the bed as the ephemeral fluid mud layers and only about 4-5 million tonnes remains dispersed in the overlying water column. On the entrainment phase after each neap tide settlement, anaerobic near-bed layers rise into the water column leading to a short term natural dissolved oxygen sag. Both the high turbidities, coupled with the regular oxygen depletion, lead to problems for pelagic species.

III ■ BIOLOGICAL RESPONSE OF THE ESTUARY

As may be anticipated from understanding of the above, recruitment into the Severn from seawards is not a problem. The spring tidal excursion at the Holms islands extends to 43 km [5] and the area is renowned for the efficiency of vertical mixing, certainly of water if not sediment. Although initial recruitment is enormous, gaining a foothold in such a regime is extremely difficult. In some respects the area may be regarded as highly productive biologically. For example, intertidal rocks and bridge piers are extensively colonised by *Fucus* which is in turn regularly torn off on spring tides forming extensive floating windrows at the estuary surface and permitting fresh colonisation. *Sabellaria* colonies are likely to be mature if not productive. In many other attributes, however, the ecosystems of the Severn are unusually suppressed, immature and depauperate.



a) Surface substrates at Clevedon, November 1979

b) Surface substrates at Clevedon, December 15th 1979

2. Large scale erosion of tidal flat substrate at Cleveden in the Severn Estuary due to gales. The material marked as "mud" is the only sediment providing a host for burrowing invertebrates [6].

3.1 Intertidal zone

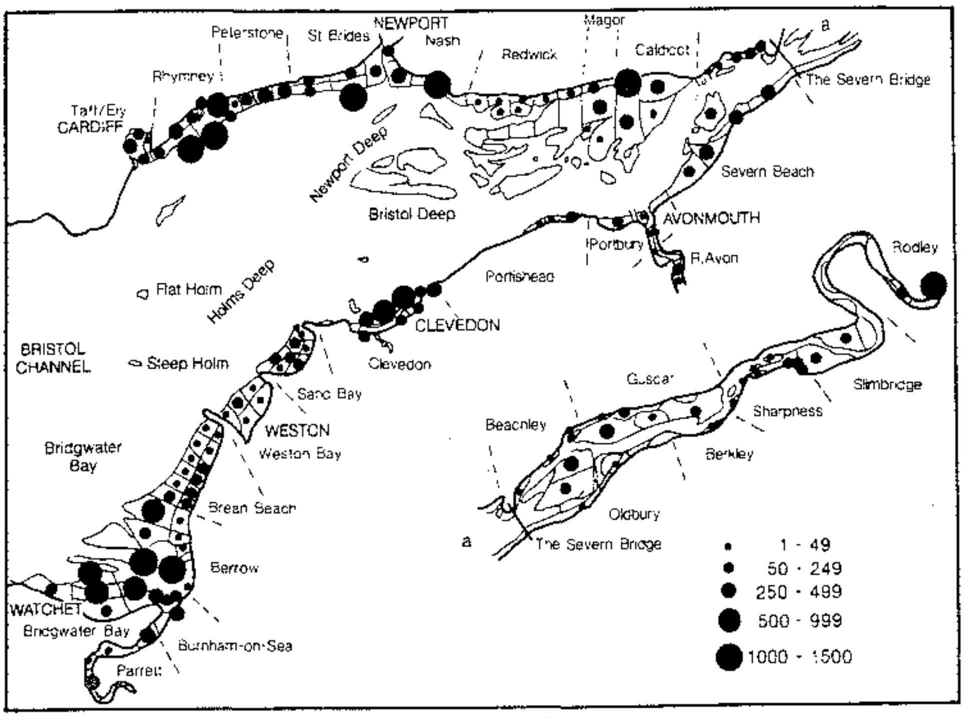
The virtual absence of a shelly fauna, as revealed by fossil deposits, persists today [10, 11, 12, 13, 14, 15]. In a few random areas and at times, massive scale spat recruitment into the thin unconsolidated sediment veneer can lead to colonisation by very large numbers of a few common and hardy species, *Nereis diversicolors*, *Hydrobia ulvae* etc... Such colonies may in the immediate term give the impression of high biological productivity. However, these remain immature pioneering communities unable to recruit other species and for the most part get wiped out by any one of the several step-changes to the intertidal sedimentary regime itemised above. The exposed overconsolidated Holocene clays and peats, in contrast, are almost always barren, other than for a summer micro-algal bloom and occasional immature *Hydrobia ulvae* on the surface. Intertidal sands also provide no useful realistic habitat, but in this case due to their extreme instability.

A direct consequence of the general impoverishment of the regime, coupled with the universally small physical size of the immature invertebrate shorebird foodstuffs which do gain a temporary foothold, is that the carrying capacity for these higher species in the Severn is lower than virtually anywhere in the UK, even than less productive sandy shore sediments elsewhere in the UK *(tabl. 1)* and, furthermore, the bird fauna are dominated numerically by a small species, the dunlin, which can sustain itself on small prey species. Those few relatively elevated areas in respect of carrying capacity *(fig. 3)*, are explained in the one case by existence of an intertidal shelduck roost and in the others by enhanced levels of shore bird prey species in the immediate vicinity of sewage outfalls.

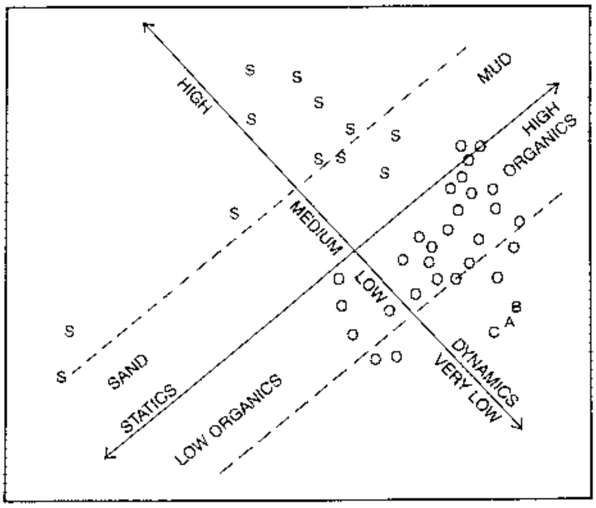
An attempt has been made to quantify the natural variability of intertidal prey species faunas in the same general geographical area as the Severn Estuary. Variability in a number of manifestations was tested *(fig. 4)* [15, 16]. Without exception, Severn faunas fell outside the natural envelope of variability which characterises adjacent shores. This separateness was provisionally attributed not so much to the exceptional tidal range at the site and its size but more to the stressful nature of its physical regime imposed through the aspects of the sedimentary regime outlined above. The question driving this latter study was whether and in what respect the intertidal invertebrate faunal community would alter due to construction of a Cardiff-Weston Barrage.

Table 1. — Bird Burdens — UK Estuaries

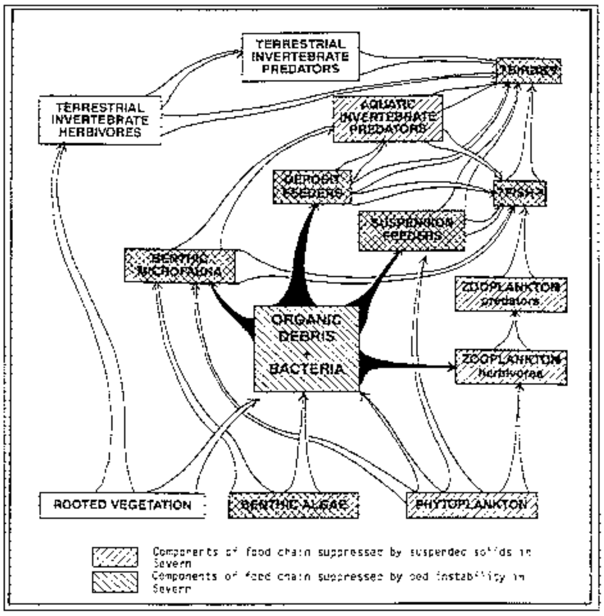
Location	Area (km²) of intertidal zone	Wader months Nov-Mar	Winter wader mths/km²	Mudshore Substrate
Moray Firth (Inner)	23.9	28,922	1,210	Sandy
Forth	49.8	131,251	2,636	Muddy & Sandy
Wash	270	744,981	2,759	Sandy & Muddy
Medway	19.9	96,914	4,870	Muddy
Southampton Water	13.4	43,397	3,239	Muddy
Severn	196	218,222	1,114	Muddy
Dee	81	280,788	3,466	Sandy
Mersey	45.4	92,413	2,036	Muddy & Sandy
Ribble	91	209,117	2,298	Sandy
Morecambe Bay	303	744,981	2,759	Sandy & Muddy
Solway	205	252,363	1,231	Sandy



3. Average total number of waders and Shelduck present at low tide on intertidal areas in the Severn during the 1987/88 winter. Other than off Berrow, where nucleation is due to a Shelduck roost, the sites with elevated numbers are around sewer outfalls. (Data from BTO).



4. Multi-dimensional scaling ordinations for invertebrate abundance data from the Severn Estuary (S), other estuaries in SW Britain (O) = Southampton Water, Poole Harbour, Exe, Plym & Tamar Estuaries ; and La Rance (A,B & C) showing distributions of stations relative to sediment static and dynamic factors. A plot of biomass versus the same sediment factors would look very similar. Constructing a Severn Barrage would alter the sediment statics and dynamics, shifting Severn invertebrate abundance and biomass into the region occupied by other estuaries and La Rance. [15].



5. Diagram showing food chain of the main ecological groups of estuarine animals. Arrows go from food to consumer. Aspects of the fine sediment regime in the Severn impinge on the ecosystem as indicated.

3.2 Subtidal zone

Other than in a number of hard grounds where *Sabellaria* colonies proliferate, the darkness, instability, sediment load and regular deoxygenation of the nearbed zone renders it a difficult one for organisms to colonise. In addition to the general immaturity of those few individuals from pioneering species which are found, another notable feature of the faunal assemblages is the complete absence of filter-feeding organisms. The latter are, of course, especially susceptible to gill-clogging from the ambient suspended sediment load. In those infrequent situations when subtidal faunas are discovered, they are distinguished by these site-specific attributes, namely immature examples of a very narrow range of common detritus-feeding pioneering species and lacking the filter-feeding component of a balanced community [17, 18].

3.3 Water column

It has been explained that recruitment into the Severn is large in scale and constant. Elsewhere one might anticipate a prolific ecosystem. That this is not so is chiefly explained by the very high suspended sediment concentration and the semi-perpetual mixing which maintains it. This leads to inhibition in photosynthetic activity [19, 20, 21, 22, 23, 24]. In the Outer Bristol Channel Joint & Pomroy [19] estimated an annual primary production of 164.9 grams of carbon/m^2/year as an indication of phytoplankton activity, which falls to 6.8 gCm^{-2} yr^{-1} in the Inner Bristol Channel and to zero in the turbid waters of the Severn. Frequently the photosynthetic depth is as little as a few centimetres whilst mixing is sufficiently intense that photosynthetic micro-organisms only experience exposure to sunlight very occasionally and for too short a time period to become established. The large scale inhibition of phytoplankton growth implies that the dependent higher foodchain is also inhibited *(fig. 5)* [25].

Higher species such as vertebrate fish appear to cope with this attribute of the environment but evidently adopt specific strategies to cope with the regular fortnightly dissolved oxygen sags of the main estuary in the region of Avonmouth and above. Evidently they are able to regulate their movement and remain down-estuary until the inclement conditions ameliorate. Such strategies are especially important for migratory species such as salmon which must penetrate the inner reaches of the main estuary and the tributary river estuaries in order to reach their spawning grounds.

That the Severn is well supplied with spat by the large scale recruitment and that the suspended sediment population is a determining control is evident from impounded dock systems on either side of the estuary [25]. Estuary water, suspended sediment and spat are added to the dock during locking operations and to maintain dock water level. In the quiescent docks the sediment settles and mature colonies of filter feeders such as mussels, which never gain a toehold in the estuary, can develop.

It is arguably the case that the conservation value of the Severn is naturally and in some cases rapidly deteriorating. The intertidal zone is becoming narrower and steeper as well as increasingly sensitive to erosion. There is circumstantial evidence that the overall turbidity of the estuary has increased with time. Increased water turbidity, if it were real, would steadily degrade the already highly marginal subtidal bed habitats, as well as perpetuating the photosynthetic and regular dissolved oxygen problems induced by the sediment load. Arising from this one might pose the question whether a tidal barrage, and the regime changes it would induce, is or is not an asset in conservation terms. To be able to consider this, one would need to know how the regime would change due to construction.

IV ■ POST-BARRAGE SEDIMENTARY REGIME

The Severn Barrage, as most recently configured along the Cardiff-Weston line, would take about nine years to construct. The latest design is such that the sedimentary regime, other perhaps than the degree of local coast protection afforded, would remain invariant or nearly so until the time of closure. There would, consequently, be no transitional phase. At closure the tidal range would shift from hypertidal to macrotidal, mean low water mark would rise by about 3.0 m and the semi-lunar variation in tidal range within the basin would become negligible, as a by-product of maximising energy output. This hydrodynamic change would induce major shifts in the sediment regime.

4.1 Intertidal sedimentary regime

Raising mean water level within the basin is estimated to lead to the loss of 62 % of the intertidal area. The wave and current regime of the 38% remaining would also change. In the longer term the cross-sectional shape of tidal mudflats in a number of areas is likely to evolve from their present low and concave to a high and convex profile due to deposition. Where these revisions occur, salt marshes may re-establish or become stable at the top of the shore. The nature of the substrate will also change in a significant way. The unconsolidated sediment veneer providing the host for invertebrates will become more extensive and more stable. Fortnightly fluid mud deposition will cease. The effect of fixing the tidal range may be important, especially in view of the relatively prolonged stillstand at high tide. An eroding notch may be created to offset the trend to deposition elsewhere in certain intertidal profiles. The decrease in the efficiency of grain-size fractionation may result in more mixed substrates developing. At present the sands are largely confined to offshore banks.

Following the rise in mean water level, the area of such exposed mid-channel deposits will reduce drastically. Offshore sand banks at present tend to accumulate mud in the protected megaripple troughs. In the somewhat more benign macrotidal regime, more uniform mixing of the sand with a minor mud fraction to create muddy sand substrates is likely in some areas.

Outside the basin in Bridgwater Bay the tidal range will change little and the tidal flats will remain unchanged in their low and concave shape and eroding condition.

4.2 Subtidal sedimentary regime

At closure extensive near-bed fluid mud deposits would be induced, mainly in subtidal channel sites, as routinely occurs at neap tides at present. Subsequently, these would consolidate, initially increasing the area of mud substrates compared to sand. Newport Deep is already muddy so no change would be detectable, but mud deposits are likely to be emplaced in the Holms Deep and in Bristol Deep at least from Clevedon backing up-estuary beyond Avonmouth into the inner estuary. The tributary river estuaries will also experience such once-off large scale deposition. In the revised regime, bed stability will increase greatly and neap tide fluid muds and their neap to spring entrainment and dissolved oxygen sag will to all intents and purposes disappear.

The short, sharp flood tide is likely to mean that up-estuary sand transport and fractionation will continue, possibly at a lower rate. The fact that the barrage will physically sever the link between the inner Bristol Channel, the long term source of sand, and the Severn will not lead to undue sand starvation in the enclosed basin adjacent to the barrage on grounds that this source is already virtually exhausted.

The extreme separation of mud and sand populations which characterises the present estuary will change, with sediment types being more evenly spread.

Seaward of the barrage the subtidal sedimentary regime in Bridgwater Bay will experience little change, although dividing the embayment off from the Severn and reducing the erosion of its extensive tidal flats, coupled with probable loss of suspended material entrained by maintenance dredging operations at the ports, will reduce the siltation rate around the offshore periphery of the mud patch.

4.3 Water column

Arising from the reduction in current strength, the total suspended load of the estuary will diminish from in excess of 30 million tonnes on springs to more modest values possibly close to 5 million tonnes. Moreover, other than in Bridgwater Bay, the fortnightly cycling of sediment between the water surface and the bed, leading to regular fluid mud formation, will cease. Mean water column turbidities will lie in the normal range for macrotidal estuaries and can already be predicted from a large existing data base. The basin-wide reduction and termination of fortnightly cycling, with its accompanying short term dissolved oxygen sag, will all have an impact on the estuarine water quality.

Outside the basin spring/neap oscillations of the same magnitude as today would continue. In Bridgwater Bay, which is the only area of significant unconsolidated sediment seaward of the barrage, the turbidity may be expected to reduce compared to today both on account of the prolonged high tide stillstand and partial physical separation from the sediment sources in the Severn caused by the barrage.

V ■ POST-BARRAGE BIOLOGICAL RESPONSE

5.1 Intertidal zone

In Bridgwater Bay the steady and progressive intertidal deterioration is likely to continue much as it is today and the flora and fauna are unlikely to alter. Within the enclosed basin a marked change can be anticipated. A more normal macrotidal invertebrate faunal community will develop characterised by a wider range of species, animals growing to full maturity and the area becoming suited to the wide range of filter feeders present in ecosystems elsewhere. These more stable and prolific communities can be expected to increase further the physical mixing of sediment types, as a wider spectrum of sediment grades will be co-deposited. Not just mud or sand faunas, but sandy mud and muddy sand communities are inevitable.

Although the intertidal area will reduce by 62 %, bird carrying capacity in the remaining 38 % of the area will at least double or treble [26], more than accounting for any birds displaced by simple area loss calculations. The bird community, dependent as it presently is on the small size of prey species, will no longer be limited in this way. The dominance of dunlin, *Calidris alpina*, in the shorebird fauna will decline in relative terms due to larger foodstuffs suited to larger birds being available.

Mid-estuary sites, currently unused by shorebirds, are likely to experience an increase in carrying capacity due to a rise in stable sand and muddy sand invertebrate communities. Greater biological productivity can be expected to lead to an increase in vertebrate fish numbers and variety.

5.2 Subtidal zone

The generally stunted and suppressed faunas of the subtidal zone within the basin will change due to the increase in stability and absence of fluid mud veneers. Mud and sandy mud faunal communities can be expected to expand the most. Very large scale colonisation of currently inclement and barren substrates will lead to the formation by bioturbation of extensive muddy sand and sandy mud communities.

5.3 Water column

The very major decrease in turbidity, coupled with the reduced scale of semi- diurnal cycling, will greatly increase light penetration, leading to a large scale increase in photosynthetic activity and releasing the entire food chain from the perpetual inhibition which characterises the area. Estuarine waters will not quite resemble impounded dock waters but will move towards this condition. Increased micro-organism activity may have an impact on nutrients introduced from the drainage basin which have not been fixed in the water column in the inner reaches heretofore. The large scale of barrage tidal flushing will not induce any tendency for plankton blooming to occur.

VI ■ CONCLUSION

Arising from the extreme degree of control imposed upon the present ecosystem by the physical regime in general and a variety of attributes of the fine sediment in particular, constructing a tidal power barrage along the Cardiff-Weston line in the Severn would inevitably give rise to all-pervasive modification to the ecosystems of the shore and bed and of the water column.

Society would need to judge whether future changes the estuary may experience are desirable or otherwise. It is recognised that, irrespective of barrage construction, when secondary sewage treatment replaces the present primary treatment that shorebird carrying capacity will experience an inevitable and major decline. In such circumstances, is improving sewage treatment with its implication for shorebird sustainability an environmental improvement ? Furthermore, our understanding of the system is sufficiently advanced that we recognise that the ecosystems of the Severn are naturally degrading in the longer term. A tidal power barrage is one route towards maintaining or enhancing the number, variety and stability of floras and faunas. Building such a barrage would lead to shorebird numbers increasing in spite of the decrease in area. For some reason this aspect of the entire ecosystem is subject to a disproportionate level of public interest in the UK. Consequently, we need to consider whether barrage construction is environmentally beneficial or otherwise.

In its 30th anniversary year, the tidal power barrage at La Rance provides ever more important lessons about construction, operation and optimisation of such systems and the necessity for rigorous environmental monitoring. It has less to teach us about the effects of construction in an estuary so dominated by its fine grained sediment as the Severn.

Whether a tidal power barrage is ever built or not, the review above reveals that the Severn is an example of an estuary crying out for sensible management.

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