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The Ecological Impact of Estuarine Barrages

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Foreword

This booklet was produced following a two-day workshop in Swanage, Dorset. There, the first draft of each section was written by one or more of the invited participants and, in a collaborative effort, all sections were discussed and re-drafted by most participants. The task of collating and editing (which, as it turned out, was largely a matter of reducing in volume) fell to me, but the information and views remain those of the group - the views not necessarily being of any of the organisations which employ us.

The expertise available for this task guaranteed that most of the issues surrounding the ecological impact of estuarine barrages were aired. Indeed, the measure of agreement about the predicted response of the biota to tidal barrages gives lie to the fact that ecologists are unable, or unwilling, to generate predictions from their science. Here, we predicted a series of effects based on our understanding of the systems with which we are dealing. Admittedly, with so few real examples to test these predictions, the risks of being seen to be wrong are smaller. Nonetheless, I hope that, as well as being informative, the booklet conveys something of the enthusiasm with which the problems of defining questions, refining models and making predictions have been addressed. Our thanks go to the BES for affording us the opportunity to do so.

Alan Gray
ITE Furzebrook

ECOLOGICAL IMPACT OF ESTUARINE BARRAGES

CONTENTS

1. INTRODUCTION

1.1 Background

Estuaries are semi-enclosed coastal water bodies which have an open connection with the sea but in which sea water is measurably diluted by fresh water; this includes the mouths of most rivers. Each estuary has a unique combination of features derived from its shape, catchment, connection to the sea, tidal régime and exposure. Commonly, estuaries are highly productive, not only producing much new organic matter through the growth of marsh plants, benthic diatoms and phytoplankton but also processing large quantities of dead organic matter (detritus) derived from the marshes and the surrounding catchment. In most cases, and especially when turbid water reduces the light needed for phytoplankton growth, the fauna is dominated by species that can utilise detritus. This community in turn supports large populations of fish and birds. Some of these move freely between estuaries, creating biological connections between them that may extend over very long distances. Estuaries are also constantly changing, caused by sea level changes and the continuous flux of materials from land and sea. Added to this is the immense variety of human impacts: impoundment, pollution, industrial and residential developments, recreation and other activities in both the estuary and its catchment. Thus, each estuary is an extremely complex system and, in order to evaluate the consequences of human impacts in the past, present and future, the system must be understood as a whole.

In recent decades, barrages have been proposed for many estuaries for tidal power generation, protection against storm-surges, to provide transport, impoundments for recreation and fresh water storage. Some have been built, and these illustrate not only the benefits but also that there is a potential for unexpected ecological effects. Rising public concern for the environment requires all future proposals for estuary modification to be carefully evaluated, with full recognition of the estuary's natural complexity. In the special case of tidal power barrages, it is necessary also to compare the environmental consequences of a barrage with those incurred by other forms of power generation. This booklet deals with the ecological significance of barrages.

1.2 Types of barrage

Barrages vary in purpose and design. In many recreational impoundments and some protective structures the barrage is complete, eliminating tidal movements on the landward side, and allowing only for seaward flow of water from the catchment. Storm-surge barriers, such as the Oosterscheldt and Thames, remain open to tidal flow except when storms are imminent and, therefore, have different and largely temporary effects on tidal flow. In the case of the Oosterscheldt, however, the barrier also involves partial closure of the estuary mouth, resulting in a decrease in the tidal range upstream. Barrages constructed for tidal power purposes, on the other hand, are fitted with sluice gates and turbines which are opened according to the power generation cycle. As a result of extensive studies of tidal barrages in recent decades, much more is known about the ecological consequences of this kind of barrage. With caution, this understanding can be used to evaluate the potential effects of estuarine barriers of many kinds. The state of our present knowledge of tidal barrages is described below.

Tidal power is an old technology. Tidal mills have been used for more than a thousand years, but the tidal generation of electricity by turbines is a 20th century concept. Modern proposals (Table 1) tend to be large, involving barrages consisting of embankments, ship locks, sluices and turbine housings, which vary in length and number according to the shape of the estuary and the optimum configuration selected to maximise energy output. Turbines operate when sufficient difference in water levels exists between the two sides of the barrage, and can be designed to run in one ('single effect') or both ('double effect') directions. Consequently, it is possible to generate power both on the rising and falling tides although the cost of building a turbine that works both ways is much higher. The 'double effect' approach was used initially at the La Rance station (France), but the other plants that have been built, or are being considered now, operate by capturing water behind a barrier at high tide, holding it while sea level falls, and then passing it out through the turbines during the ebb tide. This single effect method of operation produces power for about five to six hours in each 12-hour tidal cycle, but is

Table 1
Existing tidal energy barrages, and sites considered in the UK. Modified from Price (1991).

Site	Mean tidal range (m)	Basin area (sq.km)	Installed capacity (MW)	Approx. output (TWh/y)	In service
La Rance (France)	8.00	17.00	240.00	0.54	1966
Kislaya Guba (CIS)	2.40	2.00	0.40	---	1968
Jiangxia (People's Republic of China)	7.10	2.00	3.20	0.01	1980*
Annapolis (Canada)	6.40	6.00	17.80	0.03	1984
Various (People's Republic of China)	---	---	1.80	---	Various
Severn (UK)	7.00	520.00	8640.00	17.00	---
Mersey (UK)	6.50	61.00	700.00	1.50	---
Wyre (UK)	6.00	5.80	64.00	0.12	---
Conwy (UK)	5.20	5.50	33.00	0.06	---

*First unit in 1980, sixth in 1986

considered more cost-effective. Power output depends upon the difference in water level between the basin (up-estuary or landward of the barrage) and the sea. This difference can be increased by pumping water into the basin near high tide, when the water level difference is small; the additional water will yield more energy during turbining than was used in pumping, because of the extra height differences achieved.

Estuaries suitable for tidal power generation are limited to those with relatively high tidal range (*e.g.* 5-16m), usually with large tidal volumes. They are to be found in many parts of the world.

The environmental changes induced by a tidal power barrage are different on the seaward and landward sides. It is important to recognise that the natural processes which connect each estuary with its catchment and with the nearby sea may mean that changes induced by construction of a barrage can be very far-reaching.

1.3 Physical effects seaward of the barrage

Building a barrage across an estuary alters the hydrodynamic régime. On the seaward side effects vary, depending both upon the estuary concerned and the precise position of the barrage. In the case of the proposed Severn Tidal Power Development, the tidal range is expected to decrease by about 0.5m adjacent to the barrage, but further seaward (*e.g.* at Swansea) the effect becomes less than 0.2m on all tides. In contrast, a tidal power barrage proposed for the upper end of the Bay of Fundy (which in many other respects is similar to the Severn Estuary/Bristol Channel system) would cause a decrease in tidal range near to the barrage but a progressive increase in range at greater distances toward the sea. In the Gulf of Maine, about 400km away, the tidal amplitude will be increased by 15-20%.

Waves derived from local storms, or ocean swells, entering the estuary mouth will be reflected by the barrage and their energy dissipated seaward of the barrage line, with potential consequent effects on the shores close to the barrage. The precise impact on the wave climate of the estuary depends upon how far above the mouth the barrage is located. The direction and velocity of tidal currents close to the barrage will also be affected.

1.4 Physical effects landward of the barrage

Landward of the barrage, tidal range would be reduced (in the Severn by about one half), with associated decreases in average current velocity, not necessarily near the sluices and turbines. The low water

level would correspond to the pre-existing mid-tide level, but because of the slope of the estuary bottom, this difference will disappear in the innermost parts of the estuary. High water levels would generally be reduced (*e.g.* by about 1m in the Severn), with consequences for both sediment erosion and salt marsh distribution, but this reduction could be mitigated to some degree by pumping. Pumping could potentially either shorten or remove the high water stand (the time when water remains at the same level) in the basin associated with ebb tide generation (Fig. 1). The reduction in intertidal area and increased high water stand is important for both sedimentological and ecological processes, because of wave effects and the settlement of suspended sediments resulting from decreased current velocities. The alteration in the tidal régime would increase the volume of water in the estuary, and hence change the flushing time, which has important consequences for pollutant retention within the estuary.

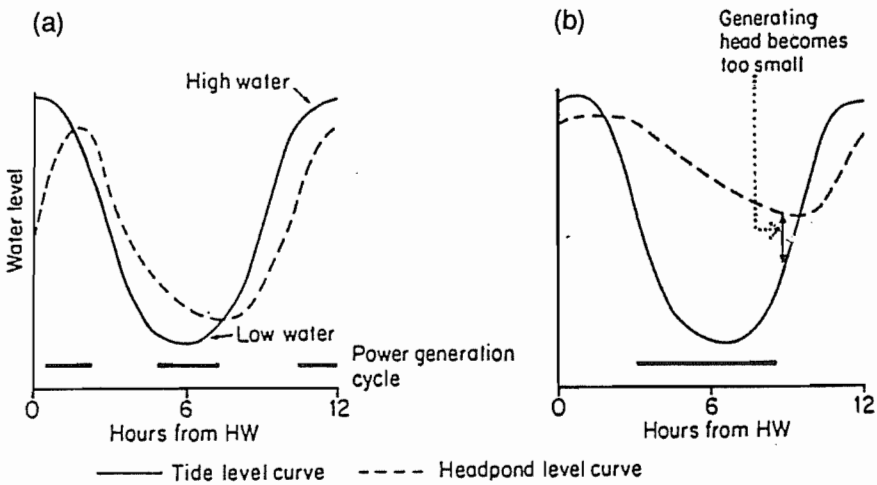

Figure 1
Profile of change in tide curves landward of a barrage operating (a) both on ebb and flow tides, or (b) on the ebb tide only.

Estuaries considered for tidal energy schemes are highly dynamic and, consequently, the salt water and fresh water are well mixed, both laterally and vertically, depending upon the tidal range and the volume of fresh water flow from the river. Under the modified régime, however, the tidal energy responsible for this vertical mixing will be reduced and, therefore, there will be a greater tendency for the lighter fresh water to remain at the surface, and the denser salt water to remain below, leading to a partially-mixed condition. These changes are important in relation to primary production processes and the distributions of invertebrates and fish.

The position of the barrage in the estuary is important: the larger the surface area of the basin, the greater the potential for wind-generated waves to arise behind the barrier, with consequent effects upon the shoreline. Within the basin itself, although reduced fetch would limit the production of waves, these may act for a longer period of time near the high water mark (because of the protracted high water) increasing erosive effects on the shoreline. These changes are discussed in detail in Section 2.

Such effects are based upon the relatively open system associated with a tidal power barrage. Barrages constructed for recreation, water storage or flood protection are largely closed to tidal influence and the ecological consequences are quite different. Such schemes may produce entirely fresh water bodies, with consequent loss of marine or estuarine species, and the development of fresh water communities. Where salt water is unable to escape, as in some of the early Dutch barrages of the Rhine Delta, created for protection against storm-surges, the result may be a brackish lake, often developing anaerobic conditions as a result of the lack of tidal mixing.

2. TIDAL AND SEDIMENTARY EFFECTS

2.1 Introduction

As mentioned above, partial or "semi-permeable" barrages result in a decrease in tidal energy within the basin; usually there is a modest decrease in high water level and a more substantial increase in low water level over most of the estuary, although both of these will depend on barrage operating practice. Maximum flood and ebb tide velocities also decrease, with the ebb experiencing the greater reduction. The timing of these maxima within the tidal cycle also changes. The lower velocities result in a decrease in the bed shear-stresses, which exert an important control on sediment transport. All this can lead to changes in net sediment transport over a tidal cycle.

While swell waves from the sea will be deflected, the activity of waves generated within the basin by wind can be increased in two ways: firstly, the raised low water level increases the time-averaged fetch length in the estuary, thus allowing more wave energy to be generated; secondly, this increased energy is concentrated over a reduced intertidal area, due to the decrease in post-barrage tidal range.

Reduced velocity and greater low water depth tend to increase vertical density gradients, although this may be counteracted by any increase in wave activity. The combined changes in tidal and wind-wave energy may lead to long-term changes in estuarine sediment distribution and morphology, often observed as short-term erosion and deposition.

2.2 Sediments

Although there is a complex distribution of sediment sizes in estuaries, there is usually a trend of decreasing grain size along the long axis from the mouth to the limit of saline intrusion, and across the estuary from the main channel to the high water mark. The concentration of sediment suspended in the water tends to increase in a landward direction from the mouth, reaching a maximum at the limit of the saline intrusion - the turbidity maximum.

Feasibility studies for several specific barrage schemes have demonstrated that the tidal velocities over substantial lengths in the basin may be reduced by about half; thus the new spring tide velocities would be similar to the original neap tide values. Field data show that this change would result in a reduction in suspended solids concentration by a factor of about ten in most of the basin. At the landward end, however, where low water levels are less affected by the barrage the changes in velocity and suspended solids concentration will be less marked and well-defined turbidity maxima will probably be maintained.

2.3 Intertidal morphology

Intertidal zones are characterised by a seasonal dynamic equilibrium involving overall wave-induced erosion during winter and accretion during summer (although these trends may be disrupted by storm and calm periods). Barrage construction leads to complex changes in this balance. In the region immediately landward of the barrage, where swell-waves from the sea have been excluded, a general decrease of erosion might be expected.

However, the increase in the storm-wave energy upstream of the barrage, and the slower rate of water level variation on ebb tides, could prolong and intensify exposure of the intertidal zone to waves. Moreover, recovery of the intertidal zone during summer will be less rapid than under pre-barrage conditions, because reduced tidal velocities and lower suspended sediment loads reduce accretion rates. On balance, therefore, it is likely that there will be net erosion in this part of the basin until a new equilibrium is achieved.

Fine sediments eroded from the intertidal zones by the mechanisms outlined above will tend to be transported landwards due to processes such as the dominance of flood-tide currents and the inhibition of sediment transport by ebb tide stratification of the water column. This could lead to enhanced accretion in the more landward reaches of the basin.

2.4 Salt marsh morphology

The increased influence of storm-wave activity above the barrage will erode the upper mudflats, possibly resulting in a salt marsh cliff or, if one already existed, an increase in its height. Retreat of the salt marsh edge may occur due to wave activity during the protracted high water stand.

The decrease in suspended sediment concentrations in the main post-barrage basin will lead to a general decrease in vertical accretion rates on the salt marshes. This will be exacerbated if there is a reduction in high water level which could, in some cases, also lead to desiccation of the surface, and even destruction of the vegetation cover (see Section 4).

By contrast, the landward reaches of the post-barrage basin, usually relatively unaffected by wave energy, may see an increase in the horizontal extent of salt marsh, possibly after the landward transport of sediments eroded from further seaward.

2.5 Subtidal morphology

At any point in an estuary with mobile beds, the area of cross-section is determined by the landward tidal volume. The effect of barrage construction will be to reduce the tidal volume, and hence there is a potential for accretion at the given point in order for the cross-sectional area to reduce to a new equilibrium value. There are three potential sources for the sediments needed to achieve such a decrease in cross-sectional area. These are the sea, the river or the intertidal erosion mentioned above. Deposition of such sediments in the deeper subtidal channels could then be facilitated by the decreased bed shear-stresses which are predicted in the post-barrage estuary (see Figure 2). The reduced shear-stresses will, however, decrease the rate of transport so that this infilling process may be a protracted one. These lower bed shear-stresses will also mean that the bed of the subtidal channels will be characterised by finer sediment grain sizes than those pre-barrage.

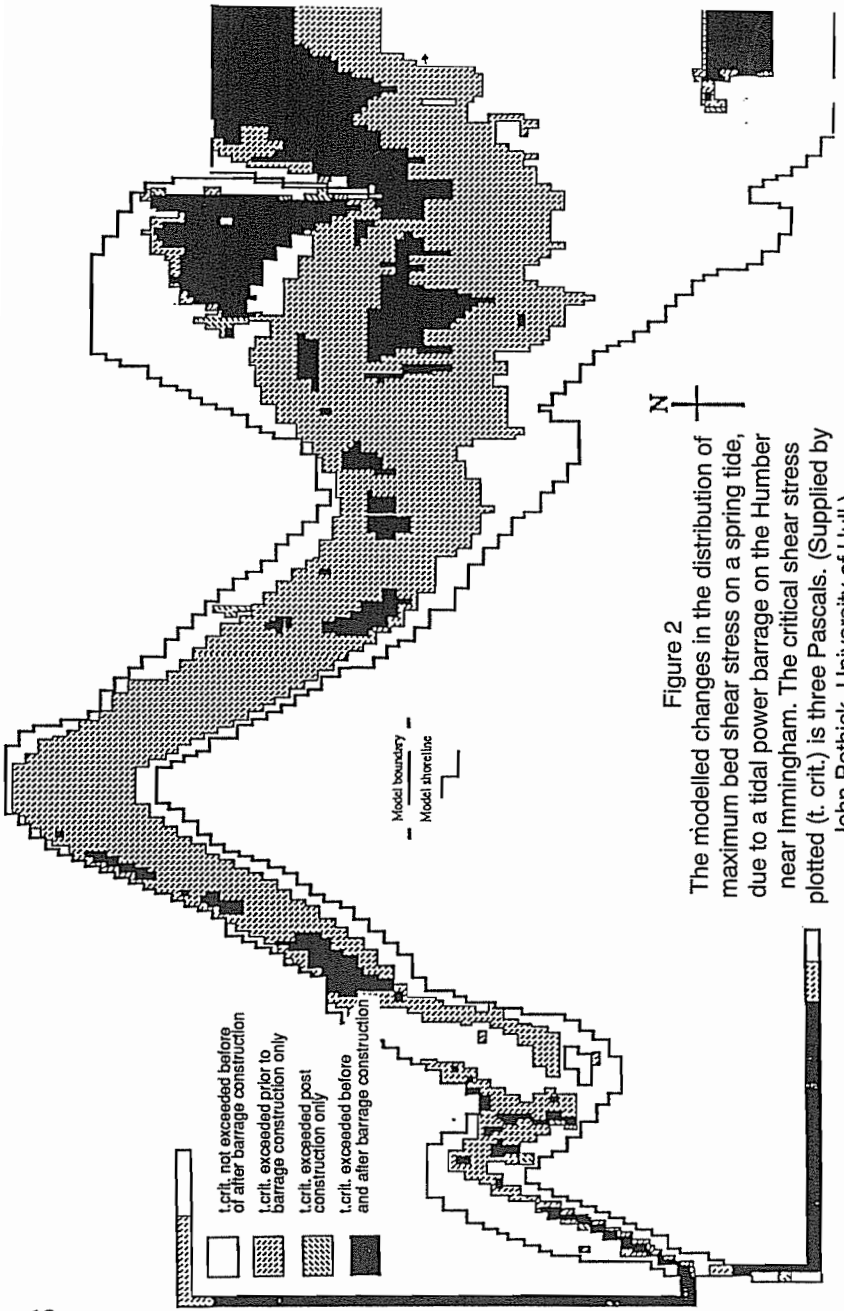

Figure 2
The modelled changes in the distribution of maximum bed shear stress on a spring tide, due to a tidal power barrage on the Humber near Immingham. The critical shear stress plotted (t. crit.) is three Pascals. (Supplied by John Pethick, University of Hull.)

Accretion of sediment eroded from the intertidal zone may be limited by main channel velocities and the volume available may be small if the main channel is substantially wider than the intertidal zones. In such cases, rates of accretion will be controlled by the availability of sediment from the head of the estuary.

2.6 Post-barrage estuarine morphology

Post-barrage estuarine cross-sectional profiles will tend to decrease in area due to deposition within the subtidal channels, and possibly on the lower intertidal zone in areas sheltered from prevailing winds. This could be counteracted partly by the erosion of the upper intertidal zone in more exposed areas. The raised low water levels and the erosion of the upper mudflats will cause a net decrease in the area of the intertidal zones in the post-barrage basin.

In a longitudinal direction, the transfer of sediments from the seaward reaches of the basin towards the landward end could result in slight changes in the plan morphology of the estuary involving a seaward movement of the tidal limit.

3. EFFECTS ON PLANKTON AND WATER QUALITY

3.1 Phytoplankton

Two important environmental factors controlling the growth of phytoplankton are light penetration and water column mixing. The latter is important in transporting nutrients from deep water to the illuminated surface and in mixing planktonic cells throughout the water column. In estuaries, light supply, mainly controlled by turbidity, is likely to be the dominant factor affected by barrage construction.

Physical changes already discussed will lead to a reduced vertical mixing landward of the barrage. Strong stratification (the formation of a sharp interface between two layers distinguished by salinity and temperature) is unlikely in basins retaining a strong tidal flow but, nevertheless, some degree of enhanced stratification and water column stability can be expected. Further, the slower currents landward of a tidal barrage will retain much less fine sediment than was the case prior to barrage operation. The reduced turbidity, and thus enhanced water clarity, will lead to greater light penetration through the water column. Phytoplankton photosynthesis responds very rapidly to changes in light intensity, and rapid phytoplankton production may occur earlier in the year and for longer periods.

This enhanced primary production will have consequences for the water quality of the estuary, as it will raise oxygen concentration in the surface waters. However, certain phytoplankton species, such as *Phaeocystis*, are not edible to secondary producers. Very dense blooms of such algae may persist, and eventually die and sink, thus contributing to a large biochemical oxygen demand (BOD) in the bottom waters and sediments. This has been observed in Lake Ijsselmeer (Holland), where increased nutrient supply has caused an increased incidence of algal blooms.

Normally, the primary production within an estuary is rapidly grazed by the zooplankton and zoobenthos. Any enhanced primary production caused by lower suspended sediment concentrations and possible

layering should therefore be transferred to the ecosystem as a whole. In the Severn Estuary, for example, this effect is predicted to be quite dramatic because the present naturally high turbidity not only limits primary production but also prevents colonisation by suspension-feeders, which cannot filter algae when there are such high background levels of suspended particulates. In the less turbid waters following a barrage, however, zooplankton would be able to feed on the increased primary production. Quite large populations of suspension-feeders could be formed, which might become a new food source for various species of birds. Neither would present populations of deposit-feeders necessarily decline in the Severn, if the detritus supply that is present prior to the barrage was still available. They will also benefit from the organic particles passed to the benthos by the suspension-feeders.

3.2 Pollutants

As we have seen, reduced currents landward of a barrage may lead to the deposition and consolidation of large quantities of fine, cohesive sediment. In an estuary receiving contaminants, many of which have an affinity for fine particles, these deposited sediments may contain trace metals, heavy metals, radionuclides and persistent organic pollutants. Episodic erosion of sediments by extreme spates or storms will lead to desorption of these contaminants into the water column, with potential adverse effects on the biota. Also, any changes in the distribution of oxygen concentrations in the water column and sediments could alter the mobility of contaminants and, similarly, bioturbation by benthic organisms may alter contaminant mobility. In an estuary with a long flushing time, any desorbed contaminants may be transported slowly seawards.

The focus of human economic activity around estuaries has led to the discharge into them of domestic sewage and industrial pollutants. If reduced tidal currents due to a barrage also lead to reduced longitudinal mixing in the estuary, this will produce an increased concentration of any conservative pollutant. However, if the reduced tidal energy causes pronounced stratification or layering of the water column then the less saline water, containing higher concentrations

of pollutants, could be transported more rapidly in the surface layers to the sea. In this case, the average level of the pollutant in the basin will be reduced.

Even if non-persistent pollutants are retained within the basin for a longer period than without a barrage, they do not necessarily attain higher concentrations because they are discharged into a greater mean volume of water. For the Severn Estuary, it was computed that the concentration of ammoniacal nitrogen within the basin would be little changed from the pre-barrage situation.

The bacterium *Escherichia coli*, which is often used as an indicator of sewage dispersal, can be considered as the biological form of a pollutant which is destroyed by both saline water and solar radiation. Again in the Severn, its concentration was computed to be unchanged by the presence of a barrage. Such computations need to be specific to the estuary and barrage location under study. The BOD caused by raw sewage and other particulate carbon discharges shows similar characteristics. Unfortunately, no general rule can be made about the impact of a barrage on oxygen concentrations because it depends on a complex balance between oxygen supply from the atmosphere, primary production by algae, and the demand from decomposition. Bacterial and nutrient loadings to estuaries will change in the future as the amount of crude sewage discharged is reduced to meet EEC water quality criteria.

4. EFFECTS ON ESTUARINE VEGETATION

There has been relatively little research on the possible impacts of tidal barrages on plant communities such as eelgrass beds, salt marshes and macro-algae. Most insights as to the likely effects have come from the Dutch experience. Much of the uncertainty about post-barrage plant distributions stems from the imprecise predictions of physical and sedimentary changes. Broadly speaking, the distribution and floristic composition of intertidal vegetation is influenced strongly by tide-related factors, although the exact rôle of interrelated factors such as submergence, turbidity and current speed is not fully understood.

4.1 Salt marsh

The major interacting factors determining whether salt marsh is likely to expand or contract inside a tidal barrage are the effects of reduced tidal range, on the one hand, and of increased wave energy at specific points, on the other. The former will tend to produce an accreting environment, and possible downshore spread of existing salt marshes, whereas the latter will cause salt marsh erosion and retreat. Current predictions (see above) suggest that both forces may operate within a single estuary and that the balance between them will be site-specific and depend on estuary shape and sediment supply. In addition, increased stability of low water channels within the basin may also enable salt marsh to develop in areas where it was not previously possible.

In those situations where accretion is predicted, existing knowledge of the factors determining the lower limit of the salt marsh may be used to predict the new lower limit. For example, the distribution of *Spartina anglica* is closely related to tidal range, fetch, position on the estuary and other physical variables. The species' lower limit is frequently below MHWN level in estuaries with a spring tidal range of less than 7m. Whether this potential lower limit is achieved in a post-barrage basin will depend on the effect of increases in wave energy.

As well as affecting the expansion or contraction of salt marsh, the changed tidal régime will also cause changes in the vertical distribution of individual species within the salt marsh. A reduced frequency of submergence at higher levels will allow species from the upper salt marsh to move downshore. These changes are likely to be mediated via competition between perennial species with different degrees of tolerance to tide-related factors, and is likely to have a regional component. Plants such as *Halimione portulacoides* or *Spartina anglica*, for example, near their northern limits in the estuaries of northern England, may be replaced there more readily by northern species such as *Puccinellia maritima* than further south.

The major floristic changes are likely to occur at the higher elevations close to the high tide mark. Here, invasion by non-halophytes is possible, and may threaten several uncommon species. In both the Ijsselmeer polders and the Versemeer area of the Delta, species such as *Aster tripolium* and *Juncus gerardii* were replaced by species such as *Sonchus palustris*, *Urtica dioica* and *Cirsium palustre*. The rate of replacement was strongly affected by grazing, which generally delays the succession to non-halophytes.

Recent studies in the Eastern Schelde in south-west Holland have demonstrated that major, irreversible changes may occur on salt marshes following the cessation of tidal flooding. On these marshes, physical changes included cracking and shrinking of the soil, the collapse of salt marsh creek edges and the deposition of sediment in the creeks. Chemical changes which followed the removal of the tide included desalination of the surface layers, the oxidation of pyrite (FeS_2)in the formerly anaerobic soils and the neutralisation of sulphate by calcium carbonate ($CaCO_3$). The most important vegetation changes were the invasion of nitrogen-loving species (*Suaeda* and *Atriplex* species in the lower zones and *Matricaria maritima* and *Sonchus arvensis* higher up) and the death of *Spartina anglica* and *Halimione portulacoides* over a large area.

Any management of the post-barrage basin which withheld the tide from the marshes for a prolonged period and then allowed reflooding

is therefore likely to result in irreversible soil structural and floristic changes. Salt marsh plants are generally adapted to periodic submergence, but where this becomes unpredictably irregular or aseasonal, damage may occur. For example, prolonged summer inundations when inflorescences are fully developed has a severe effect on growth. In some barrage schemes (*e.g.* in certain options for a River Wyre barrage), the upper levels may actually be submerged more frequently than before, presumably with quite different effects. This illustrates the potential importance of water level control by regular pumping in barrage schemes.

Other factors which may affect salt marsh plant communities within a tidal basin include water quality, changes in the shape of creek banks, the possibility of increased icing due to fresh water layering, increased frost damage at the higher, reflooded, levels and altered drainage characteristics associated with water table changes. With some barrages, salinity changes, particularly in the upper estuary, will allow the downstream migration of brackish and fresh water species, such as *Phragmites australis* and *Scirpus maritimus*.

The general prediction of slightly raised high water levels seaward of the barrage in some schemes points to increased flooding of the higher salt marshes. This is likely to have an effect opposite to that within the basin and may lead to the loss of individuals of some species at their lower vertical limits. How important this effect is will depend on the location of the barrage within the estuary and other site-specific factors. Similarly, close to the barrage either erosive and accretionary effects may be evident, depending on the position of sluices and turbines and the change in tidal volume. Quite specific predictions should be possible from physical or mathematical models of tidal range.

4.2 Zostera *beds*

Where eelgrass (*Zostera*) species occur within the basin, changes in distribution may follow barrage construction. In general terms, lower turbidity and greater sediment stability on the lower mudflats, sandflats and sub-tidal beds will lead to expansion of *Zostera* beds.

Eelgrass beds require sheltered conditions and, therefore, changes in the distribution of sand and gravel banks within the estuary may affect the existing *Zostera* sites. In Britain, these occur mostly in estuaries of lower tidal range, which suggests that reducing the range by barrage construction may favour the spread of *Zostera* (although increased nutrients would favour epiphytes to the detriment of *Zostera*).

4.3 Macro-algae

These species rarely form a major component of the intertidal vegetation in estuaries where barrages are currently being proposed. Nevertheless, significant changes in their distribution may occur, particularly where new structures are provided, such as the walls of the barrage itself. Reduced tidal range and altered submergence patterns may narrow the vertical zonation. There is potential for invasion by generally deep-water species, such as *Laminaria* species and *Sargassum muticum*, which are presently limited by turbidity.

4.4 Reclaimed land

Many estuaries are flanked by low-lying areas of former intertidal salt marsh which has been embanked and supports a characteristic and often species-rich assemblage of plants in its grassland and ditches. Such areas are vulnerable to changes in ground water levels and inputs of saline water, both of which may occur in reclaimed areas landward of a barrage. The change from gravity- to pumped-drainage is likely to provide greater control over both ground water levels and the uses of land fringing the barrage lake.

5. EFFECTS ON THE MACROBENTHOS

5.1 Estuarine benthos

Differences between estuaries in the composition of the macrobenthos are usually related to dynamic variables, such as tidal range and wave climate, whereas within estuaries species distributions relate to static variables, such as sediment type and salinity, which display strong gradients. Tidal ebb and flow, and episodic events such as storms, cause wide fluctuations in environmental variables over short timescales. This instability, and the resulting high physiological stress to which the benthic invertebrates are subjected, is reflected in a low species diversity, though tolerant species are persistent, and may be highly productive. Wide fluctuations in density, both in time and space, are common, but some populations of mussels, regulated by density-dependent processes, are remarkably stable.

In estuaries where there is vertical mixing of the water, much of the surface production of organic matter by phytoplankton settles towards the bottom. Here it is consumed by suspension-feeding invertebrates and other organisms buried in the sediment (the benthic 'infauna') or by more mobile animals living on or near the sediment (the 'epibenthic' fauna). In stratified estuaries, where lighter river water overlies heavier sea water, much of the surface production is carried out to sea and the food of the benthos may be limited. Where tidal range and turbidity are higher, more of the primary production is associated with diatoms inhabiting the sediment surface in the intertidal zone. These diatoms are grazed by deposit-feeders, including gastropods, bivalves, amphipods and worms. Many estuaries have productive salt marshes that are a source of detritus. The detritus supply is often augmented by sewage and other organic wastes and estuarine communities are well suited to process human waste because many of the benthic and epibenthic organisms (and bacteria) are natural detritus-feeders. However, over-enrichment leads to anoxia and depressed species diversity.

5.2 Effects of a barrage

In the long-term, building a tidal energy barrage across an estuary might be expected to produce a more stable habitat by providing shelter from storms and reducing tidal currents and thus reduce disturbance-related fluctuations in invertebrate population densities. However, there may be other confounding effects and, in the short- and medium-term, major changes in sediment distributions are possible which will also affect benthic invertebrates.

Seaward of a barrage, changes in tidal range and current flows will vary according to design and site. Decreases will favour the deposition of finer sediments, increases will favour their erosion. In either case, the benthic communities will respond according to their preferred sediment type.

Above the barrage, benthic infauna may be expected to respond to the major physical effects discussed previously. First, reduced tidal range will lead to a narrowing of the intertidal area and increase in the sublittoral area (this may be modified when a new equilibrium is reached). It is unlikely that the upper mudflat populations will be affected greatly by the lowering of the high water level, but much of the mid- and low-level sandflats will be permanently inundated as the low water level rises towards mid-tide level. The relative distribution and biomass of intertidal and sublittoral communities may, therefore, be expected to change accordingly.

Reduced tidal flow and increased shelter are expected to result in a rapid (days to weeks) reduction (up to 10-fold) in the suspended sediment load. This could have two main effects: the first, in extreme cases, *e.g.* in the Severn, Humber and Gironde estuaries, could be a rapid deposition of fine particles, equivalent to 2.5cm depth, over the entire area. What this will do to the benthic infauna is unknown, but most adults would probably survive, providing the sediment consolidates fairly rapidly. However, should this coincide with larval recruitment, many might fail to settle or be smothered. In predominantly sandy estuaries with low suspended sediment loads, this effect will be small, leading only to a slight increase in the range of

sediments and, therefore, species diversity. The addition of even a small proportion of fine grains to the coarse sand banks which occupy a large part of the sublittoral zone of larger estuaries, such as the Severn, can increase invertebrate populations. Reduction in sand-bank mobility will encourage colonization but, even when stable, coarse sands do not support a rich fauna. A second major effect of reduced sediment loads in estuaries may be a sufficient decrease in water turbidity to allow an increase in phytoplankton production and, as mentioned earlier, a consequent increase in the food supply for benthic suspension-feeders, such as mussels, oysters and scallops. Modelling studies for the Severn tidal power barrage predict that the suspension-feeders will increase within the basin community. It is possible in estuaries such as the Severn that suspension-feeders, currently rare, could be favoured to the extent that important shell fisheries might be developed. However, intertidal populations will be affected by changes in their availability to aerial (wading birds) and aquatic (crabs, fish) predators.

The increased retention/flushing time will enhance the estuary's ability to trap nutrients and organic matter. Increased nutrients in the water will tend to increase plankton productivity, favouring filter-feeders. Increased nutrients will also favour increased production of benthic diatoms, increasing food supplies for some species, such as *Corophium* and *Hydrobia*. Because of their mucilaginous excretions, diatoms help to stabilise the sediment surface, at least in the summer months. However, the development of dense algal mats, e.g. *Enteromorpha* and *Ulva*, can lead to deoxygenation of the underlying sediments and death of the infauna, but increased production of surface-grazers, e.g. *Hydrobia*. Reduced tidal mixing may increase the likelihood of salinity/density stratification and, if this is coupled with organic enrichment, there will be an increased risk of deoxygenation of the bottom waters in deeper channels, killing the benthic infauna. However, strong flood-tide currents make this unlikely and in the long term organic detritus may even decrease, depending on site-specific changes in sediment redistribution and salt marsh erosion.

The closure of storm-surge barrages could result in submergence or exposure of the intertidal sediments and their benthic infauna for periods longer than the normal tidal cycle. Prolonged submergence has relatively little effect, other than increasing the risk of predation by the epibenthos, *e.g.* crabs and fish, but exposure to air for more than two days has been shown experimentally to kill most invertebrates.

5.3 The epibenthos

Unlike many of the infauna, which as adults have only limited mobility and must tolerate any detrimental changes in their habitat, the epibenthic species, including crabs, mysids, crangonid and caridean shrimps, are fully mobile and will respond to changes by avoiding areas of low dissolved oxygen and invading newly-disturbed sediments. Most of them are omnivorous, capable of utilising whatever food is available. They will undoubtedly respond favourably to any increase in total food available, and their swimming ability means that their distribution will change within the basin, making them especially abundant in calmer waters where detritus will accumulate. Evidence from the Bay of Fundy suggests that this group is very important as food for resident and migratory fish.

6. EFFECTS ON BIRDS

6.1 Introduction

Several groups of birds depend on the coastal habitats that might be affected by barrage construction. Most dependent are waders and wildfowl, but seabirds, passerines and raptors also use these habitats. The three main habitats concerned are salt marsh, intertidal flats and inshore waters.

Although some birds are resident throughout the year, the majority occur in the coastal zone only in certain seasons. Some live there only during the breeding season while others either spend the winter or stop to feed while on migration. In temperate latitudes, some species move to the shore during severe weather when the normal inland habitats are frozen over or snow-bound.

Species also vary in their response to diurnal and tidal cycles. The many thousands of non-breeding waders and wildfowl that feed in intertidal habitats at low water, roost for long periods over high tide and form large flocks in salt marshes or undisturbed inland sites. In contrast, large numbers of geese and gulls that feed inland during the day use the safe coastal flats and waters to roost at night. Birds that breed in the coastal zone can do so only on the high marsh or high up on the beaches out of reach of all but the highest spring tides.

How birds will be affected by barrages depends simply on how they use the coastal zone and on the type of barrage. Amenity barrages, for example, which retain a standing body of fresh water, will prevent most birds from using the area as they had before, the intertidal habitat having become permanently inundated (except for birds which roost on coastal waters if the reservoir provides a safe roosting site). Other barrages have less clear-cut effects and simply modify the habitats rather than completely inundate them. Tidal power barrages illustrate most clearly the issues involved for the birds. These can be considered under three habitat groups: salt marsh, intertidal flats and inshore waters.

6.2 Salt marsh

Some birds, especially gulls and terns that breed on salt marshes or beaches, nest in colonies and require large, undisturbed areas above the normal high tide. The parents feed either in the inter-tidal zone or inshore waters. So long as a suitable nesting area is left post-barrage, and adequate feeding grounds remain, such birds may not be affected. However, in many species, such as passerines and waders, pairs nest within large, exclusive territories and require particular sorts of vegetation to conceal their nests. For these, we have to predict any net change in the area of higher level marsh, and the extent to which vegetation will be modified. Nests of marsh-breeding birds are frequently destroyed by exceptionally high tides, but a barrage could reduce this risk by lowering the highest spring tides. Indeed, a barrage could be deliberately operated to prevent flooding during the nesting season.

A number of wildfowl species specialise in feeding on salt marsh vegetation; in north-west Europe, for example, many tens of thousands of wigeon *Anas penelope* graze on *Puccinellia maritima*. Some passerines, notably the twite *Acanthis flavirostris*, eat the seeds of salt marsh plants. During periods of snow-cover inland, many other passerines may use salt marshes, where snow settles only in extreme circumstances. Again, we need to predict how the abundance, seed production and species composition of the salt marshes will change as a consequence of barrage construction.

Only a large reduction in the salt marsh area will affect the many birds that roost there at high water on spring tides; on neap tides, they can still roost on the higher-level flats that remain exposed over the high water period, but because the high water period would be extended by a barrage, the importance of secure and undisturbed roosting sites on spring tides may be increased. Some provision of artificial roosting sites, close to the main feeding areas may be needed where a barrage causes a substantial net loss in the area of high-level salt marsh.

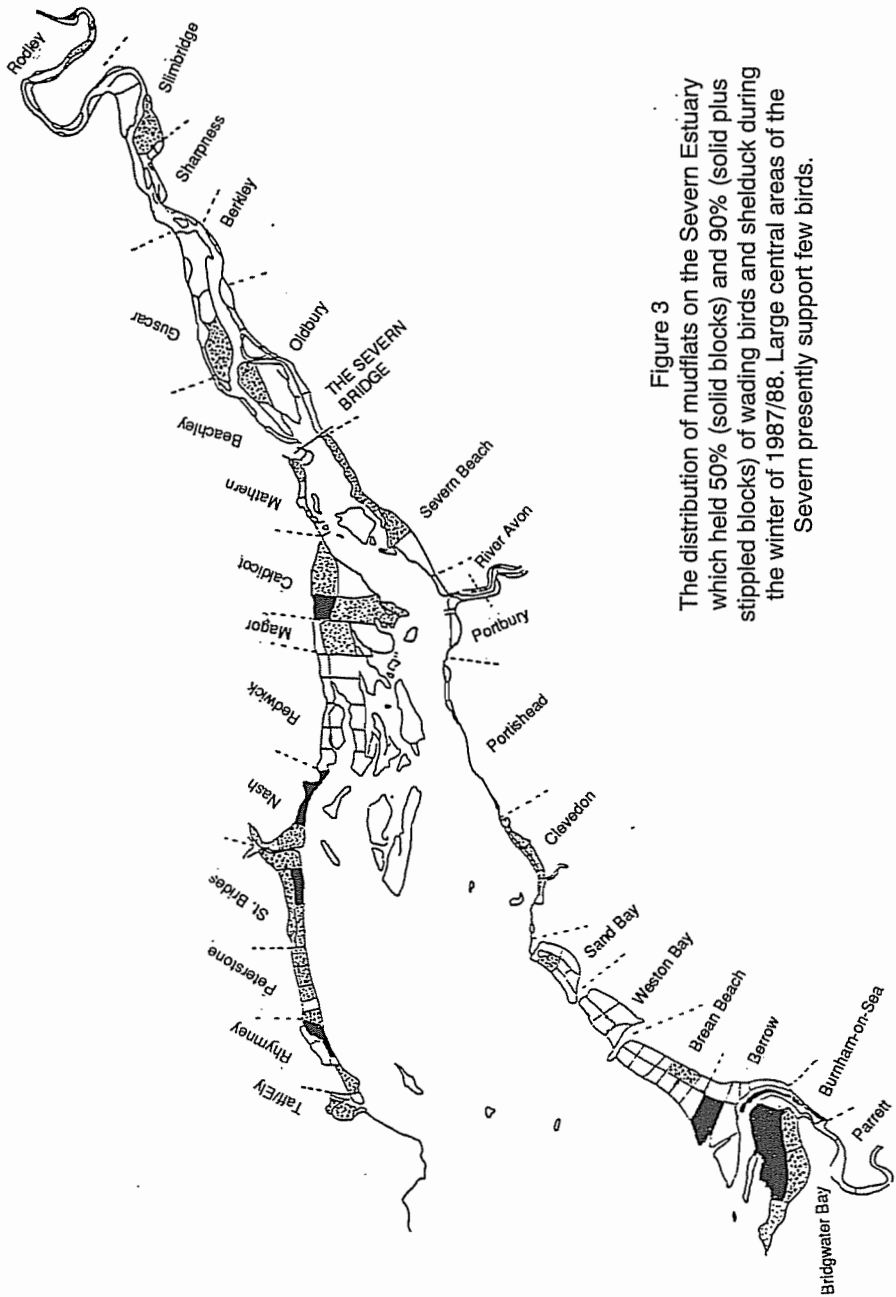

Figure 3
The distribution of mudflats on the Severn Estuary which held 50% (solid blocks) and 90% (solid plus stippled blocks) of wading birds and shelduck during the winter of 1987/88. Large central areas of the Severn presently support few birds.

6.3 Intertidal flats

The immediate effect of a barrage on the intertidal feeding grounds would be a substantial reduction in both the area available and in the time for which that area is exposed, and so is accessible to birds, over the low water period. Subsequently, however, a number of other changes will affect feeding conditions for birds. Depending on the new balance between erosion and deposition, new shore profiles may develop which offset the reduction in intertidal area following inundation of the lower levels. Furthermore, in very high tidal range estuaries, there are large areas of mobile and coarse sediments that are currently unsuitable for the macroinvertebrates eaten by birds (Fig. 3). If large populations of invertebrates, do develop in these areas (p.23), the proportion of the estuary that is suitable for feeding birds will increase.

Predicting the effects on intertidally-feeding birds involves two central issues: first, predicting the post-barrage distribution and abundance of the invertebrate prey; second, predicting how any changes in the food supply will affect the number of birds the area can support. The effect on bird numbers depends on how changes in the food supply affect the ability of individual birds to satisfy their food requirements. A major consideration here is the level of competition between the birds themselves and with other predators, such as fish and crabs, that exploit the same food.

Competition between birds takes two forms. Interference between individuals occurs when the mere presence of another bird nearby reduces the foraging rate. For example, when a redshank walks over the mud, its main prey, the crustacean *Corophium volutator*, retreats into its burrow to avoid being eaten (Fig. 4). If another redshank feeds in the same area shortly afterwards, it is less likely to find prey at the surface. If a barrage causes a net reduction in the feeding area, the density of foraging birds would inevitably be increased in the reduced space. Birds would more frequently forage in places that had recently been visited by another bird and it would become more difficult to obtain their requirements in the time available over low water. The second form of competition depends on the direct consumption of prey

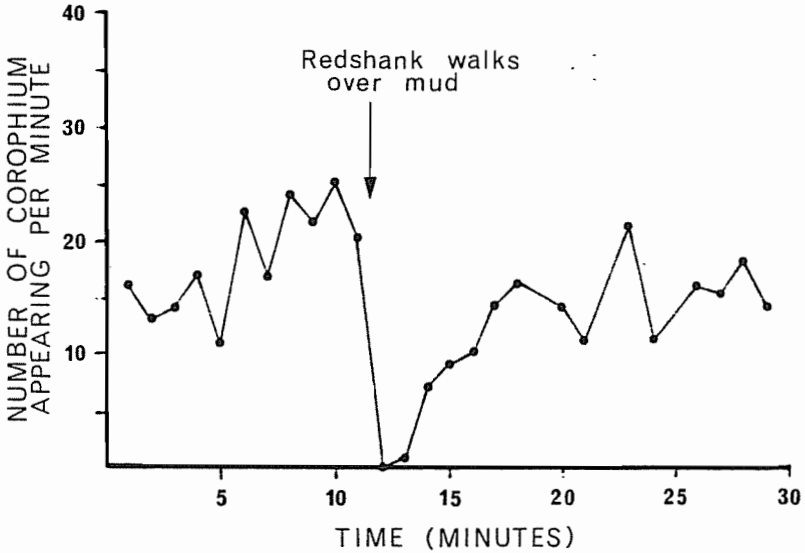

Figure 4
Wading birds interfere with each others feeding indirectly through the avoidance behaviour of their prey. This shows that *Corophium* disappear down their burrows after a redshank has walked over the mud. Numbers appearing at the surface do not recover for perhaps 5-10 minutes. Therefore, any crowding of birds into smaller areas of mudflat could reduce feeding, even if prey numbers are not substantially depleted.

by birds over the winter. Since the rate at which a bird feeds depends, in part, on the density of prey in the sediments, food would become increasingly difficult to collect as winter progressed and the food supply became depleted.

Whether competition does intensify depends on whether there is a net change in the feeding area and in the abundance of the invertebrates themselves; clearly, competition would have less impact were the

density of invertebrates to increase. The main challenge is to predict the net effect that a barrage would have on the ability of birds to feed. The next step is to predict the effects of net changes in the feeding conditions on the fitness of individual birds. In the temperate zone, conditions are most critical in mid-winter, when the short day-length and low temperature make it difficult for birds to achieve their food requirements. In periods of strong wind and very low temperatures, many birds die directly of starvation. Others are killed by birds of prey, the weakened shorebirds putting all their efforts and attention into seeking food rather than watching out for predators. Any change in feeding conditions would affect the chances of birds surviving such periods and thus the proportion surviving the winter. The feeding conditions in winter and spring can also affect how long it takes birds to accumulate the fat reserves required to fly to their distant breeding grounds, which in many species are in the Arctic. They must also arrive there with some fat reserves remaining, both to survive a late onset of snow-melt and to have the body reserves required to breed. When birds return from breeding grounds, they must renew all their feathers before the onset of winter. This, too, is very demanding of energy.

The net effect on bird numbers of a change in feeding conditions can be considered at two scales. First, interference in competition could limit local density on the feeding ground. Individuals most seriously affected will leave the area to seek food elsewhere. If their chances of survival, or subsequent breeding success, are reduced, overall population size may be affected. Alternatively, improved feeding conditions due to local increases in prey densities could lead to an increase in bird numbers, both locally and overall, if survival is increased. Predictions on net changes are presently uncertain.

Recent experience in the Delta region of The Netherlands underlines the need to understand fully the implications of changes in the management régime of barrage schemes. Following an engineering problem, the storm-surge barrier was closed and the intertidal feeding grounds were inundated for a prolonged period in autumn, at a time when birds were laying down fat reserves for the winter. When

a cold spell arrived later, many more birds than normal died of starvation because they had not been able to store sufficient fat reserves to last through a period of severe weather.

Though most species eat the invertebrates in the intertidal area, a few feed on the specialised plants that may also live there, in particular the eel-grass *Zostera* spp. As mentioned earlier, this plant may flourish in the clearer water that would be found in post-barrage estuaries.

6.4 Inshore waters

Unlike their effects on the other two habitats, the predicted changes in inshore waters seem likely to work only in one direction - and that is to improve the feeding conditions. The less turbid, clearer water will allow fish-eating birds, such as terns, grebes and saw-billed ducks, to detect their prey more successfully. The overall increase in productivity would also increase food abundance. Finally, any fish killed or disorientated after passing through the turbines make easy pickings for many birds, including gulls and terns.

7. EFFECTS ON FISH AND OTHER VERTEBRATES

7.1 Introduction

In common with other organisms, fish are affected by changes to their physical environment. In addition, fish are potentially subject to mortality caused by passage through the barrage turbines. Tidal power barrages are not unique in killing fish. Thermal energy power stations invariably draw cooling water from open water - rivers, lakes or open sea - and these contain fish that are killed when the water is filtered before passing to the condenser systems. The mortality so caused has been assessed as minor compared to exploitation by commercial fisheries. Such yardsticks are needed to judge whether the mortalities which tidal barrages may induce are acceptable or not.

7.2 Fish feeding and distribution

The majority of estuarine species of fish are benthic feeders; consequently, their populations may alter in response to changes in their prey species' abundance. Thus, a positive change in the benthic community will probably produce a positive response in the fish populations, and conversely with a negative change. The same basic rule will apply to pelagic species which feed on the plankton. Therefore, predicting the potential changes in fish populations following the building of a barrage requires an accurate model for predicting changes in secondary production.

Assuming the estuary does not have an oxygen deficiency, the most important chemical variable affecting distribution of estuarine fish is salinity. Fresh water species extend into the uppermost reaches of the estuary, where salinity is virtually zero. With decreased vertical mixing in the barrage basin, the fresh water layer which overlies the saline intrusion might extend further seaward. This reaches its extreme where a tidal exclusion barrage is built and a fresh water lake forms. Thus, fresh water species might occur further downstream, most noticably along the shoreline as the deeper channels hold the denser saline water. Similarly, the saline wedge of sea water underlying the fresh water, predominantly in mid-channel, might extend further landward and permit some wholly marine or estuarine fish to

move further upstream than previously. These changes in distribution need not imply any change in absolute abundance of either the marine or fresh water populations.

7.3 Juvenile and small fish

Fish frequenting estuaries can be divided into four broad categories (Fig. 5): species resident throughout their life, species for which estuaries provide a nursery area, species whose adults enter the lower estuary (usually to feed), and species that pass through the estuary on spawning migrations.

Species resident in estuaries throughout their lives are typically small and short-lived, *e.g.* gobies. Such species are unlikely to show any significant change in abundance or distribution following construction of a tidal power barrage, other than in response to the major factors of food and salinity mentioned above.

Fish present mainly as juveniles fall into a similar category to the small species. Either they are spawned in the estuary, *e.g.* mullet, or the juvenile fish drift into estuaries as planktonic organisms, *e.g.* some flatfish and bass. Fish at the planktonic stages face minimal risk from the barrage, partly because of their small size (although they may be vulnerable to major pressure fluxes) but also because the planktonic stages already suffer natural mortality rates of around 90% per day. Following metamorphosis, and while on the nursery grounds in the barrage basin, juvenile fish populations occupy a niche similar to the small species' populations and will respond in the same manner to environmental changes. Only when these juvenile fish have grown to 15-30 cm, and it is time to leave the estuary, does their situation change. Then they must pass the line of the barrage to join the mature stock of fish at sea. In most cases, emigration will occur on the ebb tide and expose the fish to the risks of passing through a turbine. Therefore, provision should be made for fish to migrate seaward without passing through barrage turbines. It may not always be practical to meet this stricture, either for reasons of barrage design or fish behaviour. However, most fish biologists would conclude that even if all emigrating juveniles of marine species were

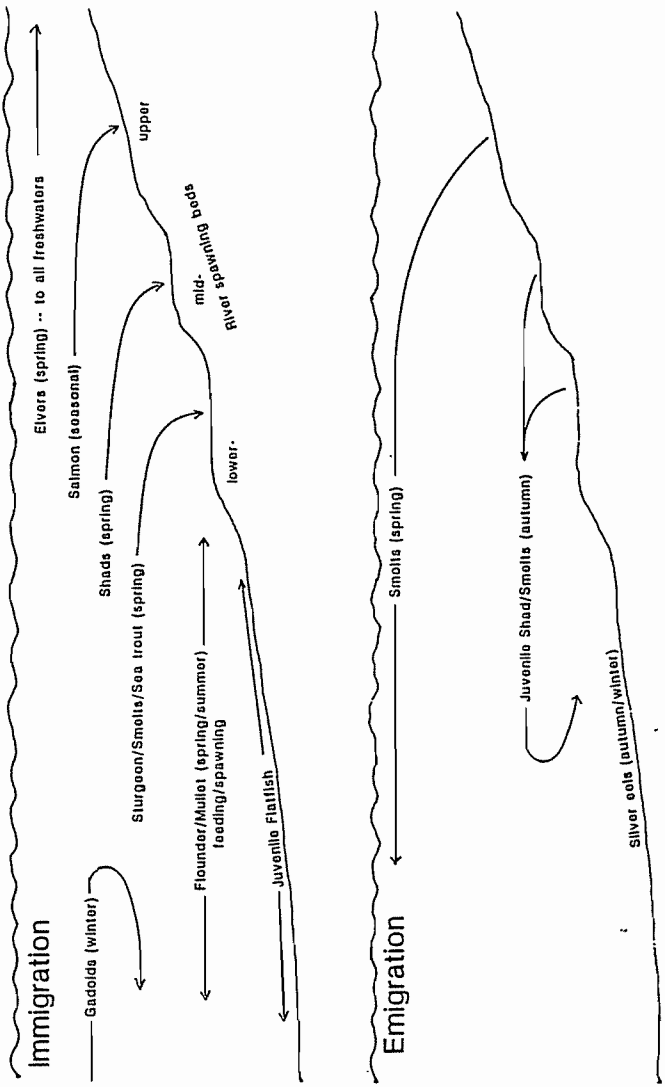

Figure 5
Simplified presentation of some important fish which occupy estuaries at some stage in their life history; major immigrations are shown above and emigrations below.

killed in a particular estuary, the mature stock at sea would probably not decline significantly. Fish stocks which spawn at sea will rarely be so dependent on a single estuary for their juvenile nursery ground that the loss of one nursery's production would have a measurable impact on the long-term stability of the adult stock. The planktonic drift following spawning offshore is so variable from year to year that recruitment to nursery grounds from individual spawning stocks also tends to be variable and 'broadcast' rather than site-specific. This strategy buffers stock abundance from failure on an individual nursery ground.

7.4 Catadromous and mature marine species

A similar basic principle applies to catadromous species, *i.e.* fish that mature in fresh water but return to the sea to spawn. Certainly in the case of the European eel, *Anguilla anguilla*, the recruitment of elvers to a given estuary bears no parent-offspring relationship, neither in kind nor abundance, to the mature eels which left that estuary earlier. The number of estuaries suitable for tidal power barrages is small in relation to the total number of estuaries through which eels migrate. Thus, although individual estuaries will be affected, the impact of tidal power barrages on the long-term stability of eel populations is unlikely to be significant (and in any case it is unlikely that European eels ever reach the Sargasso Sea to spawn).

Species that spawn offshore but in which some of the mature stock enters an estuary to feed or overwinter (*e.g.* some flatfish and Gadidae) are likely to be similarly affected, the geographic spread of the stock as a whole being sufficient to safeguard the stock's survival. This has been the experience over the 25 years since the commissioning of the tidal power station on La Rance in northern France, where there is no specific provision for fish to by-pass the turbines.

7.5 Anadromous species

This generally sanguine view of the impact of power barrages on marine and catadromous fish population dynamics does not apply to anadromous species (fish that mature at sea and return to fresh water

or estuaries to spawn). Among the most famous of these are the salmon, which spawn on clean gravel beds in the headwaters of their natal river system. Lower down the river system may be found spawning beds for a variety of anadromous clupeids (herrings, etc.), sturgeons, lampreys and, in the estuaries, mullets and some flounders or flukes. All of these species must be able to emigrate from the estuary of their spawning ground without suffering significant mortalities, caused by the barrage turbines, if the stock which uses the estuary is to survive. There can be few estuaries that are suitable for tidal power generation in which one or more of these anadromous species are not found. A central issue for future research is to develop systems that minimise the risks of damage or that enable fish to cross the line of a barrage without passing through the turbine tunnels.

7.6 Crossing the barrage and future research on fish

Although other species would benefit from turbine by-passes, the demands for the survival of anadromous species is what provides the impetus for research. In the UK, in particular, there is an urgent need to solve this problem for both adult and juvenile salmon (smolts). A suitable by-pass route for smolts may serve other small pelagic species and mature salmon may lead the way for other large species. A system of spillways (small waterfalls) spaced along the upper surface of a barrage may be suitable for the surface-swimming smolts, while downstream fish passes or tunnels may be the answer for the larger fish. To increase the use of these by-passes, and to inhibit fish from approaching the potentially lethal turbine tunnels, bubble screens, flashing light systems and sound sources to enhance the deterrent effect of turbine noise are being considered. Preliminary research at the Annapolis tidal power station, Nova Scotia, has shown that acoustic devices can effectively drive adult shad away from the turbine intake, but further research is needed. Similarly, the behaviour of mature salmon (and other species) needs to be studied in detail, probably by radio tracking, before final decisions can be reached on fish pass design.

Although research will be aimed at minimising the risk, it is inevitable that some fish will pass into a turbine tunnel. Here they are

vulnerable to a variety of traumatic effects. Most obvious of these are direct strikes from the turbine runner blades, travelling at speeds approaching 100 kph, which will invariably be fatal. Less obvious are effects that fish may suffer from a pressure flux which approaches plus and minus 1 atmosphere in less than 2-3 seconds. This is in addition to the random pressure fluxes and shear effects of turbulent water flow which, together with back-roll immediately to seaward of the barrage, can be extremely disorientating. Disorientation may leave fish particularly vulnerable to larger predatory fish and, if they remain at or near the surface, to seabirds. Clearly, the turbine tunnels represent a hostile environment but if specific causes and effects can be identified, it may be possible to influence turbine design and/or operations to reduce the impact on entrained fish. Research into these aspects of the problem has begun.

7.7. Effects on marine mammals and reptiles

Within European waters, marine mammals which may occur in estuaries suitable for tidal power barrage construction are seals, dolphins, porpoises and otters. Elsewhere the list might be extended to include sealions, dugongs, manatees, some of the larger cetaceans and large reptiles - marine crocodiles and turtles. Most of these species are subject to national and international conservation or management measures.

Hitherto, no specific research effort has been directed towards assessing the potential impact of tidal power barrages on these groups of animals. If they enter the turbine draft tubes during power generation, they will be at great risk of damage and fatal injury. However, the numbers involved are unlikely to be sufficient to affect the majority of stocks adversely, though some local stocks or endangered species might be vulnerable.

It is reasonable to assume that marine mammals are likely to shun noisy artefacts like generating turbines. Seals and small cetaceans are seen occasionally in ship locks and might use these to avoid turbines when moving downstream. When moving upstream, they can pass through the sluice gates with no more harm than momentary

disorientation. Alternatively, where mammals and reptiles enter estuaries in abundance, the nets and barriers deployed to keep trees and other macrodébris from the turbine draft tubes, might be designed to guide these animals towards by-passes or holding-pens, where they could be recovered and transported across the barrage manually.

8. NATURE CONSERVATION ASPECTS

8.1 Introduction

When compared with other threatened habitats worldwide, estuarine and coastal areas within western Europe are relatively well-known, and conservation reviews have been carried out by several organizations (*e.g.* RSPB's 'Turning the Tide' Campaign and NCC's 'Nature Conservation and Estuaries in Great Britain').

The practice of nature conservation depends on research to describe the character, distribution and abundance of natural features, to measure any changes in time and location, and to study causal and other relationships. Baseline and monitoring surveys are the cornerstone of this science base and must be sufficiently extensive and comprehensive to enable data from localised sites to be assessed in broader national or international contexts.

Ideally, survey and monitoring schemes should be in place in advance of specific developments which may bring about damaging environmental change, and this is indeed the case for some resources in estuarine and coastal areas within the British Isles. A Nature Conservation Review, the Geological Conservation Review and the Marine Nature Conservation Review each identify and assess a series of key biological and earth sciences sites. The NCC salt marsh survey and the BTO/NCC/RSPB/WWF Birds of Estuaries Enquiry are specific examples of baseline or ongoing single resource surveys.

In many instances, available data are inadequate and it may be necessary to conduct baseline surveys of each unsurveyed site facing a perceived threat. The need for such survey work is now recognised in European planning controls, and feasibility or environmental impact assessments have become an accepted part of the planning phases of many development schemes within the UK. Much emphasis has tended to be placed on high-profile groups such as birds, but there has been a welcome trend towards broader-spectrum surveys encompassing the nature conservation resource as a whole.

8.2 Evaluation of the resource

Evaluating the conservation importance of individual estuaries is largely qualitative, although in some cases, as with birds, there are specific agreed criteria. The European Community Directive on the Conservation of Wild Birds requires members to designate sites, which include many estuaries, as Special Protection Areas and defines qualitatively how these should be identified. The Ramsar Convention for the Conservation of Wetlands of International Importance (ratified by the United Kingdom Government in 1976) is more quantitative and sets international standards for the appraisal of the nature conservation importance of waterfowl populations on estuarine sites: specifically 20,000 individuals or 1% of the flyway population of a single species. Thirty-six UK estuaries, including all those most likely to be subject to barrage developments, qualify for such international recognition.

8.3 Implications for nature conservation

Barrage construction may affect the nature conservation interests of estuarine and coastal areas in three ways. Features of importance may be totally lost, they may be diminished, or they may be enhanced. Nature conservationists must assess what losses, if any, might be acceptable, and whether these losses are offset by any gains, bearing in mind that the full conservation interest of most estuarine and coastal sites is likely to be derived from habitats or species in several different groups.

Whilst the exact nature of gains and losses may be difficult to predict in general terms, barrage construction will inevitably change the physical and hydrodynamic character of an estuary; such characteristics may be of intrinsic conservation importance. For example, the Severn has one of the largest tidal ranges in the world, which results in an unusual ecosystem. Nature conservation is concerned with diversity of habitat features on a local and global scale and such extreme examples are important, even if they do not support rich or diverse plant and animal communities. Paradoxically, this loss may be accompanied by an increase in other resources of conservation importance, but generally this would be at the expense of a further step towards an ecosystem more influenced by humans.

9. CONCLUDING REMARKS

The foregoing pages suggest that research in the past few decades, particularly on tidal power barrages, has brought us to a general level of understanding of their likely impact on the ecology of estuaries. The complexity of estuaries has demanded an integrated approach to predicting the effects of a barrage and a major recommendation is that this approach is retained. Determining the net outcome of positive and negative effects requires modelling, and as word models are generally inadequate, a mathematical and quantitative treatment is needed.

Aside from this general picture, it is clear that a range of site-specific studies will be needed to flesh out detailed predictions. Several of the priorities for this research within individual subject areas have been given in the text above and range from fundamental research on phytoplankton growth in estuarine waters to the design of fish passes. With the rising interest in renewable energy sources and increasing concern from conservationists about the possible adverse effects of barrages, there continues to be a major need to test and develop further our understanding of estuarine ecosystems.

10. SUMMARY

This booklet reviews our understanding of the ecological impact of estuarine tidal energy barrages. The following general points emerge:

- Not all the effects are deleterious. Populations of some species may be increased in size by the changing conditions.

- We understand more about the likely effects landward of the barrage, where tidal and hydraulic changes have the most predictable impact.

- Increases in phytoplankton abundance may lead in turn to more filter-feeding invertebrates and thence to increased density of bird populations in some areas.

- Erosion of the upper mudflats and salt marshes presents one of the major potential impacts on the estuarine flora and fauna. Salt marshes are likely to be particularly affected.

- Pollution will not necessarily increase behind a barrage.

- Whilst most marine estuarine fish stocks are unlikely to be altered greatly by an individual barrage, local populations will be affected and fish passes will be needed for migratory species.

11.FURTHER READING

Much of the research on tidal energy barrages has been published in the so-called 'grey' literature of Government reports, contracted studies for engineers or local agencies. However, the more widely available articles listed below should provide a general guide to the literature.

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