Plankton Benthos Res 5(Suppl.): 174–184, 2010

Plankton & Benthos Research

Review

Ecological restoration of tidal estuaries in North Western Europe: an adaptive strategy to multi-scale changes

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Received 8 June 2010; Accepted 23 July 2010

Abstract: Estuaries are subject to increasing pressures due to local human activities. In addition, global change is affecting coastal habitats. Such disturbances impinge on goods and services provided by these ecosystems. The paper is devoted to efforts to restore environmental quality in some industrialised estuaries during the few past decades. It then compares strategies to recover damaged habitats and methods to restore lost ecological functionalities. Case studies are taken from the Seine in France, the Humber in England, the Scheldt in Belgium and the Netherlands and the Elbe in Germany. The article retraces briefly the morphological and ecological changes which have been inflicted on the estuaries over the last century. It puts into light actions which have been successful in improving their ecological functioning. Through comparing the various restoration schemes, policies are assessed. Details are given on efforts made lately in the Seine estuary which has lost more than 90% of its intertidal areas in about 150 years. Recently, losses due to an extension of harbour facilities in le Havre ("Port 2000") have been compensated by the rehabilitation of a former mud flat and various constructions such as an artificial island for birds.

The discussion confronts the present management of tidal estuaries to future challenges, including global changes. Such changes will not only include global warming and its consequences (sea level rise, biogeochemical cycles alteration . . .), but also socio-economic adjustments and a possible geo-political reorganization expected to take place in relation to increased harbour activities and the increasing need for more space dedicated to natural habitats and leisure activities (sports, tourism . . .).

The conclusion puts together the various approaches from the considered European estuaries. Resting on a rigorous scientific approach, it proposes a synthetic approach to restoration:

1. Efficient procedures of socio-ecological evaluation,
2. A methodology to assess the ecological quality of systems considered,
3. Rigorous monitoring programs, resting on a relevant choice of indicators, and
4. Participation of local communities,

in order to define strategies compatible with conservation and sustainable development at the local, regional and European levels.

Key words: climate change, English Channel, integrated management, North Sea, restoration, tidal estuaries, TiDe European project

Introduction

Coastal ecosystems, estuaries especially, are among the most ecologically and socio-economically important environments on Earth. Coastal environments have huge socio-economic value through food production, nutrient and pollutants recycling, recreation and transportation (Crossland et al. 2005). However, in addition to the numerous anthropogenic disturbances that affect them leading to habitat modification and changes in ecosystem function, these ecosystems, along with goods and services they provide, are threatened by global climate change. Changes in climate (e.g. temperature rise, sea-level rise, increased risks of floods and droughts) may increase the risk of abrupt and non-linear changes in many ecosystems, which would affect their composition, function, biodiversity and productivity. When subjected to climate change, including changes in the frequency of extreme events, ecosystems may be disrupted

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as a consequence of differences in response times of species (IPCC 2007).

In recent years there has been an upsurge of interest in climate change impacts in marine systems, but most of the literature is focused on the effect of the temperature and most work is conducted at the level of individual organisms. A few studies have focused on the impact of large-scale weather events, such as flooding, on the functioning of communities (e.g. Salen-Picard & Arlhac 2002, Salen-Picard et al. 2002). For instance, extreme rain events may have implications for the ecosystem functioning. According to Norkko et al. (2002), catastrophic clay deposition associated with severe flooding can have markedly deleterious effects on estuarine macrobenthic communities.

In addition to climate change, coastal ecosystems such as estuaries are naturally subjected to a variety of anthropogenic stressors which can damage the health and fitness of the resident organisms. Multiple stressors including pollutants, excess of nutrients (e.g. eutrophication), altered habitat and hydrological regimes as well as floods and droughts can impact resources through single, cumulative or synergistic processes, lowering the overall system stability (Vinebrooke et al. 2004). Anthropogenically induced global climate change has profound implications for marine ecosystems and the economic and social systems that depend upon them. However, recent work has revealed that both abiotic changes and biological responses in the ocean will be substantially more complex. Responses of biota to these environmental stressors are the integrated result of both direct and indirect processes which can be manifested as changes in abundance, diversity and fitness of individuals, populations and communities (Adams 2005). The accelerating rate of biological impoverishment may render ecosystems incapable of compensating for the loss of biodiversity, thereby reducing their resilience to environmental change. Distinguishing and integrating the effects of natural and anthropogenic stressors is an essential challenge for understanding and managing coastal biotic resources (Vinebrooke et al. 2004, Groffman et al. 2006). Figure 1 shows the components of the climate which are currently changing and their effects on coastal ecosystems.

Among the impacts, habitat loss represents one of the worst observed on estuaries. The loss can be temporary, by increase or decrease in water and sediment quality (e.g. salinity, temperature, dissolved oxygen, turbidity) or by decrease in water quantity. This type of perturbation is dealt through remediation. The loss can be permanent, most often by removal of wetland through polderisation. Such degradation can only be addressed by restoration or re-creation of lost biotopes (Ducrotoy 2010). According to SERI (Society for Ecological Restoration–International Science and Policy Writing Group 2004), ecological restoration can be defined as the process of assisting the recovery of an ecosystem which has been degraded, damaged or destroyed. In order to understand what actions are needed to restore disabled ecological functions in an estuary, the watershed and coast need to be considered as a continuum through the estuary. This kind of approach was adopted in several

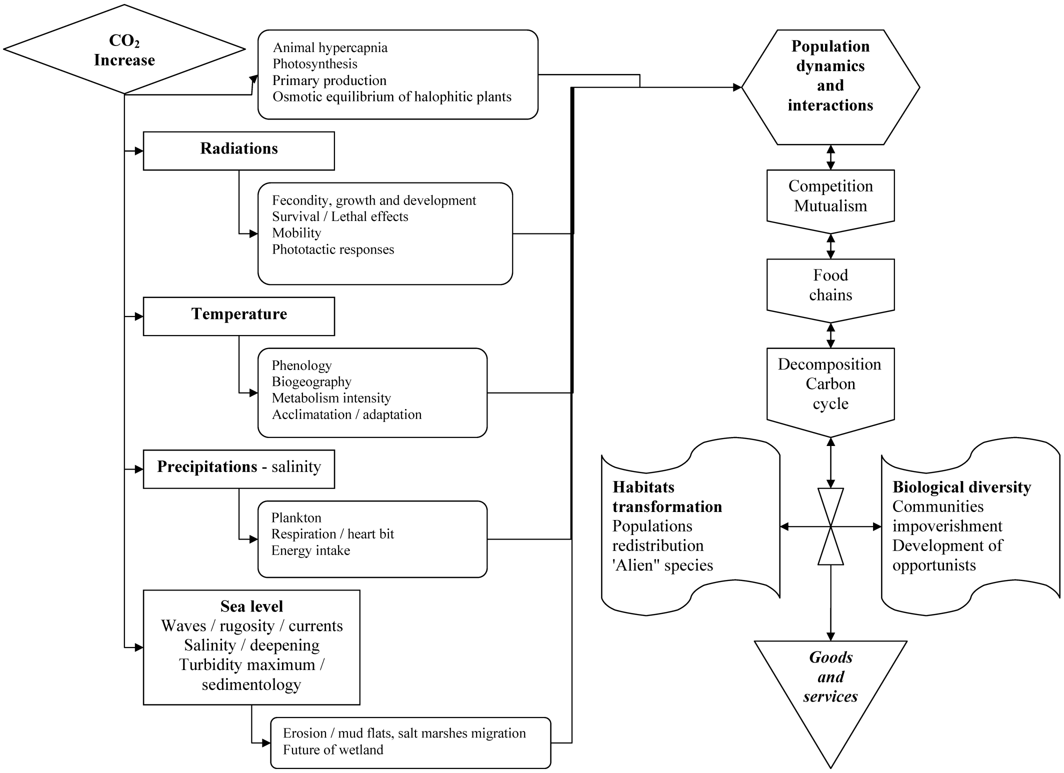

Fig. 1. Possible biological effects of climate change on coastal ecosystems.

macrotidal estuaries of the North Sea and the English Channel in Europe: the Elbe in Germany, the Scheldt in Belgium and the Netherlands, the Humber in England and the Seine in France. These estuaries are presented here and compared in their management because they have common features which are of interest to scientists and decision-makers. They were all partially filled by marine sediments because of the Flandrian marine transgression which started about 3000 years ago. As a result plugging has occurred, with sedimentation prograding seawards. Flood plains, as part of the estuarine complex, have been claimed by humans and changed into terrestrial habitats, notably since the beginning of the 20th century. With increasing industrialisation and the development of shipping activities, the trend has accelerated resulting in considerable loss of intertidal areas and drastic changes in the local geomorphology. What is interesting is that the restoration of damaged habitats and of ecological functions in each estuary has benefited from quite different managerial approaches.

All the selected estuaries belong to the North Sea in north-west Europe. Geographically, the North Sea was defined by the North Sea Task Force as including the English Channel, the Scandinavian straits (the Skagerrak and the Kattegat) and the northern North Sea south of 62°N (NSTF 1994). The North Sea is a large epi-continental sea (750,000 km^2) of the north-east Atlantic. It is one of the few major marine ecosystems to have been formed by the recent flooding of a landmass which took place 20,000 years ago. From a bio-geographical point of view, it is therefore a rather young ecosystem (Ducrotoy 1995, Ducrotoy et al. 2000). It consists of a shallow (mean-depth of 90 m) semi-enclosed coastal marine ecosystem. The Southern Bight, where three of the selected estuaries are located, is relatively shallow, with strong tidal currents; the depth increases progressively towards the North where the basin largely opens to the Atlantic Ocean. The fourth estuary, the Seine opens to the English Channel, known for its high tidal range.

Examples of restoration of habitats in tidal estuaries of North West Europe

The Elbe: From a «natural» to a shipping estuary

The River Elbe (Germany) is one of the major rivers of Central Europe. It originates in the Krkonoše Mountains of the Czech Republic. Its total length is 1,094 km. The Elbe river basin, comprising the Elbe and its tributaries, has a catchment area of 148,268 km^2. The Elbe estuary is macrotidal. Today, the tidal range reaches about 3 m in the mouth (but in 1880 it measured around 1.9 m) due to canalization in order to facilitate shipping activities. The morphology of the Elbe estuary was shaped by work done on the river to improve access to the harbour of Hamburg (Germany) situated 110 km inland. The building of dikes along the River Elbe has affected the hydrodynamic and morphologic situation over the past centuries (Plüss 2004). In the 11th century, the natural landscape began to change due to agricultural and pasture farming land reclamation and hydraulic engineering. Important harbour development took place in the 19th century. In order to facilitate access of larger and larger vessels, extensive sediment relocation started to happen and developed during the 20th century, due to erosion and resedimentation, sometimes increased by heavy storm surges (Jensen & Mudersbach 2007). In relation to periodic flooding, different freshwater and brackish water zones did develop in those areas, but the overall functioning of the estuary was offset. Since 1950, foreshore areas and flood plains of the tidal Elbe river have been reduced by 180 km^2. With the construction of river barriers, flood plains formerly occupied by tributaries were also no longer tidal. This meant that even more intertidal areas had disappeared (Fickert & Strotmann 2007).

Nowadays, about 4 million people live in the metropolitan region of Hamburg in an area of approximately 19,000 km^2. However, the influence of the Elbe river extends far beyond this area. The Port of Hamburg is the second largest in Europe but the harbour authorities encounter more and more difficulties in maintaining the shipping channel through the estuary as the drainage of the hinterland has become more and more difficult. Although some measures within the mouth of the estuary helped to restrict storm surges, Siefert & Hanoe1 (1988) showed that the building of dikes led to an increase of the maximum peak water level of almost half a meter in Hamburg during storm surges.

Recently, the Hamburg port authority has confronted an important increase of dredging amounts in the area of Hamburg. All along the Elbe, an upriver transport of suspended sediment has taken place. This sediment used to settle in downstream marshes and is now carried into the harbour of Hamburg. Due to the hydrodynamic changes there is a risk of an increase of the tidal wave height at Glückstadt with the associated risk of enforcing the residual transport of sediments upriver. In order to restore both habitats and navigability of the estuary the port authority proposed the concept for a sustainable development of the tidal Elbe river as “an artery of the metropolitan region Hamburg and beyond” (Dücker et al. 2006). The proposed engineering measures would rely principally on sediment management objectives and included:

1. Dissipation of the incoming tidal energy by hydraulic engineering constructions especially within the mouth of the estuary;
2. Establishing flooding areas in the middle estuary; and
3. Optimising the sediment management considering the whole system.

Without appropriate measures, the accretion of sediment within the upper tidal Elbe system would continue and ecological degradation would happen. Increasing effort to maintain the water body and berths of the port of Hamburg would be required. Deepening of access channels is no longer a permanent economic solution to provide the required water depths for navigation. The sediment management concept therefore intends to relocate fresh, non contaminated sediments in areas where there is less possibility for them to return to the place where they were dredged. The opportunity was taken to improve environmental quality in association with engineering work realised to reverse negative geomorphological effects. Measures for restoring natural conditions along the river were taken, including conservation and development of shallow water areas, creation of alluvial forests, salt marsh development in front of dikes. In the meanwhile, protected areas became attractions for tourists (Bergemann 2006).

The re-creation of inter-tidal areas including salt marshes was initiated in order to increase floodable areas. It was aided by the installation of flood polders as buffers in case of storm surge. These restoration actions also provided flood risk protection in reducing storm surge water levels. Both recreational and commercial fishing will further benefit from the creation of shallow water zones. These are important spawning and hatching zones for fish and prey. An enhanced connection of tributaries also had a positive effect on the functioning of the estuarine ecosystem as migrating fish species could now reach their breeding areas with less effort. According to the Hamburg Port Authority, on the long run, the diversification of the system and the ecological improvement of the water and sediment quality very likely will increase the number of species (Dücker et al. 2006).

To achieve these aims and objectives there is a need for further research and action. This should be done in co-operation with the adjoining states and the federal state (Von Storch 2008). Actions needed were listed as follows:

- Synchronising integrated hydraulic engineering and sediment management strategies;
- Planning and establishing measures to be taken collaboratively between states;
- Developing sub-regional nature conservation objectives as a basis for the implementation of the Habitats and Birds European directives (Dücker et al. 2006).

The Scheldt: protecting human populations from inundation and fighting eutrophication

Nowadays, the Scheldt estuary (Belgium and the Netherlands) is characterised by a high hydrodynamism which varies greatly according to the part of the estuary considered. It is a typical rain-fed river which conditions the salinity through the variability of its discharge. This explains the importance of the freshwater estuary up to 235 km upstream where sluices limit the penetration of the tide. The tidal range is macro-tidal. It varies from 3.8 m in the mouth to 5.0 m in Antwerp and 2.0 m in Gent. Nevertheless, the estuary is polyhaline only over the upper 40 km. Overall, the river is 335 km long with its source situated in France (St Quentin) with a catchment area 21,863 km^2. Ten million inhabitants are distributed in the watershed with an average density of 477 inh km^{-2}.

The upper part is in Belgium (Zeeschelde) with a single ebb flood channel bordered by small mudflats and marshes. In this section of the tidal river, it is often bordered by quays and wharves with no tidal zone. The middle and lower estuary lie in the Netherlands (Westerschelde) and are 58 km long (Bolle et al 2010). Waters are well mixed but two maximum turbidity zones might be observed: one at the fresh-seawater interface, the other originating from tidal asymmetry in the middle estuary.

The morphology of the estuary is complex with intertidal flats and salt marshes. Because of land reclamation for agriculture and industry, construction and reinforcement of dikes, and the deepening of shipping channels, large areas of tidal marshes have been removed or eroded from the Scheldt estuary during the last 150 years. At the beginning of the 21st century, more than 50% of the tidal river lacked tidal marshes in front of the dike (Temmerman et al. 2004, Maren et al. 2009).

At present, large scale dredging guarantees the safe access to the port of Antwerp, at the bars where ebb and flood channels merge. With increasing dredging, deep waters tend to create highly dynamical areas with, consequently, a decrease of low dynamic areas and an increasing penetration of the tides and, hence, increasing risks of inundation. Land use and urban activity in the catchment of the Scheldt river system have changed during the last 50 years. 1500 years ago, the tidal wave did not reach beyond Antwerp, but presently the maximum is consistently moving up (Wang et al. 2002).

Because of human-made changes in the morphology of the estuary, the water quality of the drainage network and the fluxes of nutrient transferred to the estuary and to the sea have been affected. A very severe deterioration of water quality (with deep oxygen depletion) occurred in the beginning of the 1960s, while a clear trend to improvement was apparent in the late 1980s. The yearly fluxes of nutrient delivered by the river to the estuary and the sea show a severe depletion of silica with respect to nitrogen compared with the requirements of diatoms, and a clear shift from the early 1990s from nitrogen to phosphorus potential limitation (Billen et al. 2005). Seasonal variations of nutrient delivery are however much more pronounced for nitrogen, with fewer inputs during the dry seasons, while phosphorus inputs, mainly from point sources are more constant, so that nitrogen limitation can still occur during summer. However, the Scheldt basin does not deliver higher specific fluxes of nutrient (presently about 2,000 kgN km^{-2} yr^{-1}, 80 kgP km^{-2} yr^{-1}, and 1,000 kgSi km^{-2} yr^{-1}), owing to very efficient processes of nutrient retention (Billen et al. 2005). Hydrological, geomorphological and biogeochemical changes have further had consequences on the maintenance of biodiversity in the last two centuries. Bad water quality has affected benthic communities both in the saline and in the freshwater parts of the estuary which are original and specific to the river Scheldt. Until recently fish was almost completely absent form the freshwater parts. Despite poor aquatic biological diversity, the site remains important for birds as it is one of the main estuaries along the migration route in North Western Europe (230,000 individuals annually) (Ysebaert et al. 2000).

In the 1990s, it was felt that tidal wetland restoration would be necessary in order to compensate loss of habitat (Eertman et al. 2002). In combination with a master plan to protect the population from storm surges, an opportunity arose to restore areas under tidal influence. One specific option of combining safety and ecology was the creation of flood control areas under the influence of a controlled reduced tide (CRT) (Maris et al. 2007). These specific areas differ in many ways from fully tidal areas but can fulfil important ecological functions with effects on aeration, nitrification, denitrification, sedimentation and primary production in the estuary. Opportunities for ecological development within a CRT have been investigated for a specific case. The ecology within a CRT was shown to be very case specific, depending e.g. on the morphology of the area, the sluice design and the local water quality (van den Bergh et al. 2005). Depending on the sluice design, water quality can be improved and sedimentation can be influenced. A scientific approach to the management of these sensitive areas made it possible to design CRTs with a rich habitat variation (Maris et al. 2007).

The Humber: New strategy for estuary management—Giving a "healthy" shape, creating new mudflat and new marshland

The Humber Estuary (England) is a shallow, well-mixed macro-tidal estuary with a maximum tidal range of 7.2 m. Mean water depths vary between 8 m at the mouth and 3 m in the inner estuary. A salinity gradient from north to south bank exists in the outer estuary, due to the incoming tide flowing along the north bank, while the freshwater keeps to the south bank as it discharges to the sea. Average freshwater flow into the Humber from the rivers is 250 $m^3 s^{-1}$, ranging from 60 in drier periods to 450 $m^3 s^{-1}$ in wet periods (Gameson 1982). Peak flows of up to 1,500 $m^3 s^{-1}$ have been recorded during floods. The average tidal excursion into the Humber is 15 km, much greater than the seaward displacement caused by freshwater input during the tidal cycle, resulting in a damming effect on inputs of effluent to the estuary. The estimated residence time for freshwater in the estuary is 40 days, and up to 60 days in summer (Uncles et al. 1997). For sediment, it reaches 18 years (Millward & Glegg 1997).

The estuary is 62 km long from Trent Falls (the confluence of the rivers Ouse and Trent) to its mouth at Spurn Head, where it enters the North Sea. Although the maximum limit of salt intrusion is further inland, the head of the estuary is generally defined as Trent Falls. The surface area of the estuary is approximately 265 km^2 (Andrews et al. 2000). The coastline within the estuary is 120 km long, from Trent Falls to the estuary mouth at Spurn Head. The extended outer coastal zone affected by the Humber plume is approximately 100 km long (Morris et al. 1995). It stretches along the North Sea coast from Flamborough Head to the north and to Skegness to the south, where it joins the coastal zone of the Wash. The estuary is surrounded by high-grade agricultural land, within two areas of high population/industry—around Kingston-upon-Hull on the north bank and Grimsby/Immingham/Cleethorpes on the south bank. Continuous dredging maintains shipping channels to a depth of 11 m in the inner estuary and 16 m in the outer estuary (Cave et al. 2003). Occasional capital dredging is carried out for new port and industrial installations. Most of this dredged material is disposed of to dump sites within the estuary, or at Spurn Head. Continual research is carried out by the port authorities on the hydrodynamics of the estuary, and in theory the dumping of dredged sediments within the estuary maintains the sediment balance. In practice, however, there is only limited understanding of the effects of moving large quantities of sediment from one place to another within the estuary.

A total of 70% of the land area in the catchment is arable land or grassland, and this exceeds 80% in the estuary hinterland. Approximately 10% of the catchment is built-up, with the remainder being mostly heathland and woodland. The area around the Humber is low-lying, and much reclamation of wetlands and supratidal zones has been carried out in the last two centuries, as well as reclamation of parts of the intertidal zone. The mid–outer estuary changed from a region of low water erosion in the 19th century to one of accretion in the 20th century; nonetheless, a net loss of intertidal zone of some 3,000 ha has taken place since the mid-19th century. Around the estuary some 894 km^2 of land are below the 5 m contour and are protected by extensive coastal defences (Environmental Agency 1999). This area around the estuary is dissected by land drains, which empty into the estuary via pumping stations. Most of the sediment entering the estuary comes from the North Sea, rather than from the rivers, and a large part of it comes from the continuing erosion of Holderness cliffs, which form the coastline to the north of the estuary mouth (Hardisty 2001).

A legacy of contaminated sediments exists in the Humber catchment (Hudson-Edwards et al. 1999) due to mining activities carried out since Roman times in upland areas where the rivers originate. Effluent from industrial sources is discharged both directly to the rivers and estuary, and to the sewage system. Some of this effluent discharged directly has a very high biological oxygen demand, which when compounded by discharges from sewage treatment works can lead to low dissolved oxygen in the tidal rivers, thus harming aquatic life. Other effluents are high in metals such as copper. Coal-fired power stations in the tidal reaches of the Ouse catchment can, each, release annually up to 1 t of copper, cadmium and lead to the atmosphere, as well as up to 1 t of copper to the river. Nutrients in the Humber Estuary come from riverine, industrial, urban sewage and agricultural sources. Up to 1993, the Humber was responsible for up to 30% of the input of N and P to

UK waters. Nowadays, primary and secondary treatment is completed for all sewage entering the river system and the estuary.

Pollution and eutrophication needed to be tackled (Mazik & Elliott 2000, Mazik 2004) while setting back the shore line was required in response to sea level rise. A large scale experimental site was chosen in the 1990s for depolderisation and habitat (re)creation. In 2010, the Humber estuary was the site of three existing managed realignment sites (former agricultural land) with the primary role of direct compensation for habitat loss. A fourth site was being created as part of a flood defence scheme. Creation of a further five sites, with the primary aim of mudflat creation, is planned over the next 20 years (Environment Agency 2009).

Comparisons between the newly created habitats and the existing mudflats in the estuary were made by Mazik et al. (2010). The macrofaunal communities found within one of the areas as a whole were considered to be characteristic of the area with low species diversity, high abundance and small body size. The community within the managed realignment site was still in an early successional stage after three years with low abundance and diversity in comparison with other sites within this part of the Humber. However, the community biomass increased.

Given the importance of nature conservation in the Humber area, depolderisation has the dual role of coastal protection and habitat restoration. Coastal managers aim for a win-win-win situation whereby environmental improvements, economic benefits (as the result of not having to raise dykes or maintain sea walls) and public safety benefits from flood protection were all achieved. Current restored sites compensate for habitat loss elsewhere (Environment Agency 2005). All sites are subject to a five-year monitoring plan.

The Seine estuary: compensation measures after port developments

The Seine estuary (France) is a megatidal environment situated in The English Channel (la Manche), linking the Atlantic Ocean to the North Sea through the Dover Strait (Pas de Calais). What characterises the Seine is that its estuary is plugging rapidly, mainly due to human actions. Tidal amplitudes vary between 3 m at neap tides to 8 m at spring tides with an active turbidity maximum where suspended matter reaches a concentration of 500 at 1,000 mg L^{-1}. The mean annual discharge of the river is 480 $m^3 s^{-1}$, with highest flow rates $>$2,200 m^3 and minimum of 40 m^3. This leads to a mean annual sedimentation rate $>$5 million m^3.

The watershed of the Seine estuary is large (79,000 km^2) covering 14% of France area. The river flows through Paris, the capital city, and two important harbours: Rouen and le Havre, concentrating 16 million inhabitants (26% of the French population). 40% of the national economic activity takes place in the basin with 50% of the national fluvial traffic. Overall, the tidal estuary has lost more than 90% of its intertidal areas in about 150 years with the most important human-made modifications taking place from 1975 to 2005. In the 1990s, an extension of the port of le Havre (Port 2000), situated in the north of the estuary, was built. A strategy group was installed by authorities, facing the necessity of adopting a global managerial approach at the scale of the ecosystem (Moussard et al. 2008). Following legal action by environmental groups, the Government decided to launch a remediation plan. Numerous preservation measures to induce and control protection followed. Later on, a management plan was set up covering the whole of the estuary. The objective of the management plan was to favour economic diversification (port development and logistics) of the estuary relying on industrial developments, tourism promotion and fishing activities, and conservation and restoration of the natural functioning of the estuary. The construction of Port 2000 was the occasion for managers and politicians to stress the importance of research for reaching a balance between the development of economic objectives and the protection of natural aquatic environments towards an integrated management of the estuary. The new harbour installations required the reclamation of existing wetlands (Ducrotoy & Dauvin 2008). Such an operation presented threats for safeguarding the sedimentary balance in the estuary and the future of mudflats. Decision makers decided that accompanying measures should be taken to minimize the hydro-sedimentary impact and to rehabilitate threatened intertidal mudflats durably. Various options were selected after mathematical modelling of circulation patterns of sediments in the estuary. The ones which were adopted consisted mainly in restoring a damaged mudflat, building a resting place for birds on dune and constructing a small island, also to be a resting place for birds. Some habitats were re-created on part of the land claimed from the estuary with a view to facilitating the growth of charismatic plants (Scherrer & Galichon 2002, Dauvin et al. 2006, Port Autonome du havre 2007):

In order to retain fine sediment deposits and to create a new mudflat (Bessineton 1988), a 550-meter long groin, perpendicular to tidal currents, was set up in the Northern area of the estuary. Upstream of the affected area, a channel was dug. In addition, more than 3.5 million tonnes of sand were excavated downstream the bridge, in order to maintain a circulation in the existing pit. Owing to cutting openings in the existing embankments at the foot of the Normandy bridge and to digging out the channel, the ebbing tide could flow in again. This alleviated the earlier problem caused by the construction of the bridge, which prevented the tide to come in. This operation of environmental engineering resulted in the filling up of part of the area by sand and fine sediments and, therefore, to the revival of a former mudflat.

The creation of a resting place for birds (especially waders and ducks) was carried out to replace the site where those birds used to live before the construction of Port 2000. At the time of the initial design of the resting place on dune (45 hectares), observations were made on the behaviour of bird populations in the area. Ornithologists and benthologists suggested maintaining a permanent hydraulic exchange between the estuary and the new resting place. A section of dam of a hundred meters was thus destroyed for this purpose. At the conclusion of approximately one year of scientific monitoring of the frequentation of the resting place by the birds, it was noted that controlled management of the water level in the resting place could increase its attractivity to birds. So, in order to improve the control of water levels, it was decided to reconstitute the destroyed element of dam and to integrate into it a sluice for the regulation of the water level. The North part of the resting area was redesigned to allow avocets to nest (protected species in Europe). Other developments were also made in order to regulate and even sometimes limit the height of water levels, in order to increase the capacity of shelter during highest tides. Two observation huts were built on the periphery of the site in order to allow the public to watch birds.

A new island was built for birds at the south of the estuary. The idea of creating an island in the southern part of the estuary came from the observation of birds moving across the estuary and the necessity to offer birds more than one resting place. This development aimed at reinforcing the ecological value and the biodiversity of the adjacent Nature Reserve. The 5-hectare island at low tide is composed of 3 islets at high tide. A few Harbour seals living in the Seine are also attracted by this island.

Soil humidity was controlled through digging in some selected areas of the new harbour reclaimed land. Protected species (plants, birds, amphibians) settled down and remained stable and in some cases, grew in numbers owing to the measures taken. A beach was set up, in the periphery of Port 2000. This 4.5-hectare beach is composed of a succession of sand expanses with pebbles and gentle slopes. It was set up with materials coming from the digging of shipping access ways. The beach aimed at recreating a new habitat for plantstypical of wet land and pebble. Seakale *Crambe maritima* L. was planted. In complement to civil engineering works, agri-environmental measures were taken including sound farming practice (spatially organised cutting of hay and reed, late cutting after the nesting period, partial cutting to keep safe zones of refuge). Compensatory allowances were paid to farmers willing to adopt these new practices.

In the meanwhile, since compensation sites have been achieved in 2008, new projects have come up. They relate to developments by both the port authorities of Rouen and le Havre. In the first instance, the Seine river will be deepened in order to give access to much larger ships up to the harbour of Rouen. In the second instance, improvements to access the river from le Havre harbour will be realised by prolonging an existing large capacity canal through the northern parts of the estuary. A third crossing downstream the Seine was deemed necessary to increase rail transport and to facilitate road access to Port 2000. Requests for aggregate extraction from the Bay of Seine were recently submitted with a view at meeting the demand for house building and public works, including the above. Some scientific work has started in parallel, in order to facilitate environmental restoration and return ownership to its local users. Experimental sites are currently being studied by local scientists from the perspective of launching the restoration of selected biotopes and ecological engineering actions. For instance, river banks were currently made of concrete and proposed actions may consist in the restoration of riparian vegetation, the reconnections of old channels, and the re-establishment of tributaries confluences. The main objective of this new research programme (2009–2012) was the improvement of the estuarine system as a whole.

Towards a holistic approach to restoration

Estuaries are open systems and are essential interfaces between rivers and the coast. They constitute main transition zones or ecotones between land, the ocean and the atmosphere. The role of the tide is paramount in all case studies presented in this article. Geomorphology is essential to understand when comparing them. They are also greatly influenced by changes in the watersheds. The main factors affecting the hyporheic zone are the width and the depth of river bed, the river flow and constructions by humans. In the four estuaries presented here, the erection of dykes and the reclamation of land has dislocated the hydrosystems and limited access to estuarine animal and vegetal communities. Longitudinally, there has been an increase of tidal effects and salinity which forced estuarine species out of the estuary. The turbidity maximum also has a tendency to move outwards. Transversally, dykes have broken connections between aquatic habitats and reduced the area and diversity of wet land, including intertidal flats and salt marshes. In all ecosystems, there has been a parallel decrease of fresh water tidal habitats for fish, birds, and the benthos on which they feed.

Despite radical changes in their morphology over the last 150 years, the Elbe, the Scheldt, the Humber and the Seine estuaries are still productive marine ecosystems. In all estuaries, biodiversity reflects their ecological value, not necessarily in terms of species richness, but mainly in terms of habitats and biotopes (Ducrotoy 2010). Biotopes constitute sub-units of ecosystems and are displayed as a mosaic in each estuary (Olenin & Ducrotoy 2006). They seem to be similar in all 4 estuaries but what makes each estuary special is the physical, chemical and biological (biogeochemical) links between the biotopes. These interrelations depend upon hydrology, sediment transport, nutrient transfer and biological cycles. Naturally, other variations between the 4 estuaries exist. The main structuring environmental factors appear to be salinity, water movements and turbidity. They affect the heterogeneity (or structure) of each ecosystem, as well as their complexity (in terms of relations between structural attributes).

Despite the pressure exerted by human societies on their ecology, the four estuaries presented here, stand as assets to humans. The same ecological functions were found, which provide valuable goods and services to human societies (Costanza et al. 1993). Amongst those, biogeochemical cycling, in particular nutrients, water purification and mitigation of floods are much looked for. However, the carrying capacity and the assimilative capacity of ecosystems might be overrun and signs such as pollution show that their functioning is affected (Arrow et al. 1995). Tett et al. (2007) suggested that an ecosystem impacted by anthropogenic factors may, because of its resistance to disturbance, initially show little response to increasing pressure. Pushed beyond a certain point, however, change becomes rapid, and may culminate in a radically altered state from which recovery would be slow. An example would be the occurrence of extensive deep water anoxia, resulting in the widespread elimination of the benthos and fish in the Scheldt and the Seine in the 1990s. A key operational need is to detect a trend towards such a widespread undesirable disturbance before the ecosystem has reached the limit of its resistance (Diaz & Rosenberg 2008). The case studies presented here show however that ecosystems do not return to the same state after removal of a pressure, but to a different one. Re-estuarisation often implies re-creating or "restoring" damaged habitats. Through the example of the Humber, it was demonstrated that connectivity between the various aquatic components of ecosystems is the key to all restoration actions. The Elbe case study showed how important it is to understand the local sediments dynamics in order to control navigability through the tidal areas (volumes, distribution, quality . . .). Application of scientific results led to interesting operational aspects when dealing with dredging of huge volumes of sediments. For instance, the use of models made their management more effective. In the Seine, the relevance of future experimental restoration measures will depend on the adequacy of scientific research in helping to build a long term vision of the estuary.

Climate change will affect managers' views on the perennity of estuarine socio-ecosystems. In the future, the restoration of damaged habitats will be instrumental in adapting socio-economic activities (Folke et al. 2002, Hughes et al. 2007) to changing environmental conditions (Diaz et al. 2004). In this context, sea level rise, presently estimated at 30 cm per century and expected to increase, according to the prognosis of IPCC2, in the second part of the century, is a paramount challenge (IPCC 2007). Besides the enlargement of tidal capacity, a reduction of the cross-section profile at the mouth of the estuaries ought to hold back part of the tidal energy in the event of a storm surge. What will be the implications of such events for estuarine ecological restoration? Climate change will make "habitats" of interest more fragile and less resilient. The Scheldt example has shown that a patrimonial view of ecosystems is not necessarily compatible with promoting new functions in an estuary. The Seine compensation measures showed how important habitats are as there is a need to allow species to adapt to new biophysical conditions. Nevertheless, ecosystems are dynamical and restoration needs to focus on ecosystems (and how they function) not species (Elliott et al. 2007).

The consideration of the carrying capacity of the estuarine ecosystem (Arrow et al. 1995) has been instrumental in putting together the restoration plan of the Scheldt estuary, in particular measuring the importance of re-creating tidal systems. Some ideas for the future should emanate from that approach. Any future estuarine management plan should take into consideration the type and the proportion of each habitat which needs to be (re)-created in order to provide the ecosystem with expected functionalities (Diaz et al. 2004). In parallel, expected goods and services to be provided should be adapted (Folke et al. 2002, Hughes et al. 2007). The main requirement to sustain the perennity of such measures is that they should ensure resilience and adaptability. So, planning should include actions to mitigate or to reverse the local effects of climate change (e.g. sea level rise) and slow down the global change (e.g. through CO_2 sequestration).

In summary, the main objective of estuarine habitats restoration is to achieve the gradual restoration of ecological functions, leading, on the long-term (20–50 years), to the (re)-establishment of typical estuarine communities. This can be accomplished through increasing fluxes of water circulating in the estuary and re-establishing connections between the various aquatic components of ecosystems. Adopting such an objective means considering the estuary as a whole including peri-estuarine areas such as the flood plain, associated marshes and land claimed by humans essentially over the last 150 years.

General conclusions

In coastal areas, bays and estuaries around the world, the geomorphology is evolving because of natural processes (mainly hydrological, due to sea level rise and increasing tides). Human activities, mainly through reclamation, have accelerated these natural morphological processes and worsened the degradation of estuarine resources (Berkes et al. 2006). Despite radical changes inflicted on them, the 4 estuaries presented in this paper (the Elbe in Germany, the Scheldt in Belgium and the Netherlands, the Humber in England and the Seine in France) stand out as specific and valuable socio-ecosystems. They consist in highly dynamical systems and the global change is increasing the speed of change.

Past management and expected changes have had a negative impact on the delivery of ecosystem services by the estuaries and hence on the resilience of the systems (Folke et al. 2002, Gunderson & Folke 2005). This resulted in growing socio-economic problems (e.g. inundations, eutrophication, siltation . . .) in the various instances considered. The piecemeal application of present environmental legislation has not been sufficient to change the negative trends and integrative management plans are required at the scale of each estuary (Harris et al. 2006). All of the sites considered in this article have benefited from management schemes in order to re-establish some of the lost ecological functions: in the Elbe, the sediment dynamics, in the Scheldt, the control of floods, in the Humber, the restoration of specified ecological processes. In the Seine, compensation measures were implemented. What is interesting is that despite the different managerial approaches applied in the various countries, all actions included some degree of ecological restoration of habitats. Such actions involved more or less large-scale engineering work. From comparing these various managerial approaches in the different estuaries, it appears that only conservation objectives can translate the aim to reduce negative developments. It would seem that the best way to formulate such objectives is in computing and calculating surfaces of the different habitats necessary to sustain the resilience of the ecosystem (Folke et al. 2002, Gunderson & Folke 2005), including geomorphological, hydrodynamic, ecological and quality aspects. Such an approach does give the possibility to sustain each estuary in a healthy state to reduce management costs and increase benefits from goods and services obtained from them. In order to do so, a holistic approach is needed where the system characteristics are considered in such a way that negative developments are stopped or at least slowed down. This requires a major investment in research to better understand the system functioning and the interactions between the different compartments, including socio-economics, identify services and calculate surface of habitat needed for delivering the required services and providing the expected goods to humans. In order to define strategies compatible with conservation and sustainable development at the local, regional and European levels, environmental aspects must be integrated in the management of estuaries, which must rely on thorough collaboration between and mutual understanding of all actors and stakeholders. Resting on a rigorous scientific approach, restoring ecological functionalities in an estuary is dependant on efficient procedures of socio-ecological evaluation including a methodology to assess the ecological quality of systems considered (Bingham et al. 1995, Costanza et al. 1998, de Groot et al. 2002). For making interdisciplinarity work, socio-economics need to be considered in the early stages of the elaboration of any restoration programme.

Putting the project in a scientific perspective implies the application of fundamentals of ecology. Because of the popularity of certain concepts, including biodiversity, productivity, etc., definition and use of important terms may have been misinterpreted (Ducrotoy & Yanagi 2008). For example, most often, the general public thinks that biodiversity is at the basis of robust and productive ecosystems. Recently, Elliott & Quintino (2007) have put into light the quality paradox of estuaries, where poor species richness supports high production and stability (Holling 1973, Peterson et al. 2010).

The concept of habitat is therefore essential as a species might disappear but a habitat remain available for shifting species. Unfortunately, European and national legislation aimed at protecting habitats are species based, locked by conservation management. With the arrival of "new" species, whether they will move in response to the climatic change or they were introduced artificially, conditions should be made to avoid "fossilisation" of protected habitats. It might be necessary to accommodate shifts in spatial distribution and alien species. However, one may ask whether the legislative framework is fit for purpose when habitats will need to be adapted to changing biophysical conditions (Harris et al. 2006). Breakdown in geographical barriers or deliberate and inadvertent transport of species could be at the origin of new "emerging" ecosystems, of which the functional characteristics are unknown today. From all examples given, it has been shown that it is impossible to freeze an ecosystem at a particular stage of its evolution and that it is further impossible to return backward in time. Fundamental research needs to address the issue of better understanding future shifts in ecological niches. Rigorous monitoring programs, resting on a relevant choice of indicators, should be linked to research and data used more efficiently and on the long-term (Ducrotoy 2010).

Restoring functions at ecosystem level will undoubtedly help guarantee assets to human societies which depend on them. Ensuring resilience and adaptability will allow adjusting goods and services both to new environmental conditions and to emerging human needs. But, over and above, integrated management of estuaries will be essential in adapting to local changing conditions (e.g. sea level rise) and slowing down climate change at global level. It is why, in the future, participation of local communities will be essential for the success of measures taken. Communicating with existing groups will help making visible actions taken and creating synergies with other development plans. Research and education clearly stand out as a means to achieve governance (Folke et al. 2005).

Acknowledgements

I wish to thank Prof. J-S Hong for inviting me to the Korea and Japan Joint Symposium on Biology of Tidal Flats, Suncheon, Korea, in June 2009. This invitation gave me the opportunity to present case studies taken from the European Interreg IVb Programme TiDe (Tidal river Development). I am particularly indebted to Mr Heinz Glindemann (Hamburg Port Authority) and Professor Mike Elliott (Institute of Estuarine and Coastal Studies, University of Hull) for encouraging me in taking part in that programme.

References

Adams SM (2005) Assessing cause and effect of multiple stressors on marine systems. Mar Pollut Bull 51: 649–657.

Andrews JE, Samways G, Dennis PF, Maher BA (2000) Origin, abundance and storage of organic carbon and sulfur in the Holocene Humber Estuary: emphasising human impact on storage changes. Geol Soc Lond 166: 145–170.

Arrow K, Bolin B, Costanza R, Dasgupta P, Folke C, Holling CS, Jansson B-O, Levin S, Mäler K-G, Perrings C, Pimentel D. (1995) Economic-Growth, Carrying-Capacity, and the Environment. Science 268: 520–521.

Bergemann M (2006) The Elbe estuary. In: North-Atlantic Estuaries: Problems and Perspectives (ed Dauvin J-C). Seine-Aval special issue, Rouen, pp. 43–46.

Berkes F, Hughes TP, Steneck RS, Wilson JA, Bellwood DR, Crona B, Folke C, Gunderson LH, Leslie HM, Norberg J, Nyström M, Olsson P, Osterblom H, Scheffer M, Worm B (2006) Ecology—Globalization, roving bandits, and marine resources. Science 311: 1557–1558.

Bessineton C (1988) La création de vasières artificielles. Actes Colloque l'IFREMER 22: 111–121.

Billen G, Garnier J, Rousseau V (2005) Nutrient fluxes and water quality in the drainage network of the Scheldt basin over the last 50 years. Hydrobiologia 540: 47–67.

Bingham G, Bishop R, Brody M, Bromley D, Clark E, Cooper W, Costanza R, Hale T, Hayden G, Kellert S, Norgaard R, Norton B, Payne J, Russell C, Suter G (1995) Issues in Ecosystem Valuation—Improving Information for Decision-Making. Ecol Econ 14: 73–90.

Bolle A, Bing Wang Z, Amos C, De Ronde J (2010) The influence of changes in tidal asymmetry on residual sediment transport in the Western Scheldt. Cont Shelf Res 30: 871–882.

Cave RR, Ledoux L, Turner K, Jickells T, Andrews JE, Davies H (2003) The Humber catchment and its coastal area: from UK to European perspectives. Sci Total Environ 314–316: 31–52.

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1998) The value of ecosystem services: putting the issues in perspective. Ecol Econ 25: 67–72.

Costanza R, Kemp WM, Boynton WR (1993) Predictability, Scale, and Biodiversity in Coastal and Estuarine Ecosystems—Implications for Management. Ambio 22: 88–96.

Crossland CJ, Bairn D, Ducrotoy JP (2005) The coastal zone: a domaine of global interactions. In: Coastal Fluxes in the Anthropocene (eds Crossland CJ, Kremer HH, Lindebaum HJ, Marshall-Crossland JI, Le Tissier MDA). Springer, Berlin, pp. 1–37.

Dauvin JC, Desroy N, Janson AL, Vallet C, Duhamel S (2006) Recent changes in estuarine benthic and suprabenthic communities resulting from the development of harbour infrastructure. Mar Pollut Bull 53: 80–90.

de Groot R, Wilson MA, Boumans RMJ (2002) A typology for classification, description and valuation of ecosystem functions, goods and services. Ecol Econ 41: 393–408.

Diaz J, Rosenberg R (2008) Spreading Dead Zones and Consequences for Marine Ecosystems. Science 321: 926–929.

Diaz RJ, Solan M, Valente RM (2004) A review of approaches for classifying benthic habitats and evaluating habitat quality. J Environ Manage 73: 165–181.

Dücker P, Glindemann H, Witt H-H, Thode K (2006) Concept for a sustainable development of the Tidal Elbe River as an artery of the metropolitan region Hamburg and beyond. (http://www.tideelbe.de/pdf/Strategiepapier_Tideelbe_eng.pdf)

Ducrotoy JP (1995) The North Sea. In: Europe's Environment: the Dobris Assessment? (eds Stanner D, Bourdeau P). Office for the Official Publications of the European Communities, Luxembourg, pp. 136–140.

Ducrotoy JP (2010) The use of biotopes in assessing the environmental quality of tidal estuaries in Europe. Estuar Coast Shelf Sci 86: 317–321.

Ducrotoy JP (2010) La restauration écologique des estuaires. Lavoisier, Paris, pp. 196.

Ducrotoy JP, Dauvin JC (2008) Spatio-temporal scales in estuarine conservation and restoration. Mar Pollut Bull 57: 208–218.

Ducrotoy JP, Elliott M, De Jonge V (2000) The North Sea. In: Seas at the Millenium (ed Shepard C), Elsevier, London, pp. 43–63.

Ducrotoy JP, Yanagi T (2008) Tools and concepts on ecological quality of coastal and estuarine environments. Mar Pollut Bull 57: 1–2.

Eertman RHM, Kornman BA, Stikvoort E, Verbeek H (2002) Restoration of the Sieperda tidal marsh in the Scheldt estuary, the Netherlands. Restoration Ecol 10: 438–449.

Elliott M, Burdon D, Hemingway KL (2007) Estuarine, Coastal and Marine Habitat and Ecosystem Restoration: confusing management and science. Estuar Coast Shelf Sci 74: 349–366.

Elliott M, Quintino V (2007) The estuarine quality paradox, environmental homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas. Mar Pollut Bull 54: 640–645.

Environment Agency (2005) Humber estuary flood defence strategy: Paull Holme Strays. Environmental monitoring report 2005. Environment Agency, pp. 46.

Environment Agency (2009) Humber tides news: the Humber Strategy. Environmental monitoring report 2009. Environment Agency, pp. 8.

Fickert M, Strotmann T (2007) Hydrodynamische Entwicklung der Tideelbe. Coastline Reports Nr. 9: 59–68.

Folke C, Carpenter S, Elmqvist T, Gunderson L, Holling CS, Walker B (2002) Resilience and sustainable development: Building adaptive capacity in a world of transformations. Ambio 31: 437–440.

Folke C, Hahn T, Olsson P, Norberg J (2005) Adaptative governance of social-ecological systems. Annu Rev Environ Resources 30: 441–473.

Gameson AHL (ed) (1982) The Quality of the Humber estuary 1961–1981. Yorkshire Waters Authority, Leeds, 88 pp.

Groffman P, Baron J, Blett T, Gold A, Goodman I., Gunderson L, Levinson B, Palmer M, Paerl H, Peterson G, LeRoy Poff N, Rejeski D, Reynolds J, Turner M, Weathers K, Wiens J (2006) Ecological thresholds: The key to successful environmental management or an important concept with no practical application? Ecosystems 9: 1–13.

Gunderson L, Folke C (2005) Resilience—Now more than ever. Ecol Soc 10: 22.

Hardisty J (2001) Physical Processes in the Humber Estuary. Report prepared for the Environment Agency on LOIS Special Topic 56–6ST/02/747: Modelling and In Situ Measurement of Sediment Flux in the Lower Humber with Particular reference to Freshwater Controls, Tidal and Storm Forcing, Environment

Agency/University of Hull, Hull, 53 pp.

Harris JA, Hobbs RJ, Higgs E, Aronson J (2006) Ecological restoration and global climate change. Restoration Ecol 14: 170–176.

Hays GC, Richardson AJ, Robinson C (2005) Climate change and marine plankton. Trends Ecol Evol 20: 337–344.

Holling CS (1973) Resilience and Stability of Ecological Systems. Annu Rev Ecol Syst 4: 1–23.

Hughes TP, Gunderson LH, Folke C, Baird AH, Bellwood D, Berkes F, Crona B, Helfgott A, Leslie H, Norberg J, Nyström M, Olsson P, Österblom H, Scheffer M, Schuttenberg H, Steneck RS, Tengö M, Troell M, Walker B, Wilson J, Worm B. (2007) Adaptive management of the great barrier reef and the Grand Canyon world heritage areas. Ambio 36: 586–592.

IPCC (2007) Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team (eds Pachauri RK, Reisinger A). IPCC, Geneva, pp. 104.

Jensen J, Mudersbach C (2007) Zeitliche Änderung von Wasserstandszeitreihen an den deutschen Küsten. Ber Dtsch Landeskunde, Heft 2: 99–112.

Maris T, Cox T, Temmerman S, De Vleeschauwer P, Van Damme S, De Mulder T, Van den Bergh E, Meire P (2007) Tuning the tide: creating ecological conditions for tidal marsh development in a flood control area. Hydrobiologia 588: 31–34.

Mazik K (2004) The influence of a petrochemical discharge on the bioturbation and erosion potential of an intertidal estuarine mudflat (Humber estuary, UK). Unpublished PhD thesis, University of Hull.

Mazik K, Elliott M (2000) The effects of chemical pollution on the bioturbation potential of estuarine intertidal mudflats. Helgol Mar Res 54: 99–109.

Millward GE, Glegg GA (1997) Fluxes and retention of trace metals in the Humber Estuary. Estuar Coast Shelf Sci 44, Supplement A: 97–105.

Moussard S, Ducrotoy JP, Dauvin JC (2008) Gestion Globale de l'Estuaire de la Seine: de sa dégradation à la restauration de ses fonctionnalités écologiques. In: Intégrer la biodiversité dans les stratégies des entreprises (ed Houdet J). Orée-FRB, Paris, pp. 334–339.

Norkko A, Andrew N, Thrush S, Cummings V, Schwarz A-M, Hawes I, Mercer S, Budd R, Gibbs M, Funnell G, Hewitt J, Goring D (2002) Ecology and biodiversity of coastal benthic communities in McMurdo Sound, Ross Sea: development of sampling protocols and initial results. Final Research Report for Ministry of Fisheries Research Project ZBD2001/02.

North Sea Task Force (1994) The quality status report of the North Sea (eds Ducrotoy JP, Pawlack J, Wilson S). International Council for the Exploration of the Sea, OSPAR Commissions, Olsen and Olsen, Fredensborg, 132 pp.

Olenin S, Ducrotoy JP (2006) The concept of biotope in marine ecology and coastal management. Mar Pollut Bull 53: 20–29.

Peterson GD, Allen CR, Holling CS (2010) Ecological resilience, biodiversity and scale. Ecosystems 1: 6–18.

Plüß A (2004) Nichtlineare Wechselwirkung der Tide auf Änderungen des Meeresspiegels im Übergangsbereich Küste/Ästuar am Beispiel der Elbe. In: Proc Klimaänderung Küstenschutz, pp. 129–138.

Port Autonome du Havre (2007). Port 2000 and the river Seine estuary. PAH, le Havre: 26 pp.

Salen-Picard C, Arlhac D (2002) Long-term changes in a Mediterranean benthic community: relationships between the polychaete assemblages and hydrological variations of the Rhône River. Estuaries 25: 1121–1130.

Salen-Picard C, Darnaude AM, Arlhac D, Harmelin-Vivien ML (2002) Fluctuations of macrobenthic populations: a link between climate-driven river run-off and sole fishery yields in the Gulf of Lions. Oecologia 133: 380–388.

Scherrer P, Galichon P (2002) Port 2000—La combinaison d'un projet portuaire et d'un projet environnemental d'amorce de réhabilitation de l'Estuaire de la Seine. VI$^{\text{èmes}}$ Journées Nationales Génie Civil-Génie Côtier, Anglet, France, 15–17 Mai 2002, Paralia, pp. 499–511.

Society for Ecological Restoration International Science & Policy Working Group (2004). The SER International Primer on Ecological Restoration Society for Ecological Restoration International. SER, Washington DC, pp. 13.

Temmerman S, Govers G, Meire P, Wartel S (2004) Simulating the long-term development of levee-basin topography on tidal marshes. Geomorphology 63: 39–55.

Ten Brinke WBM, Dronkers J (1993) Physical and biotic aspects of fine-sediment import in the Oosterschelde tidal basin (The Netherlands). Neth J Sea Res 31: 19–36.

Tett P, Gowen R, Mills D, Fernandes T, Gilpin L, Huxham M, Kennington K, Read P, Service M, Wilkinson M Malcolm S (2007) Defining and detecting undesirable disturbance in the context of marine eutrophication. Mar Pollut Bull 55: 282–297.

Uncles RJ, Joint I, Stephens JA (1997) Transport and retention of suspended particulate matter and bacteria in the Humber-Ouse estuary, UK, and their relationship to hypoxia and anoxia. Presented at the ECSA 26 and ERF 96 Symposium (Organiser: Heip C), Middelburg, The Netherlands, 16–20 September 1996.

Van Den Berghe E, Van Damme S, Graveland J, De Jong D, Baten I, Meire P (2005) Ecological rehabilitation of the Schelde Estuary (The Netherlands-Belgium; Northwest Europe): Linking ecology, safety against floods, and accessibility for port development. Restoration Ecol 13: 204–214.

van Maren DS, Winterwerp JC, Sas M, Vanlede J (2009) The effect of dock length on harbour siltation. Cont Shelf Res 29: 1410–1425.

Vinebrooke RD, Cottingham K, Norberg J, Scheffer M, Dodson SL, Maberly SC, Sommer U (2004) Cumulative impacts of multiple stressors on biodiversity and ecosystem functioning: the role of species co-tolerance. Oikos 104: 451–457.

von Storch H, Gönnert G, Meine M (2008) Storm surges—An option for Hamburg, Germany, to mitigate expected future aggravation of risk. Environ Sci Policy 11: 735–742.

Wang ZB, Jeuken MCJL, Gerritsen H, de Vriend HJ, Kornman BA (2002) Morphology and asymmetry of the vertical tide in the Westerschelde estuary. Cont Shelf Res 22: 2599–2609.

Ysebaert T, De Neve L, Meire P (2000) The subtidal macrobenthos in the mesohaline part of the Schelde Estuary (Belgium): influenced by man? J Mar Biol Assoc UK 80: 587–597.