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The Science of the Total Environment 314–316 (2003) 31–52
the Science of the Total Environment
An International Journal for Scientific Research into the Environment and its Relationship with Man
www.elsevier.com/locate/scitotenv

The Humber catchment and its coastal area: from UK to European perspectives

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Received 7 November 2002; accepted 2 January 2003

Abstract

The present water quality of the Humber rivers and coastal zone depends on a complex interplay of factors, including physical ones, such as the underlying geology, which influences soil type, climatic ones, such as the rainfall, which influences runoff, socio-economic ones, which influence present-day human activities in the catchment, and the legacy of former activities, such as contaminated sediments from mining. All of these factors affect the fluxes of nutrients and other contaminants to the rivers and coastal zone. The Water Framework Directive (WFD) requires the production of a river basin management plan intended to lead to the achievement of good chemical and ecological status for all water bodies in the catchment over the next two decades. This paper provides an overview of the current environmental and socio-economic state of the Humber catchment and coastal zone, and broadly examines how socio-economic drivers affect the fluxes of nutrients and contaminants to the coastal zone, using the driver–pressure–state–impact–response (DPSIR) approach. This is followed by an overview of future research, describing the use of scenarios to simulate future fluxes and provide a consistent framework to evaluate potential policies to improve water quality in the estuary. The Humber catchment is one of eight case studies within a European research project, EUROCAT (EVK1-CT-2000-00044), which aims to achieve integrated catchment and coastal zone management by analysing the response of the coastal sea to changes in fluxes of nutrients and contaminants from the catchments. For the Humber case study, the research focuses on the fluxes of two nutrient elements, N and P, and four metal contaminants, As, Cu, Pb and Zn. The project requires the integration of scientific and socio-economic approaches, bringing together quantitative environmental data garnered for individual river catchments and coastal zones in previous research programmes, and local and regional socio-economic data, to aid decision-makers in their search for integrated and sustainable coastal zone management strategies.

Keywords: Catchment; Contaminants; Driver–pressure–state–impact–response (DPSIR); Economic analysis; Estuary; EUROCAT; Humber; Metals; Nutrients; Policy; Scenarios; Water quality; Water Framework Directive (WFD)

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doi:10.1016/S0048-9697(03)00093-7

1. Introduction

A number of research projects carried out over the last decade have included studies of the Humber catchment and coastal zone. The largest of these is the 5-year study of the UK east coast river catchments carried out as part of the Land–Ocean Interaction Study (LOIS) which ran from 1993 to 1997 (Wilkinson et al., 1997; Leeks and Jarvie, 1998). The data collected for the Humber rivers and estuary during this project were augmented by data collected routinely by the Environment Agency, and its predecessor, the National Rivers Authority (NRA) (Leeks et al., 1997), providing an extensive database for analysis and modelling. As a result of the work carried out during LOIS and in a range of other projects on the Humber, a significant body of work exists on the quality of the water in the Humber rivers during the 1990s, on the variability of the fluxes of nutrients, metals and other contaminants through the river system, and on the transformations and attenuations that take place between inputs of substances to the rivers and estuary and their outputs to the North Sea (Neal and Turner, 2000). Subsequent to LOIS, major projects involving the Humber include the Department for Environment Food and Rural Affairs/Environment Agency (DEFRA/EA) Estuaries Research Programme, the Natural Environment Research Council (NERC) thematic programme on Urban Regeneration and the Environment (URGENT), the NERC Lowland Catchment Research Programme (LOCAR), and the ongoing Humber Wetlands Survey, one of several large-scale archaeological surveys of wetlands in England funded by English Heritage. The Joint Nutrient Study (JoNuS) which researched nutrient behaviour in UK east coast estuaries between 1990 and 1993, also included significant research on the Humber (Sanders et al., 1997).

Most of the inputs of dissolved and particulate material to the Humber rivers have been perturbed from their natural background values by anthropogenic activities, with adverse effects on the water quality of both rivers and estuary. However, studies that explore the links between socio-economic activity in the catchment and water quality downstream are few (Oguchi et al., 2000). The Humber Estuary has long exerted a significant influence on the type and development of socio-economic activities in its catchment. It has, for centuries, provided a safe anchorage for shipping. Up to the 1970s, a major part of the UK fishing fleet was based at the port of Grimsby (Gray, 1995). It is a landing point for much of the oil and gas from the North Sea oilfields, providing major refining capacity. Since the Industrial Revolution in the 18th century, it has acted as a major trade route from the interior of the country, via the rivers, canals, roads and railways, to the rest of the UK and continental Europe. Its rivers provide cooling water for power stations and industrial processes, and act as a waste disposal unit for urban sewage and industrial effluent. Its flat and fertile floodplain has provided the basis for intensive agricultural production. The estuary also provides important recreational and conservation amenity, and has the potential to increase these significantly in the future. In the context of the European Water Framework Directive, the current state of the catchment and coastal zone must now be assessed, both from a natural science and a socio-economic point of view, in order to understand better how both present-day and future human activities in the catchment may affect the future water quality of the rivers and coastal zone. This paper presents an overview of the current state of the Humber Estuary in relation to its catchment, from both a natural science and a socio-economic perspective, using the driver–pressure–state–impact–response framework. It then examines some future scenarios for the Humber, and assesses how the insights these provide may be used to evaluate integrated coastal zone management strategies.

1.1. The Humber catchment

The Humber catchment (Fig. 1) covers an area of approximately 24 240 km^2, more than 20% of the land area of England (Jarvie et al., 1997a), while the mean freshwater input from the Humber Estuary to the North Sea is 250 m^3 s^{-1} (NRA, 1993). The rivers Trent and Ouse, which provide the main freshwater flow into the Humber, drain large industrial and urban areas to the south and

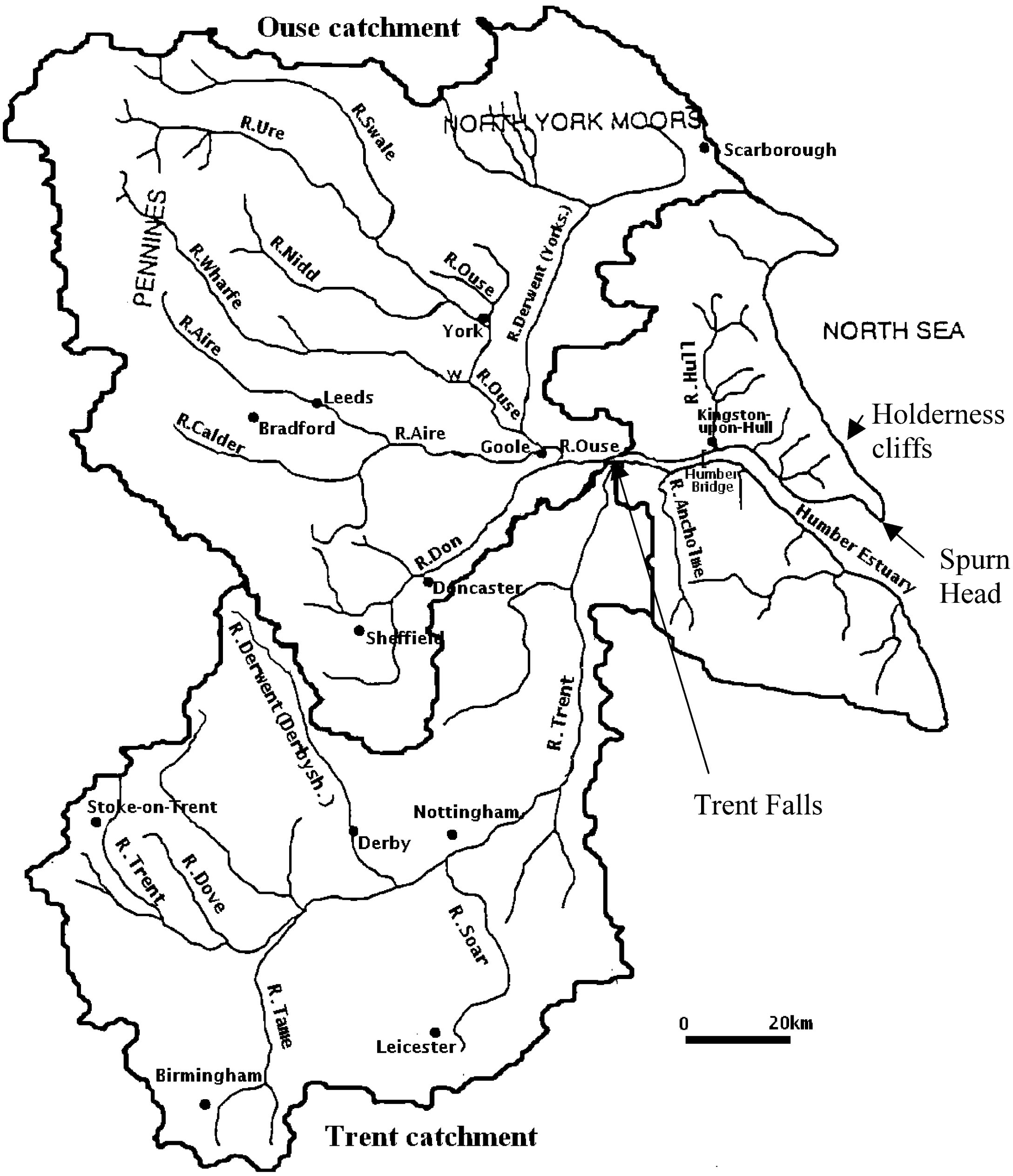

Fig. 1. The Humber catchment (after Edwards et al., 1997). The rivers Trent and Ouse are the two main sources of freshwater to the Humber Estuary, draining approximately one-fifth of England between them.

west (River Trent), and less densely populated agricultural areas to the north and west (River Ouse). These two drainage basins are almost identical in area. The River Trent is tidal for approximately 85 km upstream of its confluence with the Ouse at the head of the estuary (Jarvie et al., 2000). The maximum extent of seawater intrusion is at Gainsborough, some 40 km inland (Freestone, 1995). The tide is excluded from its tributaries by tidal gates and sluices. The present tidal limit of the River Ouse is at Naburn Weir near Acaster, 62 km upstream of the Trent/Ouse confluence (known as Trent Falls), while the maximum extent of seawater intrusion is at Boothferry, approximately 20 km inland of Trent Falls (Freestone, 1995). The rivers Wharfe, Aire and Don, tributaries of the Ouse, have weirs upstream preventing tidal incursion, at Tadcaster (15 km), Chapel Haddlesley (25 km) and Doncaster (32 km), respectively. A fourth tributary of the Ouse, the River Derwent, was tidal for 24 km upstream until a barrier was built in 1975, close to its confluence with the Ouse.

On the north bank of the Humber Estuary the principal river is the Hull, with a tidal length of 32 km, up to Hempholme Weir. The Hull provides only approximately 1% of the freshwater input to the estuary (Sanders et al., 1997), with a mean flow of 3.4 m^3 s^{-1}. On the south bank, the River Ancholme enters the Humber at South Ferriby, but a sluice and a tidal lock exclude the tide. Mean flow is 0.6 m^3 s^{-1}. Altogether, the total tidal length of rivers and estuary is 313 km (NRA, 1993).

The climate is Transition Maritime, with a typical mean January temperature of 1 °C, mean July temperature of 21 °C and mean annual precipitation of 576 mm (averages of 1961–1990 data from Finningley Meteorological. Station) although average annual precipitation in the upland areas of the catchment is as much as 1000 mm.

1.2. The Humber Estuary and coastal zone

The Humber Estuary is a shallow, well-mixed macro-tidal estuary with a maximum tidal range of 7.2 m, the second largest in the UK and comparable to other macro-tidal estuaries worldwide (macro-tidal = tidal range >4 m). Mean water depths vary between 8 m at the mouth and 3 m in the inner estuary. Continuous dredging maintains shipping channels to a depth of 11 m in the inner estuary and 16 m in the outer estuary. A salinity gradient from north to south bank is evident 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 1500 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., 1998b), and for sediment is 18 years (Millward and Glegg, 1997).

The estuary is 62 km long from Trent Falls (the confluence of the rivers Ouse and Trent, Fig. 1) 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 defined as Trent Falls for the purposes of this study. 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/Donna Nook. The extended outer coastal zone affected by the Humber plume (Morris et al., 1995) is approximately 100 km long. 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 only two areas of high population/industry—around Kingston-upon-Hull on the north bank and Grimsby/Immingham/Cleethorpes on the south bank.

1.3. Environmental designations

Under the 1991 EC Nitrates Directive, 66 nitrate-vulnerable zones (NVZ) were designated in the UK in 1996. Of these, 11 fall within the Humber catchment, several of which impinge on the tidal rivers and estuary (Fig. 2). These are zones where controlled waters (groundwater, rivers and estuaries) are prone to excessive pollution from nutrients, and within these areas, restrictions are placed on farmers with regard to timing and quantity of fertiliser application, and spreading of

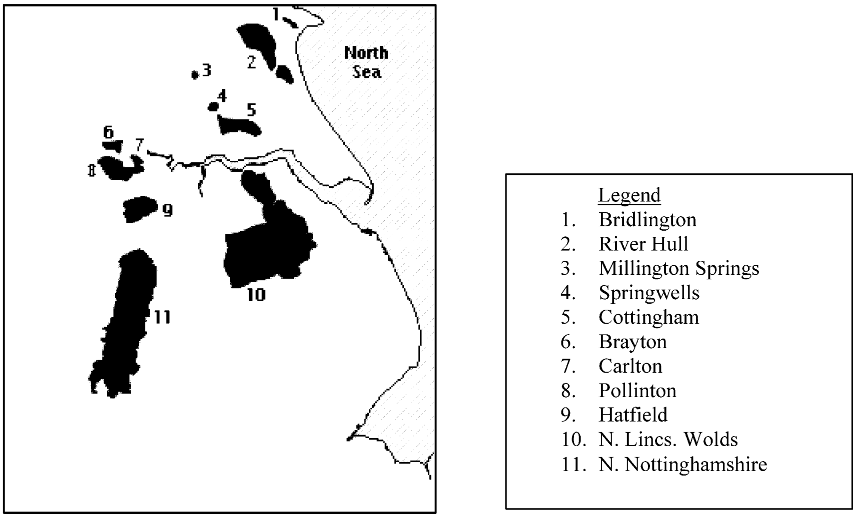

Fig. 2. Nitrate-vulnerable zones in the Humber catchment, designated in 1996 (source: DEFRA). The UK government plans to extend the NVZs to cover almost the entire Humber catchment.

manure from livestock. Following consultation in 2001–2002, the NVZs are now planned to be greatly extended and will cover more than 50% of England (DEFRA, 2001; 'How should England implement the 1991 Nitrates Directive?'). The 2002 designations mean that almost the entire Humber catchment will be designated as an NVZ, with the exception of small areas along the coast, the lowest reaches of the Ouse and Trent, part of the Pennines area which hosts the headwaters of the Aire and Wharfe, and the North York Moors which host the headwaters of the Yorkshire Derwent. Within the existing NVZs there are a number of designated nitrate-sensitive areas (NSA). The NSA is a voluntary scheme whereby farmers are compensated for significantly changing their farming practices to help protect valuable supplies of drinking water (MAFF and ENTEC, 1998).

The entire Humber Estuary has been proposed as a marine special area of conservation (mSAC) and much of the estuary is already designated as Phase I Ramsar sites/SACs (Binnie et al., 2001), with areas above mean low water (MLW) designated as national sites of special scientific interest (SSSI). The Humber is also proposed as a designated site under the Shellfish Waters Directive (79/923/EEC) for mussels and cockles. A summary of the policy and legislation regime that is relevant to the Humber catchment–coastal continuum is presented in Fig. 3.

2. The DPSIR framework for the Humber

In order to predict how future socio-economic changes in the Humber catchment might affect the water quality, it is first necessary to describe the present state of the catchment and coastal waters, and the impacts of past and current socio-economic drivers and pressures on water quality. Once the link between drivers, pressures and impacts is understood, policy responses can be formulated that will act to reduce the pressures created by certain drivers, and the impacts of certain pressures, on water quality. However, any policy implemented to improve water quality is likely to have wider implications, which must be considered, and these can be assessed using future scenarios. The Humber catchment is one of eight case studies within a European research project, EUROCAT, which aims to achieve integrated catchment and coastal zone management by analysing the response of the coastal sea to changes in fluxes of nutrients and contaminants from the catchments. The driver–pressure–state–impact–response

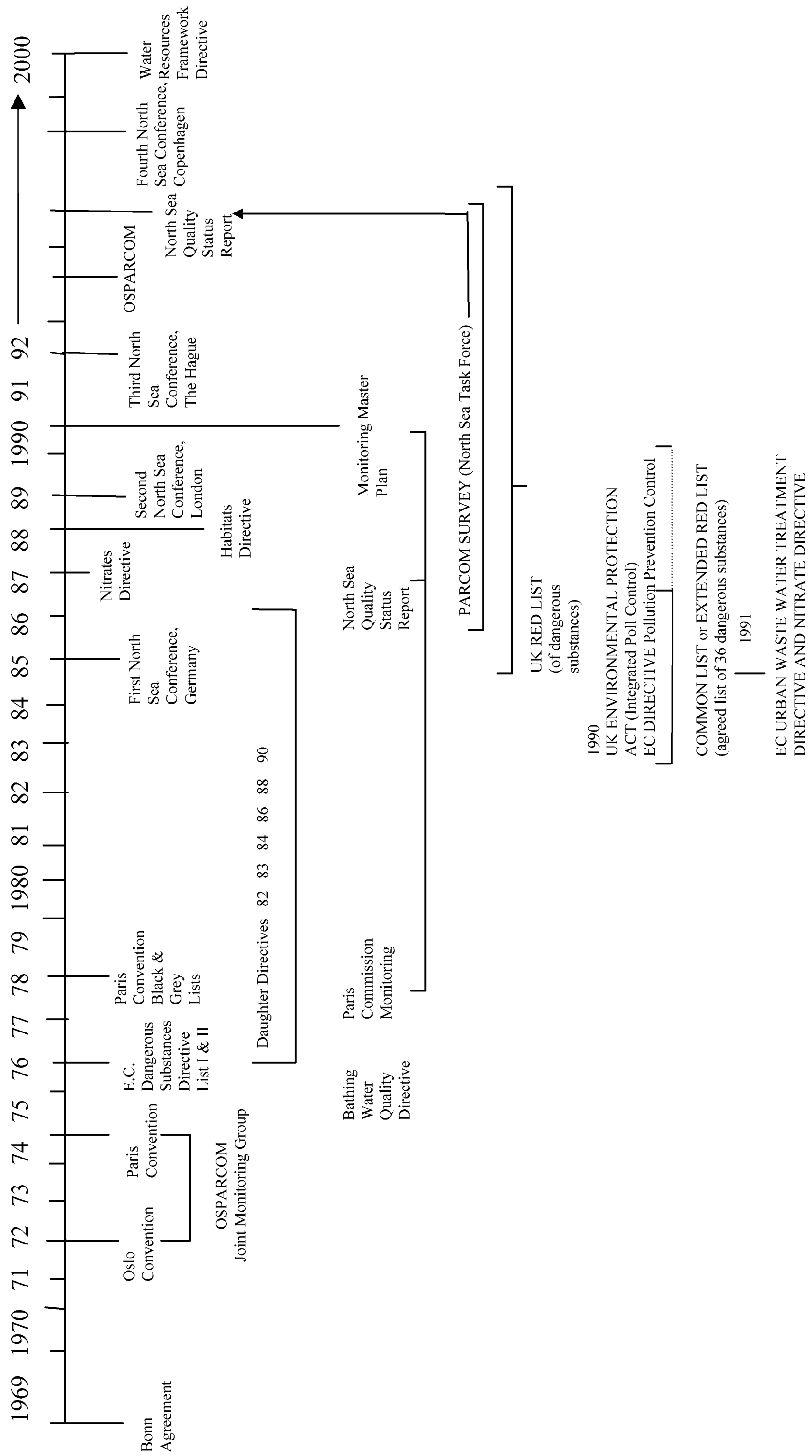

Fig. 3. Evolution Of The North Sea Policy-Making Regime (1969–2000).

framework (Fig. 4) has been chosen as the common framework for analysis for all regional catchments in the EUROCAT study. It is an extension of the PSR framework developed by the Organisation for Economic Co-operation and Development (OECD, 1993). The components may be different for each catchment being studied, although some will be common to all catchments. Examples of some of the components for the Humber catchment study are given in Table 1, and extended descriptions of drivers, pressures, states and impacts are given in the following sections.

2.1. Socio-economic drivers

2.1.1. Population

There are several major urban centres within the river catchments. Nottingham, Leicester and the West Midlands/Birmingham conurbation are drained by the Trent, the Leeds–Bradford area in West Yorkshire is drained by the Aire/Calder and the Sheffield/Doncaster area in South Yorkshire is drained by the Don (Fig. 1). There is one major conurbation on the estuary itself, on the north bank at Kingston-upon-Hull, and several large industrial areas on the south bank. There are also large rural regions, the populations of which are currently experiencing high growth, while the urban areas are showing a small decline. The total population of the Humber catchment numbers approximately 13 700 000 (National Statistics for 2002). Of this, 8 4000 000 million live in the Trent catchment, including 1 000 000 in the city of Birmingham. The Ouse catchment has a population of 4 400 000, with the largest urban area being the Leeds–Bradford conurbation, totalling 1 200 000 inhabitants. The population of Humberside, immediately surrounding the estuary, grew from 465 000 in 1901 to 765 000 in 1971 (Mort and Woolley, 1994) to 884 700 in 1997. Trends since 1991 show a slowing down in population growth in the region, following the UK national trend towards counter-urbanisation (Jarvie et al., 1997a).

2.1.2. Agriculture

The total agricultural area for the Humber catchment amounts to some 2 300 000 ha, from a total land area of just over 2 400 000 ha (source: DEFRA, UK Agricultural Census Statistics for 1999). Of this, 1 000 000 ha is arable and horticultural land, growing mainly cereal crops, oilseed rape and root crops, and the remainder is predominantly grazing land (Table 2). Land use in the Ouse and Trent catchments is broadly similar, but with the Trent having almost double the urban area of the Ouse, while the Ouse has more extensive woodland, heath and bog than the Trent due to its more extensive uplands.

2.1.3. Industry

The estuary is now in a post-industrial phase, with some of the large polluting manufacturing plants previously sited in the river catchments or on the estuary now closed down (e.g. Capper Pass tin smelter), and others subject to more stringent restrictions on disposal of waste to controlled waters. In the catchment, traditional industries such as textiles and iron and steel have declined, while the chemical and petrochemical industries are thriving, as is the power industry. The largest concentration of electricity-generating power stations in the UK is located along the river Trent (Jarvie et al., 2000), largely coal-fired, direct-cooled stations. A number of other direct-cooled power stations are situated on the tidal rivers entering the estuary.

2.1.4. Port development

The Humber ports (Goole, Grimsby, Hull and Immingham) handle 13% of the UK seaborne trade (DETR, 2000). This has risen from 58 000 000 t in 1989 to 74 000 000 t in 1998. Up to 50 000 ship movements per year are handled by the Vessel Traffic Service Centre at Spurn Head, and the volume of ship traffic is expected to increase as the European Union expands over the coming years. In all, 15% of all UK crude oil capacity, 17% of refined petroleum products, 27% of the UK iron ore capacity and 25% of the natural gas requirements pass through the estuary annually (DETR (2001)). Grimsby and Immingham overtook London to become the UK leading port in 2000 with 52.2 Mt of freight traffic (DETR, 2002).

2.1.5. Climate change

In addition to the socio-economic drivers, an emerging additional driver in the Humber catch-

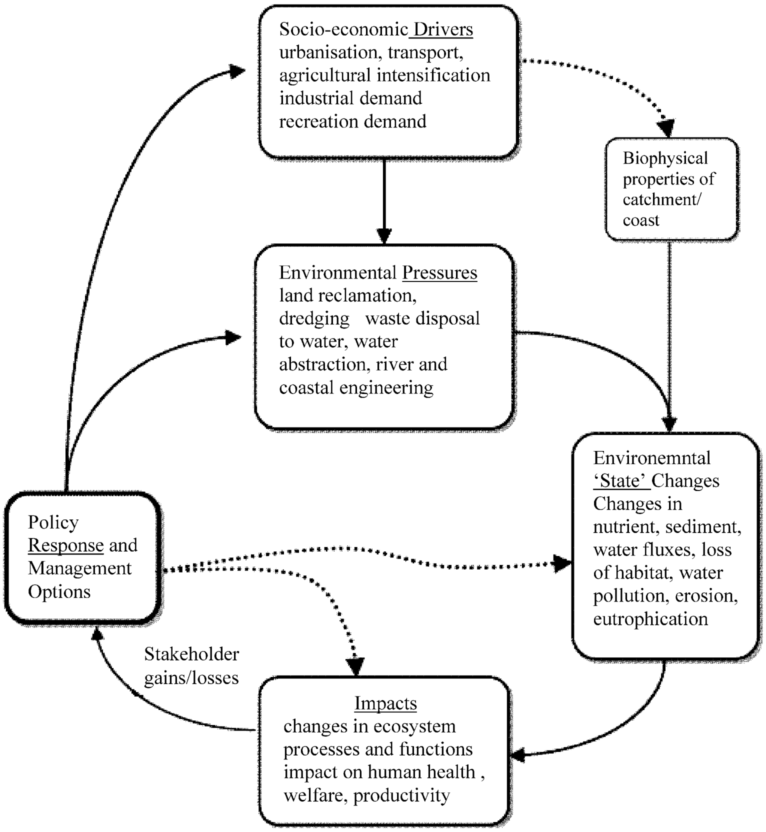

Fig. 4. The DPSIR framework (Turner et al., 1998). Socio-economic drivers create environmental pressures. These in turn lead to changes in the ambient environmental state, which may result in impacts on human welfare through e.g. health problems, losses in amenity and productivity. Policy responses are consequently formulated, which target one or more points in the environmental change process in order to mitigate damage/problems, or reorientate drivers/pressures.

ment for the foreseeable future is the necessity to cope with climate change. This includes more extreme weather events, which can lead to flooding in parts of the catchment (Longfield and Macklin, 1999) and expected sea-level rise around the estuary. Major floods occurred in the catchment in 1986, 1995 and 2000, with the Ouse catchment most affected. An area of approximately 800 km^2 around the Humber Estuary currently lies below the level of high spring tide and is protected by extensive coastal defences. This includes urban/industrial areas, high-grade farmland, infrastructure such as roads and railways, and natural reserves, e.g. wetlands. More than 280 km of defences is currently maintained by the Environment Agency (EA) in the Humber area, and it is now realised that the long-term maintenance of all these defences is not desirable either for economic or environmental reasons. Strategies are being drawn up and implemented to allow for the realignment of defences in certain parts of the estuary. Current estimates of actual sea-level rise in the Humber are 1.11 mm $year^{-1}$, based on a 33-year record (Woodworth et al., 1999). However, recommendations on regional rates of relative sea-level rise to be included in the design on new flood and coastal defence structures are 6 mm $year^{-1}$ for the Humber region (MAFF, 1995). The UK Environment Agency has plans to move back the defences in a number of places around the estuary, restoring up to 1000 ha of intertidal zone. Some of this will be used to compensate for new development along the estuary foreshore, e.g. for planned port expansion at Goole, Grimsby, Hull and Immingham.

2.1.6. Fisheries

Approximately 16 species of fish have been caught annually during surveys in the Humber Estuary over the last decade. A total of 76 fish species have been recorded in the estuary since 1970 (NRA, 1993), of which approximately six have been caught commercially (sole, plaice, thornback ray or roker, cod, dogfish and eel), although commercial fisheries are very small-scale and operate only on a part-time basis (NRA, 1995). Commercial eel fishing takes place in the upper reaches of the estuary, and in some of the rivers leading to it (Gray, 1995). Cod are fished using lines within the estuary during winter, and for the rest of the year, nets are used for flatfish. Shellfisheries in the outer estuary and the wider coastal zone exploit lobster, edible crab, whelks and cockles (Gray, 1995). During 2000, 261 t of lobster and 1150 t of crab were landed (McCandless, 1991). Severe weather periodically affects the cockle beds adversely, leading to closures, often for up to several years. Catching of migratory fish in the estuary and rivers is permitted only using rods, although drift nets are used in the wider coastal zone. With improvements in the water quality of the inner estuary since approximately 1995, migratory salmon and trout are beginning to increase in the rivers (Axford, 2001; McHarg, 2001). The EA continues to put considerable effort into developing and improving recreational fisheries in the rivers, including

Table 2
Land use in the Humber catchment

Land use	Area (ha)	% of total
Arable	941 200	39.5
Improved grass	481 600	20.2
Semi-natural grass	347 900	14.6
Suburban	194 200	8.2
Broadleaf forest	142 100	6.0
Urban	91 700	3.9
Heath	76 600	3.2
Coniferous woodland	41 000	1.7
Bog (deep peat)	28 900	1.2
Bare ground	24 200	1.0
Inland water	10 700	0.4
Coastal	1400	0.1
Total	2 381 000	

Table 1
The DPSIR framework for the Humber

Driver	Pressure	State	Impact	Response
Population Agriculture Industry	[1]Land use/emissions: [a]sewage [b]agricultural [c]industrial [2]Contaminated sediments [3]Oil pollution	High nutrient input to coastal waters[1a,b,c] High contaminant input to coastal waters[1a,b,c,2,3] Raised temperature of water in tidal rivers[1c] Low oxygen zone at head of estuary[1a,b,c]	Reduced water quality in the Humber Estuary[1a,b,c,2,3] Export of nutrients and contaminants to the North Sea[1a,b,c,2] Damage to aquatic ecosystems[1a,b,c,2,3,4,5]	Upgrading of STWs [1a,c] Designation of NVZs [1b] Changes to agricultural practices [1b] Remediation of contaminated land [1c,2] Cleanup of industrial effluent [1c,2]
Port development	[4]Dredging	Disturbed bed sediment[4]	Passage of migratory fish upriver blocked[1a,b,c]	Cessation of sewage dumping in N. Sea [1a]
Climate change Fisheries	[5]Coastal Squeeze	Reduced intertidal area[5]	Habitat loss[2,3,4,5]	Creation of intertidal areas by setback of coastal defences [1a,b,c,4,5]

Drivers are responsible for one or more pressures. Superscripts indicate which states/impacts/responses can be linked to individual pressures. This is by no means an exhaustive list, but serves to illustrate how the DPSIR framework operates for the Humber Estuary. Fisheries is currently a small-scale socio-economic activity in the Humber Estuary, but has been included due to its former, and potential future, importance. STW, sewage treatment works. Note these accept both domestic and industrial effluent. NVZ, nitrate-vulnerable zones.

restoration of habitats and reconstruction of weirs to allow the passage of migratory fish up-river. The estuary is recognised as an important nursery area for many commercially important species, such as sole, plaice and cod, giving it some potential for more extensive fisheries in the future.

2.2. Pressures

2.2.1. Land use

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 or woodland. Wetlands occupy only 1–2% of the catchment area. A breakdown of the land use for the Humber catchment is given in Table 2. This has been calculated from Institute of Terrestrial Ecology Land Cover Map for Great Britain for 2000 (LCM, 2000). The proportions of each type of land use are very similar for the Trent and the Ouse catchments, and on the north and south sides of the estuary.

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 (Humber Bridge to Spurn Head, Fig. 1) 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 3000 ha has taken place since the mid-19th century (Murby, 2001). Losses and gains of intertidal area in the inner estuary (Goole to Humber bridge) during the 20th century are being investigated (E. Coombes, personal communication). Around the estuary some 894 km^2 of land are below the 5-m contour and are protected by extensive coastal defences (EA, 1999a). 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 is believed to come from the continuing erosion of Holderness Cliffs, which form the coastline to the north of the estuary mouth at Spurn Head (Hardisty, 2001).

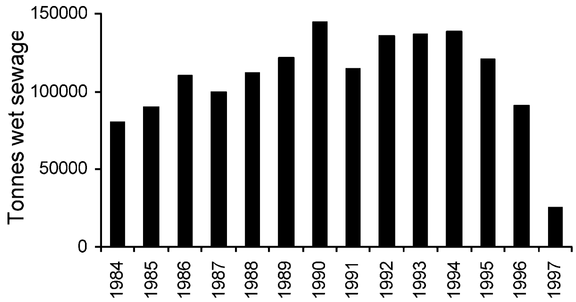

Fig. 5. Disposal of sewage to the Humber sewage sludge disposal site just outside the estuary. Data from Aquatic Environment Monitoring Reports 26–52 (MAFF/CEFAS).

2.2.2. Emissions

2.2.2.1. Domestic sewage. Untreated domestic sewage and wastewater from the city of Hull has been discharged directly to the estuary since the building of sewage system in the late 19th and early 20th century, with only large solids removed. From 2001, completion of new sewage treatment plants should ensure primary and secondary treatment of all sewage entering the river system and the estuary. Up to 173 000 m^3 day^{-1} (38 million gallons) of sewage entering the estuary from the city of Hull will be treated when the plant is finished (source: Yorkshire Water, 2001). Approximately 100 000 t of wet sewage sludge was dumped annually (Fig. 5) at the Humber sewage sludge disposal site, outside the estuary mouth (53°33′ N, 0°30′ E), a practice that was banned in 1998. None of the sewage treatment plants currently in operation take specific measures to remove phosphorus from the sewage, as although algal blooms are occasionally observed in the tidal sections of the estuary, they are not believed to have any adverse effects on the biota or water quality (source: Yorkshire Water). A total of 76 major sewage discharges were in operation in the tidal rivers and estuary in 1998 (EA, 1998b).

2.2.2.2. Agricultural emissions. Agricultural land is the principal source of nitrate to most UK rivers (Powlson, 2000). High nitrate losses occur when organic manures are applied to land in excessive amounts, or at inappropriate times, e.g. during

Table 3
Environmental quality standards (EQS) for the Humber Estuary and tidal rivers

	Estuary ($\mu g\ l^{-1}$)	Total or dissolved	River ($\mu g\ l^{-1}$)	Total or dissolved
Element				
Arsenic	25	D	50	D
Cadmium	2.5	D	5	T
Chromium	15	D	250	D
Copper	5	D	28	D
Iron	1000	D	1000	D
Mercury	0.3	D	1	T
Lead	25	D	250	D
Nickel	30	D	200	D
Zinc	40	D	500	T
Boron	7000	T	1000	T
Vanadium	100	T	60	T
Compound				
Trichlorobenzene	0.4	T	0.4	T
Hexachlorocyclohexane	0.02	T	0.1	T
Total DDT	0.025	T	0.025	T
p-DDT	0.01	T	0.01	T
Pentachlorophenol	2	T	2	T
Carbon tetrachloride	12	T	12	T
Total 'drins'	0.3	T	0.03	T
Endrin	0.005	T	0.005	T
Trichloroethylene	10	T	10	T
1,2-Dichloroethane	10	T	10	T
Tetrachloroethylene	10	T	10	T

Upper limits are reported. For nutrients, the data collected monthly over 3 years by the Environment Agency are used to determine average nutrient concentrations, on which river water quality ratings are based. Average values >30 mg l^{-1} NO_3 and >0.1 mg l^{-1} for PO_4 are designated as 'high'. This does not correspond directly to the EU Nitrates Directive standards (50 mg NO_3 l^{-1} upper limit for nitrates in fresh waters). No absolute limits are currently set for phosphates; they are considered to be of concern only where high concentrations may lead to eutrophication. Likewise, limits for nitrates and phosphates are not set for estuarine or marine waters.

seasons of high rainfall (Chambers et al., 2000), or where N is applied to crops in excess of their requirement or at an inappropriate time, particularly to 'leaky' crops and soils (Goulding, 2000). Many of the lowland areas of the Humber catchment support intensive farming, and surface water in several areas of the catchment regularly exceeds the current standard for nitrate of 50 mg l^{-1} in surface waters. These nitrate-vulnerable zones (Fig. 2) are now subject to amended farming practices. The lower reaches of the River Trent (from its confluence with the Derbyshire Derwent, south of Derby, Fig. 1) are designated as sensitive areas (eutrophic) under the Urban Waste Water Treatment Directive, 1998.

2.2.2.3. Industrial emissions. 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 (BOD), which when compounded by discharges from sewage treatment works (STWs) can lead to low dissolved oxygen in the tidal rivers, thus harming aquatic life. Other effluents are high in metals such as copper, and while an individual plant may not discharge harmful quantities of a particular substance, the discharges are summed with distance downstream, and during times of low river flow, can lead to failure in reaching the water quality standards (EQS, Table 3). Each coal-fired power station in the tidal reaches of the Ouse catchment can 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 (source: EA consent data). In 1997, the power station at Drax released more than 72 t of heavy metals (excluding cadmium and mercury) to the river. Coal-fired power stations dispose of large quantities of contaminants to the atmosphere, as well as to controlled waters. It is not known whether releases to the atmosphere provide a local diffuse source of metals to the rivers. The main power stations close to the estuary are located to the east of Leeds at Ferrybridge, Drax and Eggborough, and at Immingham and Grimsby on the estuary itself. A total of 44 major industrial plants, including power stations, were discharging effluent to the tidal rivers and estuary in 1988 (EA, 1998b). A survey carried out in 1994 to measure alkylphenols in UK rivers and their effects on fish found concentration of nonylphenol in the River Aire to be more than 100-fold that found in other rivers, approaching acute toxic levels (CEFAS, 1997). These substances are derived from extensive use of surfactants during wool cleaning in local textile factories, and enter the river via sewage treatment plants.

2.2.2.4. Contaminated sediments. 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. Floodplain sediments dated between 1250 and 1750 AD show relatively high heavy metal storage, related to lead and zinc mining, while sediments laid down post-1750 AD show even higher heavy metal storage, related in part to industrialisation (effluents from coal and metal mining, textile, chemical and other industries) and urbanisation in the Leeds–Bradford area. In 1896, the district inspector reported on more that 400 coalmines operating in Yorkshire and approximately 30 lead-ore mines (source: Peak District Mines Historical Society). Mining for barytes and fluorospar ceased in the 1960s, and the 1980s saw the closure of the last lead-ore mines in the Yorkshire dales. UK coal production has declined from 140 Mt in 1970 to less than 40 Mt in 2000, with a further 40 Mt or so being imported, principally for use in power stations (source: DTI (2003) energy indicators), many of which are situated in the Humber catchment. Increased flooding in recent years has led to large-scale remobilisation of contaminated sediments in the Ouse catchment (Longfield and Macklin, 1999).

Over 3 Mt of pulverised fuel ash (PFA) are disposed of each year at the Brotherton Ings, Gale Common and Barlow Ash disposal sites in Selby District, from three large coal-burning power stations, including Drax on the tidal river Ouse near Trent Falls, which at 4000 MW, is the largest coal-burning power station in Europe. Dumped PFA is a potential source of toxic metals to water (Pandian and Balasubramonian, 2000) and to biota (Jenner and Bowmer, 1992; Collins et al., 1994; Cordes et al., 2000). However, it is now finding a wide range of secondary uses in ameliorating mine waste (Perkins and Vann, 1995; Perkins, 1996) and as a building material (Domone and Soutsos, 1995; Davies and Kitchener, 1996; Bamforth, 1999), which should reduce landfill in the future.

Within the estuary, direct metal discharges from various chemical and power plant contribute to high levels of metals in sediments (Grant and Middleton, 1990). These include a titanium dioxide plant on the south bank, and until its closure in 1991, one of the largest tin smelters in Europe at North Ferriby (Capper Pass) on the north bank. The metal-enriched sediments appear to be uniformly distributed throughout the estuary, despite likely originating from point sources (Middleton and Grant, 1990), as has been observed in other macro-tidal estuaries such as the Severn (Grant and Middleton, 1990). There are several sites of contaminated land on the banks of the estuary, for which remediation plans are currently under development, including a former agrochemical manufacturing site near Barton-upon-Humber, a waste disposal site near Grimsby and the smelting works at North Ferriby.

2.2.2.5. Oil pollution incidents. The Humber acts as a main east coast port for the landing of crude hydrocarbons in the UK, from the North Sea and other sources. Approximately 90 tankers, each carrying up to 130 000 t of crude oil, unload at

Table 4
Oil spills in the Humber Estuary

Year	Number of incidents	Oil spilled (t)
1989	3	23.8
1995	3	4.6
1996	2	2.6
1997	1	15.0

Source: DETR.

Tetney monobuoy in the outer Humber Estuary annually. The tanker's oil discharging system is connected using floating hoses to a seabed pipeline that runs to the onshore terminal 8 km away. An underground pipeline then transports the oil to the refinery at South Killingholme, 22 km away, which has been in operation since 1969 and currently processes 230 000 barrels of oil and other feedstocks daily. Much of the refined product is exported by sea, while some travels inland as far as Leeds by way of the Aire and Calder canal. Oil tankers also berth at the large oil terminal at Immingham. Table 4 lists the size and frequency of oil spills in the Humber between 1989 and 1999. While the number of incidents is minute compared to the number of ship movements, any oil spillage can have a devastating impact on wildlife in the estuary, and potential for major damage always exists.

2.2.2.6. Dredging. Dredging is carried out continuously within the estuary by the port authorities to maintain shipping channels, and 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. An understanding of the effects of dredging on the habitat of bottom fauna is important (Newell et al., 1998)—disruption will be caused both by removal during the dredging process and by burial when dredged material is dumped (Grigalunas et al., 2001; Smith and Rule, 2001). It is also important from the point of view of possible mobilisation of chemical species by exposure to oxygenated water as contaminated dredged material is mixed with estuary water (Vanderburgt, 1994; Van den Berg et al., 2001). Fig. 6 shows the quantities of sediment dredged annually over recent years.

2.3. States and impacts

2.3.1. Nutrients and primary productivity

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. Until very recently, most of the sewage entering the estuary was untreated, apart from screening of large solids and maceration, but from 2001 the completion of new sewage treatment plants should ensure primary and secondary treatment of all sewage entering the river system and the estuary. Up to the end of 1998, approximately 100 000 t of wet sewage sludge was disposed of annually to the Humber sewage sludge disposal site, outside the estuary mouth. Ammoniacal N discharges to the estuary (1980–1990) are estimated at 9000 kg day^{-1} from urban sewage and 6000 kg day^{-1} from industrial effluent (NRA, 1993). The total dissolved inorganic N input (DIN,

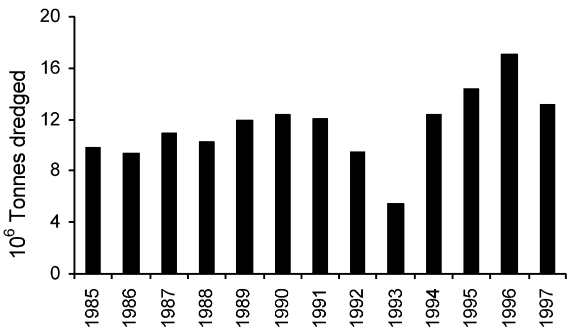

Fig. 6. Quantities of material dredged from the Humber Estuary annually. Disposal is to other sites within the estuary and to the Spurn Head site. Data from Aquatic Environment Monitoring Reports 26–52 (CEFAS).

Table 5
PARCOM low load estimates for nutrients in the Humber

Year	Load (t $year^{-1}$)	
	Total N	Ortho-P
1991	33 090	4061
1992	38 240	4694
1993	37 279	4165
1994	48 280	4383
1995	49 840	4350
1996	35 700	4790
1997	36 740	5089

Note loads are estimated from the averages of a number of measurements taken during any year. 'Low load' means that where a given measurement of a substance was below the detection limit, the amount of the substance present at that time was taken to be zero.

nitrate + nitrite + ammonium) for the Humber Estuary and tidal rivers is estimated to be 57.4×10^3 t $year^{-1}$, of which more than 95% is exported to the North Sea (Jickells et al., 2000). The total dissolved inorganic P input (DIP) is estimated to be 5.7×10^3 t $year^{-1}$, of which 15% is exported to the North Sea, while particulate P inputs from the rivers are estimated to be 2×10^3 t $year^{-1}$ (House et al., 1997b; Jickells et al., 2000); see Table 5 for PARCOM low-load estimates for the Humber (EA, 1999b). Primary production in the Humber Estuary is strongly limited by the year-round high turbidity (Jickells et al., 2000), despite the high levels of nutrient input. However, just outside the estuary, a strong spring bloom occurs in the Humber plume (Allen et al., 1998).

2.3.2. Contaminants

2.3.2.1. Trace metals. Trace metals enter the Humber Estuary in dissolved and particulate form, both from the rivers and as direct input from industrial processes and urban sewage. Total input fluxes of Cd, Cu, Pb, Ni, Zn and Fe from these three sources have been estimated for 1985–1992 (Millward and Glegg, 1997) and compared with output fluxes from the estuary to the North Sea. The large discrepancy they observed between output and input is ascribed to the retention within the estuary of metals attached to fine sediment particles. The authors estimate a particle residence time of 18 years, and the total time over which the estuary would exchange its sediments with the North Sea as 120 years. This is in contrast to the much shorter residence time of the water of 40 days. Sediments in the estuary appear to be significantly enriched in a number of metals over pre-industrial levels (Grant and Middleton, 1990).

Existing riverine flux measurements supplied to PARCOM for the Humber and other UK rivers discharging to the North Sea (Table 6) are made immediately upstream of the tidal limits (the tidal limit is considered the point at which the freshwater flow becomes unidirectional). These data are combined with direct discharges from points seaward of this sampling point to give load estimates for rivers discharging to the North Sea (Jarvie et al., 1997b).

At present, for most of the metals monitored in the estuary (As, Hg, Cu, Cd, Ni, Pb) the greatest loads come from the rivers. However, for Cr and Zn, industrial effluent input direct to the estuary is the major source, and up to the early 1990s, direct input of industrial effluent was also the major source for Cu and As. Industry also inputs orders of magnitude more Fe than rivers or sewage to the estuary through direct discharge. However, significant reductions in the quantities of metals discharged in industrial effluent have taken place since the mid-1990s (Table 7).

2.3.2.2. Organic contaminants. The Humber rivers and estuary are monitored by the Environment Agency for a range of synthetic organic compounds for which environment quality standards

Table 6
PARCOM low load estimates for trace metals in the Humber (EA, 1999b)

Year	Load (t $year^{-1}$)				
	Hg	Cd	Cu	Zn	Pb
1991	0.026	0.967	76.60	802.2	134.4
1992	0.049	1.892	84.65	883.3	101.2
1993	0.070	2.388	83.80	941.9	178.0
1994	0.030	1.965	79.94	907.6	97.3
1995	0.078	0.965	50.47	618.6	54.1
1996	0.138	0.968	44.41	471.2	38.3
1997	0.137	1.340	55.13	402.6	107.3

Table 7
Reduction in industrial effluent loads in 1994 compared to the 5-year mean (EA, 1994)

	Load (kg day^{-1})			
	Cd	Cu	Cr	As
1994	0.2	19	96	0.7
5-year mean	2.5	240	903	360

The 5-year mean is for 1990–1994. The large reduction in As is due to the closure of the Capper Pass tin smelter on the estuary in 1991.

(EQS) have been set Table 3. Compounds monitored are chlorinated solvents and biocides, including the 'drins' (aldrin, dieldrin, endrin), DDT and PCP. The principal source of these compounds to the estuary is the rivers, rather than direct input to the estuary itself. While levels in the water since the mid-1980s now regularly achieve EQS or better, the legacy in the sediments from past industrial input, e.g. dieldrin and HCH from the textile industry in West Yorkshire, is likely to mean that levels of the compounds well above a natural background will persist into the future (NRA, 1989). Recent studies in the Humber rivers (Meharg et al., 2000) indicate that the principal source of dieldrin to the rivers is now from sewage treatment plants, rather than from the textile industries. A year-long study of a comprehensive range of herbicides and insecticides in the Humber rivers found frequent occurrences of most compounds in the southern rivers with high industrial and intensive agricultural output, but concluded than none were present at levels likely to have detrimental effects on the local ecology (House et al., 1997a).

2.3.3. Water temperature

The largest concentration of electricity-generating power stations in the UK is located along the river Trent (Jarvie et al., 2000). These are principally direct-cooled coal-fired stations, and have contributed to the river's high annual average water temperature. A number of other direct-cooled power stations are situated on the tidal rivers entering the estuary. Due to the closure of a number of these plants in the last 30 years and a reduction in the use of others, the average annual temperature of the Trent at its tidal limits fell by 5 °C, from 18 to 13°C, between 1960 and 1980 (NRA, 1993). The average water temperature in the Humber below Trent Falls reduced by approximately 0.5 °C in the same period, to ~10 °C (in 1988). However, the requirements for power in the UK are likely to increase over the coming decades, which may lead to greater requirements for cooling water, potentially including the siting of new power stations on the estuary. Direct-cooled stations also cause major mortality in fish, larvae and eggs, both at the intake, due to screening, and at the outflow, due to the high temperature of the water.

2.3.4. Oxygen distribution

Low oxygen in the water began to be a problem in the upper Humber Estuary at the start of the 20th century (Morris, 1988). By the 1940s, pollution in the lower reaches of the Yorkshire Ouse had so severely affected the oxygen levels in the inner estuary that the passage of migratory fish (salmon and trout) upstream was prevented, leading to closure of the salmon fisheries. By the mid-1970s, the total polluting load entering the Humber had an estimated biological oxygen demand (BOD) of 539 t day^{-1}, with approximately 98 t day^{-1} coming from the combined river input from the Ouse and Trent, and industrial effluent contributing 143 t day^{-1}, with the remainder taken up by direct input of sewage (79 t day^{-1}) and dumping of sewage sludge (219 t day^{-1}) (Murray et al., 1980). Conditions in the River Trent have improved, but low oxygen remained a problem in the tidal reaches of the River Ouse, Don and Aire throughout the 1980s (NRA, 1993), and only in the last few years has the EQS for dissolved oxygen been generally attained in these reaches. The present-day BOD to the estuary from the combined Ouse and Trent is calculated to be 101 t day^{-1} (Neal and Robson, 2000), while direct input to the estuary from sewage is of the order of 132 t day^{-1}, and from industrial sources, 68 t day^{-1} (NRA, 1993), a total of 301 t day^{-1}.

2.3.5. Benthic fauna

Surveys of subtidal and intertidal macrofauna are carried out annually at several sites along the

Humber. Because of the shifting of channels, it is not always possible to make direct comparisons between years, so results are generally compared with the 5-year average for each site. In general, the north bank sites show lower biodiversity and communities show more stress than at the south bank sites. In the tidal rivers, most sites are dominated by pollution-tolerant taxa such as Oligochaeta species (EA, 1998a). Species counting in the tidal rivers was discontinued after 1996. Few studies have been published that document the effects of particular discharges on benthic communities (Mazik and Elliott, 2000). Although sediments in the estuary appear to be significantly enriched in a number of metals over pre-industrial levels (Grant and Middleton, 1990) and high levels of these metals are found in a number of organisms, no definitive studies showing damage to organisms in the estuary as a result of high metal concentrations have been published. The effects on benthic organisms of dredging and dumping of dredge spoil within the Humber Estuary are not known.

2.3.6. Fish species

Annual sampling using a beam trawl is carried out at several sites within the estuary, together with push-net sampling in the outer estuary. Approximately 16 fish species are regularly caught in the trawls, although up to 72 are known from the estuary. The estuary is recognised as an important nursery area for many commercially important species such as sole, plaice and cod. Improvements in water quality in the inner estuary and the lower reaches of the River Ouse, particularly improvements in oxygen saturation, have led to the return of migratory fish species such as trout and salmon. CEFAS conducted oyster embryo bioassays in 1990, 1991 and 1992 using water samples from the estuary taken at low tide, and found the water quality to be good (CEFAS, 1991). A comprehensive report on coastal fisheries on the east and south coast of England, including the Humber was produced by CEFAS in 1998 (Rogers et al., 1998).

2.3.7. Salt marshes and other intertidal areas

Approximately 1400 ha of saltmarsh exists within the Humber Estuary, making up 10–12% of its intertidal area (EA, 1998a). This is a smaller proportion than in some other UK estuaries, where the proportion of saltmarsh is up to 17% of the intertidal zone. Total intertidal area within the estuary is approximately 11 000 ha. The total area does not appear to have changed significantly in the last several decades, but significant migration of intertidal areas to different parts of the estuary has taken place over this time (E. Coombes, personal communication). The largest contiguous intertidal area is inside Spurn Head. However, the present-day intertidal area is only a fraction of the estimated pre-reclamation area of 550 000 ha (Andrews et al., 2000). This lack of present-day intertidal area is due to significant reclamation of intertidal area over the last few 100 years and the building of hard defences along the estuary to prevent flooding of reclaimed land. Intertidal areas provide habitats for large numbers of species of birds and fish, as well as acting as sediment traps.

The amount of sediment entering the estuary from rivers annually has been calculated as 300–500 kt $year^{-1}$, or 430–710 t per tide (Hardisty, 2001). However, the bulk of the sediment entering the Humber Estuary comes from the North Sea, rather than from the rivers entering the estuary. The Holderness Cliffs to the north are being rapidly eroded (approx. 1440 kt $year^{-1}$; Hardisty, 2001) and much of the fine component of this glacial till is carried into the Humber by North Sea circulation. Turbidity in the estuary is very high and a distinct turbidity maximum (TM) is always observed, although the position of this shifts from summer to winter, being closer to the tidal limits during periods of low flow and moving seaward during periods of high flow. It always occurs in salinity <11 g l^{-1} (Uncles et al., 1998a), and generally at much lower salinity (mean 2.5 g l^{-1}). Concentrations as high as 20 g l^{-1} have been recorded during the summer months, when the TM was far upstream, and as low as 0.5g l^{-1} in winter, when the TM was mid-estuary (Uncles et al., 1998a). Average suspended sediment in the estuary is of the order of 200 mg l^{-1} (Jickells et al., 2000). The high turbidity in the estuary may have arisen partly as a result of the present-day lack of intertidal area available for sedimentation to take place (Andrews et al., 2000).

2.4. Policy responses

A number of policies are currently being implemented that aim to improve water quality in the Humber catchment, either directly or indirectly (see Fig. 3). These include ongoing upgrading of sewage treatment works under the Urban Waste Water Directive, increasing the area of designated nitrate-vulnerable zones under the Nitrates Directive, continual review of discharge consents for industry and the realignment of flood defences along the estuary. This latter policy is intended to increase the inter-tidal area within the estuary, partly to compensate for planned losses due to future port expansion and partly to reduce flood defence costs. It may also have added benefits of improvements in water quality by the removal of nutrients and contaminants due to settling out and trapping of particulate matter on the newly created intertidal areas, and an increase in amenity value by providing increased habitats for bird and fish life. In order to explore the likely effect of these and other policy responses on the future water quality of the Humber Estuary, we use scenarios, described in the next section.

3. Scenarios and policy analysis

In the context of EUROCAT, scenarios are used to investigate future fluxes from the catchment to the coastal zone and to explore what type of management strategies would be best adapted to a variety of possible futures. A scenario is a possible or optional future, not a predicted one. In each scenario, there is a different objective for water quality improvement, and a different combination of policy options is likely to be implemented according to environmental objectives, but these also depend on the general socio-economic and political context. Options might be related to: control measures on agriculture or industry; sewage treatment; cleaning up or removal of contaminated sediments; or managed realignment (realigning coastal defences to create intertidal areas, which can play a role in nutrient and contaminant removal). Practical measures are likely to be a combination of options. These options can be targeted at the level of the estuary or the wider catchment. The pragmatic approach taken here is to analyse the policy options likely to be implemented in each scenario at the present time—i.e. what impact would these policy options have if they were implemented now. In a second step, the scenarios provide a consistent framework to undertake a sensitivity analysis of how the outcome of the present time analysis would change under the three different possible future scenarios.

3.1. From national to regional scenarios

To help reduce uncertainty and aid in decision-making, we focused on distinct and radically different possible futures for the Humber. Three regional variants were derived from the UK national scenarios developed by Foresight (OST, 1999) and adapted to the Humber.

3.1.1. The 'business as usual' scenario

This is the baseline scenario, corresponding approximately to the 'world markets' scenario at national level (OST, 1999). It is a forward projection of the past 20-year trends in data, ignoring the recent sustainable development strictures. In this scenario, current legislation is only complied with in a formal way. For example, expected port expansion within the Humber Estuary over the next 20–25 years would lead to a loss of 0.2% of the intertidal area in the Humber Estuary, approximately 20 ha. In terms of flood defence around the estuary, hard defences would be maintained as far as possible, exacerbating the problem of coastal squeeze. Given the commitment of the UK to implement the Habitats Directive, compensation in the form of recreated habitats would have to be provided, but we could assume that this would be on the basis of minimum compliance. We would therefore expect a net loss of habitats in this scenario. Water quality objectives are likely to include exceptions for a variety of polluting industries. The standard of sewage treatment is likely to be relatively low (until recently, there was no treatment for the large, direct sewage discharges to the estuary). At the catchment level, agriculture is likely to remain relatively intensive and based on technology (e.g. GM crops) to sustain high yields, leading to no net reduction in nitrate input to rivers. Contaminant concentrations would also remain at their current level.

3.1.2. The 'policy target' scenario

In this scenario, current and prospective legislative targets and objectives are all met on time, according to the EU schedule, with a genuine effort to comply and/or to over-comply with the objectives. The Habitats Directive is likely to be implemented in a genuine attempt to achieve zero habitat loss. This would involve compensation for loss of intertidal area by recreating equivalent or increased habitat in another area. For example, the environmental regulator is creating 80 ha of intertidal habitat at Paull (Thorngumbald by moving back the flood defences. The scheme envisages providing compensation for flood defence works having an adverse impact on designated habitats and contributing some area towards alleviating coastal squeeze. This approach is close to the idea of 'mitigation banks' or 'land banks', whereby an extensive area of habitat is recreated ahead of development or natural loss, and which could facilitate the implementation of the Habitats Directive (Ledoux et al., 2000). In this scenario, there would be a net increase in intertidal area of 1200 ha by 2025, which would include compensation for losses through coastal squeeze. Sewage treatment around the estuary is likely to be of moderate standard, i.e. all sewage will receive secondary treatment prior to direct discharges, but there would be no tertiary treatment or phosphorus removal. In agriculture, application of fertiliser per unit area will be reduced through targeted policies and will be timed to reduce the runoff to rivers. Overall reduction of the nutrient load from the catchment into the estuary would be approximately 50%, as foreseen by the OSPAR convention and the various international agreements on the North Sea. The current water quality standards would be met at all times for all contaminants.

3.1.3. The 'deep green' scenario

In this scenario environmental protection is given maximum priority. It corresponds loosely to a state between the 'global sustainability' and 'local stewardship' national scenarios (OST, 1999). This represents some environmental state beyond that which could be achieved if current policies were implemented. The economy is also likely to be more regionalised. A 'deep green' scenario would involve substantial increases in intertidal areas, compensating for any new works or extension of existing installations, over and above coastal squeeze. The creation of mitigation banks in a formal and regulated setting might contribute to a strategic approach to an increase in biodiversity (Crooks and Ledoux, 2000). A recent RSPB study (Pilcher et al., 2002) identified 2858 ha with potential for intertidal habitat creation within the Humber Estuary. In this scenario, intertidal habitat would increase to 2500 ha, i.e. more than double the area in the 'policy target' scenario. Agriculture is likely to become less intensive. Riparian zones will be created along most riverbanks bordering farmland to reduce inputs of nutrients to rivers. Environmental schemes such as reed bed treatment will be widely applied for secondary sewage treatment, rather than hard technology, and tertiary treatment will be widespread, reducing nitrogen and phosphorus in sewage effluent. In this scenario, the long-run objective would be to approach 'natural' background levels of nutrient and contaminant fluxes through the system, with due allowance for the historical contaminant legacy stored in sediments.

3.2. Policy analysis

Policy analysis of water quality improvement options within EUROCAT focuses on two complementary approaches.

One policy question is: how effective are these measures at reaching the environmental targets, and at what cost? This is a cost-effectiveness issue: what measures or combination of measures are able to reach a certain water quality target for the least cost? The Water Framework Directive requires member states to carry out this analysis in all catchments. Data collected in previous scientific research programmes, e.g. LOIS, are useful for a preliminary broad-brush analysis. Existing data enable the estimation of fluxes of nutrients and selected contaminants in sub-catchments. A typology of these sub-catchments, characterised by the main economic drivers of environmental

Table 8
River catchments in the EUROCAT study

Catchment	Receiving sea	Jurisdiction	Overview
Axios	Aegean Sea (Mediterranean)	Greece/FYROM	Eutrophication from urban sewage and metal pollution from industry impacting the Gulf of Thermaikos
Po	Adriatic Sea (Mediterranean)	Italy	Eutrophication threat from industry, tourism, urbanisation
Idria	Adriatic Sea (Mediterranean)	Slovenia/Italy	Mercury pollution from mining
Elbe	North Sea	Germany, Czech Republic (90%), two others	Post-reunification changes in fluxes of nutrients
Humber	North Sea	UK	Post-industrial legacy of contaminated sediments, high nutrient and contaminant loads to North Sea
Rhine	North Sea	Germany, Switzerland (90%), seven others	Nutrient load, ecological effects and contaminants in dredged harbour material
Vistula	Baltic Sea	Poland	Change to market economy, nutrient and toxic substance loads to Baltic Sea
Provadiiska	Black Sea	Bulgaria	Eutrophication threat, industrial and urban expansion, change to market economy

For a full description, see the project web site at http://www.iia-cnr.unical.it/EUROCAT/project.htm.

change, allows the fluxes to be related, at least in part, to economic activities, and gives a broad picture of which sectors should be targeted to improve water quality in the estuary. In order to examine how changes in fluxes from the catchment translate into changes in the water quality of the estuary, a model will be invoked, the estuarine contaminant simulator ECoS (Gorley and Harris, 1998; Liu et al., 1998; Steen et al., 2002). Further economic analyses investigating marginal costs for pollution abatement in different sectors will inform decision-makers about which policy measure or combination of measures should be implemented to reach quality objectives in each scenario for the least cost.

There are also wider policy issues. Each of the options available to decision-makers to improve water quality has wider impacts in a range of areas, e.g. on biodiversity, on regional economic growth and on unemployment rates. Multi-criteria analysis is a tool to analyse the wider impact of policy options and how they are perceived by a variety of 'stakeholders' or interested parties. Its aim is to compare policy options by reference to an explicit set of evaluation criteria. In the context of EUROCAT, stakeholders provide input in identifying possible policy packages, as well as specific criteria within three broad categories (economic, environmental, and social). They are also asked to give weights to the evaluation criteria to determine their relative importance. The impact of each of the policy packages on the set of criteria is assessed through scores, either qualitative or quantitative, determined by scientific modelling and expert opinion. Policy options are ranked according to their impacts on the criteria, taking into account the stakeholder weights attributed to each criterion. An interesting aspect of multi-criteria analysis is that it can combine monetary and non-monetary scores, as opposed to cost–benefit analysis, which uses purely monetary evaluations. This is useful, in particular for environmental and social impacts, which are not always easily evaluated in monetary terms.

4. The European perspective

The same socio-economic drivers operate across river catchments throughout Europe, but the pressures they impose and the impacts of those pressures may be different in each case, due to differences in geography, climate, and political, economic and social conditions. The Humber catchment is one of eight case studies in the EUROCAT project, looking at integrated river basin and coastal zone management, and sustainable use of water resources throughout Europe (Table 8). The regional studies focus on four coastal seas (Mediterranean Sea, Baltic Sea, North Sea and Black Sea) and eight associated catchments characterised by relevant environmental and management issues.

The objectives of the project are:

- To collect and assess available information on sources, fluxes, and concentration levels of different nutrients and contaminants for each catchment region;
- To integrate this information with socio-economic data for each region, using the DPSIR framework, in order to help policy-makers and stakeholders understand the links between socio-economic activities and fluxes through the catchment;
- To develop the DPSIR framework into a practical working tool for a wide spectrum of users, including policy, planning and regulatory bodies located throughout Europe, with local, regional, national or international jurisdiction;
- To facilitate collaboration between natural and social scientists; and
- To actively include stakeholders from industry, agriculture, environmental organisations and citizens groups in the policy-making process.

The project aims to demonstrate the potential effects of a range of management strategies on future fluxes to the coastal seas, under different climatic and socio-economic conditions. It is hoped that the results from this project will help river basin managers throughout Europe to understand better the operation of their river catchments and coastal seas. This in turn should help to produce management strategies that will lead to optimum economic and ecological outcomes for each region.

References

Allen JI, Howland RMH, Bloomer N, Uncles RJ. Simulating the spring phytoplankton bloom in the Humber plume, UK. Mar Pollut Bull 1998;37:295–305.

Andrews JE, Samways G, Dennis PF, Maher BA. Origin, abundance and storage of organic carbon and sulfur in the Holocene Humber Estuary: emphasising human impact on storage changes. In: Shennan I, Andrews JE, editors. Holocene land–ocean interaction and environmental change around the North Sea 2000. (Geol Soc Lond 166, 145–170). special publication.

Axford S. Return of salmon to the Ouse system. In: Edwards AC, editor. Fisheries and the Humber: Proceedings of a Seminar. Hull: Environment Agency, 2001.

Bamforth PB. The derivation of input data for modelling chloride ingress from 8-year UK coastal exposure trials. Mag Concr Res 1999;51:87–96.

Binnie, Black, Veatch. Scoping report and brief for the Humber ChaMP. 2001. (60 pp).

CEFAS. Monitoring and surveillance of non-radioactive contaminants in the aquatic environment and activities regulating the disposal of wastes at sea, 1988–1989 1991. (91 pp).

CEFAS. Monitoring and surveillance of non-radioactive contaminants in the aquatic environment and activities regulating the disposal of wastes at sea, 1994. 1997. (61 pp).

Chambers BJ, Smith KA, Pain BF. Strategies to encourage better use of nitrogen in animal manures. Soil Use Manage 2000;16:157–161.

Collins KJ, Jensen AC, Lockwood APM, Turnpenny AWH. Evaluation of stabilized coal-fired power-station waste for artificial reef construction. Bull Mar Sci 1994;55:1251–1262.

Cordes KB, Mehra A, Farago ME, Banerjee DK. Uptake of Cd, Cu, Ni and Zn by the water hyacinth, *Eichhornia crassipes* (Mart.) solms from pulverised fuel ash (PFA) leachates and slurries. Environ Geochem Health 2000;22:297–316.

Crooks S, Ledoux L. Mitigation banking: potential applications in the UK. Environ Waste Manage 2000;3:1–8.

Davies DR, Kitchener JN. Massive use of pulverised fuel ash in concrete for the construction of a UK power station. Waste Manage 1996;16:169–180.

DEFRA, UK Agricultural Census Statistics for 1999 website: http://www.defra.gov.uk/esg/work_htm/publications/cs/census/digest/for_1999/pdf/digest_pdf.htm.

DEFRA, 2001. The protection of waters against agricultural nitrate pollution in England. How should England implement the 1991 Nitrates Directive? 44 pp.

DETR. Modern ports: a UK policy. 2000.

DETR (2001) Focus on Ports: 2000 Edition, pp. 86. The Stationery Office, on behalf of Department of Environment, Transport and the Regions.

DETR, 2002. Transport Statistics: Maritime Statistics: United Kingdom. Provisional Ports Statistics for the United Kingdom: 2001 Data Statistical release. http://www.transtat.dft.gov.uk/tables/2002/maritime/pdf/provdata.pdf.

Domone PL, Soutsos MN. Properties of high-strength concrete mixes containing PFA and ggbs. Mag Concr Res 1995;47:355–367.

DTI (2003) UK Energy Sector Indicators 2003. A supplement to the energy white paper 'Our energy future-creating a low-carbon enconomy'. 95 pp. http://www.dti.gov.uk/energy/inform/energy_indicators/index.shtml.

EA consent data: Environment Agency consent data, available frrom http://www.environment-agency.gov.uk.

EA (1994) Humber Estuary Quality Report 1994, pp. 83. Environment Agency.

EA. Humber Estuary. State of the environment 1998 1998. (41 pp).

EA. Humber Estuary. State of the environment 1998 technical report. 1998. (68 pp).

EA. The Humber Estuary—planning for the rising tides: options consultation document. 1999. (70 pp).

EA. The state of the environment of England and Wales: coasts. 1999. (201 pp).

Edwards AMC, Freestone RJ, Crockett CP. River management in the Humber catchment. Sci Total Environ 1997;194:235–246.

Freestone R. Oxygen balance in the Humber system. 1995. (33 pp).

Gameson ALH. The quality of the Humber Estuary 1961–1981 1982. (88 pp).

Gorley RN, Harris JRW. ECoS user's guide edition. Plymouth: Centre for Coastal and Marine Studies, 1998.

Goulding K. Nitrate leaching from arable and horticultural land. Soil Use Manage 2000;16:145–151.

Grant A, Middleton R. An assessment of metal contamination of sediments in the Humber Estuary, UK. Estuarine Coastal Shelf Sci 1990;31:71–85.

Gray MJ. The coastal fisheries of England and Wales, part III: a review of their status 1992–1994 1995.

Grigalunas T, Opaluch JJ, Luo MF. The economic costs to fisheries from marine sediment disposal: case study of Providence, RI, USA. Ecol Econ 2001;38:47–58.

Hardisty J. 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. 2001. (53 pp).

House WA, Leach D, Long JLA, Cranwell P, Smith C, Bharwaj L, Meharg A, Ryland G, Orr DO, Wright J. Micro-organic compounds in the Humber rivers. Sci Total Environ 1997;194:357–371.

House WA, Leach D, Warwick MS, Whitton BA, Pattinson SN, Ryland G, Pinder A, Ingram J, Lishman JP, Smith SM, Rigg E, Denison FH. Nutrient transport in the Humber rivers. Sci Total Environ 1997;194:303–320.

Hudson-Edwards KA, Macklin MG, Taylor MP. 2000 years of sediment-borne heavy metal storage in the Yorkshire Ouse basin, NE England, UK. Hydrol Process 1999;13:1087–1102.

Jarvie HP, Neal C, Robson AJ. The geography of the Humber catchment. Sci Total Environ 1997;194:87–99.

Jarvie HP, Neal C, Tappin AD. European land-based pollutant loads to the North Sea: an analysis of the Paris Commission data and review of monitoring strategies. Sci Total Environ 1997;194:39–58.

Jarvie HP, Neal C, Tappin AD, Burton JD, Harrow M, Hill L, Neal M. The water quality of the River Trent: from the lower non-tidal reaches to the freshwater tidal zone. Sci Total Environ 2000;251:335–367.

Jenner HA, Bowmer T. The accumulation of metals and toxic effects in *Nereis virens* exposed to pulverized fuel ash. Environ Monitor Assess 1992;21:85–98.

Jickells T, Andrews J, Samways G, Sanders R, Malcolm S, Sivyer D, Parker R, Nedwell D, Trimmer M, Ridgway J. Nutrient fluxes through the Humber Estuary—past, present and future. Ambio 2000;29:130–135.

LCM, 2000 digital dataset, available under licence from the Centre for Ecology and Hydrology Monks Wood, Abbots Ripton, Huntingdon, Cambs PE28 2LS, England. Website: http://www.ceh.ac.uk/data/lcm/LCM2000.shtm.

Ledoux L, Crooks S, Jordan A, Turner K. Implementing EU Biodiversity Policy: UK experiences. Land Use Policy 2000;17:257–268.

Leeks GJL, Jarvie HP. Introduction to the Land–Ocean Interaction Study (LOIS): rationale and international context. Sci Total Environ 1998;210:5–20.

Leeks GJL, Neal C, Jarvie HP, Casey H. The LOIS river monitoring network: strategy and implementation. Sci Total Environ 1997;194:101–109.

Liu YP, Millward GE, Harris JRW. Modelling the distributions of dissolved Zn and Ni in the Tamar Estuary using hydrodynamics coupled with chemical kinetics. Estuarine Coastal Shelf Sci 1998;47:535–546.

Longfield SA, Macklin MG. The influence of recent environmental change on flooding and sediment fluxes in the Yorkshire Ouse basin. Hydrol Process 1999;13:1051–1066.

Ministry of Agriculture, Fisheries and Food. Shoreline management plans: a guide for coastal defence authorities. 1995.

MAFF/CEFAS, Monitoring and surveillance of non-radiioactive contaminatns in the aquatic environment and activities regulating the disposal of wastes at sea. Report no.s 47, 49, 51, 52.

MAFF and ENTEC. Economic evaluation of the nitrate-sensitive areas scheme. 1998. (87 pp).

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

McCandless D. Shellfisheries in the Humber and Coastal Waters. In: Edwards AC, editor. Humber Estuary Seminar: Fisheries and the Humber. Leeds: Environment Agency, 1991.

McHarg K. Salmon in the Trent. In: Edwards AC, editor. Fisheries in the Humber: Proceeding of a Seminar. Hull: Environment Agency, 2001.

Meharg AA, Wright J, Leeks GJL, Wass P, Osborn D. Spatial and temporal regulation of the pesticide dieldrin within industrial catchments. Sci Total Environ 2000;251:255–263.

Middleton R, Grant A. Heavy metals in the Humber Estuary: Scrobicularia clay as a pre-industrial datum. Proc Yorkshire Geol Soc 1990;48:75–80.

Millward GE, Glegg GA. Fluxes and retention of trace metals in the Humber Estuary. Estuarine Coastal Shelf Sci 1997;44:97–105.

Morris A. The estuaries of the Humber and Thames. In: Salomons W, Bayne BL, Duursma EK, Forstner U, editors. Pollution of the North Sea: an assessment. Springer-Verlag, 1988.

Morris AW, Allen JI, Howland RJM, Wood RG. The estuary plume zone—source or sink for land-derived nutrient discharges. Estuarine Coastal Shelf Sci 1995;40:387–402.

Mort D, Woolley M. The counties and regions of the UK. Economic, industrial and social trends in local authority areas. 3rd ed..Gower Publishing, 1994. (180 pp)

Murby P. The causes, extent and implications of intertidal change—a regional view from eastern England. PhD thesis. Kingston-upon-Hull: University of Hull, 2001.

Murray LA, Norton MG, Nunny RS, Rolfe MS, 1980. The field assessment of effects of dumping wastes atsea: 6 The disposal of sewage sludge and industrial waste of the River Humber, pp. 35. MAFF Directorate of Fisheries Research.

Neal C, Robson AJ. A summary of river water quality data collected within the Land–Ocean Interaction Study: core data for eastern UK rivers draining to the North Sea. Sci Total Environ 2000;251:585–665.

Neal C, Turner H. A bibliography for the conclusions to the special issue of Science of the Total Environment concerning 'The water quality of UK rivers entering the North Sea'. Sci Total Environ 2000;251:575–584.

Newell RC, Seiderer LJ, Hitchcock DR. The impact of dredging works in coastal waters: a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. Oceanogr Mar Biol Annu Rev 1998;36:127–178.

NRA. The water quality of the Humber Estuary 1989 1989. (33 pp).

NRA. The water quality of the Humber Estuary 1989–1990 1993. (108 pp).

NRA. The Humber Estuary. Humber Estuary Standing Conference. 1995.

OECD. OECD core set of indicators for environmental performance reviews. 1993. (39 pp).

Office for National Statistics, 2002. Census 2001: First results on population for england Wales. 61 pp.

Oguchi T, Jarvie HP, Neal C. River water quality in the Humber catchment: an introduction using GIS-based mapping and analysis. Sci Total Environ 2000;251:9–26.

OST. Environmental futures. Report for the UK's National Technology Foresight Programme. 1999.

Pandian NS, Balasubramonian S. Leaching behavior of Indian fly ashes by an odometer method. J Test Eval 2000;28:403–408.

Peak District Mines Historical Society Website http://www.tidza.demon.co.uk/page7.html.

Perkins PV. A theoretical approach to the assessment of boron phytotoxicity resulting from the amelioration of minespoil with pulverised fuel ash. Land Degrad Dev 1996;7:239–256.

Perkins PV, Vann AR. The early performance of deciduous trees grown in acidic minespoil ameliorated with pulverized fuel ash. Land Degrad Rehab 1995;6:57–67.

Pilcher R, Burston P, Davis R. Seas of change. The potential area for inter-tidal habitat creation around the coast of mainland Britain. 2002. (32 pp).

Powlson DS. Tackling nitrate from agriculture. Soil Use Manage 2000;16:141.

Rogers SI, Millner RS, Mead TA. The distribution and abundance of young fish on the east and south coast of England (1981–1997) 1998. (133 pp).

Sanders RJ, Jickells T, Malcolm S, Brown J, Kirkwood D, Reeve A, Taylor J, Horrobin T, Ashcroft C. Nutrient fluxes through the Humber Estuary. J Sea Res 1997;37:3–23.

Smith SDA, Rule MJ. The effects of dredge-spoil dumping on a shallow water soft-sediment community in the Solitary Islands Marine Park, NSW, Australia. Mar Pollut Bull 2001;42:1040–1048.

Steen R, Evers EHG, Van-Hattum B, Cofino WP, Brinkman UAT. Net fluxes of pesticides from the Scheldt Estuary into the North Sea: a model approach. Environ Pollut 2002;116:75–84.

Turner RK, Lorenzoni I, Beaumont N, Bateman IJ, Langford IH, McDonald AL. Coastal management for sustainable development: analysing environmental and socio-economic changes on the UK coast. Geograph J 1998;164:269–281.

Uncles RJ, Easton AE, Griffiths ML, Harris C, Howland RJM, King RS, Morris AW, Plummer DH. Seasonality of the turbidity maximum in the Humber–Ouse Estuary, UK. Mar Pollut Bull 1998;37:206–215.

Uncles RJ, Wood RG, Stephens JA, Howland RJM. Estuarine nutrient fluxes to the Humber coastal zone, UK, during June 1995. Mar Pollut Bull 1998;37:225–233.

Van den Berg GA, Meijers GGA, Van der Heijdt LM, Zwolsman JJG. Dredging-related mobilisation of trace metals: a case study in the Netherlands. Water Res 2001;35:1979–1986.

Vanderburgt C. Dealing with contaminated dredged materials with reference to the Oslo Convention 1972 and the New Paris Convention 1992. Mar Pollut Bull 1994;29:296–299.

Wilkinson WB, Leeks GJL, Morris A, Walling DE. Rivers and coastal research in the Land–Ocean Interaction Study. Sci Total Environ 1997;194:5–14.

Woodworth PL, Tsimplis MN, Flather RA, Shennan I. A review of the trends observed in the British Isles mean sea level data measured by tide gauges. Geophys J Int 1999;136:651–670.

Yorkshire Water, 2001 Yorkshire Water Humbercare website: http://www.yorkshirewater.com/yourenvironment/humbercare_main.html.