Coastal Zone Topics: Process, Ecology & Management

2. The Solway and Cumbrian coasts

Edited by P.D. Jones & R.G. Chambers

A volume based on a local meeting of the Estuarine and Coastal Sciences Association, Penrith, UK

April 1993

Coastal Zone Topics Editorial Panel for Volume 2:
A.L. Buck (JNCC) & J.R. Pomfret (ECSA)

ISSN 1353-6168

Coastal Zone Topics: Process Ecology & Management
is a joint publication series of the Joint Nature Conservation Committee (JNCC)
and the Estuarine and Coastal Sciences Association (ECSA).

Contents

Page

Preface

The Cumbria coast, extending from Morecambe Bay to the Solway Firth, is a region of marked contrasts. From the mouth of the Duddon Estuary to Ravenglass, parts of the coastline comprise extensive sand dunes, whilst between St Bees and Whitehaven there are steep, rocky cliffs. Inland, the terrain rises rapidly towards the fells of the Lake District and the high level of tourism within the Lake District National Park extends to the coast, particularly in areas around Ravenglass and Silloth. Some areas of the coast, such as around Haverigg and the Eskmeals Firing Range, are relatively undeveloped whilst heavy industry is sited at several points. Shipbuilding has taken place at Barrow for well over a century and in more recent times the nuclear and chemical industries have established facilities at Sellafield and Whitehaven. At a number of locations there is stark evidence of the now defunct iron and steel industry which used locally mined ore and coal. The unsightly slag and spoil heaps are obvious reminders of these previously important local industries. Although not as busy as in former times, there are commercial ports operating at Barrow, Whitehaven, Workington and Silloth and the erstwhile busy coal-exporting harbour at Maryport is now used by fishing vessels and leisure craft. Most of the population along this coastline is concentrated in this series of port towns.

The Solway Firth forms a natural boundary between England and Scotland with different legal systems operating each side of the border. The Inner Solway is characterised by its shifting channels and sandbanks which have presented hazards for shipping over the years. There are extensive areas of saltmarsh which attract large numbers of birds and because of this areas of the estuary have been designated as a Site of Special Scientific Interest, a National Nature Reserve, a Special Protection Area and a Ramsar site, and the Solway Firth is also proposed as a Special Area of Conservation. Salmon migrate through the estuary to spawn in streams in England and Scotland and there are traditional salmon-netting fisheries licensed by both the English and Scottish authorities.

On the English side, the hinterland of the Inner Firth is largely an agricultural plain, but the City of Carlisle lies just on the tidal limit of the River Eden, the largest river to discharge into the firth. The north side of the Solway Firth and the Galloway coast are relatively sparsely populated, with only a small number of towns. Much of the coastline is rocky, with some areas of cliffs, and is very attractive, and inland the area is hilly with a considerable amount of forest. Tourism plays a large part in the economy of Dumfries and Galloway Region and many coastal sites are used for recreation. There are some pockets of industry along the Scottish coast of the Solway Firth, such as at Annan where there is a large pharmaceutical works, and at Chapelcross nuclear power station. In the outermost part of the firth the busy town and port of Stranraer lies on Loch Ryan.

Overall the region has great variety with some areas of outstanding beauty, but is not without some challenging environmental problems and management issues that need to be resolved. The papers in this volume were presented at a local meeting of the Estuarine and Coastal Sciences Association (ECSA) at Newton Rigg Agricultural College, Penrith in April 1993. The topics covered were as diverse as the local geography and sixteen papers discussing the physical, chemical and biological aspects of the region were presented. The meeting culminated in a visit to the BNFL site at Sellafield and more than 30 ECSA members were shown around parts of the plant not normally accessible to the public.

Acknowledgements

The success of the meeting was largely due to the enthusiasm and hard work of the organising committee: Irene Gize, Elaine Fisher, Jane McNamara and especially Dick Chambers who acted as the local secretary.

It is a pleasure to acknowledge the assistance of the many referees who willingly gave their time, and the invaluable editing support of Ali Buck and John Pomfret as editors of the series.

Generous financial support for the publication of this volume was provided by English Nature, National Rivers Authority (now the Environment Agency), North West Water plc and Scottish Natural Heritage.

Peter D. Jones

The estuaries of the Solway and Cumbrian coasts

A.L. Buck & N.C. Davidson

There are eight estuaries along the Solway and Cumbrian coasts. Dominated by the Inner Solway Firth, this region comprises around 10% of the total estuarine resource of the UK in terms of total area and extent of intertidal flats and saltmarshes. The estuaries are of great wildlife interest for their intertidal flats, saltmarshes and associated sand dunes and are notable for a large proportion of the UK breeding population of natterjack toads *Bufo calamita*. The estuaries of the Solway and Cumbrian coasts are of major significance for their wintering waterfowl, and the Inner Solway Firth in particular is of international importance for the very large numbers of wintering waterfowl that it supports, including the entire wintering population of Svalbard barnacle goose *Branta leucopsis*. Although mostly small, the eight estuaries of the Solway and Cumbrian coasts are not subject to intensive urban and industrial use and they remain some of the least modified and unspoiled estuaries in the UK.

A.L. Buck & N.C. Davidson, Joint Nature Conservation Committee, Monkstone House, City Road, Peterborough, PE1 1JY

Introduction

There are a large number of estuaries in the UK and these vary greatly in location, size, form, the processes that shape them and the wildlife they support. Historically, many estuaries have been subject to a variety of human uses. Today they are still subject to numerous activities, some of which, such as land-claim, habitat loss and change, infrastructure developments, or the discharge of pollutants, impact on the quality of the sea and the coastal fringe. Estuaries are consequently a current focus for much of the effort in developing integrated management initiatives (e.g. English Nature 1992).

An essential basis for the management of estuaries and for other parts of the coastal zone is consistent baseline information about the features and uses of the area set in the wider context. Although there is much information on wildlife and human uses of UK estuaries, much is scattered through a wide variety of often inaccessible sources. This paper provides an overview of the estuaries of the Solway and Cumbrian coast, and sets this in a national and international context.

Sources of information

Much of the information summarised in this paper is derived from *An inventory of UK estuaries* (Buck 1993), which provides a standardised, 4-8 page summary of each of the 163 estuaries in the UK and their key wildlife features, conservation status and human uses. Coupled with the earlier national overview *Nature conservation and estuaries in Great Britain* (Davidson *et al.* 1991) the inventory provides essential baseline data for many features of conservation and management interest on the estuaries of the UK coastline. It forms one of a suite of summarised information sources for the coast compiled by the Joint Nature Conservation Committee, along with the *Directory of the North Sea Coastal Margin* (Doody *et al.* 1993) and the 17 regional Coastal Directory reports that together cover the whole UK coastline; the relevant volume including this region is Barne *et al.* (1996).

Data presented are drawn largely from material collected during 1989-90 (updated to 1993 where appropriate) for the Nature Conservancy Council's national review of estuaries (Davidson *et al.* 1991). Saltmarsh data comes from the surveys of Burd (1989), which covered saltmarshes mostly >0.5 ha; sand dune data is derived from the *Sand dune survey of Great Britain,* summarised by Radley (1994) and Dargie (1993).

The definition of an estuary is based on a broad, multidisciplinary approach derived from that used in NERC (1975): a partially enclosed area at least partly composed of soft tidal shores, open to saline water from the sea, and receiving freshwater from rivers, land run-off or seepage (Davidson *et al.* 1991). Estuaries included are those which have, or had until recently, a tidal channel longer than 2 km, or intertidal soft sediment shores 0.5 km or wider along at least 2 km of shoreline.

Features of the estuarine resource of the Solway and Cumbrian coasts

There are eight estuaries on the coast of Cumbria

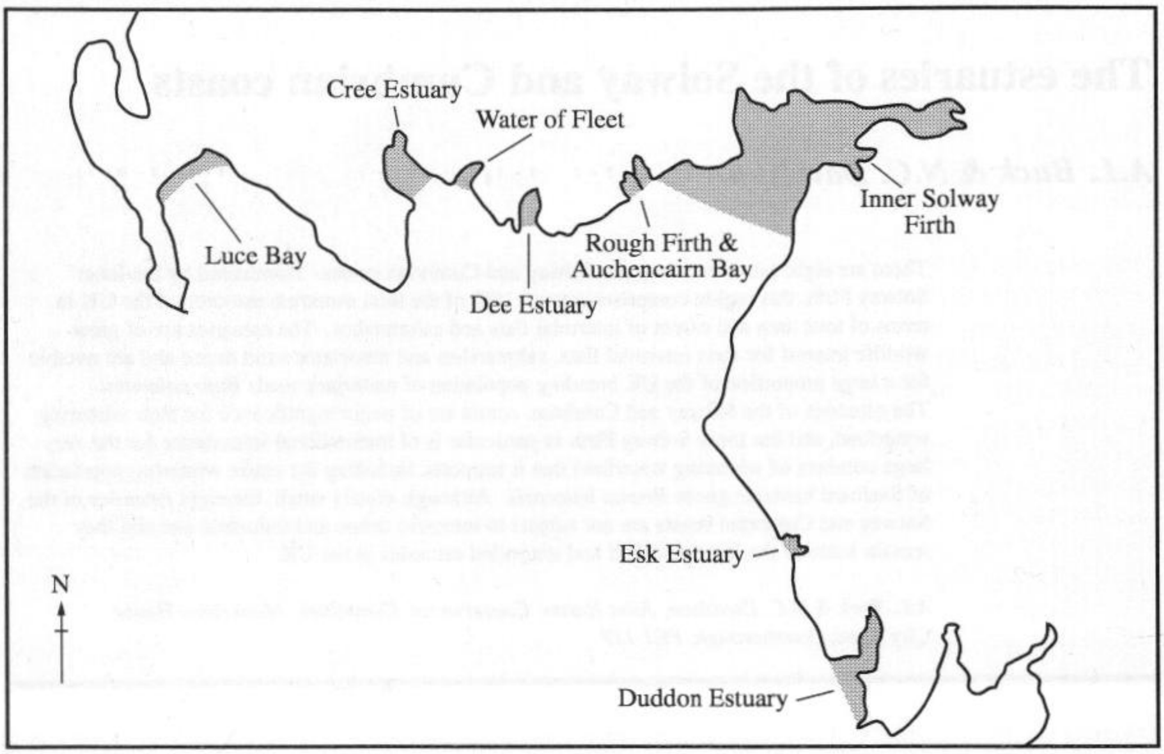


Figure 1 The location of estuaries on the Solway and Cumbrian coasts.

and the Solway Firth (Figure 1). (Morecambe Bay, the very large embayment at the mouth of five rivers, lies partly in Cumbria and in Lancashire, and is excluded from the scope of this paper.) In the south lies the sandy coastal plain of the Duddon Estuary and the bar-built Esk Estuary that is the confluence of three rivers, the Irt, Mite and Esk. The Inner Solway Firth straddles the border between England and Scotland and is of complex geomorphology, for although its hydrodynamics are similar to coastal plain estuaries, its overall size and geomorphological complexity set it apart. On the northern shore of the outer Firth there are a series of fjardic estuaries, set in the glaciated lowland coast of southern Scotland: Rough Firth and Auchencairn Bay; the Dee Estuary that flows into Kirkcudbright Bay; the Water of Fleet and the Cree Estuary which both flow into Wigtown Bay. These estuaries are relatively shallow and sediment-filled and their upper reaches are well sheltered, where the surrounding land rises steeply. Further west along the northern shore of the firth is Luce Bay, a broad linear shore with two small freshwater inflows discharging across the sandy bay into the outermost reaches of the Solway.

All of these estuaries are macrotidal (i.e. their spring tidal range exceeds 4 m) and there is a general increase in tidal range northwards and westwards along the coast, apart from the Inner Solway Firth where the funnel shape of the firth heightens the tidal range to 8.4 m. As a result of this large tidal range, large amounts of sediment are held in suspension in the waters of the Solway Firth and the intertidal sediments of the Inner Firth in particular are known to be very mobile (see Puxley, this volume).

The physical characteristics of the estuaries on the Solway and Cumbrian coasts are shown in Table 1. The largest estuary is the Inner Solway Firth which dominates the estuarine resource of the region and forms over 70% of the total estuarine area of these Solway and Cumbrian estuaries. The Duddon Estuary is the second largest estuary, followed by the Cree Estuary. Together these three estuaries form 90% of the estuarine resource of this coastline. The five remaining estuaries are small, each covering less than 1,500 ha. Correspondingly, the Inner Solway Firth, the Duddon Estuary and the Cree Estuary each have the largest intertidal areas of the estuaries in the region. Most of the estuaries in this area have only small subtidal areas, and it is only in the Inner Solway Firth, the Cree Estuary and the Dee Estuary that the subtidal area forms more than 20% of the individual estuary area.

Saltmarshes occur on all of the estuaries on this coast and the region is of note for the presence of both typically northern vegetation communities and species (e.g. saltmarsh flat-sedge *Blysmus rufus*) and typically southern vegetation communities and species (e.g. common sea-lavender *Limonium vulgare*). Saltmarshes are most extensive on the Inner Solway Firth, where the wide range of saltmarsh communities covers 2,925 ha and shows an outstanding geomorphology with terracing, dynamic creek systems and cliffs caused by

Table 1 Physical characteristics of estuaries of the Solway and Cumbrian coast.

Estuary	*Centre grid ref.*	*Geomorph. type*	*Total area ha)*	*Intertidal area (ha)*	*Saltmarsh (ha)*	*Tidal range (m)*	*Subtidal (%)*
39. Duddon Estuary	SD1977	Coastal plain	6,092	5,056	540	8.1	17
40. Esk Estuary	SD0896	Bar built	1,134	1,049	158	7.7	7
41. Inner Solway Firth	NY2762	Complex	42,056	27,550	2,925	8.4	34
42. Rough Firth & Auchencairn Bay	NX8451	Fjard	1,290	1,289	135	6.7	0
43. Dee Estuary	NX6747	Fjard	1,144	825	77	6.7	28
44. Water of Fleet	NX5753	Fjard	790	790	28	6.7	0
45. Cree Estuary	NX4655	Fjard	4,728	3,340	445	6.7	29
46. Luce Bay	NX1855	Linear shore	1,228	1,196	36	5.3	3

Source: Davidson (1996).

erosion. Although there is a range of saltmarsh vegetation on each of the estuaries in this area, cord-grass *Spartina* forms more than 50% of the saltmarsh vegetation within Rough Firth and Auchencairn Bay and the Water of Fleet.
The saltmarshes of the Solway and Cumbrian coast are of particular interest for they remain largely intact and grade into sand dune vegetation, grasslands, freshwater or other transitional vegetation. This is in contrast to many other saltmarshes in the UK, where the upper reaches of saltmarshes and their transitional vegetation have been lost to land-claim or truncated by sea defences.

There are areas on the Solway and Cumbrian coast where the land is sufficiently low-lying and where the availability of wind-blown sand has allowed the development of extensive areas of sand dunes. The sand dune systems of North Walney and Sandscale adjacent to the Duddon Estuary and Ravenglass adjacent to the Esk Estuary are considered to be of national importance. The dunes and saltmarshes of the Inner Solway Firth, the Esk and Duddon Estuaries are also of note, for between them they support around 50% of the UK breeding population of natterjack toad *Bufo calamita* (Davidson *et al.* 1991). Along the northern shore of the Solway the relatively steep surrounding shoreline has hindered the development of sand dunes, apart from at Luce Bay where the extensive sand dunes of Torrs Warren support a wide and nationally important diversity of dune vegetation.

The estuaries of the Solway and Cumbria coasts are of major importance for their wintering waterfowl populations including the presence of large numbers of geese (Table 2). Two estuaries are internationally important for the total populations that they support: the Inner Solway Firth supports an average winter population of over 50,000 waterfowl and the Duddon Estuary supports over 20,000 waterfowl. The Inner Solway Firth is of major importance for its wintering waterfowl, which is described more fully in this volume by Quinn *et al.* The Firth supports internationally important populations of 11 species of waterfowl and a further ten nationally important species, and of particular note is the entire Svalbard (Spitzbergen) breeding population of barnacle goose *Branta leucopsis* which winters exclusively on the Solway. Ten nationally important populations of waterfowl occur at the Duddon Estuary, of which two are internationally important. The Cree Estuary also supports internationally and nationally important populations and Luce Bay supports internationally important populations of two species of geese. Although the remaining estuaries (Esk, Rough Firth and Auchencairn Bay, Dee Estuary and Water of Fleet) support much smaller numbers of wintering waterfowl (Table 2), their populations contribute to those of a coastline that supports over 150,000 wintering waterfowl, with additional populations using these estuaries as moulting and migration staging areas.

Conservation of estuaries of the Cumbrian and Solway coasts

The wildlife and earth science importance of estuaries on the Cumbrian and Solway coast is recognised by the number and variety of conservation designations and protections placed upon them. All have at least part of their intertidal area notified as a Site of Special Scientific Interest (SSSI); there are thirteen SSSIs associated with these estuaries. Caerlaverock, part of the Inner Solway Firth, and North Walney, part of the Duddon Estuary, have also been declared as National Nature Reserves (NNRs). The importance of the Inner Solway for waterfowl is recognised by its designation both as a wetland of international importance under the Ramsar Convention and as a

Table 2 Wintering waterfowl on estuaries of the Solway and Cumbrian coasts.

Site (names used are bird count sites)	*5-year mean numbers of wintering waterfowl*	*1992/93 peak waterfowl numbers*	*1992/93 peak wildfowl numbers*	*1992/93 peak wader numbers*	*Species occurring at levels of national or international (*) importance*
Duddon Estuary	34,929	43,068	8,016	35,052	Pintail*, knot*, redshank, sanderling, oystercatcher, curlew, red-breasted merganser, dunlin, grey plover, shelduck
Irt/Mite/Esk Estuary	4,073	4,311	1,722	2,589	-
Solway Estuary	123,935	116,572	32,799	83,773	Barnacle goose*, pink-footed goose*, knot*, bar-tailed godwit*, curlew*, turnstone*, oystercatcher*, redshank*, pintail*, whooper swan*, scaup*, dunlin, shelduck, wigeon, ringed plover, golden plover, goldeneye, shoveler, cormorant, grey plover, black-tailed godwit
Rough Firth	1,795	2,498	419	2,079	-
Auchencairn Bay	4,208	2,825	590	2,235	-
Fleet Bay (Water of Fleet)	604	602	181	421	-
Kirkcudbright Bay (Dee Estuary)	1,363	1,434	739	695	-
Wigtown Bay (Cree Estuary)	16,603	11,870	5,292	6,578	Pink-footed goose*, whooper swan, curlew
Luce Bay	2,594	3,329	554	2,775	Greenland white-fronted goose*, greylag goose*

Source: Stroud & Craddock (1996). Key: * = species occurring at levels of international importance.

Special Protection Area (SPA) under the EC Directive on the conservation of wild birds. In addition, the Solway Firth is proposed as a Special Area of Conservation (SAC) under the EU Habitats and Species Directive.

There are numerous other wildlife and landscape conservation sites on these estuaries. Part of the Esk Estuary lies within the Lake District National Park and the Inner Solway Firth is an Area of Outstanding Natural Beauty (AONB). The Inner Solway Firth, Rough Firth and Auchencairn Bay and the Water of Fleet are National Scenic Areas, a Scottish landscape designation.

Human influences

The human uses and influences on the estuaries of the Cumbrian and Solway coasts are summarised in Table 3. None of the estuaries in this region are subject to extensive major urban or industrial use. The largest variety of human uses occur on the Duddon Estuary and the Inner Solway Firth, which include the greatest diversity of urban or industrial use on estuaries in this region. These uses are, however, few and are not intensive. On the Duddon Estuary these include the docks and chemical works on the town of Barrow. There are small urban areas around the Inner Solway Firth, namely the towns of Annan, Silloth and Dumfries which are the focus for industrial activities. Apart from the power station and chemical works near Annan, industry on the Inner Solway Firth is generally only small-scale. With very localised industrial activity and little urbanisation around the Solway and Cumbrian coasts, the water quality of the estuaries of this region is very good.

Most of the estuaries in this area have at least one small harbour, used largely by fishing craft. Fish-netting, trawling for shrimps, lobster- and crab-potting, dredging for molluscs and other forms of exploitation of the natural resource are a common feature of this part of the coastline. These activities are not intensive, although in recent years hydraulic dredging for cockles has occurred on the Inner Solway Firth. Due to concerns over its impact not only on the cockle population but also on sediment characteristics, sediment fauna, eelgrass beds and shorebirds, dredging for cockles has been banned. Dredging from boats was banned in 1992 under the Inshore Fisheries Act 1984, and subsequent to an amendment to the Act introduced in 1994, cockling using land-based vehicles was

Table 3 Human uses and influences on estuaries of the Solway and Cumbrian coasts.

Estuary	*Human use type*				*Water*
	urban	*industrial*	*rural**	*recreational*	*quality*
39. Duddon Estuary	○	○	●	●	A
40. Esk Estuary			●	○	A
41. Inner Solway Firth	○	○	●	○	(1) 2
42. Rough Firth & Auchencairn Bay			●	○	1
43. Dee Estuary	○		●	○	2,1
44. Water of Fleet			●	○	1
45. Cree Estuary			●	○	(2) 1
46. Luce Bay			●	○	(2) 1

Source: Davidson (1996). Key: * includes natural resource exploitation; ● = major human use; ○ = minor human use.

also banned. These regulatory measures are subject to regular review. Other forms of exploitation of natural resources occur on many estuaries of the Cumbrian and Solway coasts, of which grazing on sand dunes and saltmarshes, wildfowling and bait-collection are the most widespread.

The estuaries in this region are also a focus for recreational pursuits where sailing is the most widespread activity. Other water-based recreation, such as power-boating and water-skiing, occurs on many estuaries but is localised. Although there are small areas on some estuaries on the Cumbria and Solway coasts that are popular for some forms of beach recreation, these activities are, by and large, not intensive.

The national and international context

The contribution of the estuaries of the Solway and Cumbrian coasts to the total UK resource is summarised in Table 4. Overall the eight estuaries form a significant proportion of the total area of estuaries in the UK, of the total estuarine intertidal area, the area of estuarine intertidal flats and of the total saltmarsh area in the UK.

Table 4 Solway and Cumbrian coast estuaries in relation to the total UK estuarine resource.

	Total for Solway & Cumbrian coast estuaries	*% of total UK area*
Total estuary area (ha)	58,462	10.1
Subtidal area (ha)	17,367	12.8
Intertidal area (ha)	41,095	6.7
Intertidal flats area (ha)	36,751	13.1
Shoreline length (km)	466	4.8
Main tidal channel length (km)	185.3	7.0
Saltmarsh area (ha)*	4,344	10.5
Sand dune area (ha)*	2,267	4.5

*Saltmarsh and sand dune data are available only for GB (i.e. excluding Northern Ireland). Sand dune areas include those associated with estuaries and those on open coasts, with an estimated total for GB from Dargie (1996).

Within this region the Inner Solway Firth makes a major contribution to the total estuary area, as it forms 72% of the total area and 67% of the total intertidal area. It also supports 67% of the saltmarsh in the estuaries along this coast. Of the remaining estuaries, only the Duddon and Cree Estuaries make major contributions to the total estuary area (10% and 8% respectively).

Overall the 58,500 ha of estuarine habitat on the Solway and Cumbrian coast forms a small, but nevertheless significant, part (approximately 3%) of the estuarine habitat of north-west Europe (Davidson *et al.* 1991).

These eight estuaries on the Cumbrian and Solway coast are mostly small in comparison with the major estuaries and embayments on the north-west coast of England, which have been greatly modified by the proximity of large conurbations and the industrial activities that have occurred on them. In contrast, the estuaries of the Solway Firth and the Cumbria coast are some of the most unspoilt and undeveloped estuaries in the UK, and are of significant importance for their wildlife and conservation value.

References

Barne, J.H., Robson, C., Kaznowska, S.S., Davidson, N.C., & Doody, J.P., *eds.* 1996. *Coasts and seas of the United Kingdom. Region 13 Northern Irish Sea: Colwyn Bay to Stranraer, including the Isle of Man.* Peterborough, Joint Nature Conservation Committee.

Buck, A.L. 1993. *An inventory of UK estuaries. Volume 3. North-west Britain.* Peterborough, Joint Nature Conservation Committee.

Burd, F. 1989. *Saltmarsh survey of Great Britain.* Peterborough, Nature Conservancy Council. (Research and survey in nature conservation, No. 17.)

Dargie, T.C.D. 1993. *Sand dune survey of Great Britain. Volume 2. Scotland.* Peterborough, Joint Nature Conservation Committee.

Dargie, T.C.D. 1996. *Sand dunes. In: Coasts and seas of the United Kingdom. Region 13 Northern Irish Sea: Colwyn Bay to Stranraer, including the Isle of Man,* ed. by J.H. Barne, C. Robson, S.S. Kaznowska, N.C. Davidson & J.P. Doody, 48-52. Peterborough, Joint Nature Conservation Committee.

Davidson, N.C., Laffoley, D.d'A., Doody, J.P., Way, L.S., Gordon, J., Key, R., Drake, C.M., Pienkowski, M.W., Mitchell, R.M., & Duff, K.L. 1991. *Nature conservation and estuaries in Great Britain.* Peterborough, Nature Conservancy Council.

Davidson, N.C. 1996. Estuaries. *In: Coasts and seas of the United Kingdom. Region 13 Northern Irish Sea: Colwyn Bay to Stranraer, including the Isle of Man,* ed. by J.H. Barne, C. Robson, S.S. Kaznowska, N.C. Davidson & J.P. Doody, 69-72. Peterborough, Joint Nature Conservation Committee.

Doody, J.P., Johnston, C., & Smith, B. 1993. *Directory of the North Sea coastal margin.* Peterborough, Joint Nature Conservation Committee.

English Nature. 1992. *Caring for England's estuaries. An agenda for action.* Peterborough, English Nature.

Natural Environment Research Council. 1975. *Estuaries research.* Natural Environment Research Council Publication series 'B', No. 9.

Puxley, C.J. 1997. The Solway Firth: its past and present maritime usage with special reference to Silloth. *In: Coastal Zone Topics, 2:* 7-18.

Quinn, J., Still, L., Carrier, M.F., & Kirby, J.S. 1997. The importance and distribution of waterfowl on the Inner Solway Firth. *In: Coastal Zone Topics, 2:* 109-125.

Radley, G.R. 1994. *Sand dune survey of Great Britain. Volume 1. England.* Peterborough, Joint Nature Conservation Committee.

Stroud, D.A., & Craddock, D.M. 1996. Migrant and wintering waterfowl. *In: Coasts and seas of the United Kingdom. Region 13 Northern Irish Sea: Colwyn Bay to Stranraer, including the Isle of Man,* ed. by J.H. Barne, C. Robson, S.S. Kaznowska, N.C. Davidson & J.P. Doody, 140-145. Peterborough, Joint Nature Conservation Committee.

The Solway Firth: its past and present maritime usage with special reference to Silloth

C.J. Puxley

At low water the Solway Firth comprises a large area of intertidal sandbanks. Charts of the sandbanks and channels at 20-year intervals from 1840 to 1980 show that these sandbanks are very mobile and that the navigable channels have shifted dramatically. Historically, the dynamic nature of the sandbanks has influenced the development of the maritime towns of the Solway. This effect continues today, for although navigation channels have been marked with buoys, the sandbanks shift so rapidly that the buoys may not indicate the present position of channels. The consequence of the dynamic nature of these sandbanks on the development of, and access to, the port of Silloth is discussed.

Captain C.J. Puxley, Dock and Marine Superintendent, Associated British Ports, Silloth, Cumbria, CA5 4JQ

Introduction

For the purposes of this paper, the area of the Solway Firth is taken as the sea area north-east of a line drawn between Abbey Head in Scotland and St Bees Head in England (Figure 1). Between these two points is a distance of 19 nautical miles, or just under 22 statute miles. In the inner part of the Firth, the banks narrow rapidly at the mouth of the River Annan, with just 1 mile between the Scottish and English shores. The water area widens slightly further upstream before reaching the mouths of the Rivers Esk and Eden. The tidal influence of the Solway extends only a very short distance up these two rivers.

A large proportion of the Solway Firth comprises shifting sandbanks which, at low water, extend north-eastwards from a line between Balcary

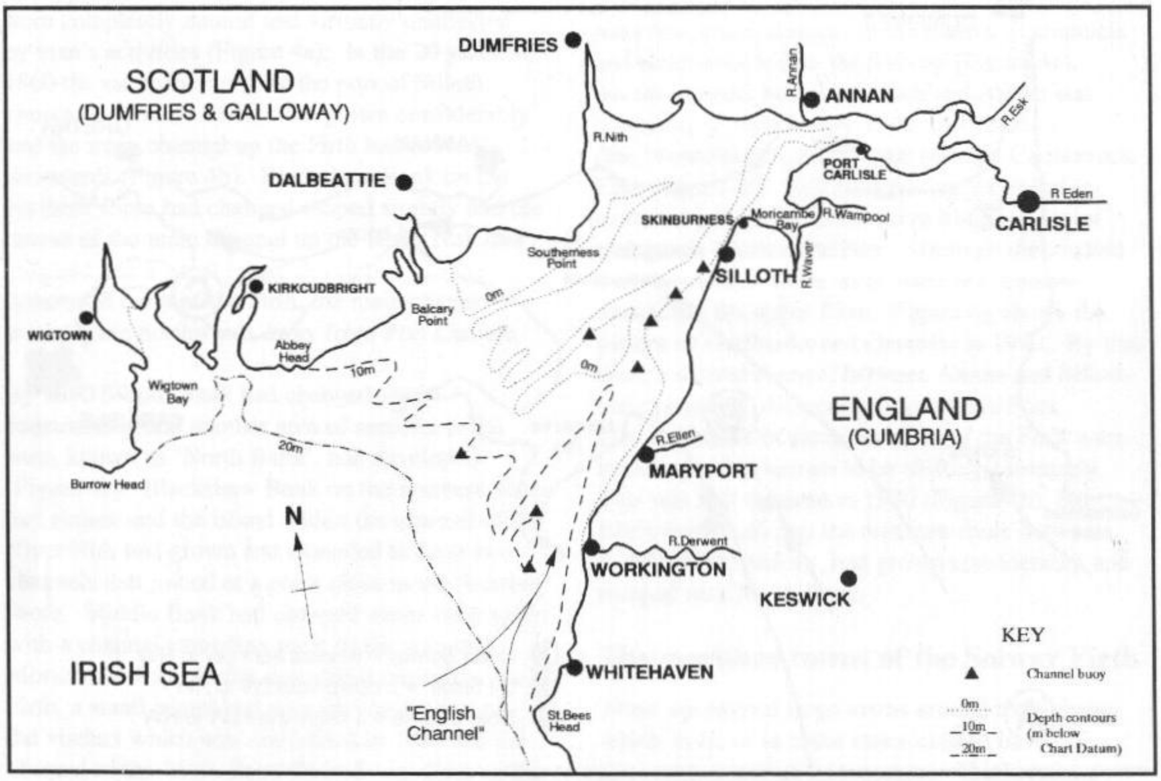


Figure 1 The Solway Firth.

Point on the Scottish shore to Maryport on the English shore (Figure 1). Today the only navigable shipping channel is on the south-east side of the Firth and it extends upstream only as far as Annan. This channel is surveyed and marked as required by the Silloth Harbour Authority, from the beginning of the shallows upstream as far as the port of Silloth. As this channel is constantly on the move, the Admiralty books and charts state that navigation of the channel, and the upper Solway in general, should not be attempted without local knowledge. The channel buoy positions may not necessarily indicate the line of the present channel, as will be described later in this paper.

Tidal streams within the Solway Firth

Strong westerly winds raise heavy seas in the Solway, which become particularly steep and irregular when the westerly wind is blowing against a strong, west-flowing ebb tide. The rising tidal stream of the Solway Firth runs generally in a north-easterly direction. However, where the sandbanks are exposed, the streams follow strongly in the direction of the channels. When the banks are submerged, the surface stream can run more weakly along the channels. The following description of tidal streams refers to the whole body of water moving up the Solway, rather than the funnelled concentrations of water in the narrow channels only.

Off Silloth, the spring tidal rate increases to 4 nautical miles per hour (knots) approaching High Water. It reaches speeds of 5 knots off Southerness and 6 knots off Annan (Figure 2). The duration of the ingoing stream decreases rapidly east of Southerness. At Silloth, the period of the flood tide is just 5 hours in an approximately 12.5 hour cycle. At the entrance to the River Eden in the uppermost reaches of the Firth, the flood tide is a mere 3 hours. In the upper Solway, the rate and range of the tide is considerable and tidal rise and fall is extremely rapid, especially at spring tides when a tidal bore can form. This very rapid incoming tide was noted in Sir Walter Scott's novel *Red Gauntlet*: "the Solway tide rising so rapidly on the fatal sands, that well-mounted horsemen may lay aside hopes of safety, if they see the white surge advancing whilst they are yet some distance from the shore".

Figure 3 shows a cross-section of the entrance to New Dock, Silloth and illustrates the tidal range at the port. The lowest astronomical tide falls 1.8 m below the bottom of the dock and without dock gates, the basin would empty completely at Low Water on spring tides. The highest ever 'predicted' height of the tide at Silloth is 8.2 m on the dock gauge. On 10th March 1993 there was a predicted height of 8.1 m but the weather was good at that time and no flooding occurred in the area.
The outcome could have been very different if the weather had been bad, for low atmospheric pressure

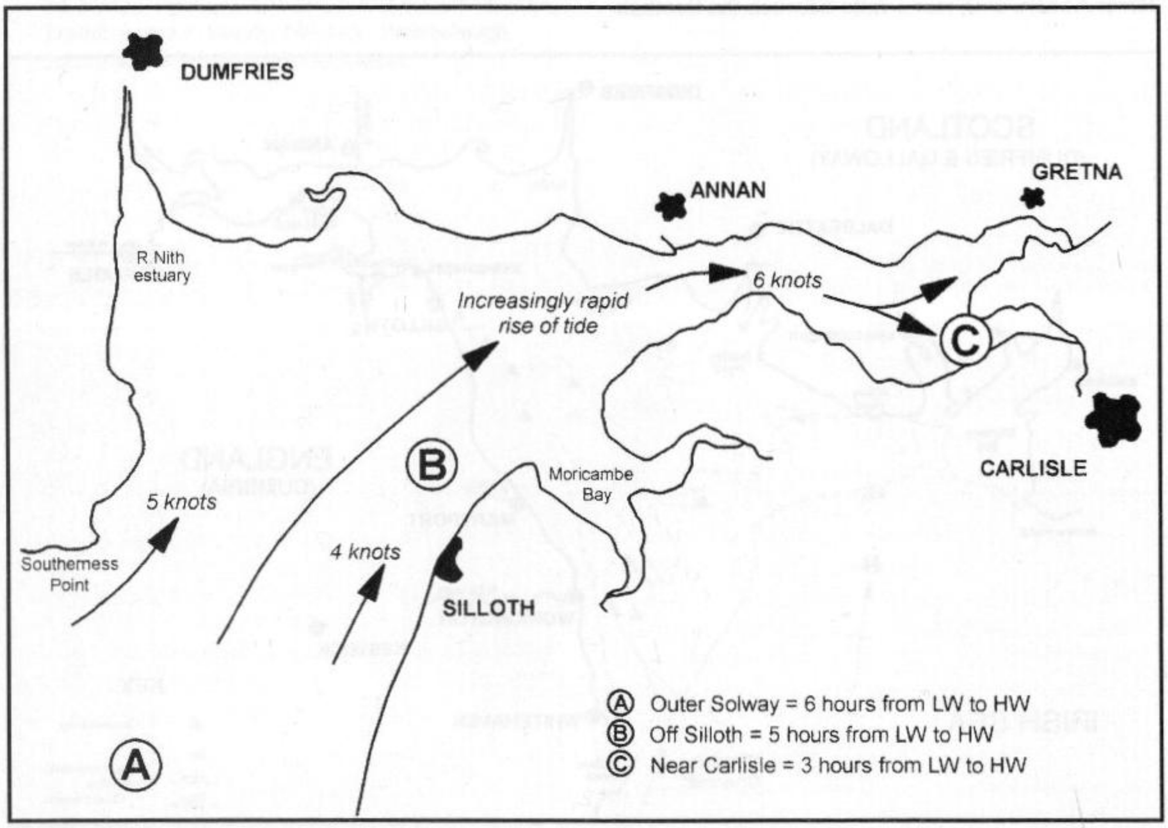


Figure 2 Spring tide flood currents in the Solway Firth.

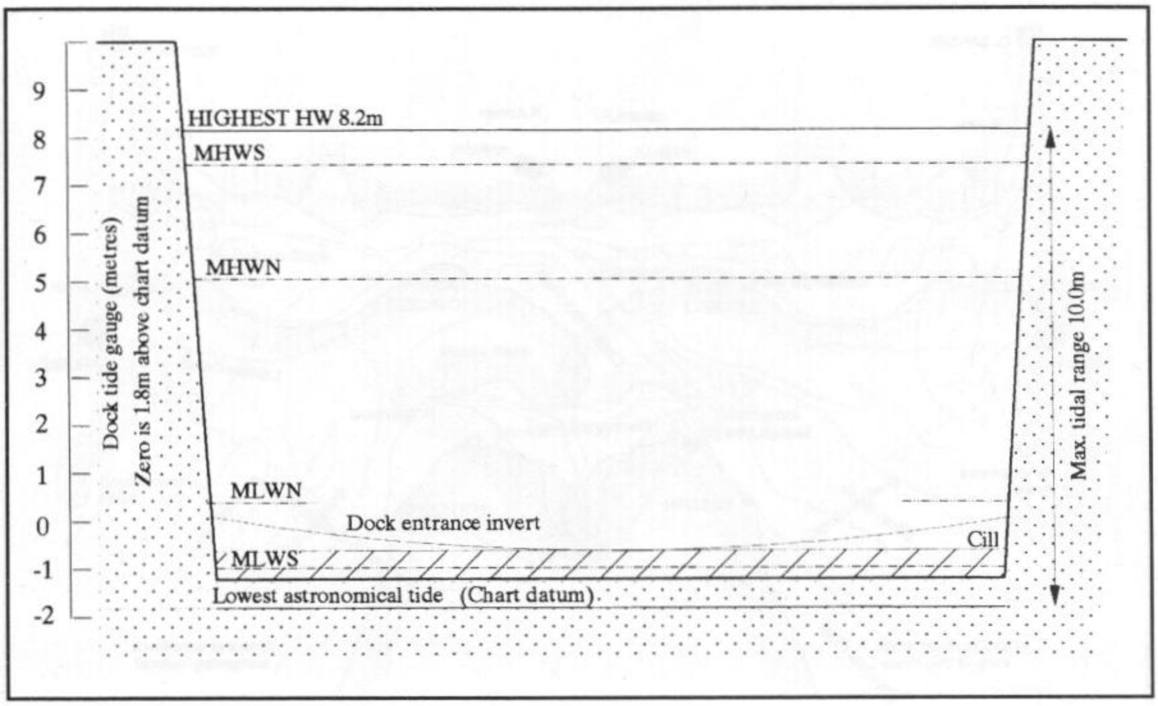


Figure 3 Profile of the New Dock entrance, Silloth.

systems over the area can increase tide heights by as much as 2 m above predicted levels.

The shifting nature of the sandbanks

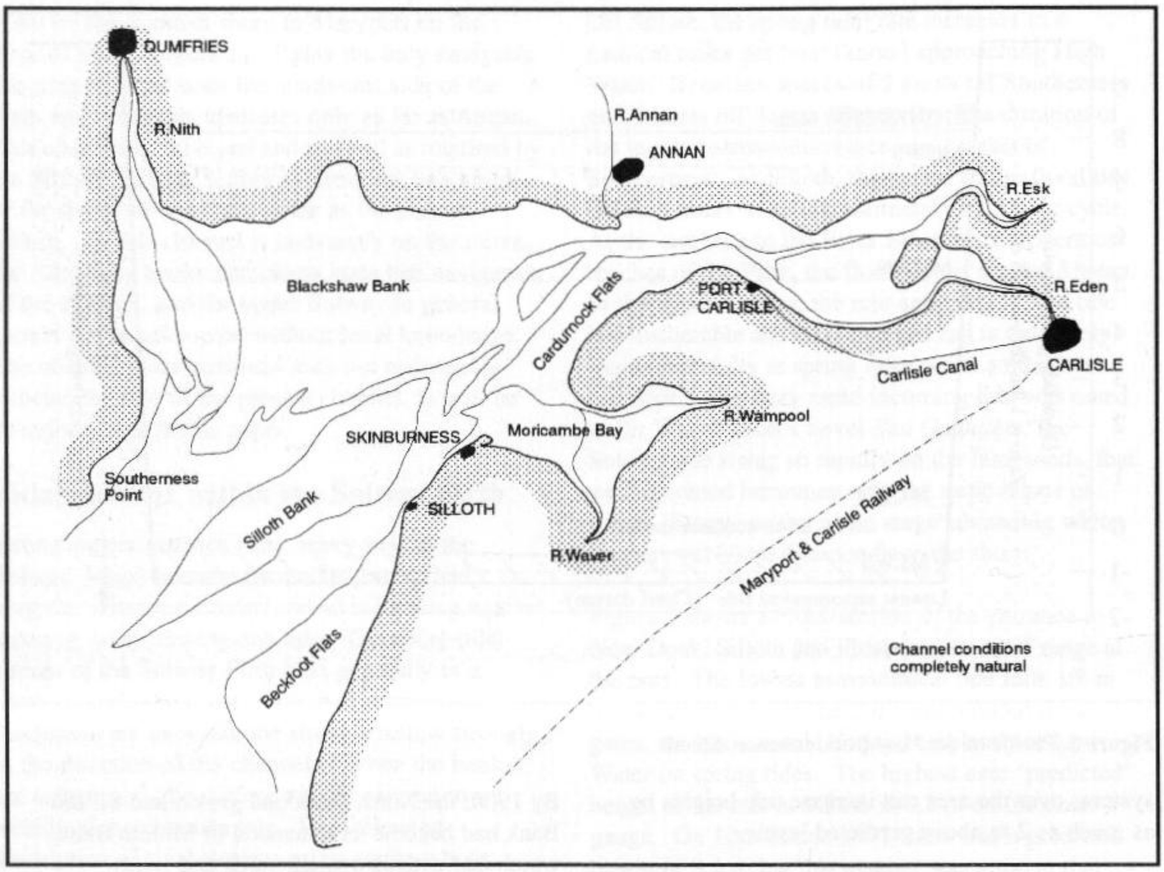
Figure 4 shows the position of the channels and sandbanks of the Solway at 20-year intervals from 1840 to 1980 and illustrates the dynamic nature of the upper Firth. In 1840 the channel conditions were completely natural and virtually unaffected by man's activities (Figure 4a). In the 20 years to 1860 the sandbank north of the port of Silloth, known as 'Middle Bank', had grown considerably and the main channel up the Firth had moved westwards (Figure 4b). Blackshaw Bank on the northern shore had changed shaped slightly and the course of the main channel up the River Nith had widened and a small island developed. In the uppermost parts of the Firth, the main channel was moving northwards away from Port Carlisle.

By 1880 Silloth Bank had changed shape considerably and another area of sandflat to the west, known as 'North Bank', had developed (Figure 4c). Blackshaw Bank on the northern shore had shrunk and the island within the channel of the River Nith had grown and extended to form two channels that joined at a point close to the Scottish shore. Middle Bank had changed shape once again with a channel extending most of the way into Moricambe Bay. In the uppermost reaches of the Firth, a small island had appeared to the east of the viaduct which was completed in 1871 and the channel of the River Eden flowed very close to the southern shore.

By 1900, the North Bank had grown and Silloth Bank had become an extension of Middle Bank, which had extended southwards and south-westwards (Figure 4d). The direct channel from Silloth through to Annan had completely closed. In the upper Solway, the island east of the viaduct had become well-established and the islands that were between the Esk and the Eden had now linked to the mainland. Between 1900 and 1920 there were few major changes in the pattern of channels and sandbanks within the Solway (Figure 4e), but the channel between Silloth and Annan was beginning to reform. By 1940, this channel (the 'Swatchway') had broken through Cardurnock Flats (Figure 4f). Silloth Bank had extended to cover very large areas and there had been major changes in Moricambe Bay. Although the viaduct was removed in 1936, there were few notable changes in the upper Firth. Figure 4g shows the pattern of sandbanks and channels in 1960. By this time, a second channel between Annan and Silloth had opened up, dissecting Cardurnock Flats. The sandbanks in the outer areas of the Firth were unsurveyed but known to be shifting constantly. This was still the case in 1980 (Figure 4h), but Blackshaw Bank, on the northern shore between Annan and Dumfries, had grown considerably and merged with North Bank.

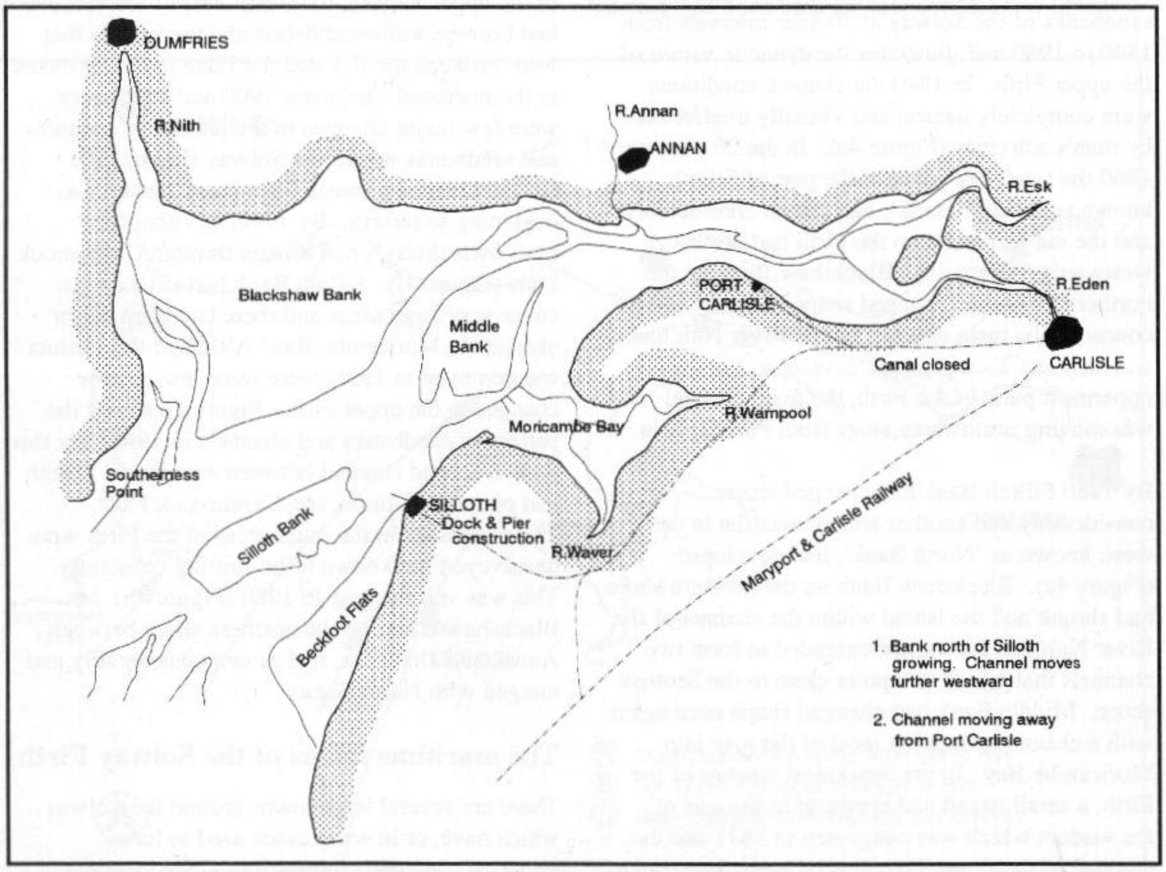
The maritime towns of the Solway Firth

There are several large towns around the Solway which have, or in some cases used to have, important maritime connections. The locations of these towns are shown in Figure 1. On the



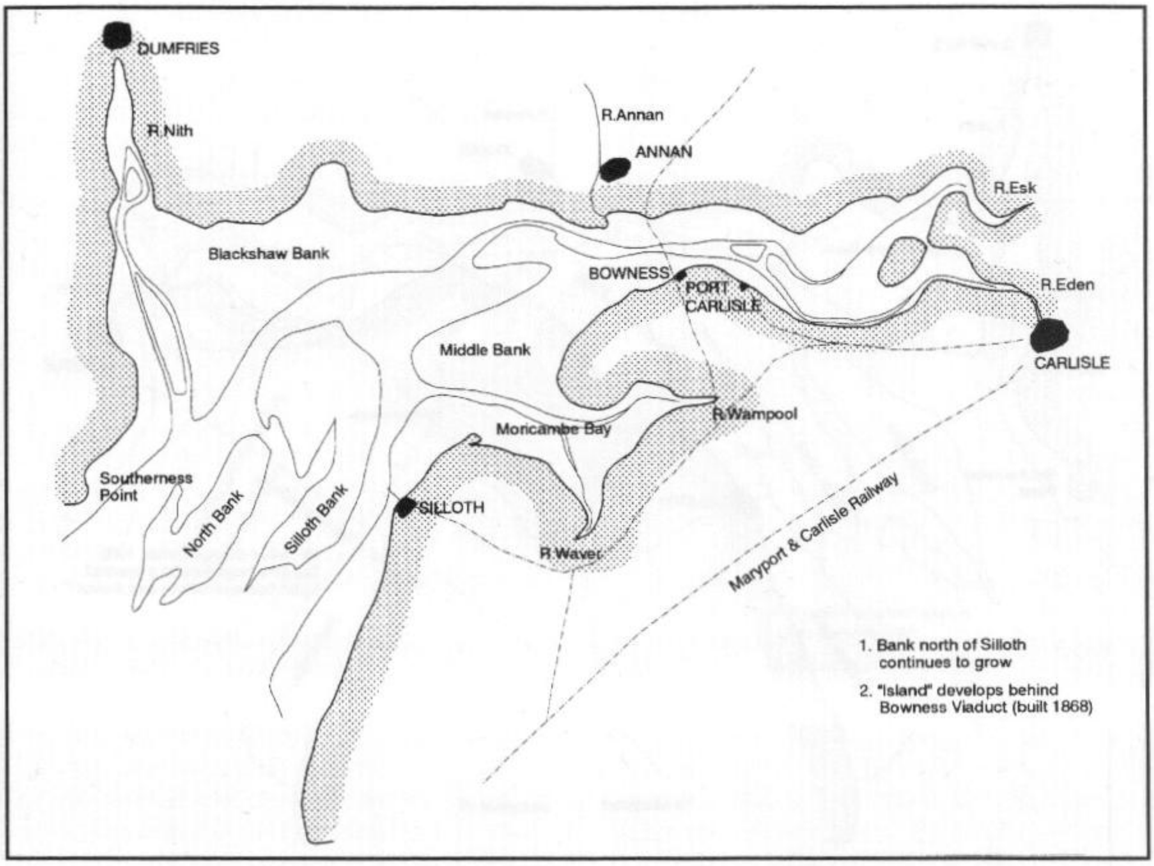
Channel conditions completely natural

Figure 4a Historical changes in the position of navigable channels in the Solway Firth 1840.



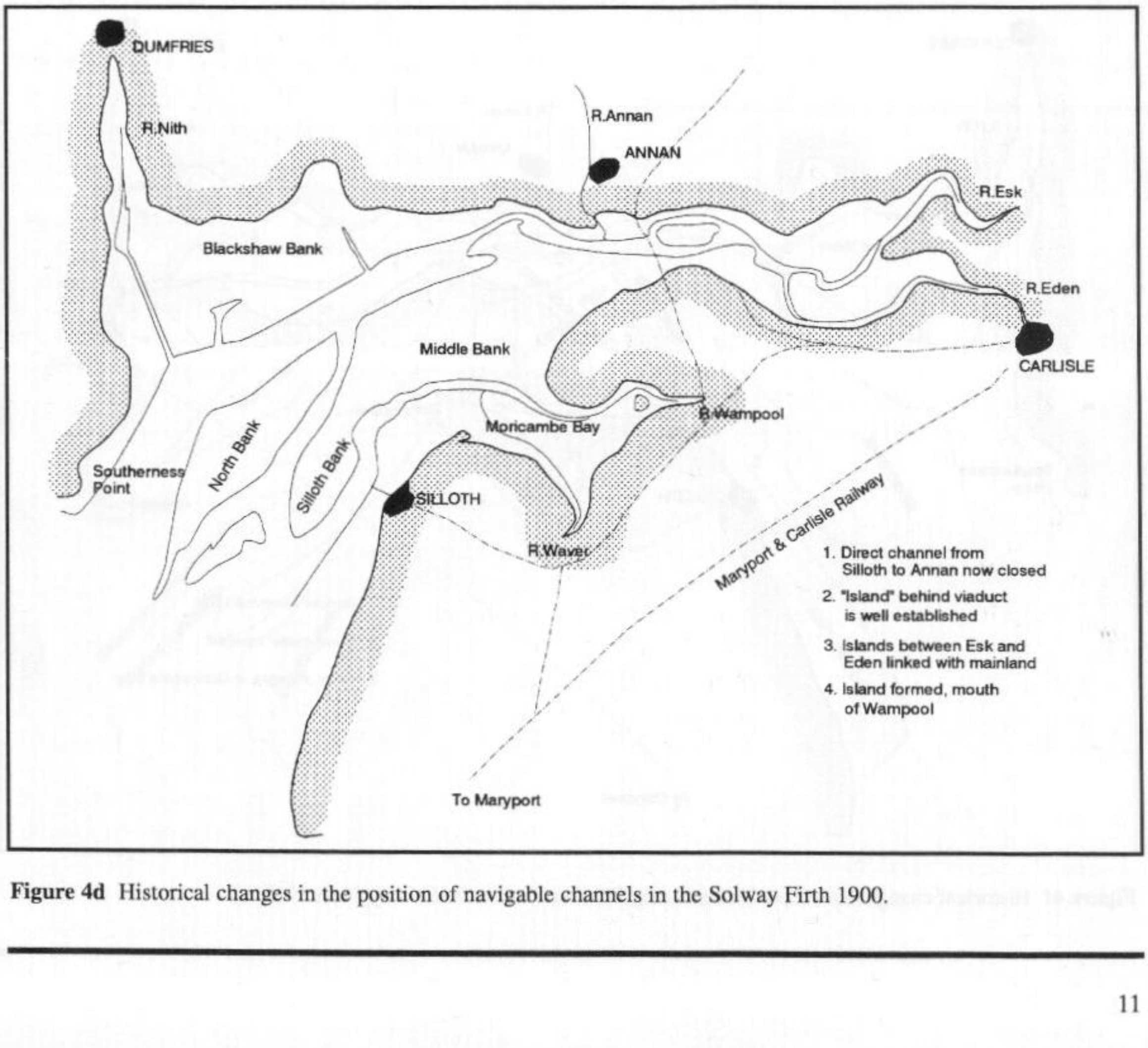
1. Bank north of Silloth growing. Channel moves further westward
2. Channel moving away from Port Carlisle

Figure 4b Historical changes in the position of navigable channels in the Solway Firth 1860.



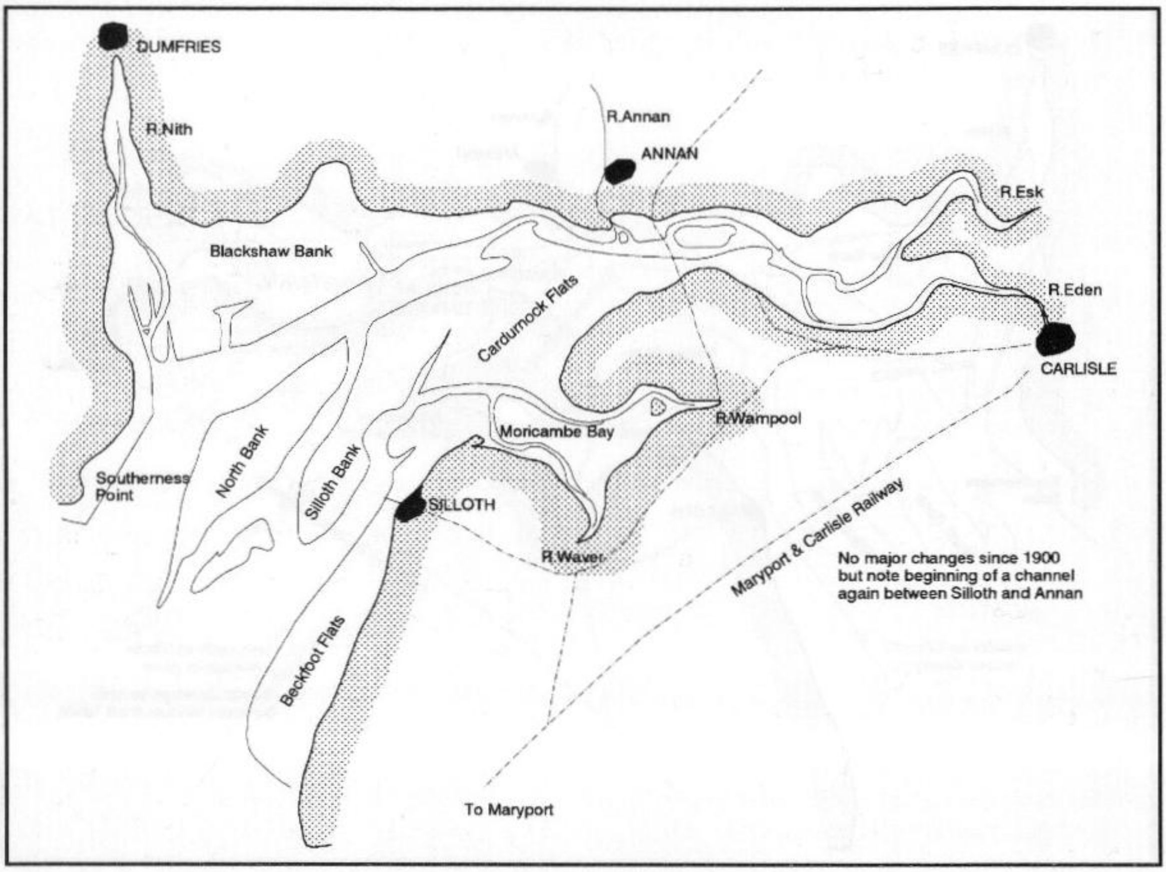
1. Bank north of Silloth continues to grow
2. "Island" develops behind Bowness Viaduct (built 1868)

Figure 4c Historical changes in the position of navigable channels in the Solway Firth 1880.



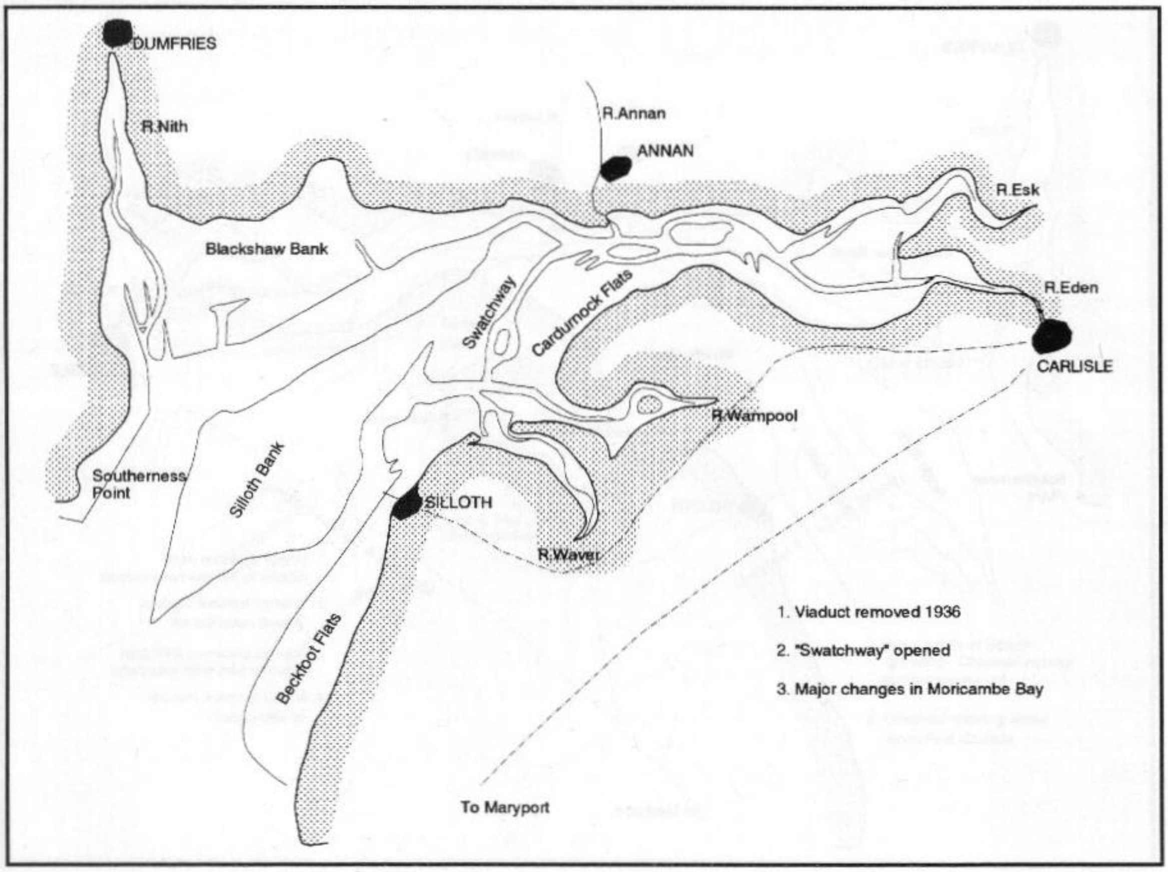
1. Direct channel from Silloth to Annan now closed
2. "Island" behind viaduct is well established
3. Islands between Esk and Eden linked with mainland
4. Island formed, mouth of Wampool

Figure 4d Historical changes in the position of navigable channels in the Solway Firth 1900.



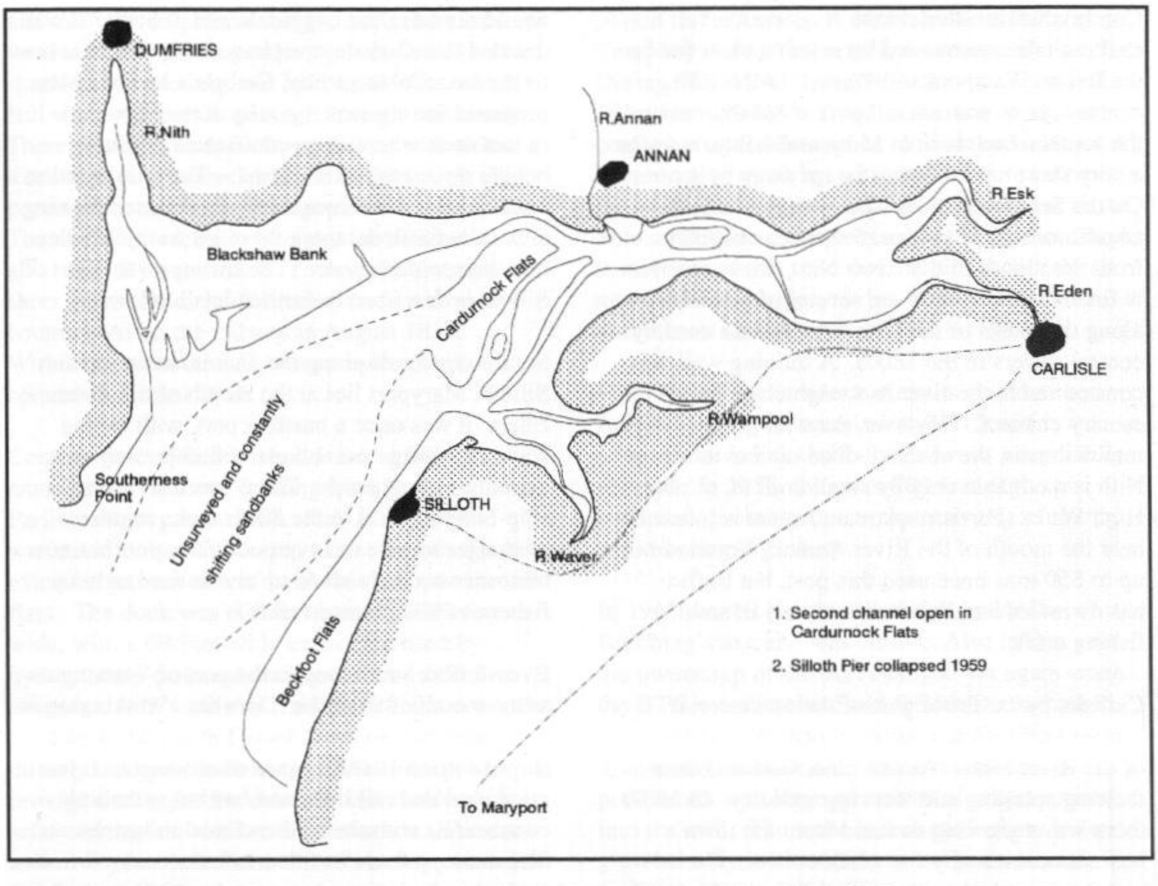
No major changes since 1900
but note beginning of a channel
again between Silloth and Annan

Figure 4e Historical changes in the position of navigable channels in the Solway Firth 1920.



1. Viaduct removed 1936
2. "Swatchway" opened
3. Major changes in Moricambe Bay

Figure 4f Historical changes in the position of navigable channels in the Solway Firth 1940.



1. Second channel open in Cardurnock Flats
2. Silloth Pier collapsed 1959

Figure 4g Historical changes in the position of navigable channels in the Solway Firth 1960.

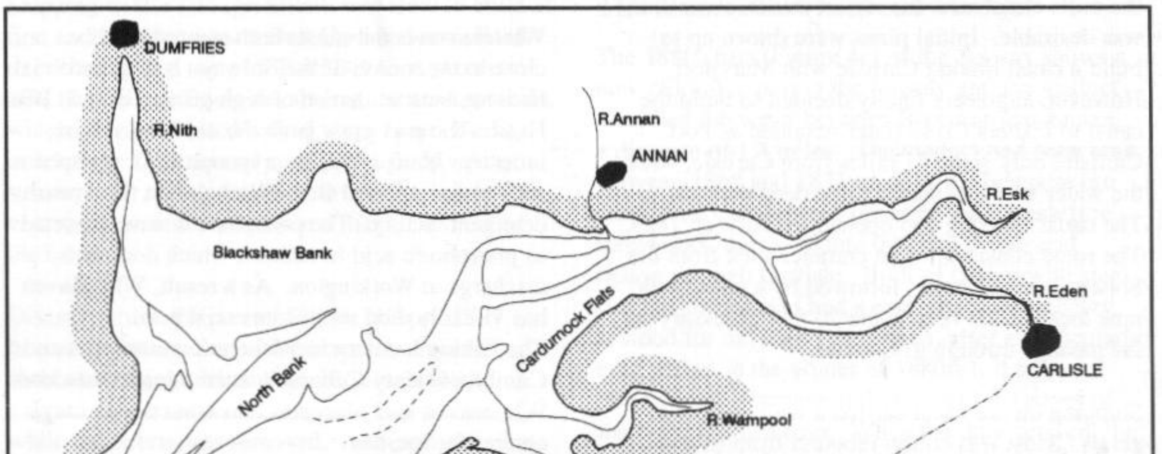


Figure 4h Historical changes in the position of navigable channels in the Solway Firth 1980.

Cumbrian coast Moricambe Bay, a wide but shallow inlet surrounded by marshland, is fed by the Rivers Wampool and Waver. In the 12th century, there was a small port at Skinburness on the southern entrance to Moricambe Bay, but after a very short time this was swept away by storms. On the Scottish shore of the Firth the largest coastal town is Dumfries, 5½ miles upstream from the mouth of the River Nith, where the river is first bridged. There are several old stone quays along the banks of the Nith, which were used by coastal traders in the 1800s. A training wall was constructed in the river to straighten and open the estuary channel. However, the wall gradually fell into disrepair, the channel silted up and today the Nith is navigable only by small craft at, or near, High Water. Further upstream Annan is located near the mouth of the River Annan. Vessels of up to 650 tons once used this port, but traffic has dwindled and now consists only of small fishing craft.

Carlisle, by far the largest of the commercial centres in the area, is situated near the mouth of the River Eden. At one time, Carlisle had a thriving spinning and weaving industry. In 1807 there was a growing demand from the town's business community for a link between Carlisle and the sea, to take advantage of the commercial seaborne trading routes. As most of the cotton for the mills came from Liverpool docks, a sea route was desirable. Initial plans were drawn up to build a canal linking Carlisle with Maryport. However, engineers finally decided to build the canal to Fishers Cross (later renamed as Port Carlisle) only some 11 miles from Carlisle, where the water was considered to be deep enough. The canal was dug and opened to traffic in 1823. The route consisted of an entrance lock from the Solway, a small basin, followed by a canal with nine locks to lift vessels the 70 feet necessary for the passage through to Carlisle.

Shipping on the canal carried a wide variety of goods. Most was cotton inbound from Liverpool and large quantities of miscellaneous goods were outbound. The canal had, however, a very short life and closed in 1853, just 30 years after it was built. After its closure, the canal was filled-in and the route used for a railway track from Port Carlisle to the city.

By 1850, it had become apparent that the shallow waters of the upper Solway, especially around Port Carlisle, were unsuitable for the growing size of shipping. One alternative was to use the Carlisle to Maryport railway, to the tidal ports of West Cumberland. There were many at Carlisle who considered that the West Cumberland mining communities would be less than co-operative and would not have the city's interests at heart. It was decided that Carlisle must have independent access to the sea. Consequently, Carlisle's businessmen proposed the construction of a deep-water port (a wet dock where ships could remain afloat behind dock gates at all times). The only location considered suitable was a largely deserted farming area called Silloth, about 20 miles from Carlisle, but close to deep water. The history of the port of Silloth is described in further detail below.

South-westwards along the Cumbrian coast from Silloth, Maryport lies at the mouth of the River Ellen. It was once a bustling port, with sailing ships exporting coal and ore and importing vast quantities of pit props. There was also a small ship-building yard in the docks and a regular passenger service to Liverpool. The port has now almost completely silted up and is used only by fishermen and pleasure craft.

Even further south-west is the port of Workington at the mouth of the River Derwent. Workington is the largest port in the Solway Firth, able to take ships of up to 10,000 tonnes dead weight. It has good road and rail links and has long-standing connections with the coal and steel industries. The main products handled include steel rail tracks, coal, chemicals, petroleum products, scrap steel, timber and liquid sulphur.

Whitehaven is the most south-westerly port, close to the mouth of the Solway. It is an artificial harbour, built in the lee of high ground near St Bees Head. The port grew from the old local mining industry. Until 1992, large quantities of phosphate rock were imported from North Africa for a nearby detergent factory. The phosphate is now imported as phosphoric acid in tankers, which dock and discharge at Workington. As a result, Whitehaven has virtually died as a commercial port.
The fishing industry in Whitehaven continues and Cumbria County Council is attempting to turn both Whitehaven and Maryport into attractive heritage centres for tourism.

The development of Silloth as a port

In 1852 a company was formed to promote a scheme under the title of *The Carlisle and Silloth Bay Dock and Railway Company.* The principal proposers were the Dixon family, who owned large cotton mills in Carlisle, Mr J.D. Carr (a local biscuit manufacturer) and the East Cumberland Member of Parliament, Mr William Marshall. They envisaged that all Port Carlisle traffic, particularly timber and cotton, would be transferred to the new dock. This would be in addition to the new trades emerging in cattle from Liverpool, wheat for the biscuit industry, sheep to Liverpool and traffic in sulphur, alabaster, coal, chemicals and fertilisers. In 1853 a prospectus was issued and a shareholders meeting was held in 1854, at which a Bill was prepared for passage through Parliament. There was a great deal of opposition, with talk of a railway line "to sandhills and rabbit warrens" passing through virtually unpopulated countryside. The ability of such a line to pay for itself was also seriously questioned. Eventually, through sheer persistence, the Bill was passed and work commenced on the railway in August 1855. Within one year the line was completed and it opened in August 1856.

Construction of the Marshall Dock at Silloth, named after the share-holding Member of Parliament, began in 1857. Half of its length was cut into the sand dunes, whilst the other half extended into an area of land claimed from the tidal flats. The dock was 600 feet long and 300 feet wide, with a 60-foot-wide entrance closed by hydraulically-powered dock gates. A 1,000-foot-long pier, with a railway track, was built on wooden piles from the south side of the dock entrance directly out into the Solway. It was intended to provide shelter for the entrance and enable ships to secure alongside at all states of the tide. The dock took two years to build and the first ship entered on 3rd August 1859.

Shipping traffic through Silloth was slow to build at first and harbour dues at Port Carlisle were raised to encourage the use of Silloth Dock. A problem affecting Silloth Dock was the regular strong winds, which often prevented sailing ships from entering or leaving. Consequently, paddle-tugs driven by steam power were purchased to tow the sailing vessels, sometimes several in a line, in and out of the harbour.

Disaster struck the port of Silloth in April 1879. In a severe storm the dock entrance collapsed without warning. More than 20 vessels were trapped inside the dock for around two weeks while the debris was removed. Although shipping was still able to use the pier, trade slumped. It was decided to create a new dock basin just inland from the existing Marshall Dock and to turn the old dock into a wet, tidal basin. The New Dock was completed in 1885 and in 1886 Carr & Co., biscuit manufacturers, built and opened a large flour mill alongside the dock. The mill still operates today. In the 1880s imports were mainly of grain, timber, cattle and phosphates and exports included coal, manure, burnt sulphate ore and general goods. During World War One passenger vessel services, which ran from Silloth to Liverpool, Belfast, Dublin, the Isle of Man and across the Solway, began to diminish, whilst freight traffic began to expand. In 1921 ownership of the port of Silloth passed to the London & North Eastern Railway Company during major national reorganisation. During World War Two, the Admiralty classified Silloth as a 'Safe Port' and thousands of tons of coal were routed through it. Silloth had a Royal Air Force station close by, where pilots were trained to fly bombers. So many trainees crash-landed in the Solway that local people renamed it 'Hudson Bay'. It was around this time that the pier at Silloth fell into disuse and began to rot. The outer 100 feet burnt down in 1942.

In 1947, the docks were nationalised under the British Transport Commission (BTC) and administrative links with the railways were finally severed. In 1959, the outer 700 feet of the pier collapsed, probably due to the activities of marine wood-boring organisms.

In 1963 the rail link to Silloth fell under Dr Beeching's axe and was closed. Also in that year, the ownership of the port changed yet again when the BTC was dissolved and Silloth Docks passed into the hands of the newly formed British Transport Docks Board. Trade remained prosperous with large quantities of wheat coming into the mill. The trade in live cattle from Ireland grew steadily, with additional traffic in animal feeds, fertilisers and building materials.

The Annan-Bowness rail viaduct

The 1880 chart (Figure 4c) of the Solway shows a new rail link crossing the Solway and the viaduct straddled the water between Bowness and Annan, a distance of 1.3 miles. The viaduct had been built between 1868 and 1871 to carry the hematite ore from West Cumberland mines to the Lanarkshire steelworks, thus avoiding the long detour and delays through Carlisle. Built of timber with steel fittings, the viaduct had a very chequered history. It stood for only ten years when, after a particularly cold period in the winter of 1880/81, the Rivers Esk and Eden became icebound and the edges of the Solway froze over. When the thaw arrived, the rivers flooded, forcing pack ice out to sea. It was reported that icebergs as big as 10 feet high and 27 yards square crashed into the wooden piles of the viaduct. After several days' battering, some pillars were wrecked and two large gaps appeared in the structure. Repairs worth £30,000 were carried out and no trains were able to cross the viaduct until May 1884.

During World War One the viaduct was extremely busy carrying train-loads of pig iron from Cumberland to Clydeside for shipbuilding, armaments and munitions. At the same time, however, maintenance was discontinued and decay and corrosion set in. By 1921, the viaduct was in such a poor condition that it was condemned as unsafe and traffic across it ceased. Demolition began in 1934 and was completed by 1936.

During its life, the viaduct affected the course of the channels upstream of the structure. As Figures 4a to 4h show, before viaduct construction the deepest water in the upper Solway was a single channel downstream of the confluence of the Rivers Esk and Eden. After construction, a large island grew just eastwards of the viaduct, forcing the channels apart. Only in recent years have the channels worked their way back to their original form.

Silloth: present-day trade and the maintenance of access

In 1983 the British Transport Docks Board was privatised and became Associated British Ports plc. Silloth remains one of 22 ports in that group, which includes giant ports such as Southampton and Hull. Trade at Silloth has fluctuated over recent years, reaching a peak in 1987 of over 133,000 tonnes. Current trade includes wheat, fertilisers, animal feeds, wood pulp, cement powder, coal and live salmon smolts. The main fisheries in the Solway Firth are shrimping and cockling and Silloth is home to a small fleet of vessels involved in these activities.

As described above, there are extensive sandbanks and shallows in the Solway Firth north and eastwards of Maryport. Fortunately, there has always been a channel of sorts along the southern part of the Solway, allowing shipping a route through to Silloth. This route is only open to sea-going vessels towards High Water, being too shallow at other times in the tidal cycle. In addition, the dock can only permit entry and exit around High Water, to enable ships inside to remain afloat.

Regular survey work is necessary to find the deepest water route through the sandbank. As Silloth is a small port which is always struggling to remain viable, sophisticated techniques incurring a large outlay and expenditure are not possible. Consequently, surveying is carried out using a small boat with an outboard motor and equipped with a yacht-type DECCA navigator. On a day with a low spring tide (which usually occur during the early morning or evening) and good weather, the boat is motored around the edges of the sandbanks. Frequent position fixes are recorded and these are plotted later on a chart. This survey is carried out at least once a year, usually in early summer, when there are longer hours of daylight and the weather is more reliable. Changes in the channel can happen quite rapidly. If reports are received from pilots or local fishermen that changes are occurring, more frequent surveys are undertaken until the situation becomes more stable.

Figures 5a to 5e show in detail the channel changes that have occurred between 1988 and 1992 off the coast between Workington and Silloth. The sandbanks off Ellison Scar and Dubmill Scar change shape slightly but more significant is the changing nature of the island sandbanks. The group of islands present in 1988 gradually expanded so as to substantially alter the course of the main channel, diverting the passage of ships to the west of these sandbanks. By 1991, these islands had merged into one large sandbank and access was once more possible through the narrow channel to the east. Note that, because of the rapidity of the changes, the buoy positions do not necessarily mark the present location of the channel, which was particularly obvious in 1990 (Figure 5c).

As there are no available facilities for lifting buoy sinkers once they are laid, the only way to adjust the buoy positions is to wait until they break adrift, recover the buoys and relay them with new sinkers in new positions as required. Each sinker weighs around 1.5 tonnes and is made of a cube of concrete, into which lumps of scrap iron and steel have been added to give greater weight. To lay

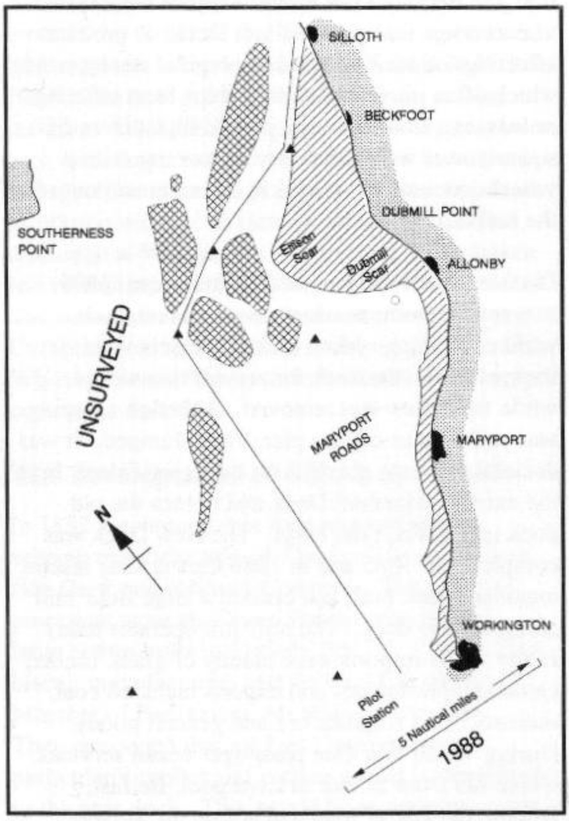


Figure 5a Recent changes in the position of navigable channels in the Solway Firth 1988.

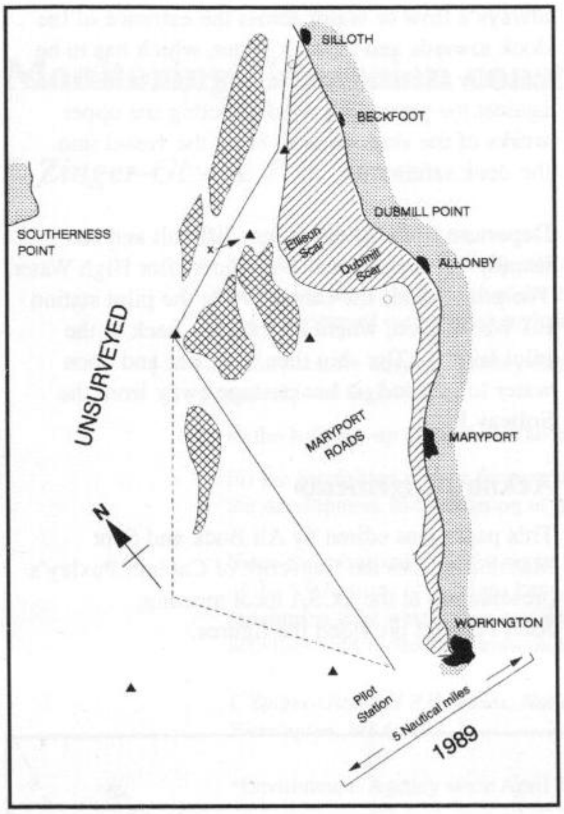


Figure 5b Recent changes in the position of navigable channels in the Solway Firth 1989.

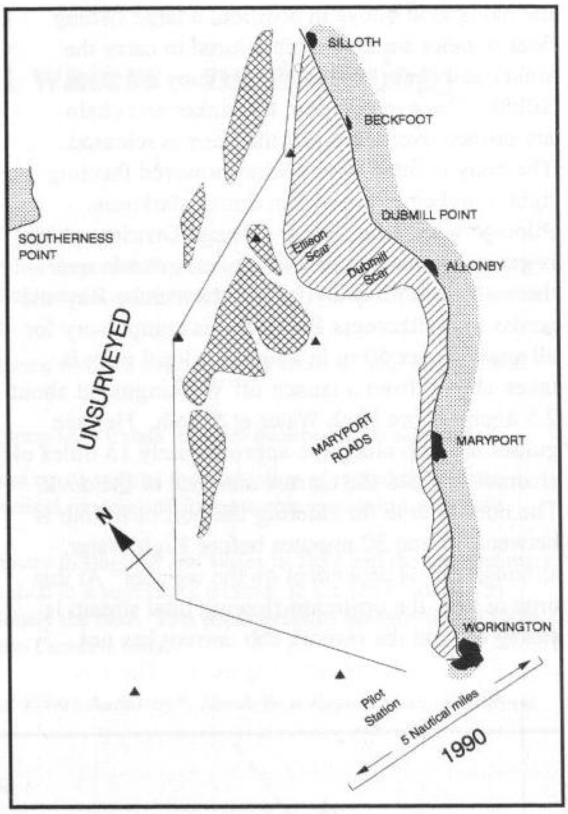


Figure 5c Recent changes in the position of navigable channels in the Solway Firth 1990.

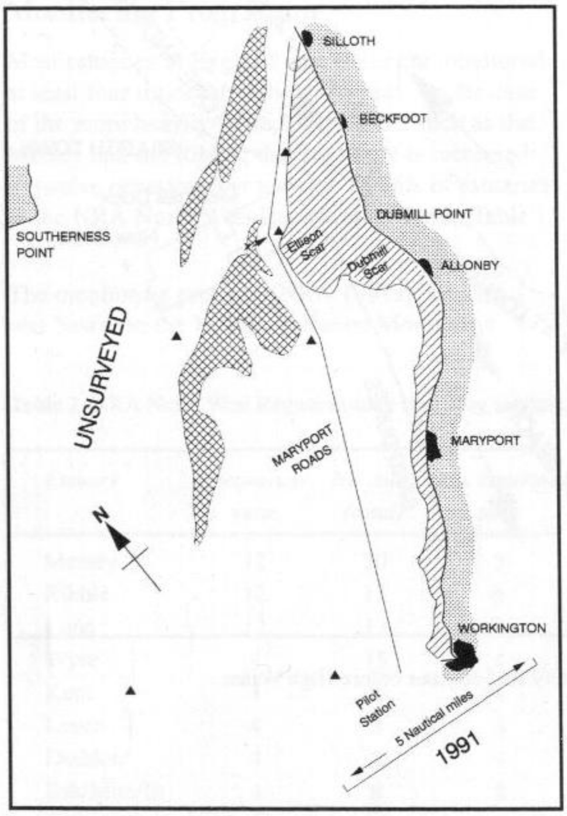


Figure 5d Recent changes in the position of navigable channels in the Solway Firth 1991.

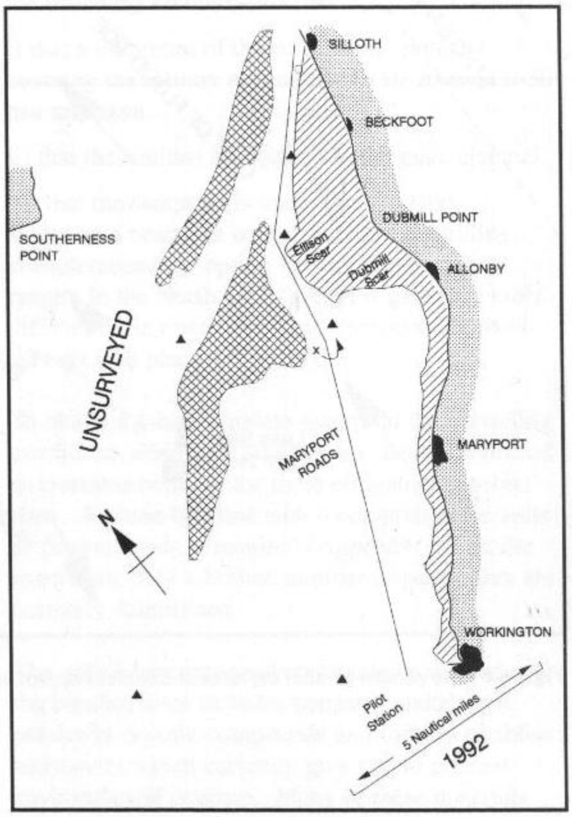


Figure 5e Recent changes in the position of navigable channels in the Solway Firth 1992.

the navigation buoys in position, a large fishing boat or other suitable craft is hired to carry the sinker and chain and to tow the buoy out from Silloth. Once in position, the sinker and chain are pushed overboard and the buoy is released. The buoy is fitted with a wind-powered flashing light to indicate its position during darkness.

Pilotage within the Silloth Pilotage District, which is granted by an Act of Parliament, extends over the sea area from Maryport to Moricambe Bay and across to Southerness Point, and is compulsory for all vessels over 50 m in length. A local pilot is taken aboard from a launch off Workington at about 2.5 hours before High Water at Silloth. He then guides the ship along the approximately 15 miles of channel and into the narrow entrance of the dock. The normal time for entering the port of Silloth is between 15 and 30 minutes before High Water, although this is dependent on the weather. At that time of tide, the upstream-flowing tidal stream is easing off and the inshore ebb current has not gained too much strength (Figure 6). There is always a flow of water across the entrance of the dock towards and at High Water, which has to be carefully allowed for. This flow must be balanced against the prevailing wind affecting the upper works of the ship, so as to bring the vessel into the dock safely.

Departure from Silloth is less difficult and can usually be carried out 1-1½ hours after High Water. The pilot guides the ship down to the pilot station off Workington, where he transfers back to the pilot launch. The ship then has clear and open water to proceed on her passage away from the Solway Firth.

Acknowledgements

This paper was edited by Ali Buck and Scot Mathieson from the transcript of Captain Puxley's presentation at the ECSA local meeting.
John Pomfret provided the figures.

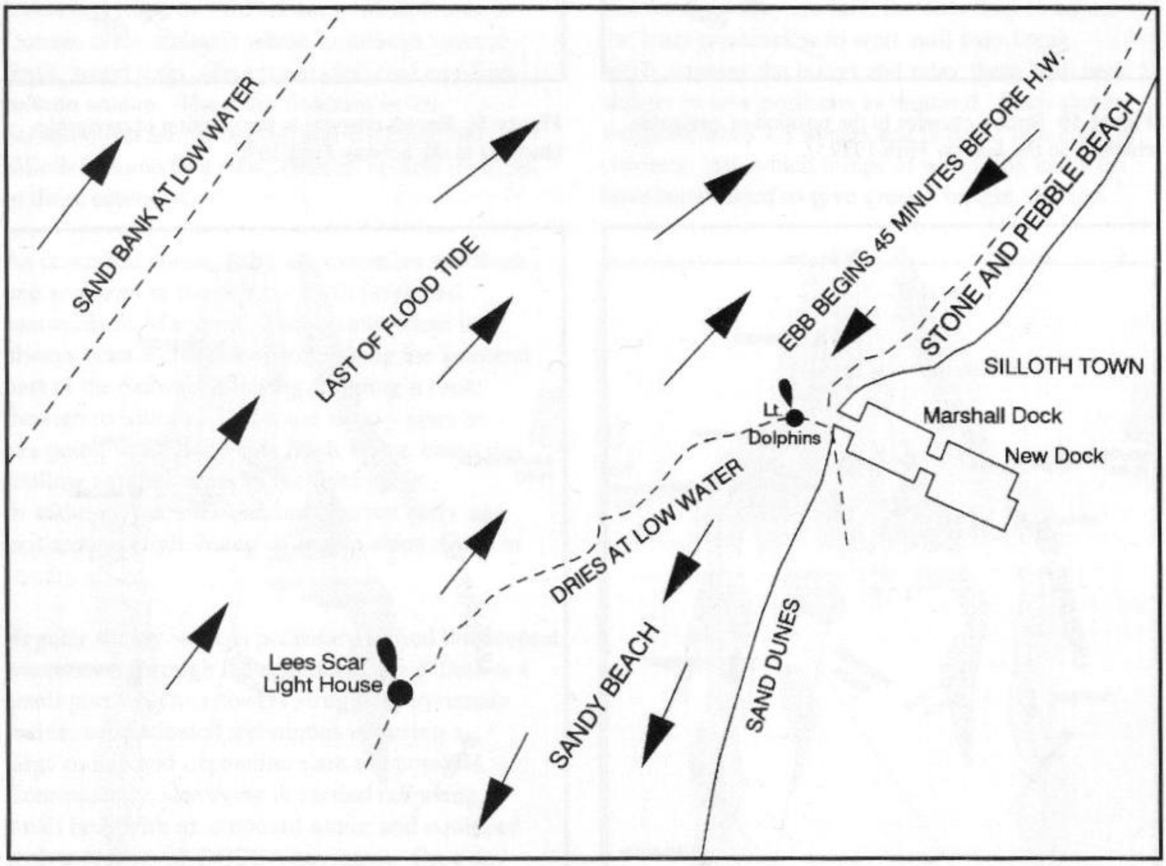


Figure 6 The pattern of tidal currents at Silloth at approximately half-an-hour before High Water.

Monitoring Cumbrian coastal waters - methodology

I. Zinger-Gize & P.D. Jones

The National Rivers Authority (NRA)* has responsibility for safeguarding, and where necessary, improving the water quality of the estuaries and coastal waters of England and Wales. This task has a number of components including:

i) the statutory duty of ensuring compliance with the standards laid down in both international and national legislation;

ii) the building-up of databases so that long-term trends in water quality can be determined;

iii) the acquisition of data for operational needs such as the evaluation of remedial schemes, the development and validation of numerical models and for post-commissioning appraisals.

Since the privatisation of the water industry in England and Wales in 1989 and the establishment of the NRA, these obligations have resulted in a significant increase in the effort devoted to monitoring tidal waters than was previously the case. This paper presents an overview of these activities with particular emphasis on the Cumbria coast.

I. Zinger-Gize and P.D. Jones, National Rivers Authority, North West Region, Knutsford Road, Warrington, WA4 1HG.*

*Environment Agency since April 1996

National Estuary Monitoring Programme

Most estuaries in England and Wales are monitored at least four times throughout the year. In the case of the more heavily-impacted systems, such as the Mersey and the Ribble, the frequency is increased to twelve occasions per annum. Details of estuaries in the NRA North West Region are given in Table 1.

The monitoring protocol (NRA 1991a), which was based on the Marine Pollution Monitoring Management Group (MPMMG) guidelines, adopted the following recommendations:

i) that a minimum of three 'baseline' samples covering the salinity regimes 0-10, 10-20 and 20-30 psu are taken.

ii) that the stations are located in the main channel.

iii) that the sampling is undertaken at High Water on a neap tide unless there are overriding considerations for opting for an alternative tidal range. In the North West, access is generally more difficult during neap tides and consequently most surveys take place on spring tides.

Table 1 NRA North West Region estuary sampling scheme.

Estuary	*Frequency/ year*	*No. sites (total)*	*No. baseline sites*
Mersey	12	20	5
Ribble	12	12	6
Lune	12	13	3
Wyre	4	15	4
Kent	4	8	4
Leven	4	8	3
Duddon	4	8	4
Esk/Mite/Irt	4	8	8
Solway Firth & associated estuaries	4	18	13

To obtain a more complete picture of the prevailing conditions, additional samples are usually collected at locations between the three obligatory baseline sites. At these baseline sites a comprehensive suite of determinands is required (Appendix 1). At the extra sites, only a limited number of parameters are normally determined.

The suite of determinands routinely monitored at the baseline sites includes nutrients, metals and persistent organic compounds and focuses on those substances which currently give rise to greatest environmental concern. Many of these materials have defined Environmental Quality Standards (Appendix 2) and a fundamental purpose of the surveys is to ensure that these levels are not exceeded.

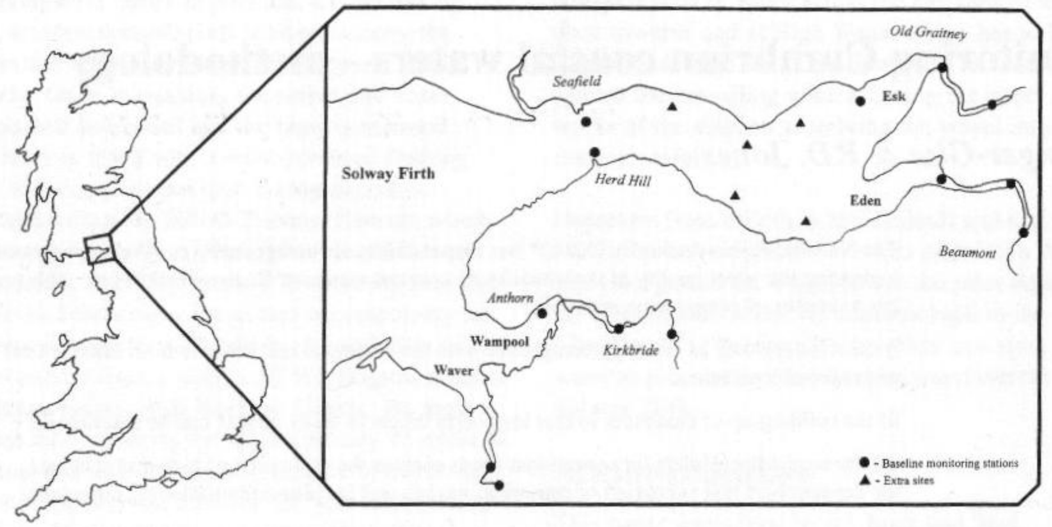


Figure 1 Schematic representation of the Solway Firth, and adjacent estuaries, showing NRA sampling locations.

By agreement with the Solway River Purification Board, chemical water quality surveys on the Solway Firth and the adjacent estuaries are undertaken on a quarterly basis by the NRA with the Solway River Purification Board taking the responsibility for the biological monitoring. This paper concentrates on chemical monitoring.

For operational reasons such as lack of good launching sites, frequently-moving channels and shallow water in the upper estuary, it has been found that the fieldwork is more conveniently carried out using a small hovercraft rather than a similar-sized inflatable boat. The locations of the stations in the Solway Firth, Esk, Eden and adjacent Waver and Wampool Estuaries are shown in Figure 1.

National Coastal Waters Monitoring Programme

Since the 1970s there has been increasing concern about the condition of our coastal waters. With the setting-up of the NRA the opportunity was taken to inaugurate a fairly comprehensive National Coastal Monitoring Survey (NACOMS). The prime objective of this work is to give immediate information on:

i) the current condition of our coastal waters;

ii) any materials present at concentrations which should give rise to concern (again this applies especially to the dangerous substances as defined in the EC Directives but in view of potential eutrophication problems also includes the nutrient elements);

iii) trends discerned.

Emphasis has been placed on those materials which have the potential to damage marine ecosystems or present a hazard to consumers of commercially-landed species. The philosophy of 'absence of evidence' is no longer acceptable and the programme endeavours to provide 'evidence of absence' or at least to demonstrate that the concentrations are below those which would require appropriate remedial action. In those instances where an established limit is exceeded, more detailed local studies are undertaken to define the extent of the problem and to assist in planning a cost-effective solution.

Each year four baseline surveys are scheduled from early January through to the autumn to cover the seasonal changes brought about by factors such as differences in water temperature, land run-off, storm-induced turbulence and primary productivity. To carry out this new role, the NRA utilises four purpose-built coastal survey vessels to cover the inshore waters around England and Wales between Berwick-on-Tweed and the Solway Firth. The vessels are operated by staff from four of the Authority's regions and are normally based at Hartlepool, King's Lynn, Poole and in the North West at Eastham on the Manchester Ship Canal. All four boats are fitted with state-of-the-art instrumentation linked to an onboard data-logging system which records (at 10-second intervals) the exact time and ship's position (obtained from differential Global Positioning System) and the various parameters of interest. Whilst there is, as yet, no standardisation of the oceanographic probes deployed on each vessel, the logging facilities are common to all. The system (Qubit Trac V/Chart V) is an upgraded version of a standard survey package widely used by military and civilian hydrographers. In addition to storing data as the vessel is underway, the system is capable of presenting the data in the form of maps or diagrams either at sea or, more typically, later ashore.

Real-time data are collected in three ways:

i) by using in-situ instruments either deployed through a moon-pool or installed in a tow-fish (an Aquashuttle - Chelsea Instruments Ltd) behind the ship;

ii) by continuously pumping seawater through in-line instrumentation permanently installed onboard;

iii) by utilising an automated chemical analyser (Skalar SANplus) to determine the ambient concentrations of the nutrient elements in the pumped seawater.

Surveying at typical cruising speeds of 8-10 knots (4-5 m s^{-1}) and at 10-second intervals between logged events gives a spatial resolution of 40-50 m- in the case of the nutrients the time-step is about 200 seconds and hence a spatial resolution of

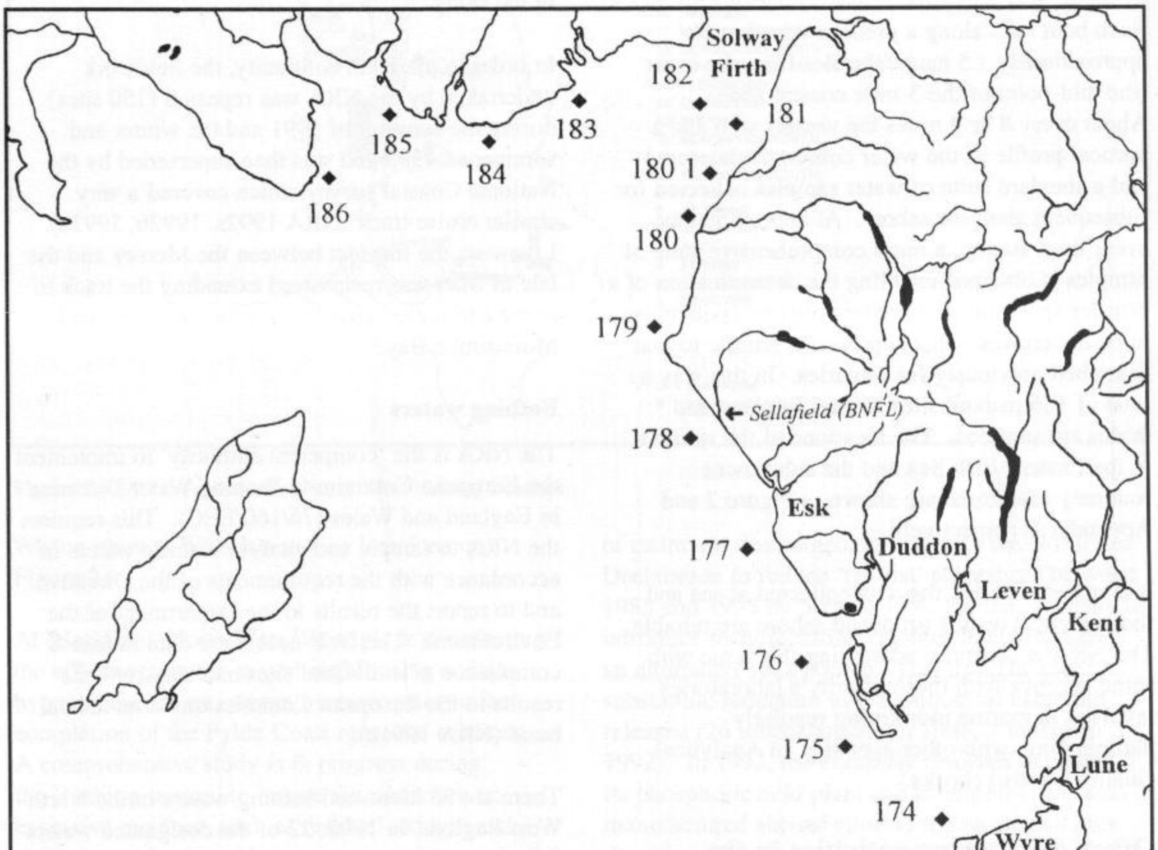


Figure 2 NRA's National Baseline Marine Survey, sampling stations, Irish sea area.

between 800 and 1,000 m. Details of the physical parameters measured are given in Appendix 3.

During the spring, summer and autumn surveys a chartered light aircraft fitted with remote sensing equipment (Compact Airborne Spectral Imager) overflies the track of each boat. Weather permitting, the synoptic measurements from the boats are used to calibrate the images produced by the airborne sensor (NRA 1993b).

Each boat sails along a predetermined track approximately 1.5 nautical miles from the coast (the mid-point of the 3-mile coastal zone). About every 8 or 9 miles the vessels stop and a vertical profile of the water column is measured and a standard suite of water samples collected for subsequent analyses ashore. At approximately every third station, a more comprehensive suite of samples is obtained enabling the determination of a broader spectrum of inorganic/organic contaminants to be undertaken - this approach is similar to that described previously for estuaries. In this way a total of 186 inshore sites around England and Wales are sampled. The locations of the stations in the Eastern Irish Sea and the substances routinely monitored are shown in Figure 2 and Appendix 1, respectively.

It is imperative that the data collected at sea and the analytical results produced ashore are reliable. The NRA is currently addressing this issue with some urgency with the Authority's laboratories involved in marine monitoring regularly participating, with other agencies, in Analytical Quality Control checks.

Other monitoring activities in the eastern Irish Sea

The UK National Monitoring Plan

This plan was drawn up by the Marine Pollution Monitoring Management Group (MPMMG 1993) following government acceptance of the need for a minimum core programme of marine monitoring for all UK waters. It comprises a network of estuarine, intermediate and offshore sites. Responsibility for monitoring the biological, physical and chemical determinands at each site falls to the appropriate NRA region or River Purification Board, or to MAFF, SOAFD or DANI/DOE Northern Ireland, depending on the location of the stations. Those sampled by the NRA North West Region are given in Appendix 4.

The EC Northern Seas Action Plan (NORSAP)

The aim of this EC-funded initiative was to establish a nutrient database for the whole of the Irish Sea (for details see Gillooly *et al.* 1992). In January 1991 the NRA collected nutrient and other relevant data in the Eastern Irish Sea between Anglesey and the Solway Firth and on a transect between the Mersey and Port St Mary. A total of over 200 sites were included (NRA 1991c). Supporting information on the longitudinal distribution of nutrients in the estuaries of the Dee, Mersey, Ribble and Solway, together with similar data from some Irish estuaries, was also included in the study.

In order to maintain continuity, the fieldwork undertaken by the NRA was repeated (150 sites) during the summer of 1991 and the winter and summer of 1992 and was then superseded by the National Coastal survey which covered a very similar cruise track (NRA 1992a, 1992b, 1993a). Likewise, the transect between the Mersey and the Isle of Man was resurveyed extending the track to cover a triangle between the original points and Morecambe Bay.

Bathing waters

The NRA is the 'competent authority' to implement the European Community Bathing Water Directive in England and Wales (76/160/EEC). This requires the NRA to sample and analyse bathing waters in accordance with the requirements of the Directive, and to report the results to the Department of the Environment. The DoE uses these data to assess compliance of individual sites and transmits the results to the European Commission on an annual basis (NRA 1991b).

There are 33 identified bathing waters in the North West Region. In 1992, 22 of the designated waters failed to meet the mandatory coliform requirements of the Directive (Figure 3).

North West Water plc, the statutory sewerage undertaker for the region, is currently engaged in a very large capital investment programme to upgrade coastal and estuarine sewage treatment facilities where these were felt to adversely affect bathing water quality. It is expected that when the majority of the remedial works are completed in 1996, most of the region's bathing waters will be compliant.

Outfall monitoring

To ensure compliance with discharge consents it is a requirement that sea outfalls are regularly monitored. As a result a number of discharges are receiving considerable attention at the present time. These include the predominantly domestic sewage discharge at Blackpool, the industrial effluent discharges at Sellafield from the British Nuclear Fuel (BNFL) facility and from the Albright and

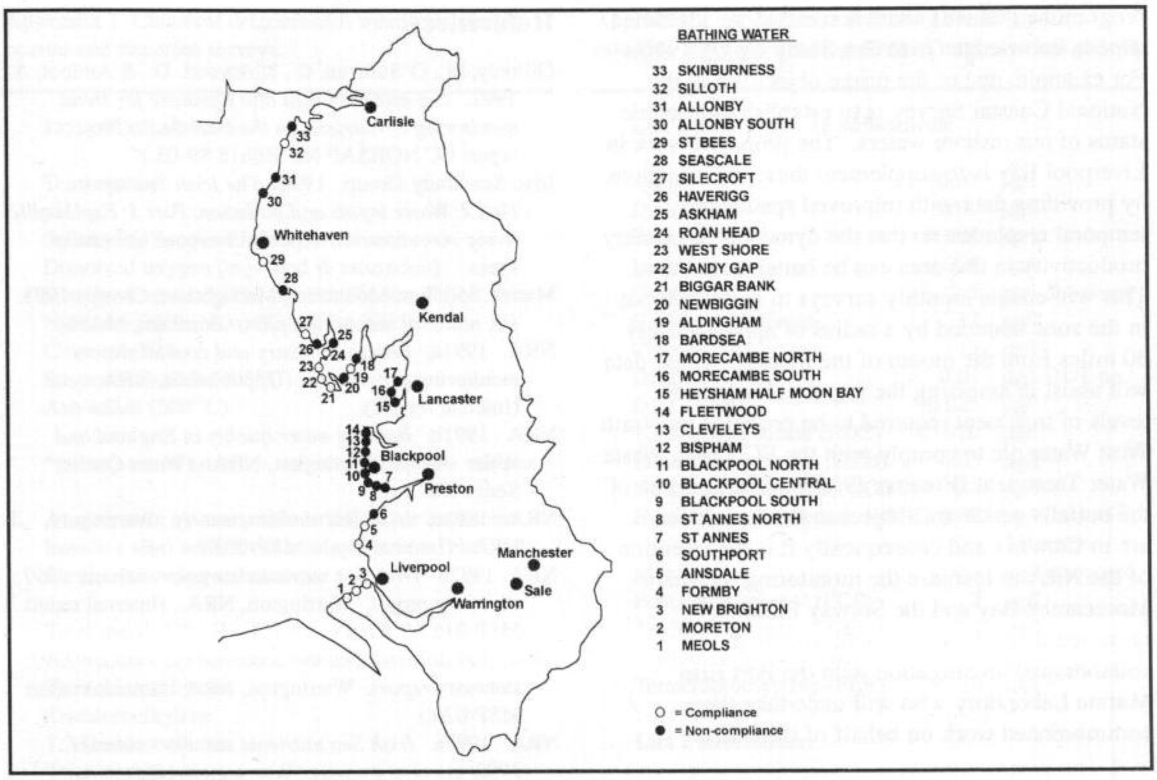


Figure 3 1992 compliance of North West bathing beaches.

Wilson plant at Whitehaven (see locations on Figure 2).

At Blackpool, North West Water plc is disinfecting the effluent from the major outfall using sodium hypochlorite, as an interim measure prior to the completion of the Fylde Coast remedial schemes. A comprehensive study is in progress during the 'bathing season' to ensure that there are no excessive residues, such as residual oxidant and oxidative and non-oxidative compounds, remaining after the disinfection of the screened sewage or harmful by-products formed in the process. Similarly, detailed studies are in hand at Sellafield, prior to the changes in the discharge regime resulting from the commissioning of the Thermal Oxide Reprocessing Plant (THORP). As the NRA has no statutory responsibilities for radioactive substances this work is specifically for non-radioactive components of the effluent such as heavy metals, nutrients and some organic solvents. Other agencies monitor radioactivity (e.g. BNFL, National Radiological Protection Board).

At Whitehaven, the manufacture of phosphoric acid at the Albright and Wilson Marchon Works using imported phosphate rock gives rise to an effluent which has both a very deleterious visual impact and contains high levels of suspended solids, phosphorus compounds and the toxic metal cadmium. The cadmium is not a process chemical but is present as an impurity in the rock imported from North Africa. Pressure to reduce the quantity of cadmium discharged, in line with the North Sea Declaration to reduce 'red list' substances between 1985 and 1995 by 50% to 70%, led the company to introduce manufacturing changes including using an alternative rock source. This brought about a substantial reduction in the amount of cadmium released (26 tonnes/annum in 1988, 7 tonnes in 1992). In 1992, the company resolved to close its phosphoric acid plant and to import crude acid manufactured abroad close to the phosphate rock deposits. These changes, together with the installation of new treatment plant to remove heavy metals from the effluent, will bring about further reductions in the emissions.

Anticipated future studies

There is currently considerable interest in the concentration of nutrient elements in European coastal waters especially in those enclosed sea areas that have restricted circulation. Liverpool Bay (and to a lesser extent most of the eastern Irish Sea) is considered to be the most heavily impacted coastal area in the UK (Irish Sea Study Group 1990).

Since the 1970s there has been a number of independent water quality investigations undertaken by several different organisations. These have mainly concentrated on assessing the impact of sewage sludge disposal but have also provided data on nutrients and a range of contaminants over a wider area. The resources now available give an opportunity to establish an 'integrated' monitoring programme that will address some of the identified gaps in knowledge (Irish Sea Study Group 1990). For example, one of the prime objectives of the National Coastal Survey is to establish the trophic status of our inshore waters. The proposed work in Liverpool Bay is to supplement these investigations by providing data with improved spatial and temporal resolution so that the dynamics of primary productivity in this area can be better understood. This will enable monthly surveys to be carried out in the zone bounded by a radius of approximately 30 miles from the mouth of the Mersey. These data will assist in assessing the impact of increased levels of treatment required to be provided by North West Water plc to comply with the EC Urban Waste Water Treatment Directive (91/271/EEC). Some of the outfalls which are subject to this legislation are in Cumbria and consequently it is the intention of the NRA to increase the monitoring between Morecambe Bay and the Solway Firth. It is proposed that this will be achieved by a collaborative investigation with the Port Erin Marine Laboratory who will undertake the commissioned work on behalf of the NRA.

In addition to boat surveys, the NRA intends to deploy a recording instrument at a fixed site in Liverpool Bay to record chlorophyll concentrations (e.g. at hourly intervals) over the productive seasons of the year. We also hope to deploy similar multi-parameter instruments at a number of estuarine sites. However, because of the generally high suspended solids concentrations this will not include chlorophyll measurements.

Over the last few years the database on the Irish Sea has grown, albeit some would say rather slowly. Whilst the available evidence indicates that in water quality terms, there is no immediate crisis, many important questions remain to be resolved and we certainly cannot afford to be complacent. We hope that the NRA can play an important part in maintaining/improving the well-being of this sea area.

Revision note

Since this paper was presented a considerable amount of additional work has been carried out and much of the proposed work came to fruition. The findings are available to interested parties from the Environment Agency (the successor to the NRA) either as internal reports or as archived data (NRA 1994, 1995, 1996a, 1996b), all available from the Warrington Office (Knutsford Road, Warrington, WA4 1HG).

References

Gillooly, M., O'Sullivan, G., Kirkwood. D., & Aminot, A. 1992. *The establishment of a database for trend monitoring of nutrients in the Irish Sea.* (Project report EC NORSAP No. B6618-89-03.)

Irish Sea Study Group. 1990. *The Irish Sea report. Part 2: Waste inputs and pollution; Part 3: Exploitable living resources.* Liverpool, Liverpool University Press.

Marine Pollution Monitoring Management Group. 1993. *UK national monitoring plan.* Burnham, MAFF.

NRA. 1991a. *Baseline estuary and coastal waters monitoring programme.* Unpublished, NRA. (Internal report.)

NRA. 1991b. *Bathing water quality in England and Wales - 1990.* Warrington, NRA. (Water Quality Series No. 3.)

NRA. 1991c. *Irish Sea nutrients survey.* Warrington, NRA. (Internal report MSP-003.)

NRA 1992a. *Irish Sea nutrients surveys - summer 1991: summary report.* Warrington, NRA. (Internal report MSP-015.)

NRA. 1992b. *Irish Sea nutrients surveys - winter 1992: summary report.* Warrington, NRA. (Internal report MSP-020.)

NRA. 1993a. *Irish Sea nutrients surveys - summer 1992: summary report.* Warrington, NRA. (Internal report MSP-025.)

NRA. 1993b. *Airborne remote sensing of coastal waters.* Warrington, NRA. (R & D Report No. 4.)

NRA. 1994. *British Nuclear Fuels Sellafield environmental monitoring 1994. Summary of results.* Warrington, NRA. (Internal report MSP-94-11.)

NRA. 1995. *NRA surveys along the Cumbrian coast (1989-1995): Consultation paper for setting a sampling programme to monitor Albright and Wilson.* Warrington, NRA. (Internal report MSP-95-06.)

NRA. 1996a. *Less sensitive areas and candidates for High Natural Dispersion Areas (HNDA) in the North West region.* Warrington, NRA. (Internal report MSP-96-04.)

NRA. 1996b. *British Nuclear Fuels Sellafield - environmental monitoring 1995. Summary of results.* Warrington, NRA. (Internal report MSP-96-10.)

Marine Pollution Monitoring Management Group. 1993. *UK national monitoring plan.* Burnham, MAFF.

Appendix 1 Chemical determinands monitored during coastal and estuarine surveys.

1. At all stations:

- Temperature
- pH
- Salinity by bench salinometer (ashore)
- Dissolved oxygen (mg/l and % saturation)
- Dissolved metals* (Pb, Hg, Cd, Cu, Zn, Cr, Ni, As)
- Nutrients (NO_2, NO_3, PO_4, SiO_2, NH_3)
- Chlorophyll *
- Suspended solids (105°C)
- Ash solids (500°C)

*in the case of estuaries only at the baseline stations.

2. At alternate or every third station (or estuarine baseline site) additional analyses are carried out for the following substances:

- Total metals (Pb, Hg, Cd, Cu, Zn, Cr, Ni, As)
- Aldrin, endrin, dieldrin, isodrin, total drins
- Tetrachloroethylene
- Trichloroethylene
- 1,2 Dichloroethane
- Trichlorobenzene
- Chloroform
- Carbon tetrachloride
- Hexachlorobenzene
- Hexachlorobutadiene
- Hexachlorocyclohexane - alpha, beta, gamma and total
- PCB congeners - 28, 52, 101, 118, 138, 153, 180 and total
- DDT-pp, DDT-op, DDE-pp, TDE-pp, and DDT total
- Atrazine
- Simazine
- Pentachlorophenol

Appendix 2 Environmental Quality Standards for estuaries and coastal waters (annual means, unless stated).

List 1 and Annex 1a substances:

Aldrin	0.01	µg/l
Dieldrin	0.01	µg/l
Endrin	0.005	µg/l
Isodrin	0.005	µg/l
Cadmium	2.5	µg/l dissolved
Carbon tetrachloride	12	µg/l
Chloroform	12	µg/l
DDT	0.01	µg/l DDT-pp
DDT (total)	0.025	µg/l
1,2 Dichloroethane (EDC)	10	µg/l
Hexachlorobenzene (HCB)	0.03	µg/l
Hexachlorobutadiene (HCBD)	0.1	µg/l
Hexachlorocyclohexane (HCH)	0.02	µg/l total of 3 isomers
Mercury	0.3	µg/l dissolved
Pentachlorophenol (PCP)	2	µg/l
Trichlorobenzene (TCB)	0.4	µg/l
Trichloroethylene (TRI)	10	µg/l
Tetrachloroethylene (PER)	10	µg/l

List 2 substances:

Arsenic	25	µg/l dissolved
Boron	7,000	µg/l total
Chromium	15	µg/l dissolved
Copper	5	µg/l dissolved
Cyfluthrin	0.001	µg/l total, 95%
Flucofuron	1	µg/l total, 95%
Iron	1,000	µg/l dissolved
Lead	25	µg/l dissolved
Nickel	30	µg/l dissolved
PCSDs	0.05	µg/l total, 95%
Permethrin	0.01	µg/l total, 95%
pH	6-8.5	95%
Sulcofuron	25	µg/l total, 95%
Tributyltin	0.002	µg/l maximum, total
Triphenyltin	0.008	µg/l maximum, total
Vanadium	100	µg/l total
Zinc	40	µg/l dissolved

Appendix 3 Parameters monitored while the vessel is underway.

1. Position: derived from Decca 53G GPS Navigator (Global Positioning System fitted with differential correction facility).

2. Depth below keel: vessel fitted with Simrad EA 300 echo-sounder.

3. *In-situ* instruments (Meerestechnik Elektronik GmbH probes):

   a) deployed in the moon-pool - temperature, salinity, pH, turbidity (transmission), dissolved oxygen

   b) fitted into the Aquashuttle - temperature, salinity, pH, turbidity (transmission), dissolved oxygen, chlorophyll, depth below surface (pressure sensor)

   c) fitted to profiling winch (for measurement between the sea surface and the sea bed when the vessel is stopped) temperature, salinity, pH, dissolved oxygen, depth below surface.

Appendix 4 MPMMG UK National Monitoring Plan - samples taken by NRA North West Region.

Location	*Site*	*Type*	*Latitude*	*Longitude*
015 Solway		I	54° 52.50'N	03° 25.00'W
655 Cardigan Bay		I	52° 21.50'N	04° 10.50'W
695 Dee	Buoy No. 2	E	53° 19.98'N	03° 12.08'W
705 Liverpool Bay	Burbo Bight	I	53° 28.29'N	03° 15.58'W
745 Mersey	E 1 Buoy	E	53° 20.11'N	02° 57.22'W
755 Mersey	Seacombe Ferry	E	53° 24.56'N	03° 00.48'W
765 Mersey	C 1 Buoy	E	53° 31.83'N	03° 08.80'W
785 off Lune/Wyre		I	53° 57.70'N	03° 02.50'W

station type: I = intermediate; E = estuarine.

Water quality improvements along the Cumbria coast

P.C. Head

P.C. Head, North West Water Ltd, Dawson House, Great Sankey, Warrington WA5 3LW

Introduction

Pollution control functions along the Cumbrian coast are exercised by the National Rivers Authority, and North West Water's role is to provide the necessary wastewater treatment facilities to comply with the consent conditions issued by the NRA (Environment Agency since April 1996). Pollution management in this area is considered in the paper by Hughes.

Within the North West Water Group PLC, which consists of about 20 companies worldwide, water supply and wastewater treatment for an area, which stretches from Wales to Scotland, are provided by North West Water Ltd. This area has a fairly extensive coastline, of the order of 470 km, including the whole of the coastline of Cumbria. In the past this coastline has suffered much from industrial development. Access to deposits of coal and iron ore led to the development of a thriving iron and steel industry which used the coastal strip as a convenient repository for its wastes, both solid and liquid. Although these industries have now virtually disappeared the results of the disposal practices are still very much with us. Remnants of colliery waste dumped on the foreshore are present along the whole of the coast and the areas of the old iron workings have large expanses of 'slagcrete' where the waste from blast furnaces was poured onto the foreshore to cool. More recently phosphate rock processing resulted in the discharge of large quantities of gypsum and potentially toxic metals, particularly cadmium. The disposal of waste water from the towns and villages along the coast was by means of short outfalls with no treatment.

The need to improve this totally unsatisfactory situation was recognised by the former North West Water Authority shortly after it was set up in 1974. However, because of more pressing problems elsewhere, such as the Mersey Estuary, and the then lack of statutory requirement to provide treatment for wastewater discharges to open coastal waters, it was not until after the implementation of the Control of Pollution Act 1974 in the mid-1980s that any real effort was directed towards determining the best means of improving the situation.

Additional impetus to actually getting something done has been provided by two pieces of EC Legislation - the 1976 Bathing Water Directive and the 1991 Urban Wastewater Treatment Directive. The rather tardy implementation of the former directive by the UK government will ensure that considerable improvements to discharges affecting designated bathing waters will be effective in time for the 1996 bathing season and the timetable for the latter will mean that improvements to any remaining significant discharges will be implemented between 1996 and 2005 at the very latest. With the general presumption of the Urban Wastewater Treatment Directive that biological or secondary treatment is required, except for certain special situations where it can be shown not to be necessary, North West Water will, as a matter of course, make provision for this level of treatment for any scheme which at present involves only settlement or primary treatment, in case it should ever be required at a later date.

Bathing waters

Although the Bathing Water Directive was adopted by the EC in 1976 it was not until 1986 that the UK Government was forced by the Commission to accept that it had real relevance in the United Kingdom and to agree to identify more than a handful of beaches where its provisions were to be met. As a result of this there are now 33 identified bathing areas within North West Water's area (see Figure 1). Thirteen of these bathing waters are situated along the Cumbrian coast from Walney Island in the south to Skinburness in the north.

Of the thirteen Cumbrian bathing waters, only five, the three Walney Island beaches and Silecroft and Silloth, complied with the mandatory microbiological standards during the 1992 bathing season. In 1991 eight passed (those that passed in 1992 plus Roan Head, St Bees and Skinburness). In previous years back to the start of national monitoring in 1986 the number of beaches complying has ranged from two to nine as shown in Table 1. There is no particular pattern in these results and no beach has passed every year.

	DISTRICT COUNCIL	BATHING WATER
33	ALLERDALE	SKINBURNESS
32	ALLERDALE	SILLOTH
31	ALLERDALE	ALLONBY
30	ALLERDALE	ALLONBY SOUTH
29	COPELAND	ST BEES
28	COPELAND	SEASCALE
27	COPELAND	SILECROFT
26	COPELAND	HAVERIGG
25	BARROW IN FURNESS	ASKHAM
24	BARROW IN FURNESS	ROAN HEAD
23	BARROW IN FURNESS	WEST SHORE
22	BARROW IN FURNESS	SANDY GAP
21	BARROW IN FURNESS	BIGGAR BANK
20	SOUTH LAKELAND	NEWBIGGIN
19	SOUTH LAKELAND	ALDINGHAM
18	SOUTH LAKELAND	BARDSEA
17	LANCASTER	MORECAMBE NORTH
16	LANCASTER	MORECAMBE SOUTH
15	LANCASTER	HEYSHAM HALF MOON BAY
14	WYRE	FLEETWOOD
13	WYRE	CLEVELEYS
12	BLACKPOOL	BISPHAM
11	BLACKPOOL	BLACKPOOL NORTH
10	BLACKPOOL	BLACKPOOL CENTRAL
9	BLACKPOOL	BLACKPOOL SOUTH
8	FYLDE	ST ANNES NORTH
7	FYLDE	ST ANNES
6	SEFTON	SOUTHPORT
5	SEFTON	AINSDALE
4	SEFTON	FORMBY
3	WIRRAL	NEW BRIGHTON
2	WIRRAL	MORETON
1	WIRRAL	MEOLS

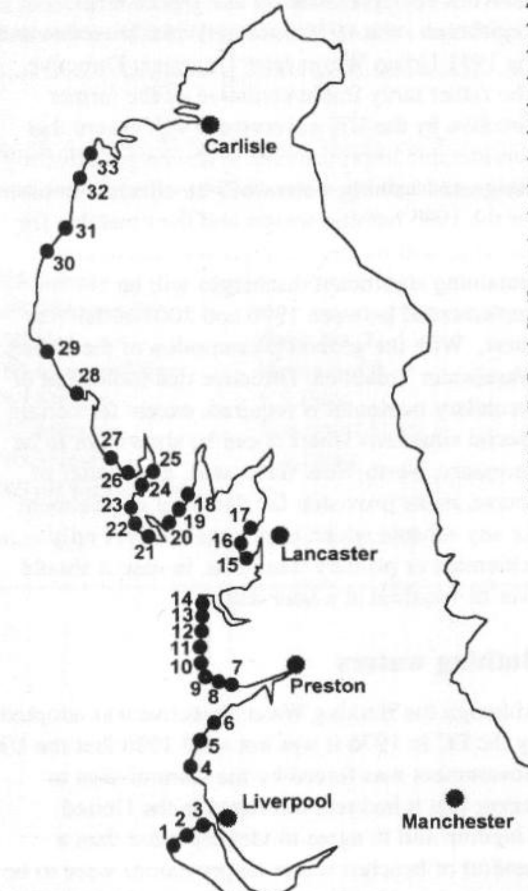


Figure 1 The location of identified bathing waters in the north-west of England.

Following the Government's agreement with the EC Commission in 1986 that the UK would take the Directive seriously, each of the then water authorities had to draw up plans for each of its bathing waters to ensure that its wastewater discharges would not lead to non-compliance with the Directive's microbiological standards by the 1996 bathing season. These plans were taken over by the water service companies on privatisation in 1989 and the costs have been agreed with the Director General of Water Services. North West Water intends that all wastewater treatment schemes for discharges affecting the Cumbrian bathing waters will be completed in time for the 1996 bathing season.

Table 1a Cumbria coast bathing waters 1986-1992: percentage compliance (faecal coliforms).

Bathing water	*1986*	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*
Walney (Biggar Bank)	100	100	100	90	95	100	100
Walney (Sandy Gap)	100	100	95	90	100	100	100
Walney (West Shore)	91	92	90	95	90	100	95
Roan Head	66	92	81	95	90	95	95
Askam-in-Furness	new spt in 1988		75	85	90	90	80
Haverigg	64	42	70	65	75	75	90
Silecroft	91	100	95	100	100	95	100
Seascale	91	100	90	90	75	70	50
St Bees	new spt in 1988		85	95	100	100	90
Allonby South	67	92	75	90	100	74	70
Allonby	100	100	70	100	100	79	75
Silloth	83	100	90	100	80	95	95
Skinburness	83	75	75	85	90	95	90
Total passes	3	9	3	6	6	8	6
Overall compliance	2	9	3	6	5	8	5

Table 1b Cumbria coast bathing waters 1986-1992: percentage compliance (total coliforms).

Bathing water	*1986*	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*
Walney (Biggar Bank)	100	100	100	100	100	100	100
Walney (Sandy Gap)	100	92	95	100	100	95	100
Walney (West Shore)	100	92	95	100	100	100	100
Roan Head	100	100	95	100	95	95	90
Askam-in-Furness	new spt in 1988		95	95	95	100	100
Haverigg	70	58	75	70	85	95	100
Silecroft	90	100	100	100	100	95	100
Seascale	86	92	95	90	85	75	90
St Bees	new spt in 1988		95	95	100	100	100
Allonby South	80	92	80	95	90	80	100
Allonby	90	92	75	100	100	95	100
Silloth	100	100	100	100	90	100	100
Skinburness	100	58	65	80	90	95	95
Total passes	6	9	9	10	8	11	11
Overall compliance	2	9	3	6	5	8	5

A review of the Company's existing discharges has shown that, in most instances, the observed microbiological quality at the bathing water sampling points can be associated with particular discharges and suitable schemes to reduce the effect to an appropriate level are fairly easily identifiable. However, in some cases the cause of occasional high bacterial levels is more difficult to identify and the determining what, if anything, needs to be done is also more difficult. Of the south Cumbrian beaches tracer work carried out during the summer of 1991 confirmed that the existing totally untreated discharge from Barrow to the southern end of the Walney Channel is probably implicated in the occasional failures of the three Walney Island beaches, although there is also a possibility that the primarily treated discharge from Millom Wastewater Treatment Works (WwTW) could also have an effect. As the Barrow discharge is also implicated in the failures at the bathing water at Newbiggin inside Morecambe Bay, full biological treatment will be provided by the spring of 1996 at the latest. This will reduce the input of bacteria by around 95%. Additionally the existing primary works at Millom will be upgraded to full biological treatment on the same timescale.

This latter scheme should lead to compliance at Haverigg and Roan Head and also ensure that the effects of a local scheme at Askam will not be prejudiced. At present it seems that disinfection of the existing biologically treated effluent from Askam WwTW will be required to ensure compliance. A trial disinfection scheme is to be operated at Newbiggin in Morecambe Bay, during the summer of 1993, using UV light as the disinfectant. It is hoped that the experience gained with this trial will be readily transferable to the situation at Askam.

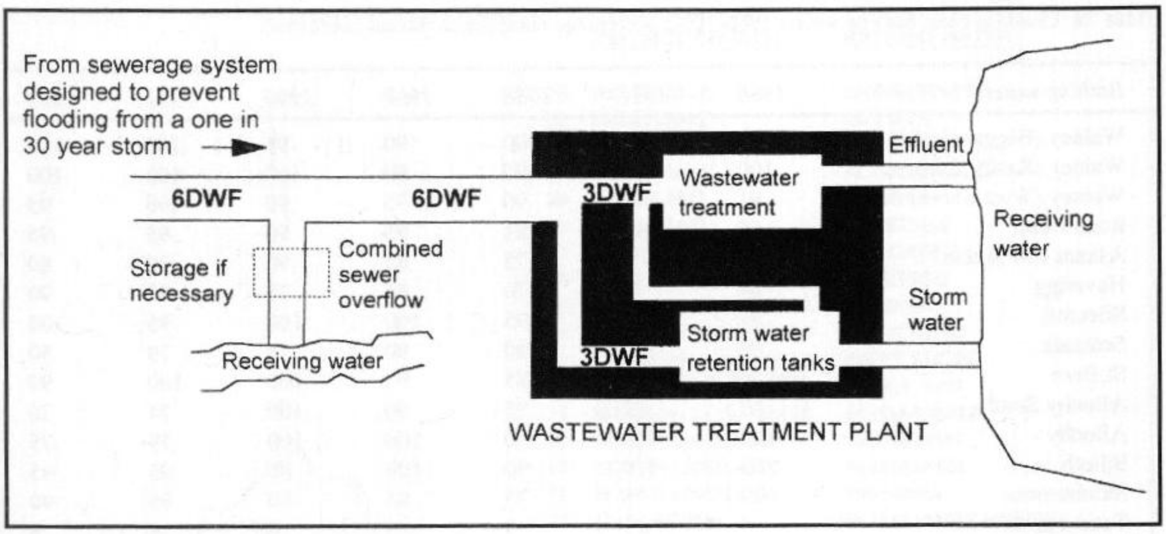


Figure 2 North West Water's general storm-water management philosophy.

There are no North West Water discharges in the vicinity of the bathing beach at Silecroft and the reasons for the occasional failure are unclear. However, since the Directive allows for a 95% compliance for samples taken, and the beach has complied for each bathing season since 1987, there are currently no plans for any further action.

Before describing the planned improvements for the remaining bathing waters and the Workington, Maryport and Whitehaven areas, it is necessary to understand the general philosophy of wastewater treatment in the UK. Figure 2 shows that with our predominantly combined wastewater network, dealing with both foul sewage and rainfall, we generally allow for about 6 x the dry weather flow (6DWF) to be transferred to the WwTW for treatment. Of this flow, in general, we would give full treatment to about 3DWF and allow a further 3DWF go to the storm tanks for retention and return to treatment if possible. In times of very heavy rain there will be a discharge of settled storm sewage from the storm tanks. For some small works or larger coastal works giving only primary treatment we quite often take the full 6DWF to treatment. Also, although we will, in general, design a wastewater network to deal with 6DWF, in some coastal areas where there are no bathing waters and storm water can be discharged to the sea we might retain only 3DWF within the network.

Turning now to Seascale, the existing highly unsatisfactory situation consists of a discharge of untreated wastewater from a summer population of around 2,000 via a short sea outfall just below the low water mark and close to the bathing beach. Additionally there are two combined sewer overflows (CSOs) which discharge storm water to Whitriggs Beck, which flows across the foreshore near the present outfall, and a further one on the foreshore, which discharges storm water near the bathing water sampling point.

Following extensive investigations involving the use of mathematical models and field work, it is proposed that this situation is replaced with a WwTW providing primary treatment and a 2 km outfall discharging to a minimum depth of 10 m, along with the provision of additional storage within the new works and the existing wastewater network to greatly reduced the frequency and impact of any storm water discharges. Following an analysis of the wastewater network draining to the works using a mathematical model and actual historic rainfall data for the area, a scheme has been designed to restrict storm water discharges to Whitriggs Beck to no more frequently than once in five years. Of the flow arriving at the works, which thus comprises domestic and trade inflows and the rainfall, primary settlement will be provided for up to about 6DWF and it will be discharged via the long outfall. Flows of between 6DWF and a one-in-five-year storm flow will be screened and also discharged via the long outfall.

Mathematical modelling of the receiving water quality suggests that this degree of treatment will easily lead to compliance with the mandatory requirements of the Directive and will allow compliance with the much more stringent guideline standards for most of the time.

Further along the coast at St Bees the existing situation is not quite so unsatisfactory as at Seascale in that there is already a primary treatment works and a tidal discharge. Nonetheless improvements are required to ensure that the occasional high coliform samples which can lead to non-compliance of the bathing water do not occur in the future. To achieve improvements it will be necessary to increase the storm water storage facilities at the works to reduce the volume and frequency of discharges to Pow Beck, which runs past the works and across the foreshore south of the bathing area. Sufficient extra storage will be incorporated to reduce storm water discharges to Pow Beck to no more than once in five years. All remaining flows will be given primary treatment and then taken to the tidal storage tank for discharge via the (existing) long outfall on the ebb tide. The tidal tank is big enough to retain all dry weather flows and the storm water.

Any influence, believed to be minor, from the discharge at Braystones, which is situated just above the low water mark on the neighbouring bathing waters at Seascale and St Bees, will be removed by a scheme to build a primary treatment works discharging via a 2 km outfall to the 10 m contour. The drainage network in this area has been progressively upgraded to provide an acceptable storm water discharge regime to the River Ehen and this arrangement will be retained for the new scheme.

Compliance problems at the bathing waters of the inner Solway at Allonby, Silloth and Skinburness will be addressed by two schemes at Allonby and at Silloth. At Allonby the present untreated tidal discharge from an outfall around low water will be improved by the installation of full secondary treatment for flows of up to 6DWF. Sufficient storage will be provided to reduce any discharges of storm water through the existing outfall to less than once in five years.

The existing screened flows from Silloth and those presently discharged from the septic tanks in Skinburness will be given full secondary treatment at a new works at Silloth. This will treat flows up to 6DWF and discharge via the existing outfall to the edge of the channel north of the harbour. Because of the proximity of this to the bathing water it will be necessary to use UV disinfection to ensure compliance. Sufficient additional storage will be built to restrict storm water discharges from the existing outfall to around three per bathing season.

Non-bathing waters

In addition to the schemes for bathing waters work is also in hand to greatly improve wastewater treatment for the main coastal towns of Whitehaven, Workington and Maryport. At present most wastewater from these is discharged to the coastal zone, without treatment, from a number of short outfalls. The need to improve this totally unsatisfactory situation has been recognised for some time but unfortunately it was not possible to arrange the necessary finance because of the large number of what were judged worse problems within the region. With the recent adoption of the EC Urban Wastewater Treatment Directive there is now a legal requirement for treatment to be provided by the end of the year 2000. However, the need to improve matters on a shorter timescale than this was recognised when the first Asset Management Plan (AMP1) was drawn up between North West Water and the Director General of Water Services shortly after privatisation and it is our intention to ensure that completion of the schemes is on a timescale similar to that required for the bathing waters, that is generally by the summer of 1996.

Modelling studies using a mathematical model of bacterial dispersion developed by the WRc in the late 1980s showed that the existing outfalls were the main sources of high bacterial concentrations along the whole of the coast between St Bees Head and Allonby. Although there is at present no requirement to meet Bathing Water bacterial standards along this length of coast the model has been helpful in demonstrating the extent of this aspect of the existing problems and the probable effect of various improvement scenarios.

Following detailed discussions with the NRA we have submitted consent applications for the schemes shown in Figure 3 which are based on two new primary treatment works, one for Whitehaven and one for Workington and Maryport, each discharging via a long sea outfall.

At Whitehaven wastewater flows from the town will be pumped northwards to the site of the old Parton works and will be treated at a new works in conjunction with flows already arriving from the Distington and Lillyhall areas, before being discharged via the existing Lillyhall outfall, which is about 800 m long and terminates in a minimum depth of about 8 m of water. The works will treat 6DWF from the Distington and Lillyhall catchments where overflows are to inland watercourses and 3DWF from Whitehaven where a new storm water overflow to the sea will be built. This overflow will be about 250 m long and discharge at a minimum depth of about 1 m. It will carry screened storm water from a new screening installation in the renovated West Strand pumping station. The decision to renovate this historic building, dating from the mid-1850s and used for some time for electricity generation, was taken because it is within the harbour conservation area.

For Workington and Maryport a scheme has been developed to treat flows from both towns and the intervening villages at a new primary works to the north of Workington. All flows from the

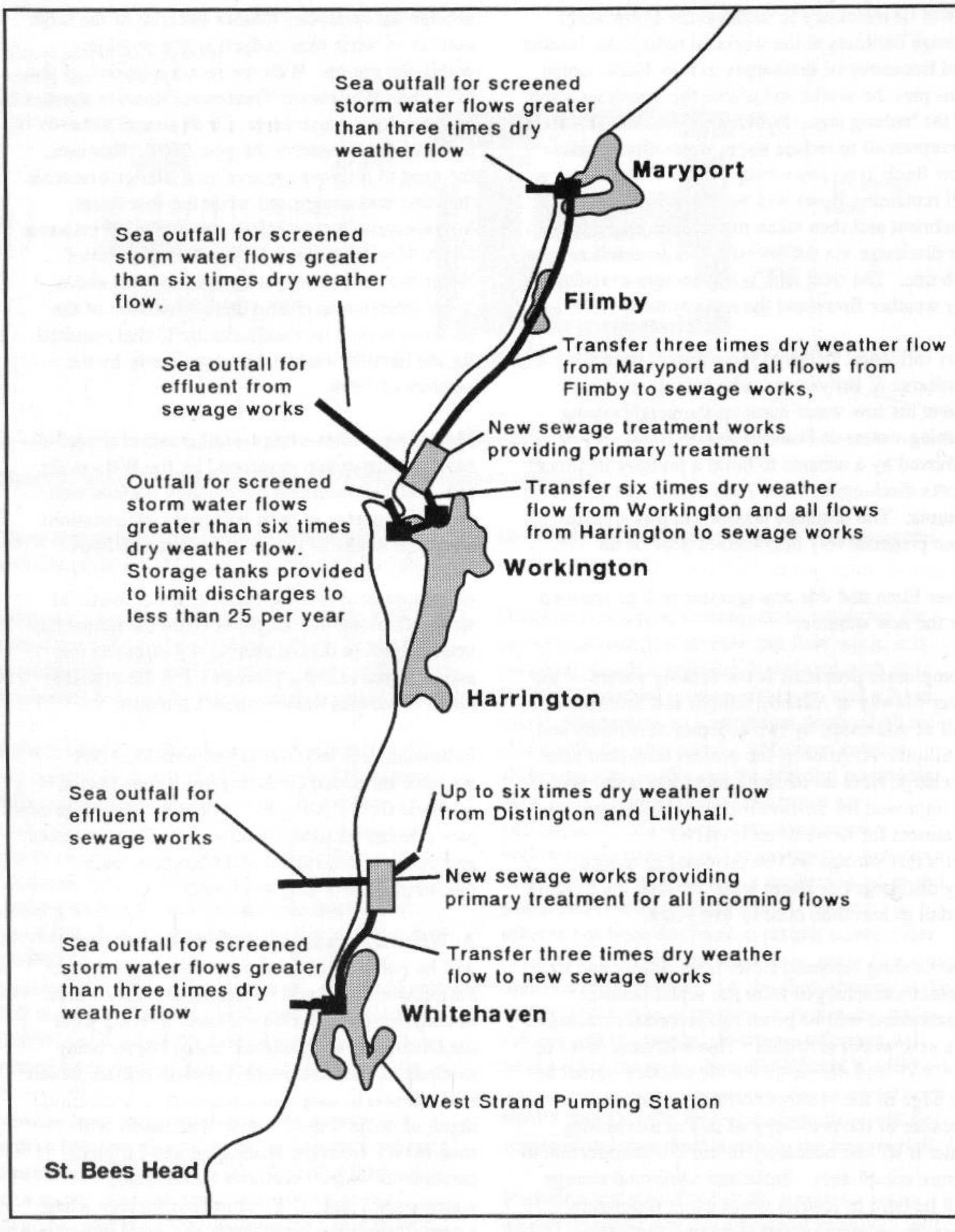


Figure 3 Proposed wastewater treatment improvement schemes for the Cumbrian coast.

Workington and Harrington areas will be pumped at a rate of up to 6DWF to the works site for treatment and discharged via a new 3 km outfall to a minimum depth of 10 m. There will be one storm sewage overflow provided for the flows from these catchments, at John Pier near the mouth of the River Derwent. Although flows from a new pumping station at John Pier will only be transferred to the works at up to 6DWF, sufficient storage will be built at the station to limit discharges of screened storm water from a new outfall to the estuary to less than 25 times per year. At Maryport flows of up to 3DWF will be pumped to the new works site and flows greater than this will be screened and discharged via a new 900 m outfall to a minimum depth of about 1 m just south of Maryport Harbour. The rising main from Maryport to the new works will also transfer all flows from the Flimby area. Depending on the flows arriving at the works from the other drainage areas, on occasions flows in excess of 6DWF from the Flimby area will be discharged, after screening only, via the long outfall. Mathematical modelling of these schemes indicates that the bacterial concentrations of the bathing waters will be near to the guideline values for much of the time.

One of the major differences in the design of the schemes for Whitehaven, Workington and Maryport and those affecting identified bathing waters is the extent of storm water management and treatment. During dry weather all the schemes should reduce bacterial concentrations in the inshore waters to near guideline levels for most of the time. The additional storm water management incorporated in the bathing water schemes should ensure that bacterial concentrations do not build up to unacceptable concentrations at any time during a typical wet summer or most of a typically wet winter. Where such extra storm management is not employed, and it is a very expensive part of the schemes, there will be relatively short periods when bacterial concentrations near the storm outfalls will exceed the standards applicable to a bathing water. However, even when this happens, the situation will be much better than that presently occurring, both temporarily and spatially.

During the course of developing all the schemes there have been extensive discussions, sometimes fairly animated, with representatives of local interests and our regulators. Additionally we carried out a considerable amount of hydrographic and both microbiological and macrobiological surveys. We have used this information along with the mathematical modelling studies as an aid to understanding the existing situation and to try to determine the effects of our proposals. Most of this information is in the form of specific reports on the particular projects but we have made some of it more available by incorporating it into Environmental Appraisal Reports submitted as part of the Planning Applications for the various new wastewater treatment works.

Coastal Zone Topics, 2: 34-36

Pollution management in the Solway Firth on the English side

L.B. Hughes

L.B. Hughes, formerly National Rivers Authority, North West Region, Chertsey Hill, Carlisle

All discharges to estuaries and coastal waters out to the 3-mile limit requires the consent of the National Rivers Authority (the Environment Agency since April 1996). However, the legislation giving powers to control pollution in these waters has come about in comparatively recent times.

A little known Act, the Border Rivers (Prevention of Pollution) Act of 1951 directed the responsible Boards on each side of the Scottish/English Border to constitute a joint committee with a duty to consider any matters in which the Boards were jointly interested. This duty was extended to the waters of the Solway Firth with the passing of the Clean Rivers (Estuaries and Tidal Waters) Act 1960 and subsequent Acts. It now takes the form of an annual liaison meeting at a very senior level and more informal liaison between local pollution staff regarding specific items as they arise.

The controlled waters of the inner Solway Firth are bounded at the seaward end by a line drawn from Silloth Pier across to Southerness Point on the Scottish side.

There are several riverine inputs to the firth from the English side, including the Rivers Eden and Esk, which are both first-class migratory fish rivers of very high water quality. Lower down the firth near Skinburness are the Rivers Waver and Wampool which join the firth in a common estuary. The quality of these waters is not as high as those previously mentioned, being compromised by a trade effluent discharge from a cellophane film manufacturing plant and a copper foil circuit printing effluent discharge. The latter closed in February 1993 and the former has plans well in hand to resolve the problem by building a treatment plant which is to be commissioned this year (1993). In the outer Solway there are two significant freshwater flows from the River Ellen at Maryport and the River Derwent at Workington. Both rivers support a good quality migratory fishery.

Discharges to the outer Solway remained without control until 1985 when the Control of Pollution Act came into force. This Act meant that any new discharge required a consent, but discharges which existed before 1985 were given legal status, provided the discharger submitted an application giving details of the nature and composition of the discharge. This application is known as a 'deemed' consent and allowed the company to discharge that effluent lawfully as long as the nature and composition was not changed in any way. Since 1985 there has been an on-going programme to 'determine' the deemed consents into new ones that reflect more accurately what is being discharged. This task has been completed for all trade effluent discharges and will be fulfilled for most of the important sewage discharges when the Cumbria Coast sewage disposal scheme is completed in 1995.

The Albright and Wilson discharge which enters the sea south of Whitehaven is a good example of the current control and how the NRA has worked with industry to resolve problems of pollution in the Solway. This factory manufactures detergents and phosphoric acid and until 1992 used phosphate rock, imported mainly from Morocco, as a raw material. The rock contained significant amounts of cadmium and other heavy metals which were discharged to the sea in the effluent. It was the single biggest point source discharge of cadmium in the UK by a large margin, and there had been a discharge from this site since 1945.

The deemed consent was determined in July 1988. This first consent did not seek to bring about a substantial improvement in effluent quality but it did reflect more accurately the existing quality and provided a framework for a better monitoring system. Successive improvements and consent reviews have resulted in reductions in cadmium, total metals, and the amount of cadmium in shellfish (Figures 1, 2 & 3). Further reductions have been achieved with the commissioning of a new plant and these will become apparent during the 1993 programme of monitoring.

Membership of the European Community has had a dramatic effect on the general environment policy

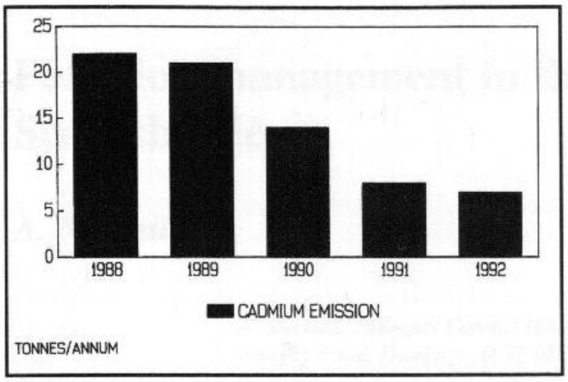


Figure 1 Cadmium emissions from Albright & Wilson, 1988-1992.

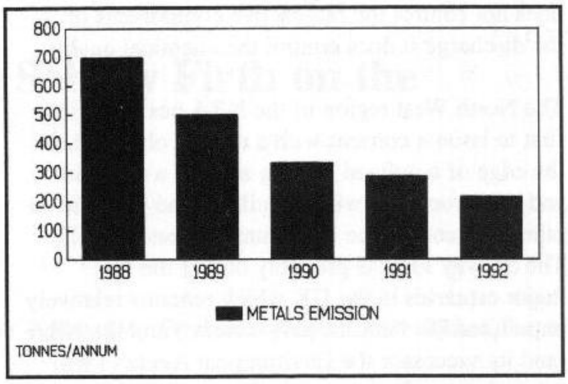


Figure 2 Metal emissions from Albright & Wilson, 1988-1992.

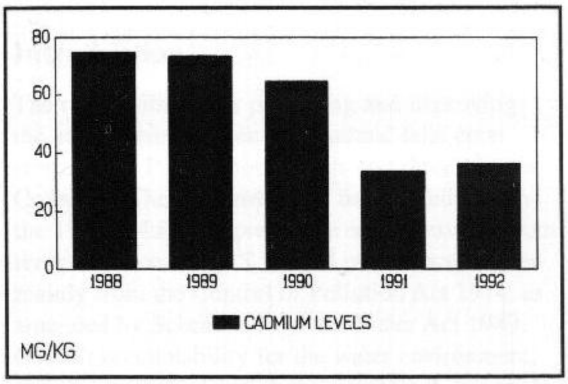


Figure 3 Cadmium levels in shellfish, Albright and Wilson, 1988-1992.

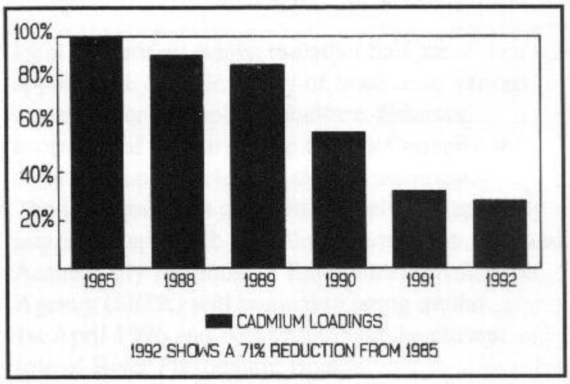


Figure 4 Cadmium loads, Albright & Wilson, 1985-1992.

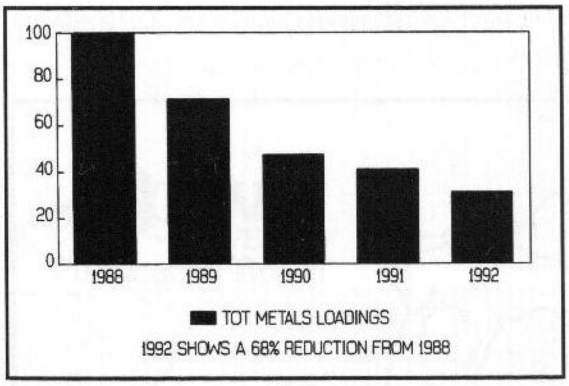


Figure 5 Total metals loads, Albright & Wilson, 1988-1992.

of the UK and in particular on the nature and scope of water pollution law. Member states must take steps to eliminate pollution caused by certain dangerous substances, which are grouped into a Black List (List I) and a Grey List (List II) on the basis of their toxicity, persistence and bioaccumulation. Member states are to eliminate pollution by List I substances and to reduce pollution by List II substances.

In this context the UK government has adopted the Environmental Quality Standard (EQS) approach, with the emphasis of control on the quality of the receiving water, working backwards to arrive at the desired quality in the effluent discharge. The NRA has to report to the DoE each year on whether or not the EQS has been met and, if not, what measures are being taken to ensure compliance in the future.

The International Conference on the Protection of the North Sea has produced a list of actions to protect and enhance the North Sea environment. Although the declaration itself was directed at improving the waters of the North Sea, the UK government intends that a consistent approach is applied to all UK waters. The main items to be achieved are a reduction of 70% for substances that cause a major threat to the marine environment (such as cadmium and mercury) between 1985 and 1995 and a 50% reduction of the less hazardous substances in the same period.

The 1992 figures for cadmium show an approximate 71% reduction since 1985 (Figure 4) and the 1992 figures for other metals show a reduction of 68% over those in 1988 (Figure 5), illustrating that these targets have been met in this example at Albright and Wilson.

Also of note is the very high profile discharge from Sellafield via a long sea outfall. Whilst the NRA does not control the radioactive components of the discharge it does control the chemical quality.

The North West region of the NRA has been the first to issue a consent with a quality objective at the edge of a defined mixing zone as a condition and this procedure will be built on and included in other consents as the opportunity presents itself. The Solway Firth is probably one of the few major estuaries in the UK which remains relatively unpolluted (E. Perkins, pers. comm.) and the NRA (and its successor the Environment Agency) will use its best endeavours to make sure it is kept that way.

Pollution management in the Solway Firth on the Scottish side

A. McNeill

A. McNeill, Pollution Control Manager, Solway River Purification Board, Rivers House, Irongay Road, Dumfries, DG2 0JE*

**now part of Scottish Environment Protection Agency (SEPA)*

Introduction

The responsibility for protecting and improving the aquatic environment in Scotland falls upon seven River Purification Boards and three Islands Councils. These Boards were first established in the 1950s whilst the present structure resulted from reorganisation in 1975. Board powers are derived mainly from the Control of Pollution Act 1974, as amended by Schedule 23 of the Water Act 1989. Overall accountability for the water environment, together with the legislation to protect it, lies with the Secretary of State for Scotland. Ultimately responsible to the Secretary of State, the Boards are non-departmental public bodies with half their membership being elected representatives from local authorities, whilst the other half are appointed by the Secretary of State from various interests, for example agriculture, fisheries, ecology and industry. The Islands Councils, in contrast, consist solely of elected members. The government is committed to providing a fully integrated approach to pollution control in Scotland. Accordingly the Scottish Environment Protection Agency (SEPA) will come into being on the 1st April 1996 and will encompass the current role of River Purification Boards.

Pollution control and prevention

In south-west Scotland, the Solway River Purification Board manages controlled waters in

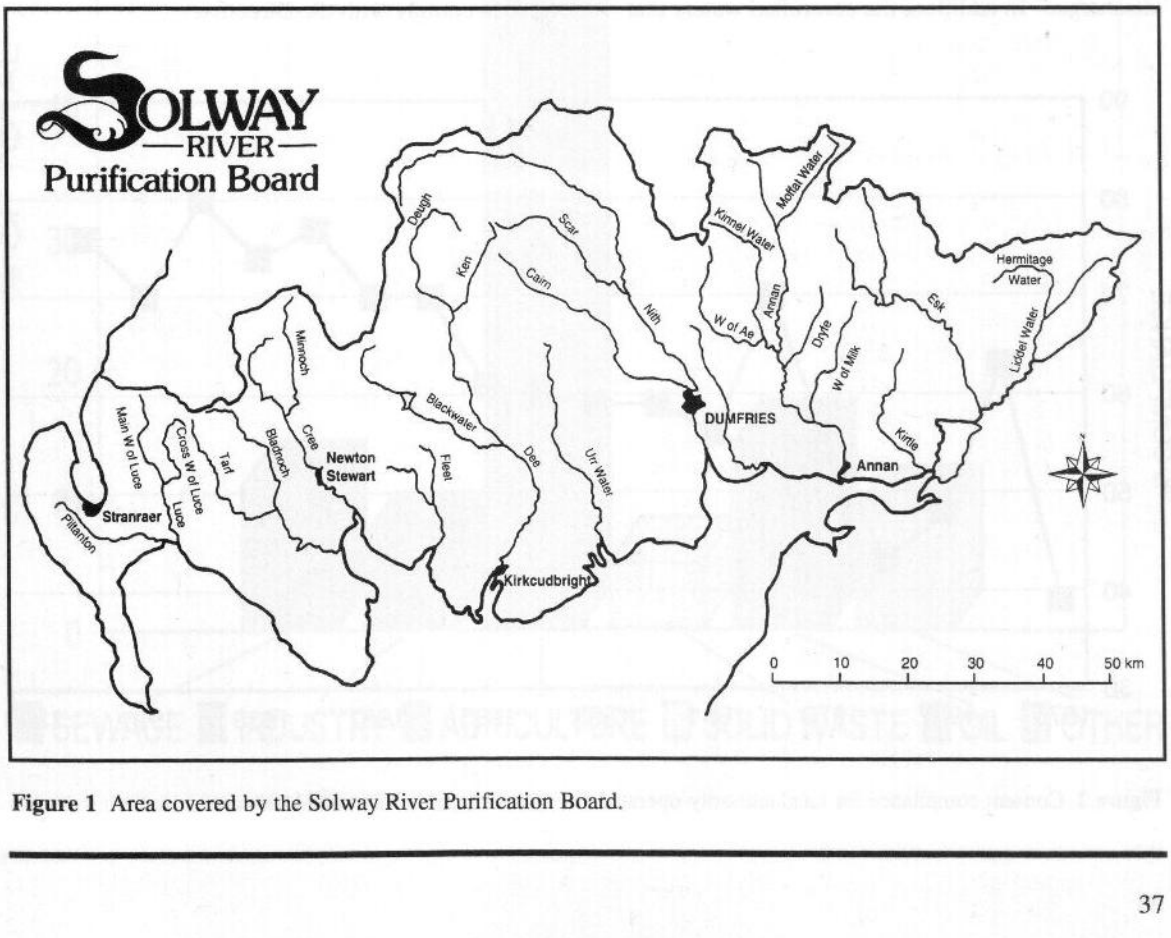


Figure 1 Area covered by the Solway River Purification Board.

an area of some 7,000 km^2 (Figure 1). Controlled waters include all rivers, lochs, groundwater and coastal waters. More than 98% of rivers within the Board's area are free from organic pollution, 263 km^2 of estuarine waters are designated Class A (best quality) and over 250 km^2 of tidal waters are satisfactory (Solway River Purification Board 1993). These high standards have been achieved by ensuring that water quality objectives meet with local, national and international targets and by enforcing the legal requirements that are placed on dischargers.

Any party wishing to discharge sewage or trade effluent to controlled waters, be it from a single house or a major factory complex, must obtain the formal consent of the Board. Consent, if granted, will incorporate a number of conditions with which the discharger must comply. To breach these at any time, regardless of whether pollution occurs or not, is an offence under the Control of Pollution Act. Consent conditions imposed by the Board are non-negotiable, although if a discharger considers that they are unduly rigid, they may lodge an appeal to the Secretary of State for Scotland within three months of consent being granted. The Secretary of State will either uphold or reject the appeal and the decision is final.

Discharges from population equivalents of 50 persons or more are routinely surveyed by the Board to make certain that standards are being complied with. Since 1992, the costs of compliance monitoring have been borne by the discharger. In addition, the controlled waters that receive these discharges are monitored chemically and biologically to assess whether or not there is any impact as a result of the effluent. Between 1975 and 1993, consent compliance improved from 40% to 70% for sewage discharges and from 47% to 74% for industrial discharges. This was achieved without any relaxation of consent standards. Figure 2 outlines the progress for consent compliance since 1975 for local authority-operated sewage treatment works, which are the single largest group of discharges controlled by the Board. It is the Board's aim to procure 100% consent compliance and it will strive to attain improvements to treatment facilities in order to accomplish this. Indeed, the advances which have been made are largely the result of the Board agreeing priorities for improvements with dischargers although, where there is a lack of co-operation and consent conditions are repeatedly exceeded, enforcement action leading to prosecution is taken.

A number of local authority-operated discharges and at least one private sewage discharge will have to meet the terms of the European Community Urban Waste Water Treatment Directive (91/271/EEC) and in some cases, in order to comply with the requirements, additional treatment will be needed. Most of the discharges that will need additional treatment are to either estuarine or coastal waters and all will have to comply with the Directive by the year 2005. Industrial discharges such as creameries, which dispose of large volumes of organic effluent to controlled waters, will also have to comply with the Directive.

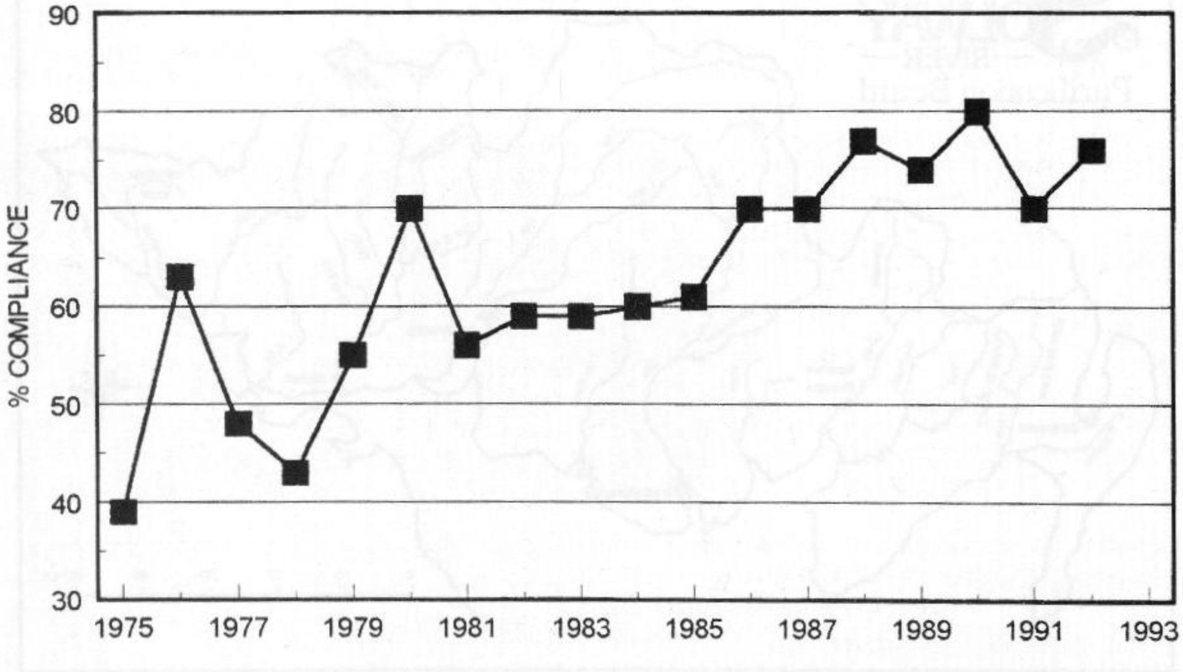


Figure 2 Consent compliance for local authority-operated sewage treatment works 1976-1993.

Some of the potentially most polluting or technologically complex industrial processes are subject to Integrated Pollution Control (IPC) under the Environmental Protection Act 1990. Traditionally, industries discharging to air, land or water were controlled by separate authorities but IPC seeks to ensure that contact is with just one enforcing agency. IPC was phased in on a rolling programme between 1992 and 1996 and the chemical industry has been the major candidate in the Board's area for this form of control. Her Majesty's Industrial Pollution Inspectorate (HMIPI) has been the enforcing authority and where a factory's processes are subject to IPC, any consent under the Control of Pollution Act 1974 will be superseded. Nonetheless, the Board continues to monitor the effluent and receiving waters, though the costs for this are reclaimed from HMIPI rather than directly from the discharger. The role of HMIPI will become a function of SEPA from the 1st April 1996 and hence the new Agency will be responsible for enforcing IPC.

Pollution incidents

Sometimes illegal discharges are made to controlled waters as the result of an accident, due to negligence, or deliberately, and the Board is dependent upon reports of such incidents from members of the public. In a time when there is an ever-increasing public awareness of environmental matters, the number of water pollution complaints has risen substantially. Every complaint is investigated immediately and the action depends on the circumstances of the incident, its severity with regard to the environment, or third party interests such as fisheries, public and private water supplies or industry. If, for example, the pollution causes a major fish kill, formal proceedings will be taken and the responsible party may be fined up to £20,000 if found guilty of the offence. In addition, the court may recommend that the defendant pays for the re-stocking of the affected waters with the equivalent number of fish lost as a result of the pollution. When pollution is of a less serious nature and unintentional, a more lenient view is

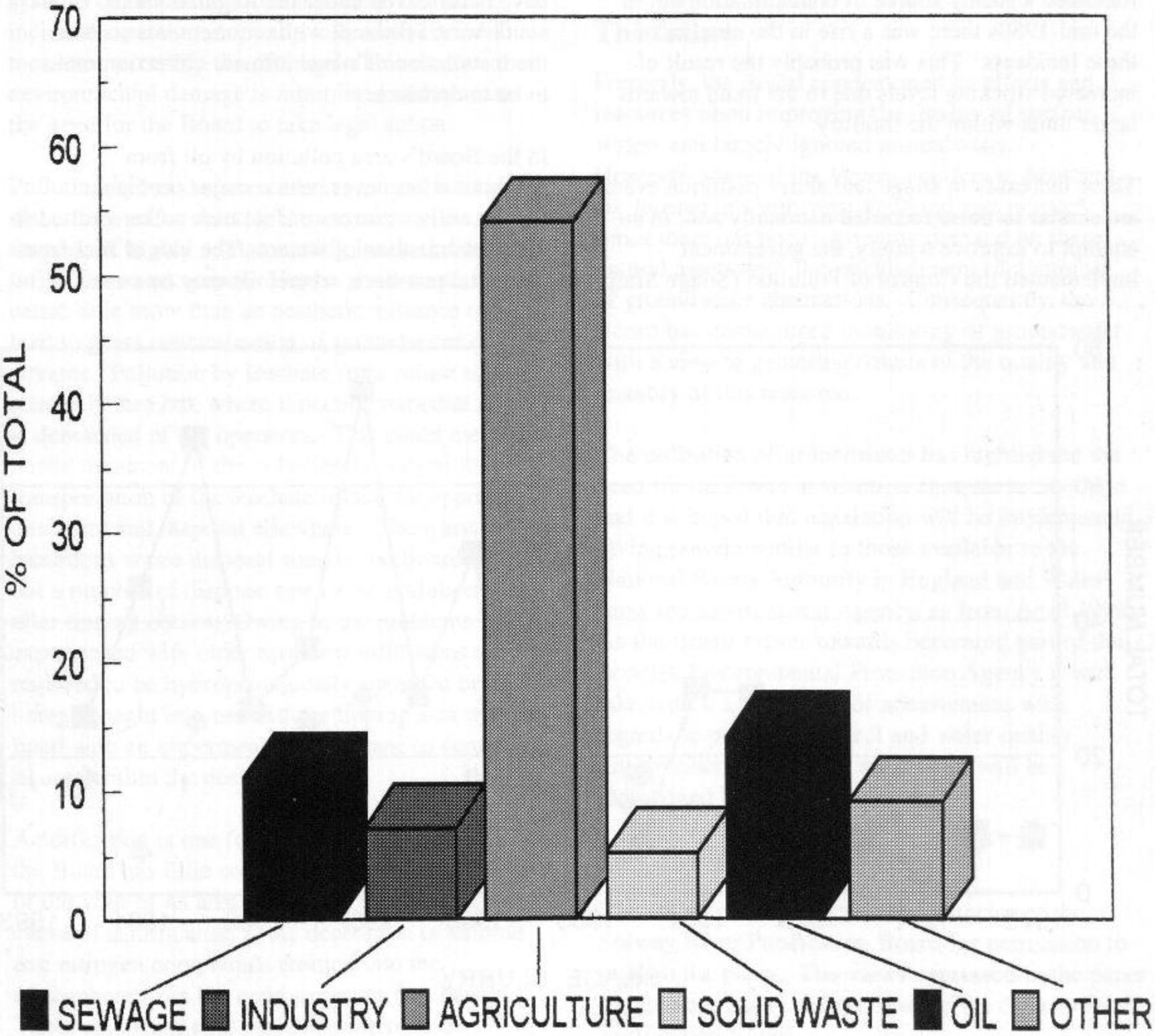


Figure 3 Pollution incidents 1975-1993.

taken, though any recurrence will lead to formal action being taken.

Since 1975, the single largest source of pollution in the south-west of Scotland had been agricultural activities (Figure 3). This is perhaps not surprising as the Board's area is largely rural and contains around 25% of Scotland's dairy industry, together with 18% of its beef cattle and 16% of sheep. The escape of strong effluents from intensive livestock production (e.g. slurry or silage) can cause major contamination of watercourses and Figure 4 shows the number of silage effluent and slurry pollution incidents from 1975 to 1992. By and large, silage pollution is seasonal, occurring during the summer months but at times when river flows can be at their lowest, and hence maximum impact can occur in the stream. Throughout the 1980s, the number of events remained high as farmers sought to produce more silage in an attempt to reduce costs of winter animal feed. The problem of silage pollution can be exacerbated by rain and, during the wet summers of 1985 and 1987, large numbers of events were recorded. Pollution by slurry has remained a steady source of contamination but in the mid-1980s there was a rise in the number of these incidents. This was probably the result of increased stocking levels due to the trend towards larger units within the industry.

These increases in silage and slurry pollution events are similar to those recorded nationally and, in an attempt to improve matters, the government implemented the Control of Pollution (Silage Slurry and Agricultural Fuel Oil) (Scotland) Regulations 1991. The Regulations gave River Purification Boards new powers to take action against any farmer who operates facilities identified as having a high risk of pollution, whether or not contamination has actually occurred. Previously, if the operator's co-operation could not be gained, the Board was powerless until controlled waters were adversely affected. All new silage and slurry storage facilities must meet the requirements of the Regulations. Those constructed prior to the Regulations coming into force remain exempt, provided they are not identified as being at risk of causing pollution. If this does occur, the operator will be asked to take remedial measures; if he fails to co-operate he may have a Notice served on him. The Notice will specify works to be carried out and the date by which this must be done. Failure to meet these terms may result in prosecution and the loss of exemption from the Regulations. In an attempt to reduce agricultural pollution events the Board has inspected the 3,000 farm units in its area and problems have been identified at around two-thirds of the premises examined. Moreover, 17 Notices have been served under the Regulations in south-west Scotland, with requirements such as the installation of silage effluent collection tanks to be undertaken.

In the Board's area pollution by oil from agriculture has never been a major problem, whereas other sources of fuel have often resulted in the contamination of waters. The loss of fuel from industrial premises, where oils may be stored in

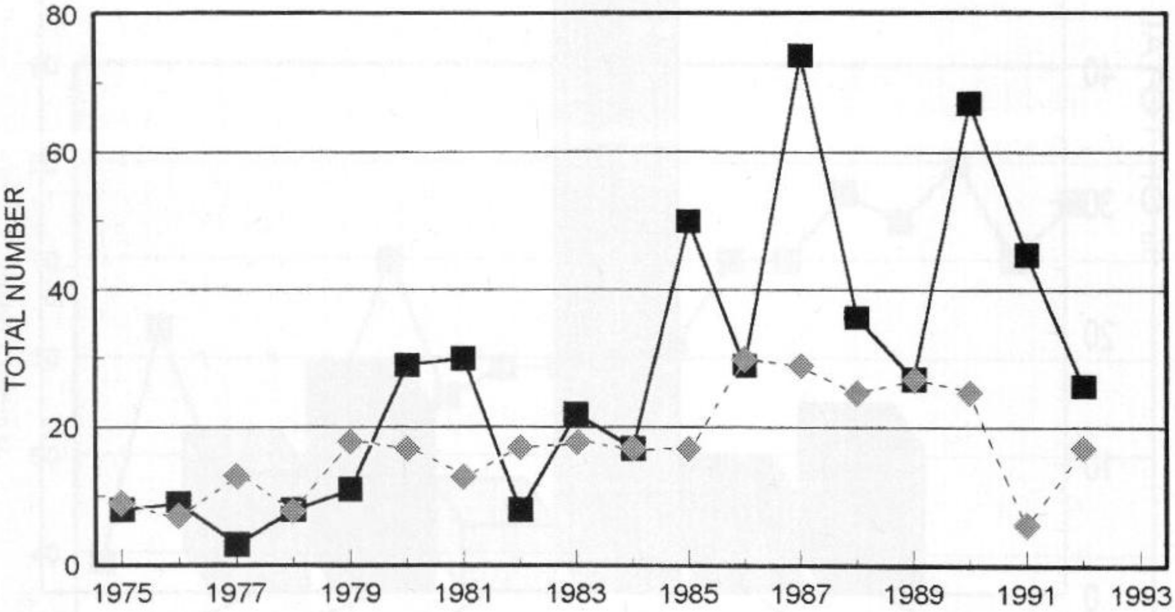


Figure 4 Silage effluent and slurry pollution incidents 1975-1993.

large quantities, is a constant threat, particularly where tanks are not properly bunded. In a recent incident 20,000 litres of heavy fuel oil escaped from a factory premises and only the containment of the fuel in the public sewerage system prevented serious environmental pollution in the coastal waters of Loch Ryan. Major trunk roads traverse the Board's area and vehicle accidents often result in fuel being spilled which can find its way into streams. In recent years incidents, often involving heavy goods vehicles, have resulted in fuel tanks rupturing and streams have been polluted by oil. The Board is automatically contacted in such events by the emergency services, and are usually able to deploy booms to contain the oil on site. Moreover, any abstractors downstream of the incident, for example fish farmers, can be advised to temporarily close off river water intakes.

Incidents relating to sewage most commonly arise when public sewers become choked and result in untreated waste being discharged to watercourses, often via storm overflow outlets. Similarly, defects may develop in privately-operated sewerage systems or industrial effluent plants. In such incidents operators normally take swift remedial measures to rectify the problem. This ensures that environmental damage is minimised and obviates the need for the Board to take legal action.

Pollution by solid waste can range from individuals discarding refuse directly into streams to the seepage of highly contaminating leachate from land infill into watercourses. Hence, solid waste may cause little more than an aesthetic nuisance or can lead to gross contamination of groundwater or streams. Pollution by leachate from refuse tips is relatively rare but, where it occurs, remedial action is demanded of the operators. This could mean the onsite treatment of the polluting liquors or the transportation of the leachate offsite for appropriate treatment and disposal elsewhere. There are no hazardous waste disposal sites in the Board's area but a number of disposal tips cause pollution long after tipping ceases. Owing to the problems experienced with older tips, new infill areas are required to be hydrogeologically surveyed before being brought into use and the tipping area must be lined with an impermeable membrane to contain all liquors within the designated site.

Acidification is one form of pollution over which the Board has little control though a substantial part of the west of its area is affected by it. The primary cause of acidification is the deposition of sulphur and nitrogen compounds emitted into the atmosphere from the combustion of fossil fuels. These emissions take place elsewhere in the United Kingdom as well as on continental Europe, and deposition occurs in the Southern Uplands. Here, several lochs, together with a number of streams, are adversely affected by acidification to an extent that they are devoid of salmonids. The problem of acidification can be exacerbated by forestry as the canopy may scavenge the pollutants from the atmosphere. As large parts of the Southern Uplands are now afforested, this clearly presents an added risk. A study at Loch Dee in 1980 to examine the effects of acidification in detail remains ongoing (Foundation for Water Research 1993).

30% of the Board's area is covered by forestry with a further 20% designated as suitable for afforestation. When developments are proposed in areas which are sensitive to acidification, the Board demands that a study is carried out on the local watercourse to assess potential impact by the proposal. Elsewhere, if new forestry is proposed, or clear-felling operations are to take place, the Board insists that the work is carried out in accordance with the Forestry Commission's guidelines (Forestry Commission 1993) to prevent water pollution from occurring.

The future

Formerly, the Board concentrated its efforts and resources upon improving the quality of surface waters and largely ignored groundwater. However, some of the largest aquifers in Scotland are located in south-west Scotland and in recent times there has been a growing demand on these natural assets with the establishment of a number of groundwater abstractions. Consequently, the Board has commenced monitoring of groundwater with a view to gathering details of the quality and quantity of this resource.

The utilisation of groundwater has highlighted the need for improved abstraction controls in Scotland and it is hoped that legislation will be implemented, giving powers similar to those available to the National Rivers Authority in England and Wales (now the Environment Agency, as from April 1996). As the Board moves towards becoming part of the Scottish Environmental Protection Agency it will take with it a high level of achievement with regards to pollution control and water quality improvement which one anticipates will be maintained by the new authority.

Acknowledgements

The author wishes to thank the Director of the Solway River Purification Board for permission to publish the paper. The views expressed in the paper do not necessarily reflect those of the Solway River Purification Board.

References

Forestry Commission. 1993. *Forest and water guidelines.* London, HMSO.

Foundation for Water Research. 1993. *Acidification, forestry and fisheries management in Upland Galloway. Proceedings of the Loch Dee Symposium, June 1993.*

Solway River Purification Board. 1993. *Annual Report.* Dumfries, Solway River Purification Board.

Radioactive contamination of the Solway and Cumbrian coastal zone

P. Kershaw

Radioactive contamination occurs throughout the Solway and Cumbrian coastal zone. Most of the contamination is of artificial radionuclides (i.e. radionuclides not found naturally) due to discharges from the nuclear industry. However, enhanced levels of naturally-occurring radionuclides have resulted from non-nuclear activities. There are considerable space- and time- variations, or 'patchiness', in the radionuclide distributions. The coastal zone represents both a source and sink for radionuclides discharged into the region.

P. Kershaw, Ministry of Agriculture, Fisheries and Food, Fisheries Laboratory, Lowestoft NR33 0HT*

**Now the Centre for Environment, Fisheries and Aquaculture Sciences (CEFAS)*

Introduction

There are several industrial sources of artificial and naturally-occurring radionuclides into the waters of the eastern Irish Sea (Figure 1). The overall distribution of artificial radionuclides in the Solway region has been dominated by discharges from the Sellafield nuclear fuel reprocessing plant on the Cumbrian coast. This has masked the effects of Chapelcross and contamination by global fallout due to weapons testing (MAFF 1993). Fallout from the Chernobyl accident did affect the region but its impact on the Irish Sea environment was rather limited (Camplin *et al.* 1986).

Discharges from Sellafield (formerly Windscale) began in 1952. The quantities and isotopic composition of the waste have varied considerably. The releases of most radionuclides peaked in the

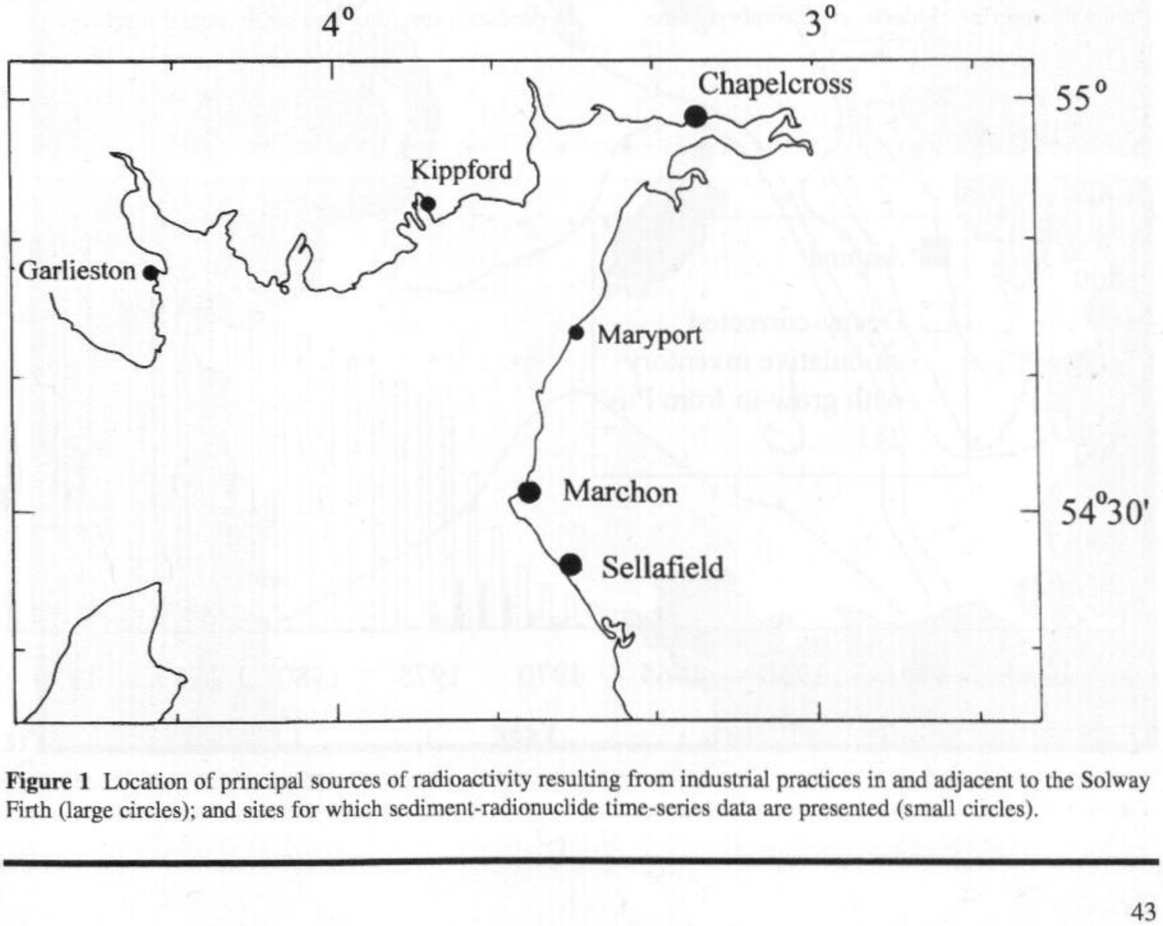


Figure 1 Location of principal sources of radioactivity resulting from industrial practices in and adjacent to the Solway Firth (large circles); and sites for which sediment-radionuclide time-series data are presented (small circles).

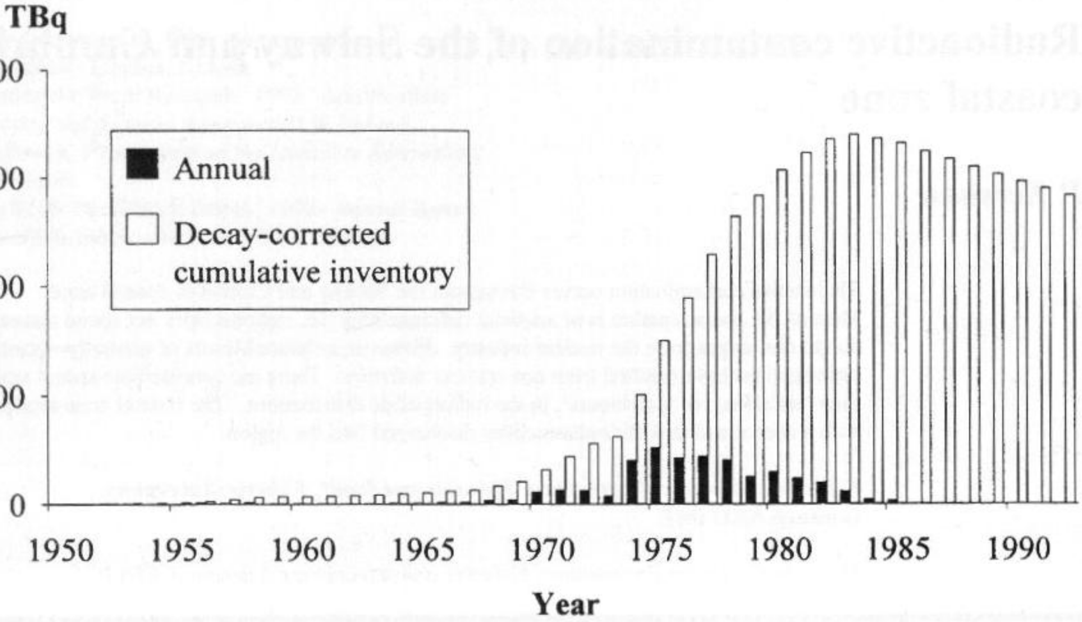


Figure 2 Annual mean discharge and decay - corrected environmental inventory of ^{137}Cs (Tbq) from Sellafield.

mid- to late-1970s (Figure 2). There have since been significant reductions as a result of improved waste treatment. However, it is important to consider the total inventory now residing in the environment. For shorter-lived radionuclides (i.e. half life $\leq$30 y) the total environmental inventory has decreased in line with the reductions in the annual discharges (Figure 2). For longer-lived radionuclides (e.g. ^{239}Pu, $t_{1/2}$ = 24,000 y) there has been no significant decrease in the inventories. Indeed, the inventory of the α-emitting ^{241}Am will increase for several decades resulting from the decay of ^{241}Pu, a ß-emitter discharged in large quantities in the 1970s (Figure 3).

The principal industrial source of naturally-occurring radionuclides in the region has been a phosphate-processing plant at Whitehaven. The phosphate ore contained relatively high concentrations of uranium and its radioactive decay products, resulting in a mean annual discharge of

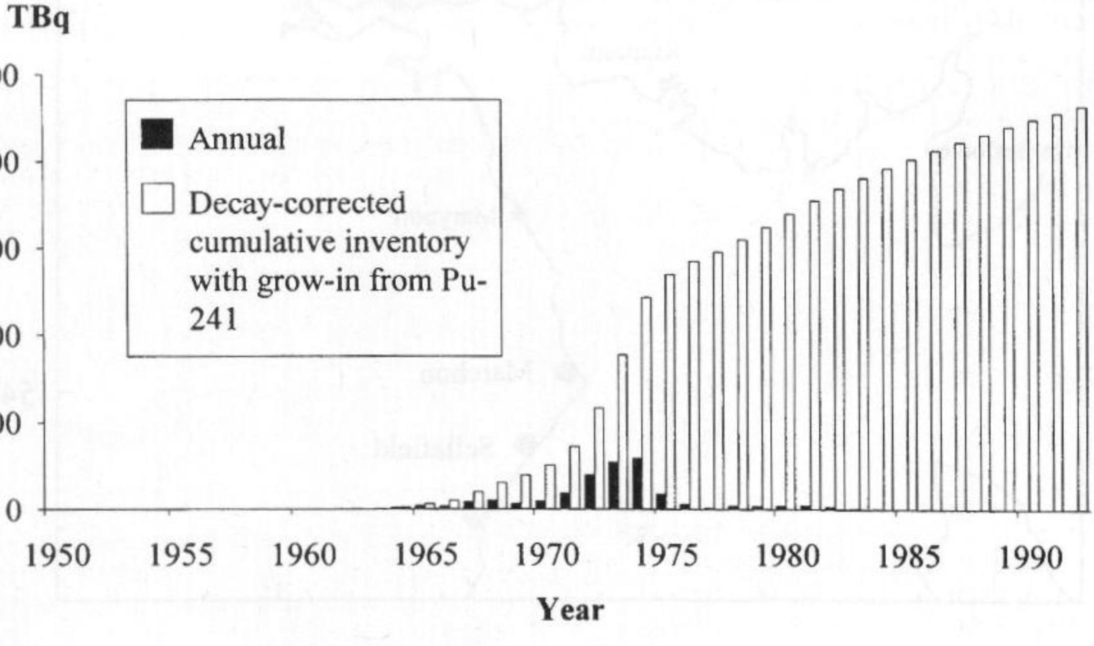


Figure 3 Annual mean discharge and decay - corrected environmental inventory of ^{241}Am from Sellafield.

about 35 tonnes uranium per annum throughout the 1970s and 1980s (cf. Sellafield ~4 tonnes uranium per annum). Processing changes at the plan brought about significant reductions in the discharge, of both radionuclides and heavy metals, during 1992.

Further details of radionuclide discharges into the Irish Sea, their distributions and effects, can be found in a recent publication (Kershaw *et al.* 1992). This includes a summary of the main sources and the quantities discharged; the mechanism by which discharges from Sellafield are authorised; the radiological impact on the local population; an outline of the many scientific studies on the distribution and behaviour of radionuclides after their release; and the environmental consequences in terms of the probability of radiation-induced damage to other organisms.

Artificial radionuclide distributions

The initial dispersion of radionuclides from Sellafield is influenced by a number of factors including variations in the discharge rate; local hydrographic conditions; the distribution of bottom sediments; and the chemical form of the radionuclides in the effluent. Those radionuclides which are relatively soluble in seawater (e.g. ^{99}Tc, ^{137}Cs, ^{90}Sr, ^{3}H) are advected principally to the north and west, leaving the Irish Sea via the North Channel with a mean transit time of about one year. A much smaller proportion is carried south via St George's Channel. Even non-conservative radionuclides, such as plutonium, are transported considerable distances (e.g. to the Norwegian Sea) but their concentrations in seawater decrease exponentially with distance from the source (McKay & Pattenden 1993).

Most radionuclides are adsorbed onto particle surfaces, to some degree, and their distributions and behaviour are intimately linked to that of the bottom sediments. The largest repository of sediment-bound radionuclides lies in an area of muddy sediments parallel to the Cumbrian coast (Figure 4), extending south towards Liverpool Bay and north across the mouth of the Solway Firth. There are steep concentration gradients decreasing both towards the shoreline and to the west of the muddy sediments. A northwards 'footprint' of higher concentrations, towards the Scottish coast, is apparent in all studies which have been reported (e.g. MacKenzie *et al.* 1987; Jones *et al.* 1988; Woodhead 1988).

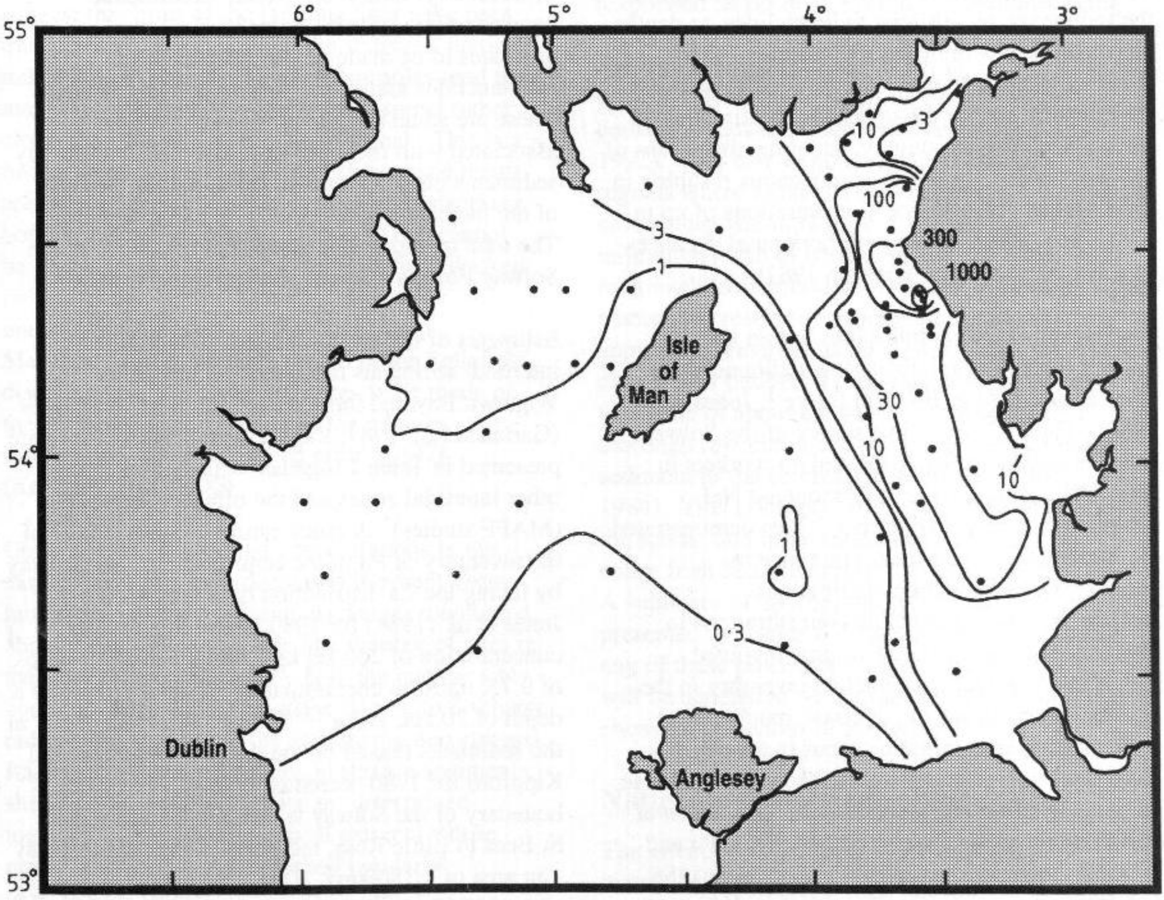


Figure 4 Distribution of ^{239,240}Pu (kBq m^{-2}) in sea bed sediment in the eastern Irish Sea, 1977/78.

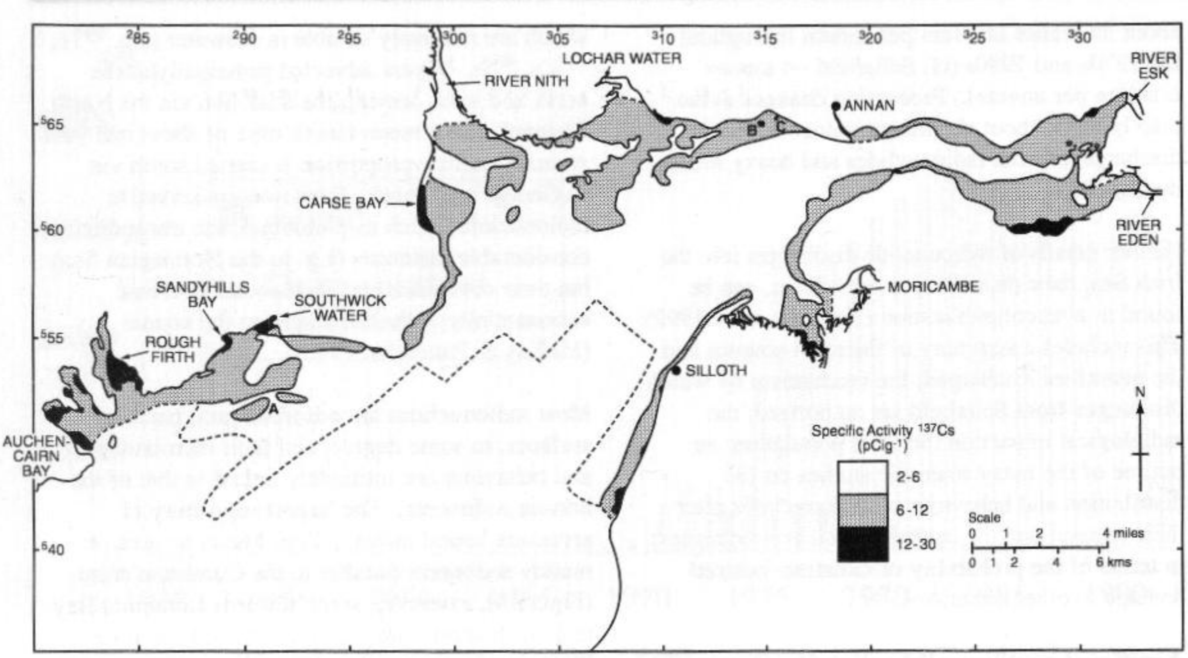


Figure 5 Distribution of ^{137}Cs (p Ci g^{-1} (x 37 Bq kg^{-1})) in surface intertidal sediments of the inner Solway, July 1980. From: Jones *et al.* (1984).

These sediments are subject to tidal and wave resuspension and extensive reworking by benthic organisms (bioturbation). The rate of sediment accumulation, of the offshore muds, appears to be low (<1 mm a^{-1}, Kershaw *et al.* 1988). However, bioturbation results in contamination of the sediments, by artificial radionuclides, to depths of greater than 1 m below the sediment-water interface (Kershaw *et al.* 1984). Bioturbation has the effect of mixing the upper few centimetres of the sea bed very thoroughly, but at depths of tens of centimetres mixing is less homogenous resulting in variations of radionuclide concentrations of up to two orders of magnitude over horizontal distances of a few centimetres (Pentreath 1987).

The large areas of mobile sands within the Solway Firth have relatively low radionuclide concentrations (e.g. 70-1100 Bq kg^{-1}, Jones *et al.* 1984). The most extensive survey of the Solway was that conducted by Jones and co-workers in July 1980, using a hovercraft-mounted NaI scintillation detector (Figure 5). This demonstrated the importance of sediment grain-size in determining radionuclide distributions. Despite the low radionuclide concentrations in the mobile sands, the large volume involved means that the total radionuclide inventory in the Solway is significant. In contrast, much higher radionuclide concentrations occur in muddy embayments, creeks and intertidal saltmarsh/merse on both the north and south shores. Garland *et al.* (1989) reported the concentrations of Cs, Pu and ^{241}Am in intertidal sediments, collected in 1985 and 1986, at several sites along the south Scottish coast. They demonstrated the influence of sediment type and geographical factors in controlling radionuclide distributions and provided evidence of the sea-to-land transfer of radionuclides in sea spray - a process causing a very low radiological impact. They were also able to show the effects of Chernobyl fallout on overall radionuclide concentrations. Such studies have allowed estimates to be made of the inventories of radionuclides associated with intertidal sediments. These are small compared with inventories associated with the more extensive offshore muddy sediments but nevertheless are important because of the increased likelihood of human interaction. The total quantity of artificial radionuclides in the Solway Firth is difficult to estimate accurately.

Estimates of the inventories of Pu (alpha) in intertidal sediments have been published for Wigtown Bay and the zone from Silloth to St Bees (Garland *et al.* 1989; Eakins *et al.* 1988). These are presented in Table 1 together with estimates for other intertidal zones and the offshore sediments (MAFF studies). A crude estimate can be made of the inventory of Pu in the central area of the Solway by taking the Cs distribution data presented by Jones *et al.* (1984) for 1980, assuming a mean concentration of 280 Bq kg^{-1} (dry), a dry/wet ratio of 0.75, uniform contamination of the sediment to a depth of 20 cm, and a ^{239,240}Pu/^{137}Cs ratio of 0.2 in the sediments (based on the data for Maryport and Kippford for 1980 presented below). The outer boundary of the Solway is taken to be a line from St Bees to Little Ross, including Kirkcudbright Bay - an area of 1,180 km^2. This gives an inventory of about 110 Tbq ^{137}Cs and 25 Tbq Pu (alpha). The purpose of this exercise is to indicate the

Table 1 Estimated sediment inventories of plutonium (alpha) in the 1980s.

Site	*TBq*
offshore - subtidal	470
intertidal:	
Silloth-Walney	5[†]
Wigtown Bay	2.3[†]
Morecambe Bay	13[†]
Duddon Estuary	1.8[†]
Esk Estuary	2**
Solway Firth (central zone)	[25]*
Total sediment inventory	519
Total cumulative environmental inventory (on basis of reported discharges)	730

† = from Eakins *et al.* (1988); * = see text for explanation;
** = from Toole *et al.* (1992)

potential reservoir of this region rather than present an accurate estimate of the actual inventory.

Cores taken from the merse/saltmarsh, at locations such as Southwick Water and Skyreburn Bay along the Scottish coast, have provided an historical record of the Sellafield discharges (MacKenzie & Scott 1982; MacKenzie *et al.* 1994). These were taken from sites of sediment accumulation and minimal disturbance. Evidence from isotope ratios suggest that most of the radionuclides have been transported to the area bound to sediment particles, rather than in solution. The core profiles tend to match the integrated environmental signal rather closer than the annual discharge signal. This is a further demonstration that the offshore sediments are subject to considerable mixing and reworking both by tides and episodic storms. They cannot be regarded as a final 'sink' for Sellafield-derived radionuclides. Cores taken in 1988 from undisturbed sediments in Senhouse Dock, Maryport, also provided a record of the Sellafield discharge and permitted estimates to be made of the Pu isotope composition of the releases - information which is limited prior to 1978 (Kershaw *et al.* 1990).

Generally, environmental concentrations in the eastern Irish Sea have decreased in recent years, in response to the declining discharges mentioned above. Routine monitoring at a number of sites in the Solway is conducted by both the nuclear site operators (as a condition of the license to discharge radioactive waste) and the authorising departments. Radionuclide concentrations in surface sediments, shoreline seawater and biota are determined together with measurements of external γ dose rates. The results are published regularly (e.g. MAFF 1993).

The concentrations of ^{137}Cs and ^{239,240}Pu in surface sediments from three intertidal sites (Maryport, Kippford, Garlieston), sampled by MAFF in the period 1977-1991, are shown in Figure 6. Concentrations of ^{137}Cs decreased consistently, with the greatest change seen at Maryport. This is not unexpected given the change in discharge rate and the relative proximity of Maryport to Sellafield. Concentrations of ^{239,240}Pu also declined significantly at Maryport, although by a lower factor. However, this trend was not apparent at Kippford or Garlieston. Indeed, at Garlieston, a small increase may be discerned. This may well be a reflection of the importance of sediment reworking and transport in influencing the behaviour of particle-reactive radionuclides, particularly for sites at greater distance from the source. However, some caution is required as there is a lack of information on sediment variability and stability (i.e. erosion/accumulation) at these sites.

Monitoring sites have been selected for a variety of reasons - in particular with regard to the need to monitor critical group doses - and do not necessarily represent the maximum concentrations, which will vary in space and time. Sites subject to continuing sediment deposition, such as saltmarsh/merse, will experience increases in the inventories of the longer-lived radionuclides (expressed as Bq m^{-2}), even if the sediment being deposited at present has lower radionuclide concentrations (expressed as Bq kg^{-1}). Such zones, subject to tidal inundation, are relatively stable for periods of tens or hundreds of years (Emptage 1992). This is in contrast to more energetic regions where rapid changes in sediment type and erosion/deposition rates (e.g. caused by channel migrations) lead to corresponding variations in radionuclide distributions, creating difficulties when placing the results of radionuclide analysis in an appropriate environmental context. The main tidal channels in the Solway migrate constantly, on a timescale of about ten years, bringing about a thorough reworking and mixing of contaminated sediment in the central part of the firth (Jones *et al.* 1984). This is simply an extreme end member of the space- and time-variability that affects the entire Irish Sea, to a greater or lesser degree.
A summary of appropriate space- and time-scales is presented in Figure 7. The relative importance of any of these processes for a particular radionuclide will be dependent on the radioactive half-life and chemical behaviour of the radionuclide.

Naturally-occurring radionuclides

The environmental impact of industrially-introduced naturally-occurring radionuclides has been of less significance than that of the artificial radionuclides, and will be dealt with briefly here.

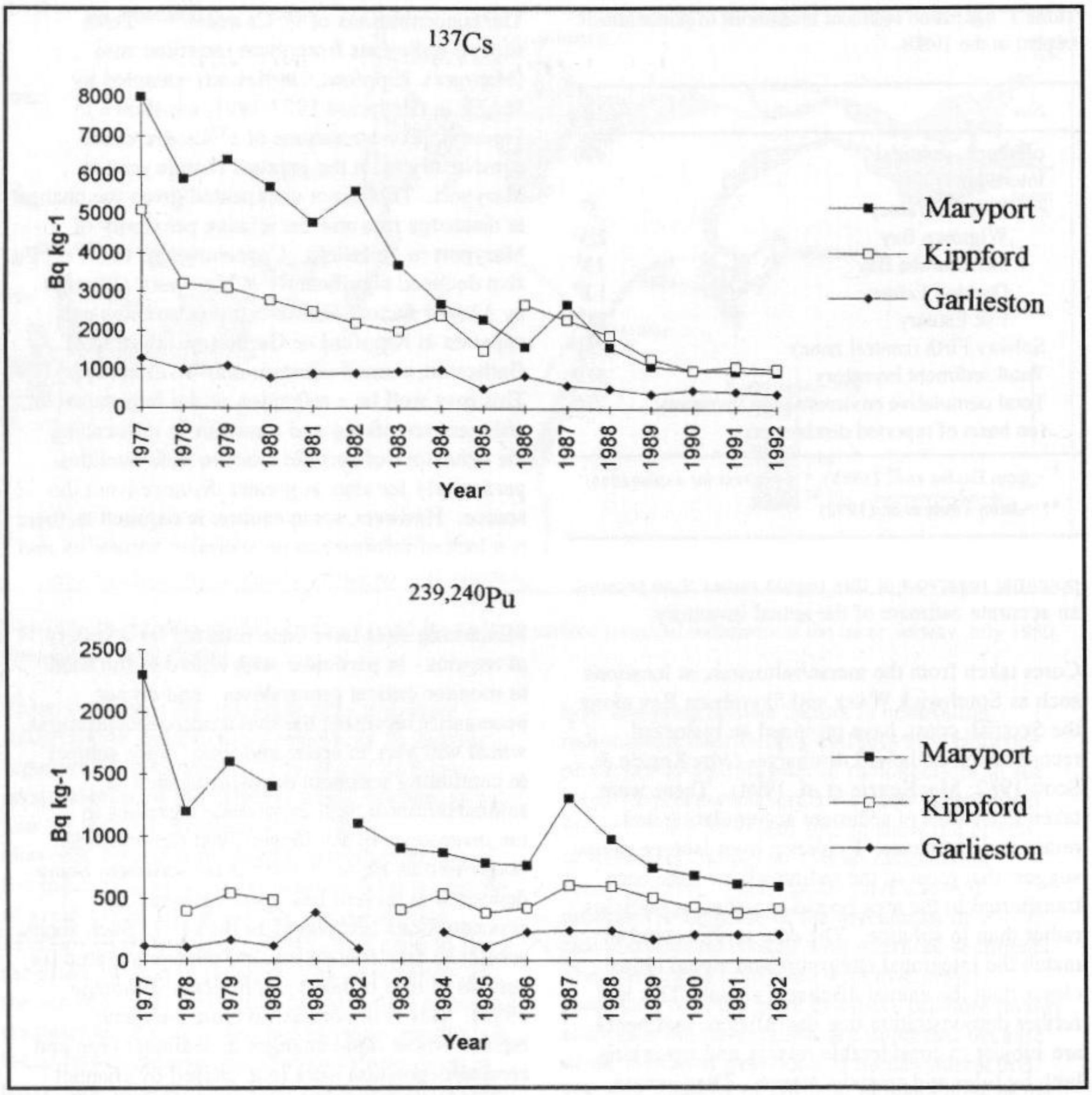


Figure 6 Concentrations of ^{137}Cs and ^{239,240}Pu in surface sediments from Maryport (mud), Kippford (merse) and Garlieston (mud) in the period 1977-1992.

The region around Whitehaven has elevated levels of uranium-series radionuclides in seawater, sediments and biota as a result of discharges from the Marchon phosphate processing plant. This phenomenon has been described in a number of publications (Kershaw *et al.* 1990; McCartney *et al.* 1990; McDonald *et al.* 1992; Rollo *et al.* 1992). It is clearly illustrated by comparing radionuclide concentrations in sediments from Whitehaven harbour - where the ore was formerly unloaded - with similar types of sediment from more distant sites. Concentrations of ^{238}U- and ^{235}U-series radionuclides are elevated in the harbour sediments, in contrast to ^{232}Th-series radionuclides which have similar values (Table 2).

Concentrations of the relatively soluble ^{226}Ra of over 60 Bq m^{-3} have been measured in seawater close to the discharge point. This is about a factor of 30 higher than the expected background concentration. Relatively high sea bed inventories of ^{210}Pb and ^{230}Th have also been detected in this area, again attributable to Marchon (Poole *et al.* in prep.). Elevated concentrations of ^{210}Po, the radioactive daughter of ^{210}Pb, have been detected in biota, especially shellfish (Rollo *et al.* 1992; McDonald *et al.* 1992) and the possible influence of elevated Cd levels on the retention of ^{210}Po is being investigated (D.J. Swift, pers. comm.).

Conclusions

- Radioactive contamination of the Solway Firth has resulted from both the nuclear and non-nuclear industries.
- Discharges from Sellafield have dominated all other sources of artificial radionuclides.

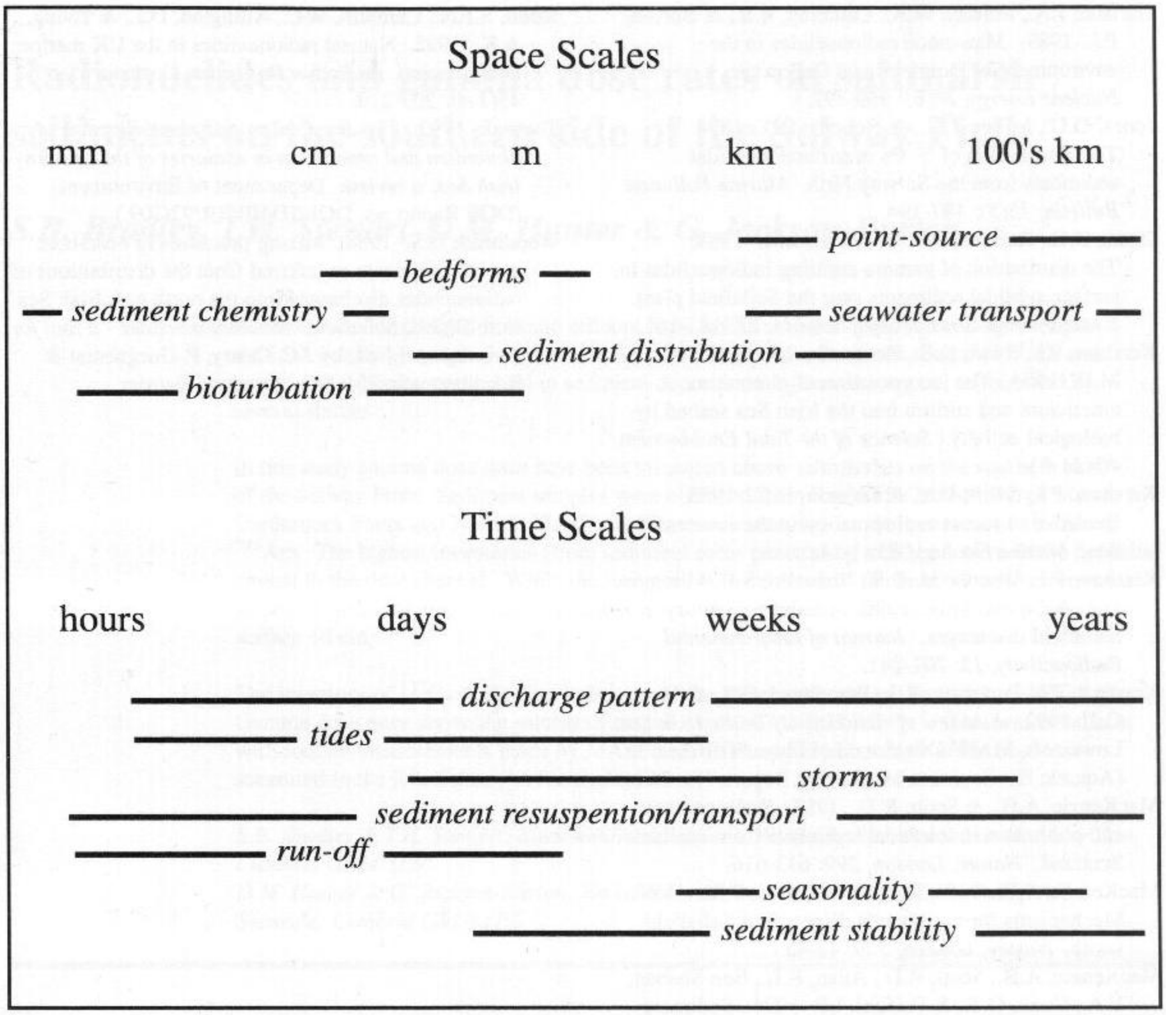


Figure 7 Space- and time-scales of processes influencing the behaviour of radionuclides in coastal waters.

Table 2 A comparison of natural radionuclide activities (Bg kg^{-1} dry) in the surface sediments of Whitehaven Harbour and the Irish Sea (from McCartney *et al.* 1990).

Location	^{238}U	^{235}U	^{234}U	^{232}Th	^{230}Th	^{228}Th
Whitehaven Harbour	300-500	13-20	300-500	10-30	500-700	10-30
Irish Sea	1-20	<1	1-20	5-30	1-100	5-30

- There is considerable patchiness in radioactive contamination. Significant space-scales vary from millimetres to hundreds of kilometres, and time-scales from hours to hundreds of years.
- The impact of past discharges is as important as present day discharges for longer-lived radionuclides.
- The coastal zone represents both a source and sink for radionuclides discharged into the region.

References

Camplin, W.C., Mitchell, N.T., Leonard, D.R.P., & Jefferies, D.F. 1986. *Radioactivity in surface and coastal waters of the British Isles. Monitoring of fallout from the Chernobyl Reactor Accident.* Lowestoft, Directorate of Fisheries Research. (Aquatic Environment Monitoring Report, No. 15).

Eakins, J.D., Morgan, A., Baston, G.M.N., Pratley, F.A., Yarnold, L.P., & Burton, P.J. 1988. *Studies of environmental radioactivity in Cumbria. Part 8. Plutonium and americium in the intertidal sands of north-west England.* Harwell, United Kingdom Atomic Energy Authority. (AERE-R 12061.)

Emptage, M. 1992. *Radionuclide distribution in relation to sedimentary processes in the Esk Estuary, UK.* Unpublished PhD thesis, Lancaster University.

Garland, J.A., McKay, W.A., Cambray, R.S., & Burton, P.J. 1989. Man-made radionuclides in the environment of Dumfries and Galloway. *Nuclear Energy, 28(b):* 369-392.

Jones, D.G., Miller, J.M., & Roberts, P.D. 1984. The distribution of ^{137}Cs in surface intertidal sediments from the Solway Firth. *Marine Pollution Bulletin, 15(5):* 187-194.

Jones, D.G., Roberts, P.D., & Miller, J.M. 1988. The distribution of gamma-emitting radionuclides in surface subtidal sediments near the Sellafield plant. *Estuarine and Coastal Shelf Science, 27:* 143-161.

Kershaw, P.J., Swift, D.S., Pentreath, R.J., & Lovett, M.B. 1984. The incorporation of plutonium, americium and curium into the Irish Sea seabed by biological activity. *Science of the Total Environment, 40:* 61-81.

Kershaw, P.J., Swift, D.J., & Denoon, D.C. 1988. Evidence of recent sedimentation in the Eastern Irish Sea. *Marine Geology, 85:* 1-14.

Kershaw, P.J., Woodhead, D.S., Malcolm, S.J., Allington, D.J., & Lovett, M.B. 1990. A sediment history of Sellafield discharges. *Journal of Environmental Radioactivity, 12:* 201-241.

Kershaw, P.J., Pentreath, R.J., Woodhead, D.S., & Hunt, G.J. 1992. *A review of radioactivity in the Irish Sea.* Lowestoft, MAFF Directorate of Fisheries Research. (Aquatic Environment Monitoring Report, No. 32.)

MacKenzie, A.B., & Scott, R.D. 1982. Radiocæsium and plutonium in intertidal sediments from southern Scotland. *Nature, London, 299:* 613-616.

MacKenzie, A.B., Scott, R.D., & Williams, T.M. 1987. Mechanisms for northwards dispersal of Sellafield waste. *Nature, London, 329:* 42-45.

MacKenzie, A.B., Scott, R.D., Allan, R.L., Ben Shaban, Y.A., Cook, G.T., & Pulford, I.P. 1994. Sediment radionuclide profiles: implications for mechanisms of Sellafield waste dispersal in the Irish Sea. *Journal of Environmental Radioactivity, 23:* 39-69.

MAFF. 1993. *Radioactivity in surface and coastal waters of the British Isles, 1991.* Lowestoft, MAFF Directorate of Fisheries Research. (Aquatic Environment Monitoring Report, No. 34.)

McCartney, M., Kershaw, P.J., & Allington, D.J. 1990. The behaviour of ^{210}Pb and ^{226}Ra in the eastern Irish Sea. *Journal of Environmental Radioactivity, 12:* 243-265.

McDonald, P., Cook, G.T., & Baxter, M.S. 1992. Natural and anthropogenic radioactivity in coastal regions of the UK. *Radiation Protection Dosimetry, 45(1-4):* 707-710.

McKay, W.A., & Pattenden, N.J. 1993. The behaviour of plutonium and americium in the shoreline waters of the Irish Sea: a review of Harwell Studies in the 1980s. *Journal of Environmental Radioactivity, 18:* 99-132.

Pentreath, R.J. 1987. The interaction with suspended and settled sedimentary materials of long-lived radionuclides discharged into United Kingdom coastal water. *Continental Shelf Research, 7:* 1,457-1,469.

Poole, A.J., Young, A.K., Kershaw, P.J., & Denoon, D.C. In prep. *The distribution and enhancement of uranium and thorium radionuclides in the sediments from UK coastal waters.*

Rollo, S.F.N., Camplin, W.C., Allington, D.J., & Young, A.K. 1992. Natural radionuclides in the UK marine environment. *Radiation Protection Dosimetry, 45(1-4):* 203-210.

Toole, J. 1992. *The distribution and remobilisation of plutonium and americium in estuaries of the eastern Irish Sea: a review.* Department of Environment. (DOE Report no. DOE/HMIP/RR/92/109.)

Woodhead, D.S. 1988. Mixing processes in nearshore marine sediments as inferred from the distributions of radionuclides discharged into the north-east Irish Sea from BNFL, Sellafield. *In: Radionuclides - a tool for oceanography,* ed. by J.C. Guary, P. Gueguenlat & R.J. Pentreath, 331-341. London, Elsevier.

Radionuclides and gamma dose rates on saltmarsh sediments on the southern side of the Solway Firth

S.B. Bradley, T.H. Stewart, D.M. Hunter & G. Jackson-Burton

Radionuclides discharged in liquid effluent from Sellafield have dispersed widely throughout the Irish Sea and beyond. In particular, Sellafield has been a dominant source of ^{137}Cs and a portion has been incorporated in sediment deposits throughout the region, as recorded by several studies.

In this study gamma dose rates have been measured above saltmarshes on the southern side of the Solway Firth. Sediment samples were collected from Rockcliffe Marsh, Burgh Marsh, Cardurnock Flatts and Newton Marsh and these were analysed for their content of ^{137}Cs and ^{241}Am. The highest inventories (from sediment cores penetrating to 50 cm) were in the deposits closest to the tidal channel. While the inventory is lower towards the land, in these more stable saltmarsh areas the fine sediment containing the majority of the radionuclides comprises the surface 10 cm.

The inventory of ^{137}Cs in the fine sediments of the saltmarshes ranged from 4.1 to 360 kBq m^{-2}. Gamma dose rates above the saltmarsh ranged from 0.07 to 0.17 μGy h^{-1}. This was consistent with routine measurements made by MAFF and BNFL and is about 30% of the dose rate measured in the Esk Estuary at Ravenglass.

S.B. Bradley & T.H. Stewart: Environmental Sciences, Westlakes Research Institute, Moor Row, Cumbria CA24 3LN
D.M. Hunter & G. Jackson-Burton: Environmental Protection Group, BNFL, Sellafield, Seascale, Cumbria CA20 1PG

Introduction

Radionuclides are discharged in liquid effluent from Sellafield into the Irish Sea. These radionuclides are dispersed widely from the point source, either with the surface water currents if they remain in solution, or with the transport of sediments if they become absorbed to sediment surfaces. Some of these sediments will be deposited along the coastal margin and here people may come into contact with the associated radionuclides. The routine monitoring programmes of BNFL and the Authorising Departments (MAFF and HMIP) include the measurement of gamma dose rates above such sediments; this is the principal exposure pathway.

Sea-washed pastures, or *merse* areas have previously been studied on the northern side of the Solway Firth (Baxter *et al.* 1988; McKay *et al.* 1991) and these studies provide a detailed picture of the distribution of radionuclides within the range of saltmarshes. These studies have shown that discharges of radionuclides from Sellafield are recorded in the sediment profiles and that the highest concentrations occur where fine sediments are deposited. Caesium-137 is the principal radionuclide and, although there are several sources of this radionuclide, the majority originates from the liquid effluent discharges from Sellafield. The saltmarshes on the southern side of the Solway have not been studied to the same detail. Measurements of gamma dose rates are available from field studies, but detailed measurements on the levels of gamma-emitting nuclides or on their distribution in saltmarsh sediments are unavailable. Although the saltmarshes on the southern side of the estuary have received less attention than their counterparts to the north, the highest concentrations of gamma-emitting radionuclides may be expected where fine sediments accumulate. These areas will also exhibit the highest gamma dose rates.

This study has been undertaken to provide detailed information on the levels of certain radionuclides in a number of saltmarshes and to investigate the distribution of these radionuclides through the sediment profile. Gamma dose rates have also been measured and these data can be compared with the results of other studies around the Irish Sea.

Study area

Four areas of saltmarsh were chosen for study (Figure 1). These were:

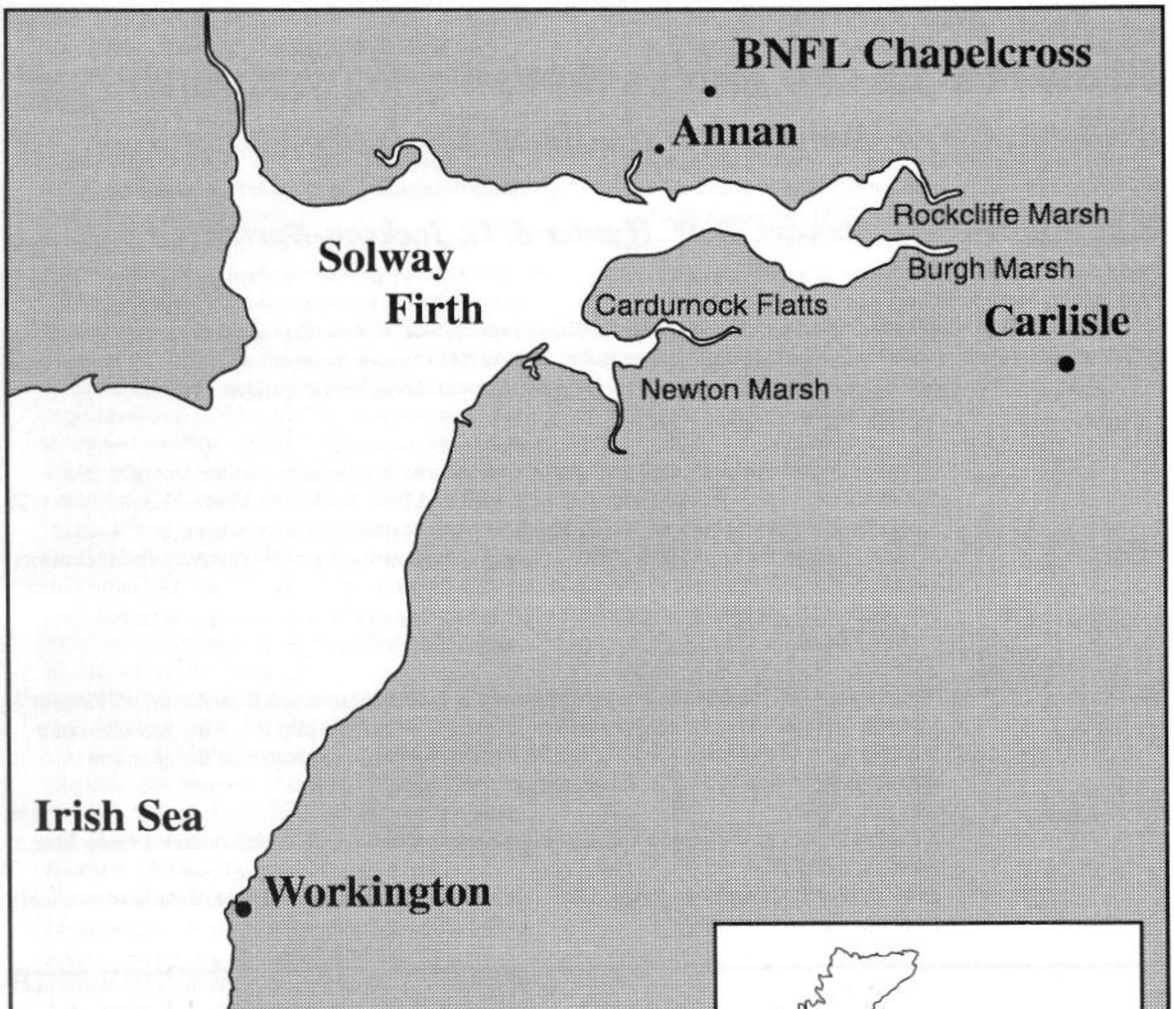


Figure 1 Location of study sites on the Solway Firth.

- Rockcliffe Marsh at the head of the estuary, an extensive area of saltmarsh (c. 5 km^2) which has access limited to wildfowling interests.
- Burgh Marsh (c. 3 km^2) is used for grazing sheep and for recreation, and a transect on the western and on the eastern part was studied.
- Cardurnock Flatts comprise coarser sediments and the area is used mainly for recreation, and again two transects were investigated.
- Newton Marsh has been investigated and parts of this site are cut to provide turf while the remainder is used to graze sheep and is also used for recreation.

Methods

Sediment cores were collected along transects normal to the coastline using either a manual or pneumatic corer. These cores penetrated to 50 cm in the saltmarsh for a surface area of either 39.6 cm^2 (manual corer) or 60.8 cm^2 (pneumatic corer) and were collected intact. At the ends of the transect and at the mid-point the sediment core was sectioned to provide 5 cm increments down the profile, yielding ten discrete samples. Nine sediment cores were collected along the transect where the saltmarsh extended more than 500 m from the land and two transects of five cores were collected on narrow saltmarshes.

Gamma dose rate measurements were made at each position where a sediment core was collected. These measurements were made with a Mini 680 instrument at 1 m above the ground for five minutes where bulk cores were collected and ten minutes where sectioned samples were collected.

In the laboratory the sediment samples were freeze-dried, disaggregated and sieved to pass a 2 mm aperture. All of the samples comprised sediments with a diameter of less than 2 mm. A portion of each sample (c. 300 g) was packed into a Marinelli beaker and analysed by gamma spectrometry. Typical count times were 15,000 seconds. Caesium-137, ^{241}Am, together with naturally-occurring gamma emitters, were the principal radionuclides observed. The organic content of the sediments was determined from the weight loss on ignition (430°C) of sub-samples (c. 5 g).

Results

Loss on ignition data for the detailed sediment profiles show the maturity of saltmarshes with distance from the tidal channel (Figure 2). The seaward profiles show no development of an organic-rich layer at the surface and they have 5% or less organic material throughout the profile. At positions further inland, the organic content of the surface layer, to about 15 cm, shows up to 45%

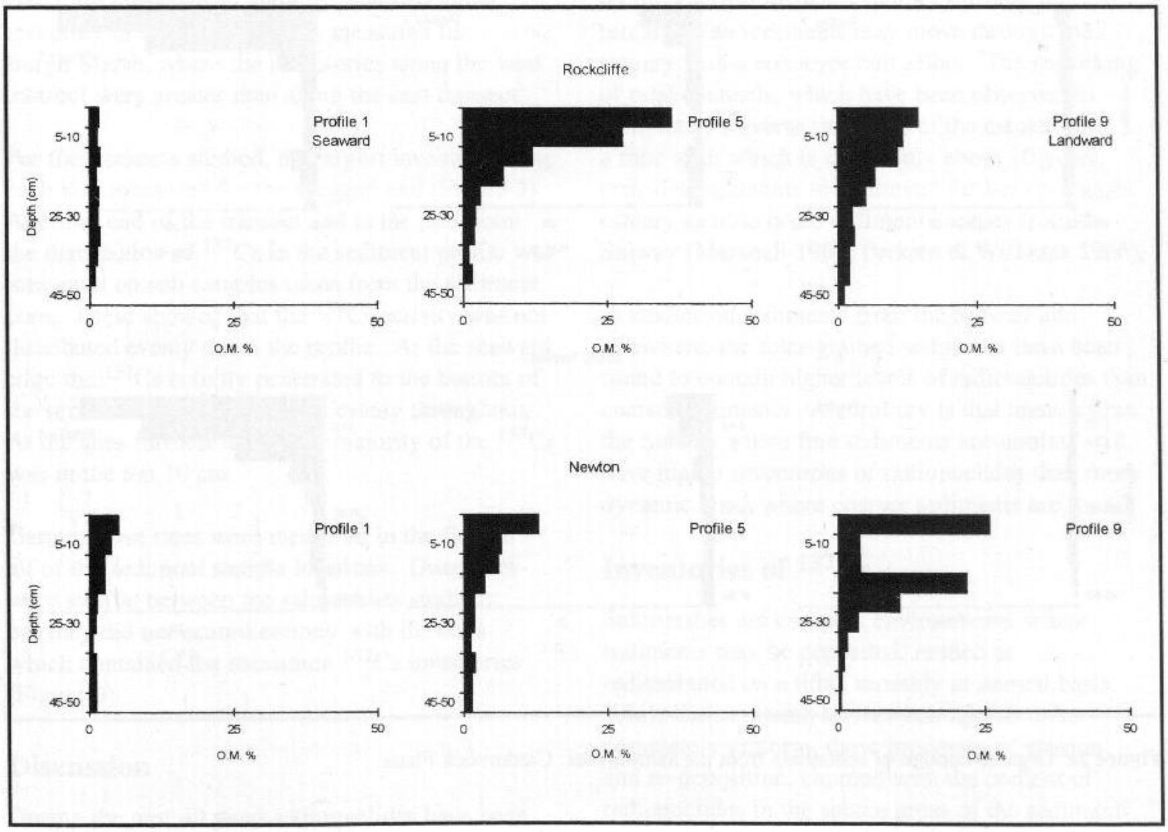


Figure 2a Organic content of sediments from the saltmarshes: Rockcliffe and Newton Marshes.

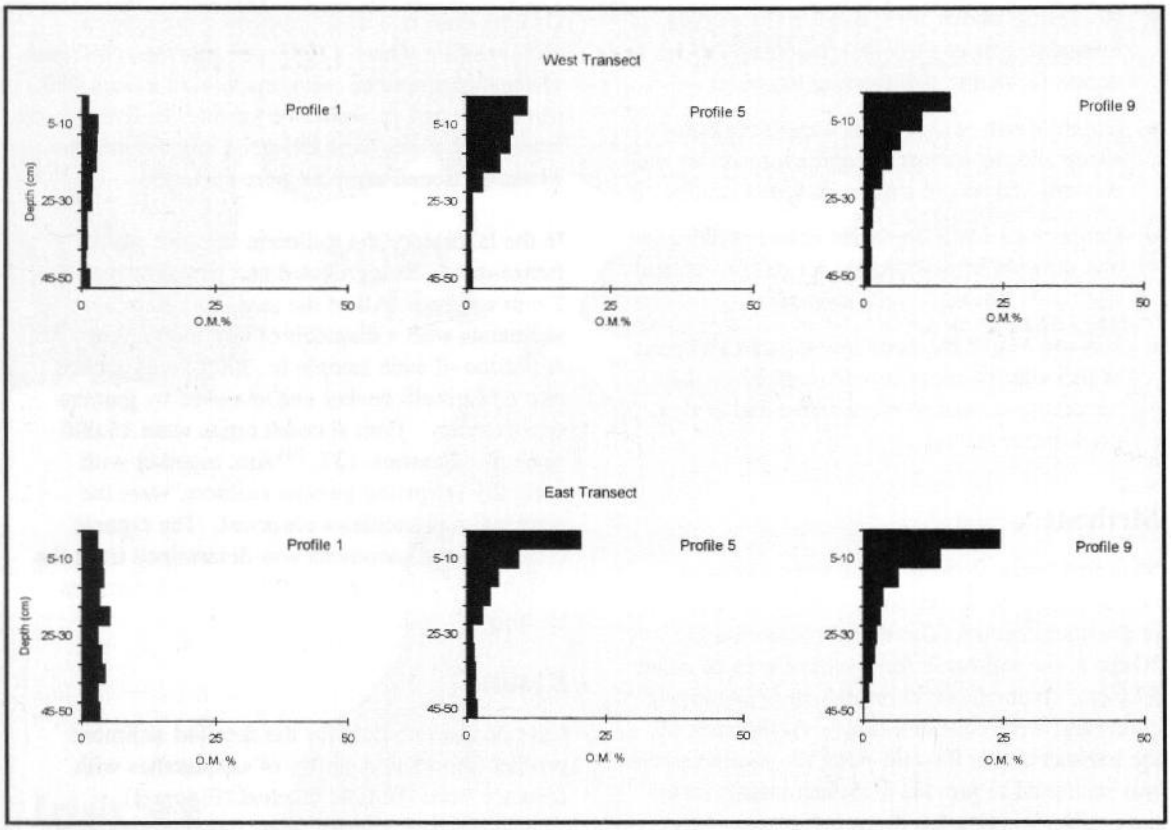


Figure 2b Organic content of sediments from the saltmarshes: Burgh Marsh.

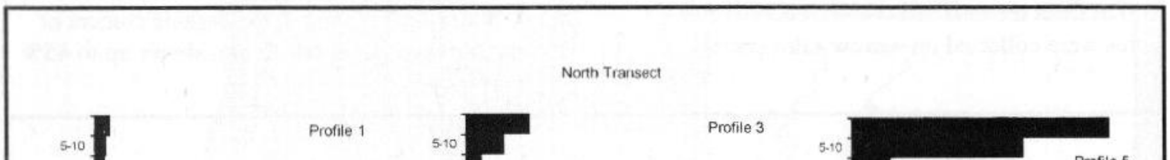


Figure 2c Organic content of sediments from the saltmarshes: Cardurnock Flatts.

Table 1 Caesium-137 inventories and gamma dose rates on saltmarshes in the Solway Firth.

Site		*Inventory (kBq m^{-2})*	*Dose rate (μGy h^{-1})*
Rockcliffe Marsh	Mean	31.0	0.10
	Maximum	123.0	0.12
	Minimum	5.7	0.08
Burgh Marsh (West)	Mean	123.8	0.13
	Maximum	360.1	0.17
	Minimum	11.1	0.10
Burgh Marsh (East)	Mean	43.5	0.10
	Maximum	97.3	0.15
	Minimum	4.1	0.07
Cardurnock Flatts (N)	Mean	147.5	0.11
	Maximum	299.9	0.13
	Minimum	17.3	0.09
Cardurnock Flatts (S)	Mean	117.4	0.11
	Maximum	166.0	0.13
	Minimum	29.8	0.09
Newton Marsh	Mean	85.3	0.13
	Maximum	138.2	0.15
	Minimum	19.9	0.11

weight loss on ignition. These sites have supported extensive vegetation over a long period.

The concentration of gamma-emitting radionuclides was measured for all of the sediment samples. Concentrations were converted to the inventory of radionuclides per square metre of saltmarsh surface. The maximum, minimum and mean inventories of ^{137}Cs are presented in Table 1. The maximum inventory of 360 kBq m^{-2} was measured for Burgh Marsh, where the inventories along the west transect were greater than along the east transect.

For the transects studied, the largest inventory along each was measured for the seaward end (Figure 3). At either end of the transect and at the mid-point the distribution of ^{137}Cs in the sediment profile was measured on sub-samples taken from the sediment core. These showed that the ^{137}Cs activity was not distributed evenly down the profile. At the seaward edge the ^{137}Cs activity penetrated to the bottom of the profile and was distributed evenly throughout. At the sites furthest inland the majority of the ^{137}Cs was in the top 10 cm.

Gamma dose rates were measured in the field at all of the sediment sample locations. Dose rates were similar between the saltmarshes studied, but they did not accord entirely with the sites which contained the maximum ^{137}Cs inventories (Figure 3).

Discussion

During the past 40 years radionuclides have been discharged in liquid effluent from Sellafield to the Irish Sea. These radionuclides have been dispersed widely, a variable amount attached to sediment or transported in solution with the surface water. Discharges from Sellafield have been a dominant source of ^{137}Cs in the Irish Sea and this has been recorded in sediment deposits throughout the region. The delivery of radiocaesium to the Solway has been by the entry of enriched water from off the Sellafield area and by contaminated sediments from seaward sources infilling the estuary. The sediments may move through the estuary with a conveyor belt effect. The reworking of tidal channels, which have been observed to completely traverse their part of the estuary on a time span which is commonly about 10 years, provides sediments to be moved further up into the estuary as little or no sediment escapes from the Solway (Marshall 1962; Perkins & Williams 1966).

In studies on sediments from the Solway and elsewhere, the finer-grained sediments have been found to contain higher levels of radionuclides than coarser sediments. A corollary is that areas within the Solway where fine sediments accumulate will have higher inventories of radionuclides than more dynamic areas where coarser sediments are found.

Inventories of ^{137}Cs

Saltmarshes are complex environments where sediments may be deposited, eroded or redistributed on a tidal, monthly or annual basis. While the saltmarsh surface can appear to be completely uniform, these processes of erosion and re-deposition, coupled with the content of radionuclides in the source areas of the sediments, can yield a mosaic of radionuclide inventories across the saltmarsh. A field programme can be

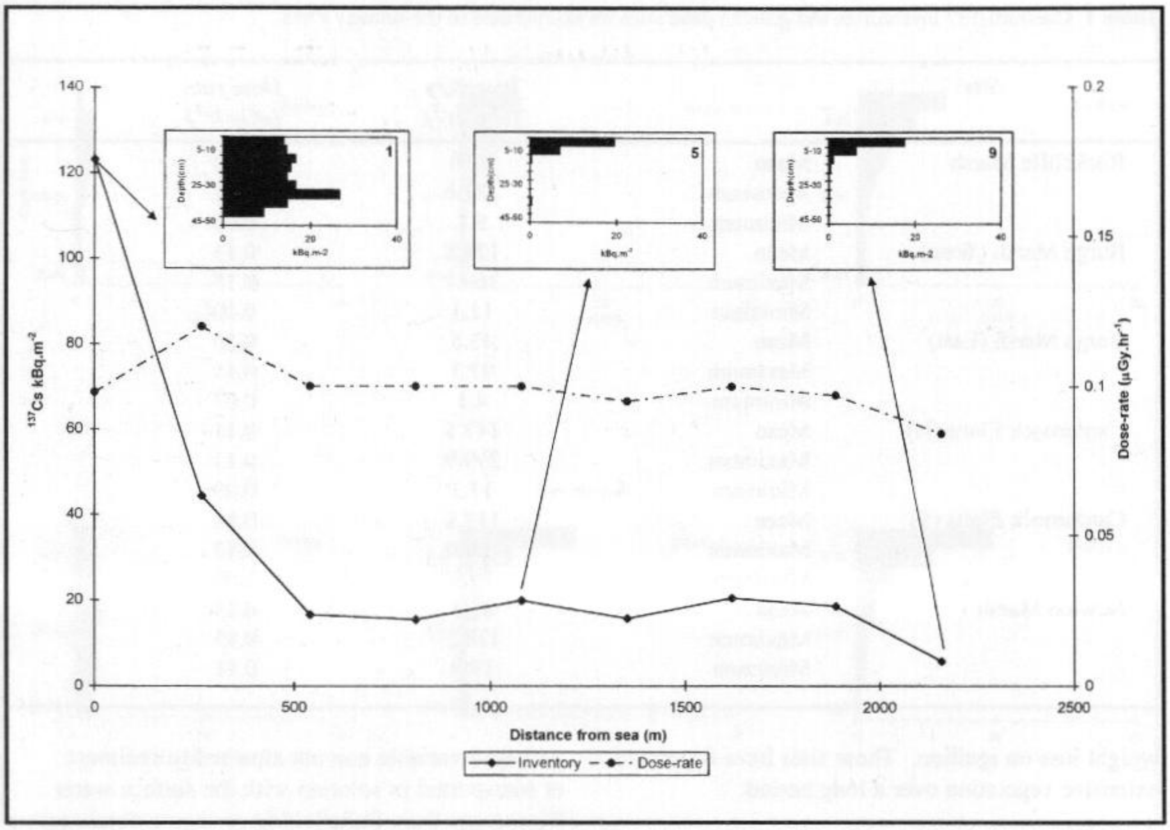


Figure 3a Distribution of ^{137}Cs in the sediment profile and the inventory and measured gamma dose rates along the transect: Rockcliffe Marsh.

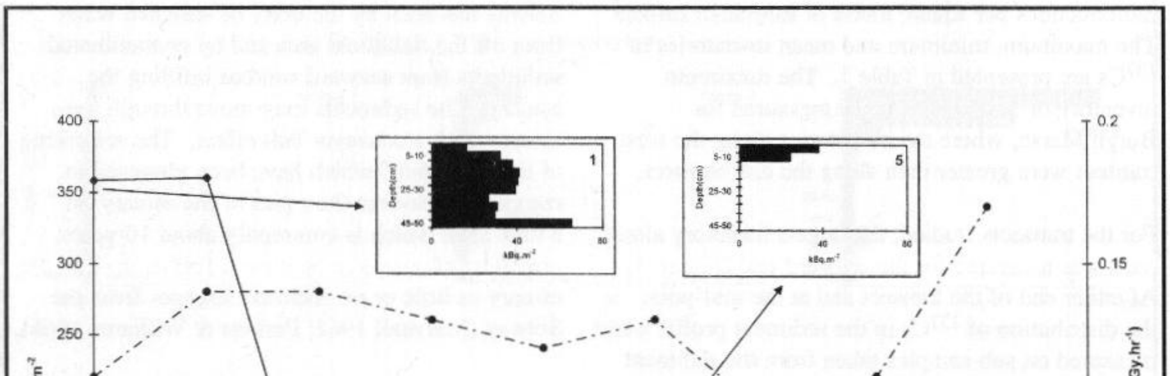


Figure 3b Distribution of ^{137}Cs in the sediment profile and the inventory and measured gamma dose rates along the transect: Burgh Marsh (West).

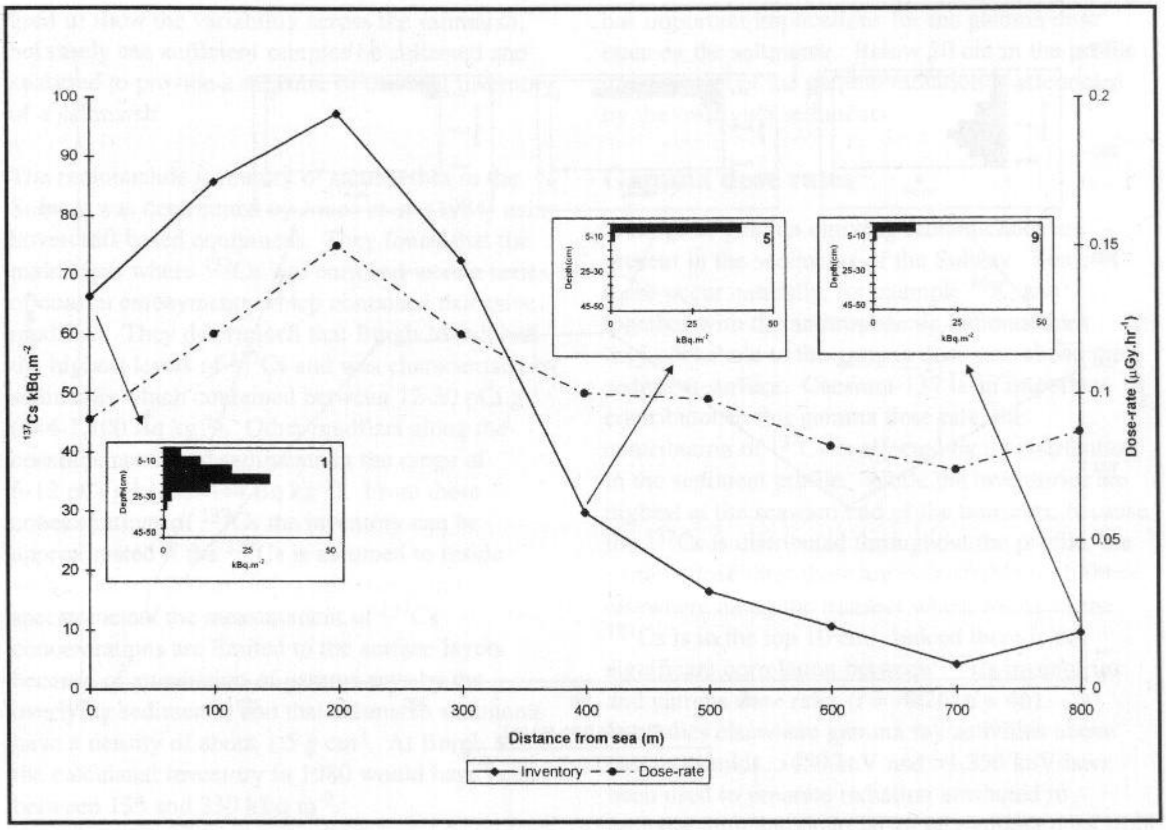


Figure 3c Distribution of ^{137}Cs in the sediment profile and the inventory and measured gamma dose rates along the transect: Burgh Marsh (East).

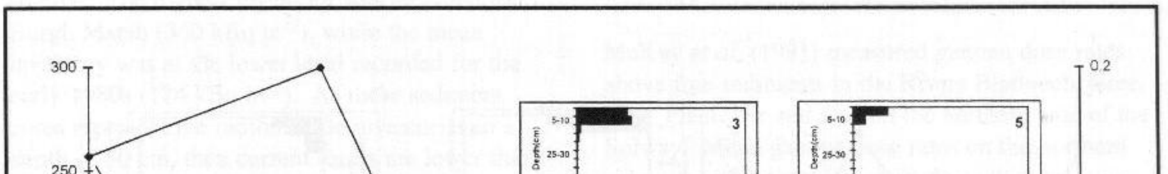


Figure 3d Distribution of ^{137}Cs in the sediment profile and the inventory and measured gamma dose rates along the transect: Cardurnock Flatts (North).

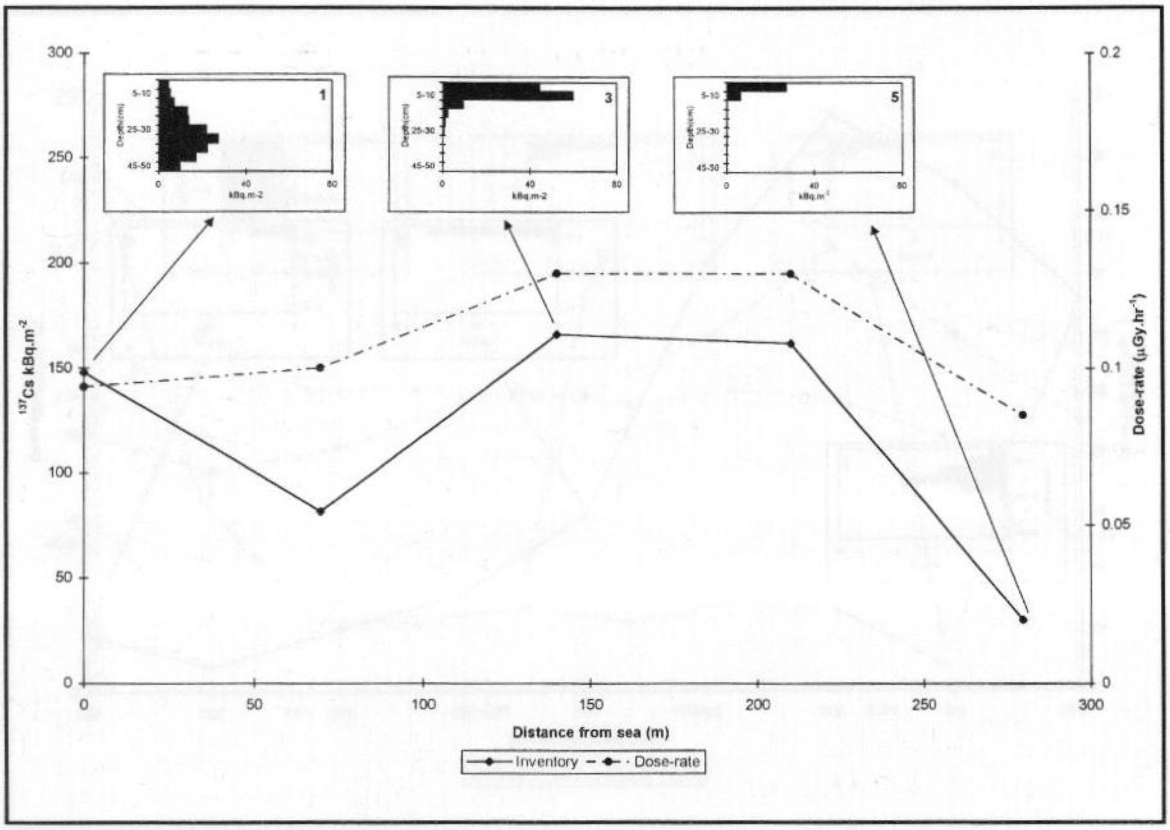


Figure 3e Distribution of ^{137}Cs in the sediment profile and the inventory and measured gamma dose rates along the transect: Cardurnock Flatts (South).

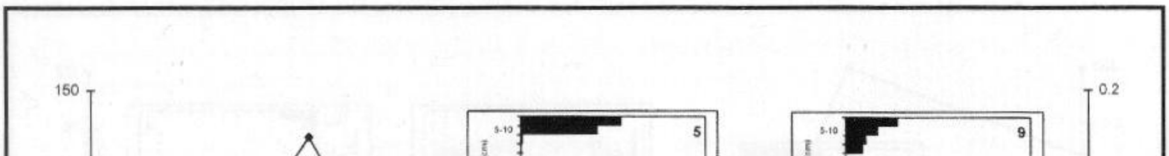


Figure 3f Distribution of ^{137}Cs in the sediment profile and the inventory and measured gamma dose rates along the transect: Newton Marsh.

used to show the variability across the saltmarsh, but rarely can sufficient samples be collected and analysed to provide a measure of the total inventory of a saltmarsh.

The radionuclide inventory of saltmarshes in the Solway was determined by Jones *et al.* (1984) using hovercraft-based equipment. They found that the main areas where ^{137}Cs was enriched were a series of coastal embayments which contained extensive mudflats. They determined that Burgh Marsh had the highest levels of ^{137}Cs and was characterised by sediments which contained between 12-30 pCi g^{-1} (444-1,100 Bq kg^{-1}). Other mudflats along the coastline contained sediments in the range of 6-12 pCi g^{-1} (222-444 Bq kg^{-1}). From these concentrations of ^{137}Cs the inventory can be approximated if the ^{137}Cs is assumed to reside within the top 20 cm (using portable gamma spectrometers the measurement of ^{137}Cs concentrations are limited to the surface layers because of attenuation of gamma rays by the overlying sediments) and that saltmarsh sediments have a density of about 1.5 g cm^{3}. At Burgh Marsh the calculated inventory in 1980 would have been between 133 and 330 kBq m^{-2}.

Sediment cores in this study show that there is a wide range in inventories in each of the saltmarshes studied. The highest inventory was recorded for Burgh Marsh (360 kBq m^{-2}), while the mean inventory was at the lower level recorded for the early 1980s (124 kBq m^{-2}). As these sediment cores represent the radionuclide inventories to a depth of 50 cm, then current levels are lower than were determined for the 1980s. Further, this study shows that in general the highest inventories are found along a narrow band at the seaward edge of the saltmarsh in areas of mobile sediments.

Caesium-137 in the sediment profile

The distribution of ^{137}Cs in the sediments at the ends and the mid-point of the transect are shown in Figure 3. At the seaward end of the transect ^{137}Cs is distributed uniformly through the profile (to 50 cm in this study). Further inland the majority of the ^{137}Cs is contained in the top 10 cm of the profile. Close to the tidal channel the saltmarsh sediments are reworked frequently and, in this dynamic environment, the sediments are mixed to the depth of sampling. Where the saltmarsh is more stable, as more cohesive, fine-grained sediments have been deposited under a less energetic regime, the presence of most ^{137}Cs within the top 10 cm signifies a low rate of accretion (c. 0.4 cm y^{-1}) while low levels of ^{137}Cs lower in the profile point to elution or transport with pore water.
The distribution of ^{137}Cs in the sediment profile has important implications for the gamma dose rates on the saltmarsh. Below 20 cm in the profile the majority of the gamma radiation is attenuated by the overlying sediments.

Gamma dose rates

A range of gamma-emitting radionuclides are present in the sediments of the Solway. Some of these occur naturally, for example ^{40}K, and together with the anthropogenic radionuclides they contribute to the gamma dose rate above the sediment surface. Caesium-137 is an important contributor to this gamma dose rate; the contribution of ^{137}Cs is affected by its distribution in the sediment profile. While the inventories are highest at the seaward end of the transects, because the ^{137}Cs is distributed throughout the profile, the gamma dose rates there are comparable with those elsewhere along the transect where >90% of the ^{137}Cs is in the top 10 cm. Indeed there is no significant correlation between ^{137}Cs inventories and gamma dose rates ($r = -0.26$; $n = 46$).
In studies elsewhere gamma ray activities above two thresholds, >450 keV and >1,350 keV have been used to separate radiation attributed to radiocaesium and other artificial radionuclides from natural radionuclides. This 'excess' gamma dose rate is normally correlated well with concentrations of ^{137}Cs.

McKay *et al.* (1991) measured gamma dose rates above fine sediments in the Rivers Bladnoch, Cree, Nith, Fleet, Urr and Dee on the northern side of the Solway. Mean gamma dose rates on the northern side were of the same magnitude as dose rates on the saltmarshes on the southern side (Table 2). The study by McKay *et al.* (1991) focused on sediment deposits within the estuaries of rivers, while this study is concerned with saltmarsh areas of the Solway as a whole. It can be expected that sediment characteristics and depositional processes will vary between these environments and this will influence the patterns of radionuclide concentrations and hence dose rates.

Routine surveys of gamma dose rates are made by BNFL and these extend between Maryport and Walney Island. There has been a consistent trend for the highest dose rates to be reported from the Esk Estuary (BNFL 1977-1991). In 1991 the highest dose rate of 0.44 µSv h^{-1} (equivalent to 0.51 µGy h^{-1}) was again reported for the Esk Estuary. The maximum dose rate recorded in this study was 0.17 µGy h^{-1} and is about 30% of the maximum dose recorded from routine surveys in the Esk Estuary.

Table 2 Gamma dose rates in the Solway.

Location	*Mean dose rate ($\mu Gy\ h^{-1}$)*
North Solway	
Bladnoch	0.06
Cree	0.06
Nith	0.06
Fleet	0.07
Urr	0.09
Dee	0.06
South Solway	
Rockcliffe Marsh	0.10
Burgh Marsh (W)	0.13
Burgh Marsh (E)	0.10
Cardurnock Flatts (N)	0.11
Cardurnock Flatts (S)	0.11
Newton Marsh	0.13

Data for North Solway from McKay *et al.* (1991)

Conclusions

1. The inventories of ^{137}Cs in the fine sediments of the saltmarshes in the Solway ranged from 4.1 to 360 kBq m^{-2}. These levels were consistent with previous determinations.

2. The highest inventories of ^{137}Cs were generally at the seaward end of the saltmarsh and the ^{137}Cs was found throughout the 50 cm profile. Further inshore the majority of the ^{137}Cs was contained in the upper 10 cm.

3. Gamma dose rates above the saltmarsh are dependant on the concentrations of artificial and naturally-occurring radionuclides, and the position of these nuclides in the sediment profile. Dose rates ranged from 0.07 to 0.17 μGy h^{-1}. This was consistent with routine measurements made by MAFF and the maximum dose was about 30% of the maximum recorded in routine surveys in the Esk Estuary at Ravenglass by BNFL in 1991.

References

Baxter, M.S., Cook, G.T., & McDonald, P. 1987. ***An assessment of artificial radionuclide transfer from Sellafield to south-west Scotland.*** London, Department of the Environment. (DoE Report DOE/RW/89/127.)

BNFL. 1977 ***et seq. Annual report on radioactive discharges and monitoring of the environment.*** Risley, British Nuclear Fuels Ltd.

Jones, D.G., Miller, J.M., & Roberts, P.D. 1984. The distribution of ^{137}Cs in surface intertidal sediments from the Solway Firth. ***Marine Pollution Bulletin, 15(5):*** 187-194.

Marshall, J.R. 1962. The morphology of the upper Solway saltmarshes. ***Scottish Geographical Magazine, 78(2):*** 81-99.

McKay, W.A., Bonnett, P.J.P., Barr, H.M., & Howorth, J.M. 1991. ***Artificial radioactivity in tide-washed pastures in south-west Scotland.*** Department of the Environment. (DoE Report DOE/HMIP/RR/91/056.)

Perkins, E.J., & Williams, B.R.H. 1966. ***The biology of the Solway Firth in relation to the movement and accumulation of radioactive materials. II. The distribution of sediments and benthos.*** Harwell, UK Atomic Energy Authority. (UKAEA PG Report No. 587.)

Reconnaissance study of heavy metals in the freshwater and coastal environment of West Cumbria

S.B. Bradley

Sediment samples have been collected from beaches, harbours and rivers believed to be representative of conditions in West Cumbria. These samples were analysed for Pb, Zn, Cu, Cd, Cr, Ni and As. The concentration of these metals in beach sands was consistent with the local geology of the area. Harbour sediments contained higher concentrations of metals than beach sands and there was evidence for enhanced concentrations resulting from human activities. The highest concentrations of metals were determined for channel sediments in the River Ehen and a point source for metal contamination was established. This study provides a general picture of metal levels in the coastal and freshwater environment of West Cumbria.

S.B. Bradley, Environmental Science, Westlakes Research Institute, Moor Row, Cumbria CA24 3LN (formerly Environmental Protection Group, BNFL Sellafield, Seascale, Cumbria CA20 1PG)

Introduction

Industrial processes invariably have an impact on the environment. This may be directly as in the case of effluent discharges or indirectly by the consumption of materials or energy, the production of which has an environmental impact elsewhere. The environmental impact may be manifest by the complete eradication of fauna and flora at one extreme or only detected by the presence of slightly elevated concentrations of materials at the other, or some position in between. Whilst it is easy to recognise environmental impacts which lay some areas barren, it can be difficult to determine whether natural variations or industrial discharges are responsible for local perturbations in other locations.

There is a long history of industrial activity on the coastal plain of West Cumbria. Whilst heavy industry associated with metal smelting and fabrication has declined, other industries have taken its place. There has also been a change governing the regulation of these industries and for the discharge of effluents in particular. While blast furnace slags were reported to be dispatched from cliff-tops directly to the Irish Sea, government agencies now regulate the discharge of all effluents by pipeline or outfall. With such a history it is difficult to apportion the impact of current industries where the remnants of earlier discharges can still be reworked from coastal sediments.

Metal concentrations in seawater or sediments have been reported for the Irish Sea (e.g. ICES 1988). These studies have focused on conditions off the Mersey Estuary where large volumes of wastes containing metals have been delivered by the Mersey directly, or dumped with sewage sludge. Little attention has been paid to the north-eastern part of the Irish Sea, with the exception of a study of the Solway Firth (Perkins *et al.* 1972). The present study has been undertaken to provide some additional information on metal concentrations in the freshwater and coastal environment of West Cumbria.

Study area

Metal levels have been investigated for the coastal environment between St Bees Head in the north and Ravenglass in the south (Figure 1). The Esk Estuary has been studied to determine the recent changes in metals circulating in this part of the Irish Sea, while the harbours at Whitehaven, Maryport and Silloth have received attention because they are a major focus of human activity. Two rivers, the Calder and Ehen, have been sampled to show metal concentrations in the freshwater environment to compare with the coastal environment. The River Calder has a largely agricultural catchment but, as it bisects the Sellafield site close to the sea, it receives some industrial discharges through outfalls. The River Ehen receives discharges from a number of villages along its course, and it joins with the River Calder in a common estuary with the Irish Sea.

Geology

The coastline between Silloth and Ravenglass has a range of geological units. In the north Carboniferous shales and coal measures outcrop, while in the south of the area the main units are

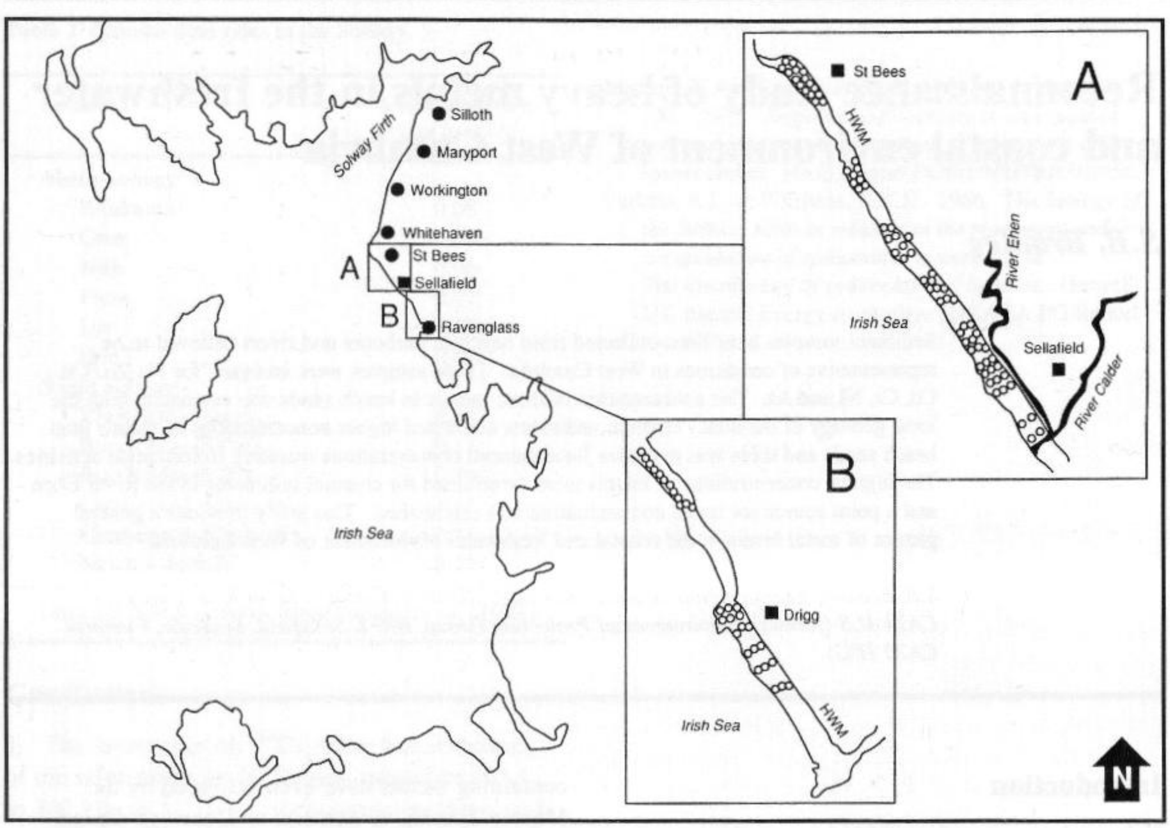


Figure 1 Study area and sampling locations for beach sands between St Bees Head and Drigg.

Permian and Triassic sedimentary sequences of sandstones and mudstones. The surficial sediments in the region are a complex mixture of these materials together with volcanic and other erratics as a result of scouring, reworking and deposition by glacial activity in the Quaternary.

Methods

Sediment samples were collected to provide an integrated record of heavy metal concentrations. 123 beach sands from the upper, middle or lower beach were collected along the coast from St Bees to Drigg (Figure 1). The surface layer to about 1 cm depth was scraped from an area of ca. 400 cm^2 using a trowel. Surface sediment samples (0-1 cm depth) were collected from the harbours at Whitehaven, Maryport and Silloth.

Three saltmarshes were sampled in profile in the Esk Estuary at 1 or 2 cm increments to a maximum depth of 70 cm. Sediment samples from the channel were also collected at a number of locations (Figure 2). At Newbiggin, the site nearest to the sea, the saltmarsh was sampled to 31 cm at 1 cm increments. At Hall Waberthwaite a deeper section, to 70 cm, was sampled at 2 cm increments, while at Muncaster Bridge a 20 cm profile was collected at 5 cm increments.

Channel lag deposits were collected from the rivers Calder and Ehen (Figure 3). These were fine sediments which had been deposited at the channel margins as the water stage fell during the previous flood event. Some overbank deposits were also collected where no channel sediment was present. Channel sediments were collected from sites between the beach and a point 11 km upstream in the upper catchment of the River Calder. For the River Ehen, samples were taken from its confluence with the Calder to a point just downstream of Egremont, nearly 10 km upstream (Figure 3).

Analytical

In total 400 sediment samples were collected for analysis. The sediments were dried (40ºC), then disaggregated using a mortar and pestle to pass a 2 mm aperture brass sieve. Experiments with clean sand which was passed repeatedly through a brass sieve had shown that there was no detectable contamination of the sample from the sieve materials. 200 g of the <2 mm diameter sediment was separated and placed in a polythene container.

Approximately 1 g of sample was weighed into a porcelain crucible and ashed in a muffle furnace at 460ºC for 24 hours. The samples were allowed to cool in a desiccator and then transferred to a clean, acid-washed, Pyrex digestion tube. Approximately 10 ml of day-old *Aqua regia* was added and the samples were digested in a thermostated heating block as:

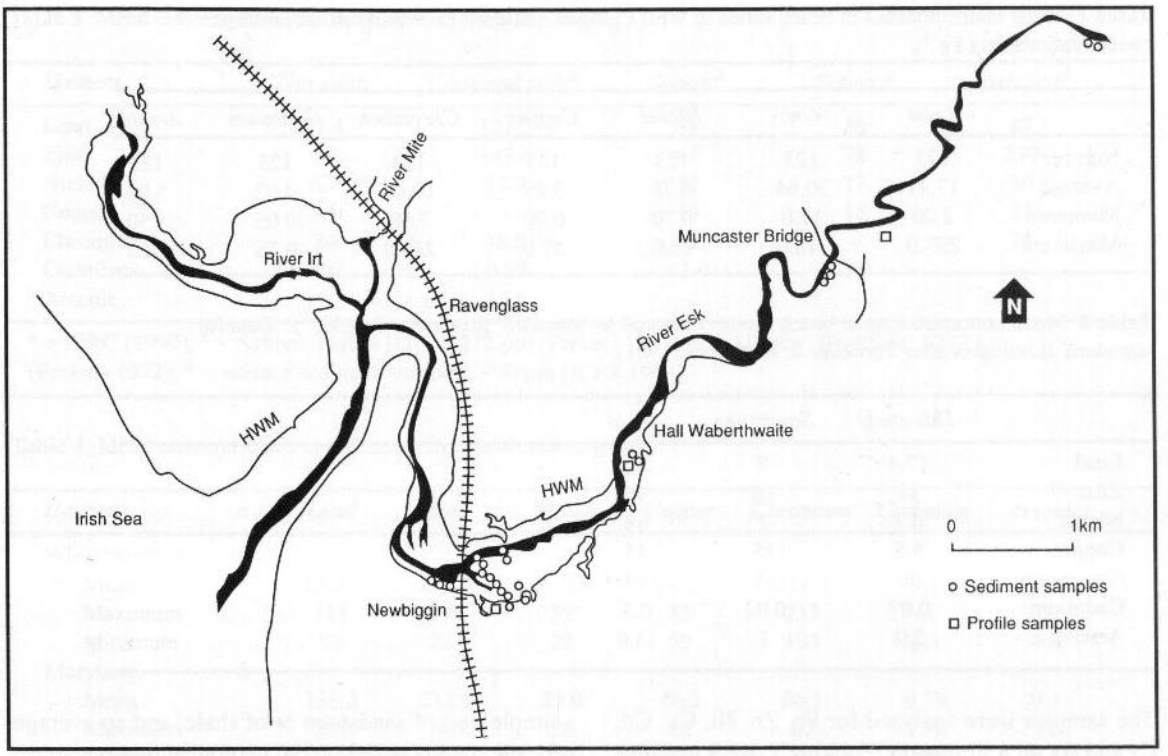


Figure 2 Sampling locations for channel sands and saltmarsh sediments in the Esk Estuary.

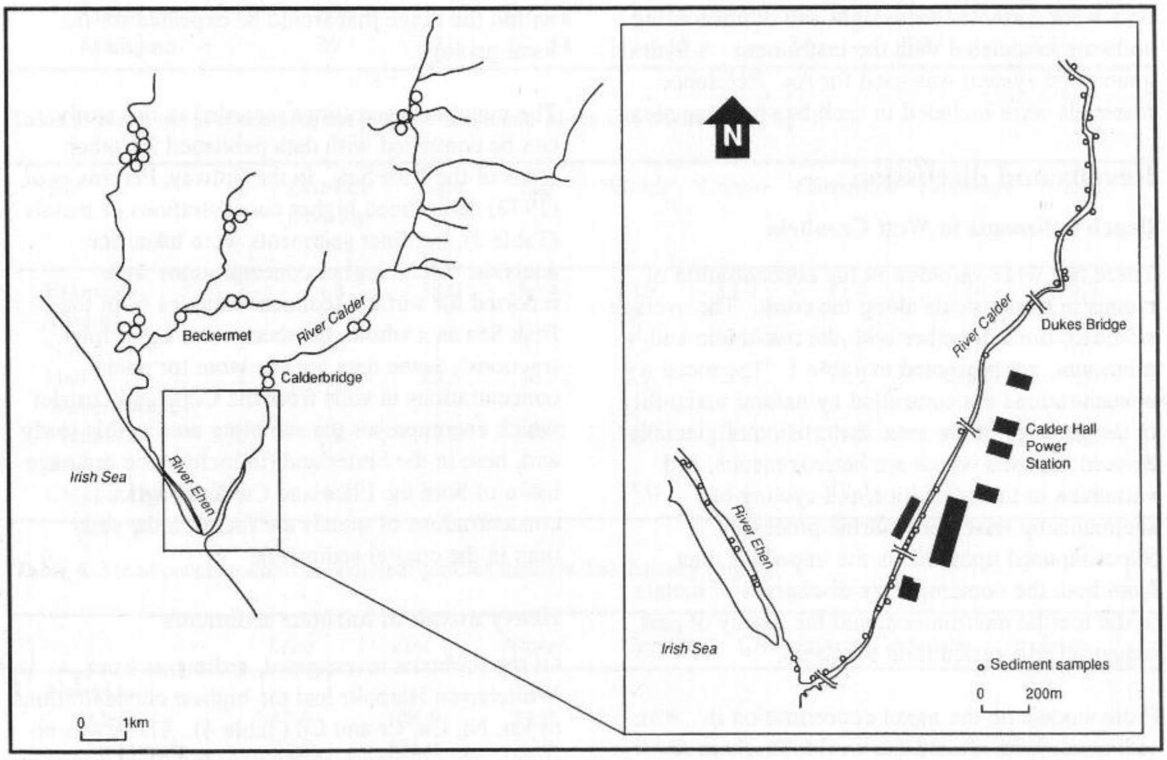


Figure 3 Sediment sampling locations along the Rivers Calder and Ehen. Inset, samples from their catchments.

2 hours at 25ºC
2 hours at 60ºC
2 hours at 100ºC
3 hours at 125ºC

When cool, the digest and residue was mixed and transferred to a centrifuge tube with about 1 ml of 10% HNO_3. The suspension was centrifuged at 3,000 rpm for 30 minutes and the residue was rinsed with 10% HNO_3, this rinse being added to the bulk liquid. The digest was made up to volume with 10% HNO_3, mixed thoroughly and transferred to a plastic vial. The neat digest was diluted by ten and this diluted sample was analysed.

Table 1 Metal concentrations in beach sands in West Cumbria. Minimum, maximum and average concentrations (mg kg^{-1}).

	Lead	*Zinc*	*Nickel*	*Copper*	*Chromium*	*Cadmium*	*Arsenic*
Number	123	123	123	123	123	123	123
Average	17.41	30.94	6.73	5.49	19.66	0.07	5.08
Minimum	2.20	11.0	0.70	0.00	7.50	0.05	1.50
Maximum	293.0	218.0	25.0	57.0	238.0	0.76	28.0

Table 2 Metal concentrations in beach sands compared to 'standard' lithologies (mg kg^{-1}). Data for 'standard' lithologies after Turekian & Wedepohl (1961).

	This study	*Sandstone*	*Shale*
Lead	17.4	7	20
Zinc	31	16	95
Nickel	6.7	2	68
Copper	5.5	15	45
Chromium	20	35	90
Cadmium	0.07	0.02	0.3
Arsenic	5.0	1	13.0

The samples were analysed for Pb, Zn, Ni, Cu, Cd, Cr and As on a Philips PU-7450 ICP-AES machine using a sequential multi-element programme, usually within one day of digestion. The raw data were corrected for weight and dilution using software associated with the instrument. A hydride generation system was used for As. Reference materials were included in each batch of samples.

Results and discussion

Beach sediments in West Cumbria

There is a wide variation in the concentration of metals in beach sands along the coast. The average concentrations, together with the maximum and minimum, are presented in Table 1. The metal concentrations are controlled by natural variability in the geology of the area, the erosion of glacially-derived deposits which are heterogeneous, and variations in the deposition and cycling of sediments by nearshore marine processes. Superimposed upon this is the impact of man from both the contemporary discharges of metals to the marine environment and the legacy of past industrial and agricultural practices.

From studies on the metal concentration in sediments from around the world, Turekian & Wedephol (1961) have compiled an index of the concentrations which may be expected from various geological types. Their indices are for unpolluted areas and reflect only the erosion of the local geology. In Table 2 the average metal concentrations in the beach sands of West Cumbria are compared with the average concentrations for a region dominated by sandstone and one for 'standard' shale. As has been explained already, the geology of the coastline of West Cumbria is not a simple unit of sandstone or of shale, and an average for the metals based on the geological units would lie between the two. The comparison shows that the average concentrations in the beach sands are within the range that would be expected for the local geology.

The metal concentrations recorded in this study can be compared with data published for other areas of the Irish Sea. In the Solway, Perkins *et al.* (1972) determined higher concentrations of metals (Table 3), but finer sediments were taken for analysis. Much higher concentrations were reported for surface sediment samples from the Irish Sea as a whole, but these were again finer fractions. Some data are available for metal concentrations in soils from the Copeland District which encompasses the sampling area in this study and, here in the hinterland (to include the drainage basin of both the Ehen and Calder), higher concentrations of metals are found in the soils than in the coastal sediments.

Heavy metals in harbour sediments

Of the harbours investigated, sediments from Whitehaven Harbour had the highest concentrations of Zn, Ni, Cu, Cr and Cd (Table 4). There was no significant difference in the concentrations between the South Harbour and the Inner Harbour. All of the sediments were fine grained (median diameter >6.5Ø; <11 µm) and were classified as silts.

Maryport Harbour sediments yielded the highest Pb concentrations while those of Zn, Ni and Cu were similar to Whitehaven. The sediments ranged from sandy silts (median diameter 6.0Ø; 16 µm) to silty sands (median diameter 3-4Ø; 125 to 63 µm). All

Table 3 Metal concentrations in the North-east Irish Sea (mg kg^{-1}).

Element	*This study*	*Copeland soils*[a]	*Solway*[b]	*Solway*[c]	*Irish Sea*[d]
Lead	17.4	121.2	37	56	87
Zinc	31	147.6	63	74	230
Nickel	6.7	11.7	38	17	30
Copper	5.5	-	10	16	31
Chromium	20	18.0	35	-	76
Cadmium	0.01	0.29	<1.0	2.9	-
Arsenic	5	11.6	-	-	-

[a] = IERC (1990); [b] = Saltom, Parton Bays, <212 µm (Perkins 1972); [c] = Allonby, Beckfoot, <212 µm (Perkins 1972); [d] = surface sediment samples, <90 µm (ICES 1988)

Table 4 Metal concentrations in sediments from harbours (mg kg^{-1}).

Harbour	*n*	*Lead*	*Zinc*	*Nickel*	*Copper*	*Chromium*	*Cadmium*	*Arsenic*
Whitehaven	8							
Mean		85.25	255.5	29.25	68.25	214.9	9.8	9.7
Maximum		113	292	35	83	235	11	16
Minimum		72	237	22	59	193	8.3	4.6
Maryport	6							
Mean		136.2	212.8	25.0	46.2	56.5	0.79	9.1
Maximum		265	308	28	65	62	1.18	11
Minimium		71	151	20	29	48	0.28	5.3
Silloth	2							
Mean		39.5	76	16	16	35.5	0.28	2.9
Maximum		40	77	18	16	37	0.33	3.5
Minimum		39	75	14	16	34	0.22	2.3

Table 5 Mean metal concentrations in active sediments of the Esk channel (mg kg^{-1}).

Site	*n*	*Distance from sea (kms)*	*Lead*	*Zinc*	*Nickel*	*Copper*	*Chromium*	*Cadmium*	*Arsenic*
Eskmeals Viaduct	7	4.8	38.0	90.4	18.9	13.7	47.4	0.34	13.3
Newbiggin	9	5.0	21.7	42.6	7.4	5.0	21.8	0.11	6.4
Hall Waberthwaite	2	6.0	13.5	46.5	7.9	3.6	15.5	0.16	7.3
Muncaster Bridge	2	8.8	47.0	141.0	26.0	19.0	79.5	0.78	16.5
Cropple How	1	11.8	36.0	51.0	11.0	4.1	47.0	0.14	14.0

Table 6 Metal concentrations in sediment profiles from the Esk Estuary (mg kg^{-1}).

	Lead	*Zinc*	*Nickel*	*Copper*	*Chromium*	*Cadmium*	*Arsenic*
Newbiggin							
Mean	57.0	108.6	22.0	16.6	51.8	0.14	10.4
Maximum	74.0	125.0	27.0	34.0	67.0	0.46	16.0
Minimum	41.0	79.1	6.0	9.6	37.2	0.07	5.7
Muncaster							
Mean	52.3	140.1	22.3	14.5	64.5	0.51	18.8
Maximum	60.0	148.0	24.1	17.2	70.0	0.58	23.0
Minimum	47.1	133.2	20.1	11.4	56.0	0.40	16.2
Hall Waberthwaite							
Mean	54.4	126.5	23.1	19.9	61.9	0.35	9.94
Maximum	71.0	168.3	38.2	31.5	83.1	0.83	15.0
Minimum	38.2	102.1	14.4	12.2	48.0	0.08	2.3

of the sediments were coarser grained than at Whitehaven.

Silloth Harbour sediments contained lower concentrations of all of the metals than either Whitehaven or Maryport. The particle size distribution of the sediment was not determined.

Whitehaven Harbour contained substantial concentrations of Cr and Cd particularly when the data are compared with representative values from Forstner and Whitmann (1981). Until recently a detergent production plant in Whitehaven was the largest discharger of cadmium into UK coastal waters and it is unsurprising that elevated concentrations are found in Whitehaven Harbour. These concentrations declined with distance up the coast. Maryport Harbour sediments contained more Pb than Whitehaven. This is contrary to the frequently observed relationship for higher metal concentrations to be found with the finer grain size fractions (Maryport Harbour sediments being much coarser than Whitehaven). Indeed this is suggestive of a source of Pb to Maryport Harbour, possibly the erosion of blast furnace slags which historically were disposed of to the sea along this part of the coastline.

Esk Estuary

Channel sediments were collected at a number of points along the estuary (Figure 2). Metal concentrations in these samples were similar to the range found for the coastal sediments (Table 5). There is little evidence that the estuary is impacted by metals from the sea, or by the transfer of metals from the catchment. Variations in metal concentrations may result from differences in grain size distribution of sediments. The highest metal concentrations were recorded for sediments collected near Muncaster Bridge. This may reflect the release of metals from vehicle exhausts and from the road surface into the river at this point, although it is known that the sediments are finer grained at this point and, consequently, such sediments are likely to have elevated metal concentrations.

The Esk Estuary has been studied in great detail for the concentration of artificial radionuclides contained within its sediments. Such studies have demonstrated that the record of radionuclide discharges from Sellafield is preserved within the sediment profile of the saltmarshes. Indeed Hamilton & Clarke (1984) proposed an average sedimentation rate at Newbiggin of 4.3 cm yr^{-1} based on the radionuclide inventory of saltmarshes. Similarly, the record of metal contamination will be recorded by these sediments. Where saltmarshes have developed over more than 50 years, that is before the construction and operation of the Windscale and Sellafield site, there will be an absence of artificial radionuclides. There will, however, be a background concentration for heavy metals.

Sediments have been analysed to determine the presence of artificial radionuclides in the profile. Where present, they have been incorporated into the saltmarsh with the emplacement of sediments during the past 50 years. Caesium-137 was present throughout the profile from Hall Waberthwaite (0-70 cm) and down most of the profile at Newbiggin (0-28 cm). The metal concentrations determined for these profiles indicate the regime of metals in the coastal/estuarine environment over the past 50 years (Figure 4). That the profiles show uniform metal concentrations points to steady state conditions in this part of the Irish Sea.

The average metal concentration for each sediment profile is greater than the concentration in the channel sediment (compare Tables 5 & 6). This is a function of grain size where saltmarshes are constructed by the deposition of fine sediments while the channel sediments are primarily of sand grade. The metal concentration varies between the profiles in a similar manner to the channel sediments, although the concentrations and the variation down the profile are similar (Figure 4).

Metal concentrations in the freshwater environment

River Calder

The River Calder flows through the Sellafield site in an engineered and straight channel. There are a number of outfalls to the river and, while these do not introduce any radioactive contamination, heavy metals are present. The impact of site discharges occurs from about 2 km upstream to the sea. Metal concentrations in the river sediments are higher than recorded for the coastal sediments (Table 7). Concentrations of Pb, Zn and Cu are highest at a point 1.6 km from the sea. This is just downstream of the outfall from the Calder cooling towers. These towers are known to be a source of these metals and investigations have suggested that wood preservatives containing these metals are slowly leached from their internal structure.

For Ni, Cd, Cr and particularly As the highest concentrations were determined for the upper catchment. This shows the influence of the local geology on metal concentrations. The upper catchment of the Calder is agricultural and there is no industry to provide a point source of metals.

River Ehen

The River Ehen is a larger river than the Calder with a number of industrial and residential

Table 7 Metal concentrations in the River Calder (mg kg^{-1}).

	Lead	*Zinc*	*Nickel*	*Copper*	*Chromium*	*Cadmium*	*Arsenic*
Through Sellafield site							
Mean	31.3	129.4	15.2	19.1	37.2	0.25	6.1
Minimum	9.0	40.0	8.2	6.8	23.0	0.05	1.6
Maximum	199.0	900.0	29.0	92.0	66.0	0.38	11.0
Above site							
Mean	30.1	92.4	18.9	10.3	47.1	0.36	13.9
Minimum	13.0	43.0	10.0	5.7	30.0	0.09	3.6
Maximum	59.0	162.0	40.0	21.0	98.0	0.95	84.0

Table 8 Metal concentrations in the River Ehen (mg kg^{-1}).

(a) All data

	Lead	*Zinc*	*Nickel*	*Copper*	*Chromium*	*Cadmium*	*Arsenic*
Number	59	59	59	59	59	59	59
Mean	113.6	607.2	26.1	66.5	51.6	0.42	14.1
Maximum	1,250.0	11,600.0	65.0	917.0	247.0	6.9	39.0
Minimum	8.2	28.0	0.7	3.8	20.0	0.05	2.3

(b) Excluding data at British Rail bridge

	Lead	*Zinc*	*Nickel*	*Copper*	*Chromium*	*Cadmium*	*Arsenic*
Number	55	55	55	55	55	55	55
Mean	58.7	97.7	24.7	23.0	41.9	0.21	13.6
Maximum	174.0	751.0	43.0	91.1	71.0	0.50	39.0
Minimum	8.2	28.0	0.7	3.8	20.0	0.05	2.3

areas within its catchment. There are no direct discharges from Sellafield to the Ehen, but the channel bounds the site. The highest concentrations of Pb, Zn, Cu, Cr, Ni and Cd in the whole study were recorded for channel sediments collected near the British Rail bridge at Sellafield station (Table 8). These concentrations of 1,250 mg (Pb) kg^{-1}, 11,600 mg (Zn) kg^{-1}, 917 mg (Cu) kg^{-1}, 59 mg (Ni) kg^{-1}, 247 mg (Cr) kg^{-1} and 6.9 mg (Cd) kg^{-1} compare with levels reported for channels contaminated from historic metal mining. Excluding the very high concentrations of metals in samples from the site at the British Rail bridge (Table 8b), the average concentrations in the Ehen were similar to the Calder.

Conclusions

The concentrations of metals in the Irish Sea have been widely reported. Studies have focused on areas where concentrations are elevated by pollution, in particular off the Mersey Estuary. Those concentrations are supported by industrial discharges to the river and from the dumping of sewage sludge at sea. Few studies have been undertaken on the coast of west Cumbria. Perkins *et al.* (1972) studied the metal concentrations of sediments in the Solway Firth, noting that the hinterland had been worked for non-ferrous metals from medieval times. Locally-mined iron ore was used following the industrial revolution, and other industries have been introduced since 1945. Each of the industries has left a legacy of waste. Blast furnace slag which was dumped at the shoreline (and some which may have been used as ballast for railway construction or for coastal defence) is still providing a supply of metals to the nearshore environment.

This study on the concentration of a range of metals in sediments from different coastal and freshwater environments provides a general picture of metal levels in West Cumbria. Generally, metal concentrations reflect the geological composition of the region. Metals in harbour sediments and samples from a short reach of the River Ehen point to local enhancement in concentrations, either from the impact of current industrial discharges or from the reworking of materials discharged in the past. There are many sources of metal-contaminated sediments along the West Cumbrian coast and this study has not attempted to assign the relative importance of past and current industrial discharges.

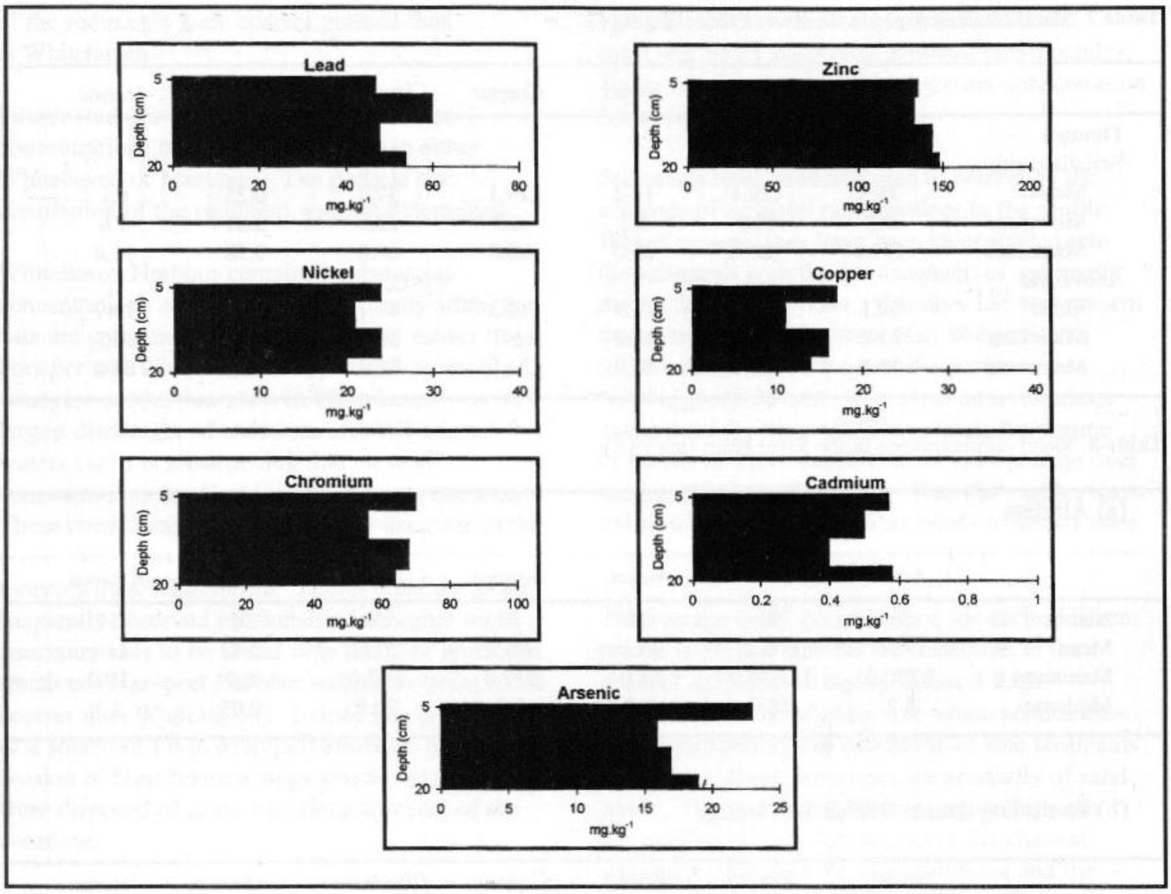


Figure 4a Metal concentrations in the soil profile: Muncaster Bridge.

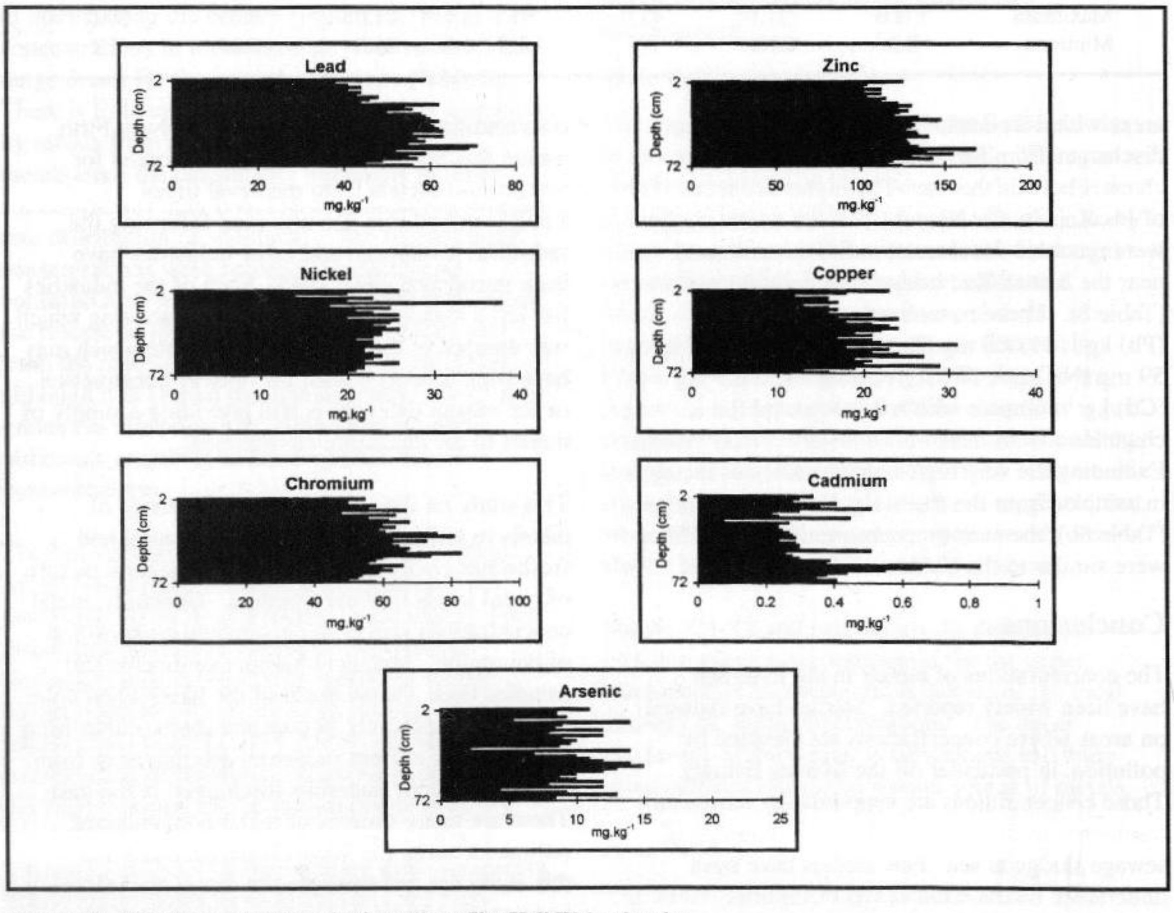


Figure 4b Metal concentrations in the soil profile: Hall Waberthwaite.

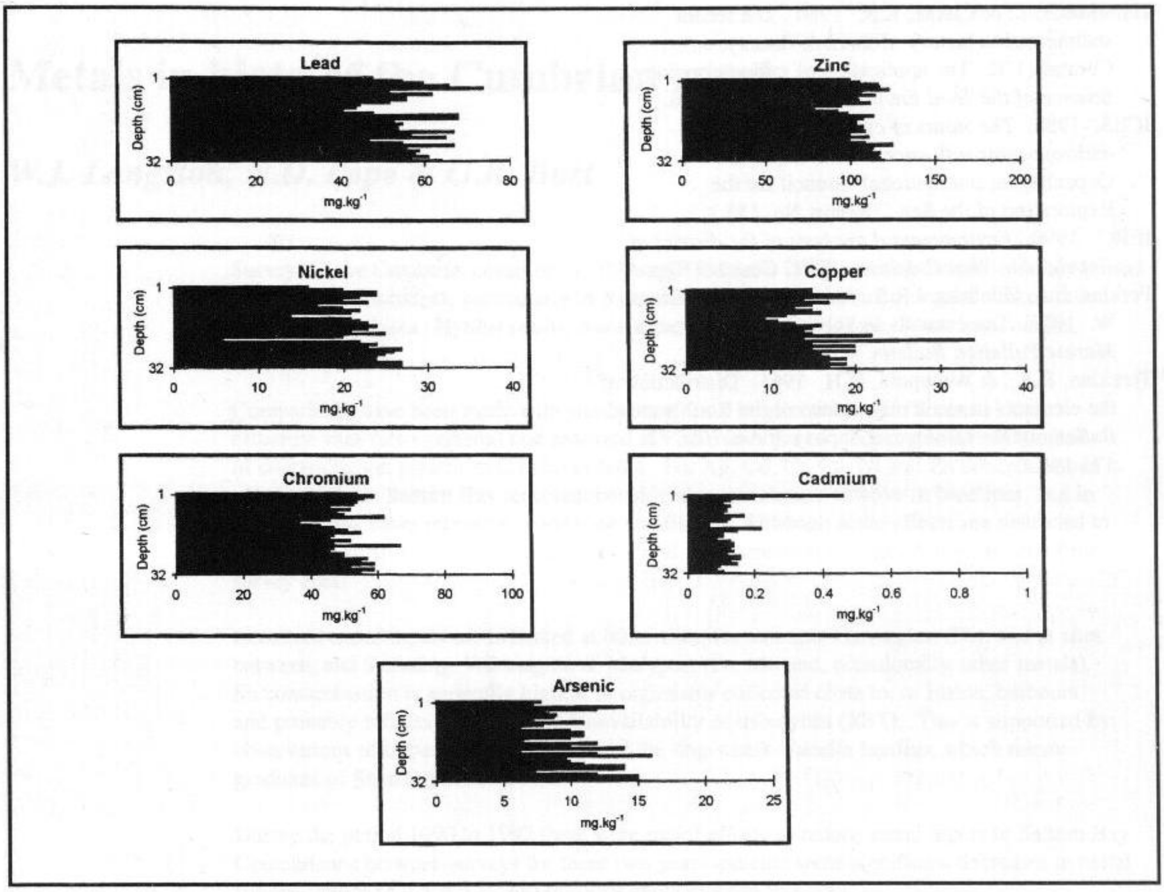


Figure 4c Metal concentrations in the soil profile: Newbiggin.

The major findings from the study are:

- The average concentration of Pb, Zn, Cu, Cd, Cr, Ni and As was determined from 123 sediment samples collected between Drigg and St Bees (Table 1). The concentrations were similar to those determined for a local geology of 'average' shale and sandstone elsewhere. From this study there was no indication of a separate sub-population of samples which might reflect contamination with heavy metals.
- Whitehaven Harbour contained sediments with higher concentrations of Zn, Ni, Cu, Cr and Cd than the other harbours investigated. Maryport Harbour had the highest concentration of Pb in the sediments, while there was a general trend for metal concentrations to decline from Whitehaven.
- The analysis of samples from profiles in the saltmarshes of the River Esk has shown a uniform concentration of metals (Figure 4). Radionuclides discharged from the marine pipeline at Sellafield provide a chronometer for the time of deposition of the sediment. The observed pattern suggests that the heavy metal regime of West Cumbria has not varied significantly over the past 50 years.

In the fluvial environment, the highest concentrations of Pb, Zn, Cu, Cr, Ni, and Cd were determined for sediments collected from the River Ehen. These elevated concentrations were found in several samples at close proximity to the rail line, and they indicate a point source for metals. For the majority of the samples, mean concentrations of metals in the Calder and Ehen were similar. In the River Calder, the highest concentrations of Ni, Cd, Cr and As were found in the upper catchment. These concentrations reflect the geology of the catchment, and the study has shown that there is no additional impact from Sellafield. For Pb, Zn and Cu the highest concentrations were found just downstream of the outfall from the Calder cooling towers.

When the data for the River Calder were compared with data for the River Ehen, the highest concentrations of metals for the whole study were for a site near the British Rail bridge on the Ehen.

References

Forstner, U., & Whitmann, G.T.W. 1981. *Metal pollution in the aquatic environment.* Berlin, Springer-Verlag.

Hamilton, E.I., & Clarke, K.R. 1984. The recent sedimentation history of the Esk Estuary, Cumbria UK. The application of radiochronology. *Science of the Total Environment, 35:* 325-386.

ICES. 1988. *The status of current knowledge on anthropogenic influences in the Irish Sea.* Copenhagen, International Council for the Exploration of the Sea. (Report No. 155.)

IERC. 1990. *Environmental analysis of the district of Copeland in West Cumbria.* IERC Contract Report.

Perkins, E.J., Gilchrist, J.R.S., Abbott, O.J., & Halcrow, W. 1972. Trace metals in Solway Firth sediments. *Marine Pollution Bulletin, 4:* 59-61.

Turekian, K.K., & Wedepohl, K.H. 1961. Distribution of the elements in some major units of the Earth's crust. *Bulletin of the Geological Society of America, 72:* 175-192.

Metals in biota of the Cumbrian coast

W.J. Langston, N.D. Pope & G.R. Burt

Surveys of the Cumbrian coastline in 1990 and 1992 have demonstrated the considerable impact of industrial discharges, particularly in Saltom Bay near Whitehaven, on metal concentrations in rocky shore biota *(Mytilus edulis, Nucella lapillus, Patella vulgata, Fucus vesiculosus, Littorina littorea).*

Comparisons have been made with similar data for a large number of UK coastal and estuarine sites (also gathered and analysed at PML) in order to place in context the degree of contamination present in Cumbrian biota. For Ag, Cd, Cr, Cu, Ni and Zn concentrations in organisms from Saltom Bay represent considerable enrichment relative to baselines, and in some extreme cases represent worst-case conditions. Although acute effects are restricted to a relatively small stretch of coastline, low-level contamination is detectable for much of the survey area.

Localised metal inputs are indicated at other sites, for example Harrington (Pb), and at sites between, and including, Workington & Maryport (Fe, Mn and, occasionally, other metals). Sn contamination is generally highest in organisms collected close to, or inside, harbours and probably reflects the enhanced bioavailability of tributyltin (TBT). This is supported by observations of imposex in populations of the dog-whelk *Nucella lapillus*, which mirror gradients of Sn along the coastline.

During the period 1990 to 1992 there were major efforts to reduce metal inputs to Saltom Bay. Comparisons between surveys for these two years indicate some significant decreases in metal concentrations (e.g. Cd, Cu, Zn) in rocky shore biota in this area.

Metal burdens in Cumbrian estuarine sediments are not exceptional by UK standards (except for Cd at Whitehaven and Mn at Maryport) and this is generally reflected in the moderate tissue burdens measured in infaunal organisms. Since estuarine sampling did not include sites in the immediate vicinity of the Saltom Bay outfall it is perhaps not surprising that levels of metal accumulation in sediment-dwellers do not approach the exceptional concentrations found in some rocky shore species. Nevertheless it is noteworthy that baseline concentrations of Ag, Cd, Cu, Cr, Ni and Pb in clams *Scrobicularia plana* and ragworms *Nereis diversicolor* from Cumbrian estuaries, like those in coastal organisms, are often higher than minimum values reported elsewhere in the UK. It is possible therefore, that despite considerable dilution, the influence of metal-rich effluent entering Saltom Bay may be detectable over a distance of 50 km or more as a result of residual currents and wind-generated surface water movements which may hold contaminated water close to the shoreline.

Reductions in metal burdens in sediments and infauna during the period 1990-1992 were much less evident than in some rocky shore species and, as expected, sediments appear to act as a relatively persistent source of metals, compared with overlying waters.

W.J. Langston, N.D. Pope & G.R. Burt, Plymouth Marine Laboratory, Citadel Hill, Plymouth PL1 2PB

Introduction

The north-west Cumbrian coastline forms the southern boundary of the outer Solway Firth, a large coastal plain estuary feeding into the north-east Irish Sea (Figure 1). The Solway has little direct input from industry at the present time, except in the portion of coastline lying between Maryport and St Bees Head, together with the nuclear facility further south, at Sellafield. However, during and following the Industrial Revolution in the late eighteenth century the coastline was very important to the coal, iron and steel industry, and, in addition, there have, in the past, been localised inputs from acid mine-drainage and tar distilleries (Perkins 1977).

Recently, attention has focused on the potential impact caused by industrial operations along the shoreline between Whitehaven and St Bees Head

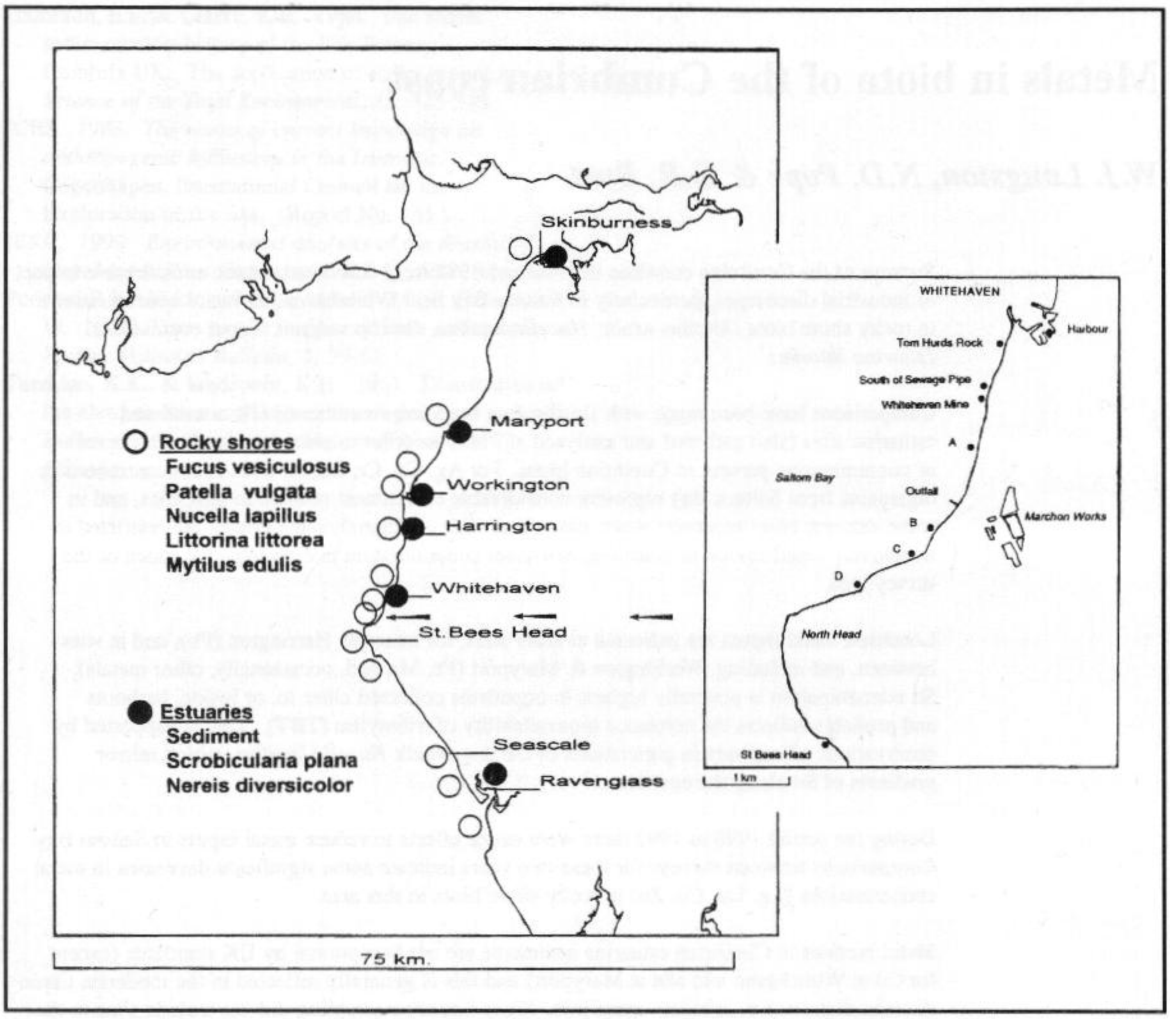


Figure 1 Sampling sites on the West Cumbrian Coast.

(Figure 1). Saltom Bay has, until the last few years, received considerable amounts of waste from coal mining activity (initiated some 250 years ago), and much of the shore was covered with colliery wastes until the 1980s, when mining ceased. Poor water quality is exacerbated by sewage which discharges over the shore 1 km south of Whitehaven Harbour (this is soon to be improved by conveying the flow to a new treatment works with a long outfall at Parton). However, the major concern is the discharge from the Marchon chemical factory located on the southern outskirts of Whitehaven.

The Marchon plant (Figure 1) has, over the last 30 years, been concerned with phosphoric acid production, for use in fertiliser and detergent manufacture. The production of phosphoric acid involves the reaction of calcium phosphate with sulphuric acid to produce orthophosphoric acid and the by-product calcium sulphate (gypsum). Until recently the plant released the majority of its wastes through a single effluent pipe, directly into the sea at Barrowmouth (Figure 1), whilst a much smaller input is known to occur approximately 1 km to the south-west of the main discharge. In the earliest days of the plant's operation, effluent spilled directly over the cliff-tops, resulting in a delta of gypsum extending for several hundred metres (Perkins 1981). This phenomenon has now disappeared following the installation of the pipeline, which discharges in the littoral zone.

The principal components of the low pH effluent are calcium sulphate, phosphoric and sulphuric acids, detergents, fluorides and heavy metals, though the actual composition is dependent on the quality and source of the initial phosphate ore, together with the chosen end point of production. The scale of heavy metal release, and the potential for accumulation by marine organisms, are of prime concern and are the major reason for the present programme of research: results from preliminary sampling along the Cumbrian coastline during the 1980s indicated some important anomalies with regard to metal concentrations in intertidal organisms.

Shortly after the first of the current larger-scale surveys, in 1990, major changes in phosphate processing were announced by the operators of the Marchon works. These involved the introduction of new procedures to eliminate metal discharges from the purification of phosphoric acid, and using a different source of phosphate ore with reduced levels of impurities, including metals.

These measures were anticipated to bring about significant reductions in metal releases and the 1992 (June) survey was designed partly to evaluate these changes. Shortly afterwards (August 1992) the operators of the Marchon plant announced yet further policy changes, in totally replacing phosphate rock imports with phosphoric acid and, by liming the effluent and storing the resultant inert solid in landfill sites, reaching the 'ultimate state of zero discharge of heavy metals'.

The main objectives of the present research were:

i) to establish data on metal levels in biota of the Cumbrian coastline;

ii) to provide the necessary information for evaluating the impact of metal emissions from industrial discharges on littoral organisms. Of particular interest was the extent of metal contamination arising from phosphate ore processing/detergent production at Whitehaven;

iii) to chart the influence of control measures taken to reduce metal inputs in this area, and to establish information as a platform for future controls which may be required to improve environmental quality;

iv) to provide comparisons of metal levels in organisms from the West Cumbrian coast with data for other coastal and estuarine sites in the UK. Owing to the extensive nature of this on-going study only a brief résumé of results is possible here.

Methods

The concept of using biological samples as indicators of metal contamination is now widely regarded as an essential component of marine monitoring programmes, to complement the traditional methods of assessment provided by water and sediment analyses (Phillips 1980; Bryan *et al.* 1985). The major argument supporting the inclusion of indicator organisms in such schemes is that they reflect and integrate only biologically-available forms. In contrast, analyses of water and sediment usually provide information concerning the total concentration of the contaminant in the environment but without defining accumulation potential and, thus, perhaps, biological impact. Since 'Environmental Quality Targets' are most frequently aimed at the protection of biological resources, the use of indicator organisms which reflect the presence of bioavailable metals is, therefore, often a preferable means of assessing contamination. Of course body-burden data should not be considered as a panacea, but merely as one component of environmental assessment: some organisms have the ability to store quantities of contaminant in a detoxified form and only by thorough physiological and biochemical study will the true extent of any deleterious effects be revealed. However, such observations are outside the scope of the current investigation, whose main objectives are to the examine the scale and extent of metal bioaccumulation in the north-west coastal zone.

Two extensive surveys of Cumbrian intertidal organisms were conducted, in 1990 and 1992. 23 sites were sampled, covering the coastline between Eskmeals near Ravenglass and Skinburness (Figure 1). The greatest concentration of sites was located between St Bees and Workington, since the major discharges of metals were thought to be situated along this part of the coastline.

The majority of intertidal sites visited provided substrates for typical rocky shore communities (Figure 1). Representative dominant species were collected, where present: these included macroalgae *Fucus vesiculosus*, mussels *Mytilus edulis*, limpets *Patella vulgata*, winkles *Littorina littorea* and dog-whelks *Nucella lapillus*. Not all species were found at every location. At six sites (Figure 1) it was possible to collect fine sediments and representative members of estuarine infaunal communities, ragworm *Nereis diversicolor* and clams *Scrobicularia plana*. However, because of their widespread distribution and proximity to major discharges, rocky shore species generally provided the most comprehensive information on spatial trends in contamination along the Cumbrian coast, particularly in Saltom Bay. Metals analysed in all sample types included Ag, As, Cd, Cu, Co, Cr, Fe, Hg, Mn, Ni, Pb, Sn and Zn.

The relative merits (as metal bioindicators) of most of the species listed above - and the benefits of a multi-organism assessment of metal contamination - have been discussed previously in some depth (for example, Bryan *et al.* 1985; Langston 1986; Phillips 1990; Rainbow 1995). Details of sampling techniques and analytical methodology, using various forms of atomic absorption spectrophotometry, are described in Bryan *et al.* (1985) and Langston (1986). Briefly, for the majority of metals, tissues and sieved (100 µm) sediment were digested with concentrated nitric acid for several days on a hotplate. (Though not strictly a total sediment dissolution this procedure was found to remove more than 90% of the HF-extractable metal present in various estuarine

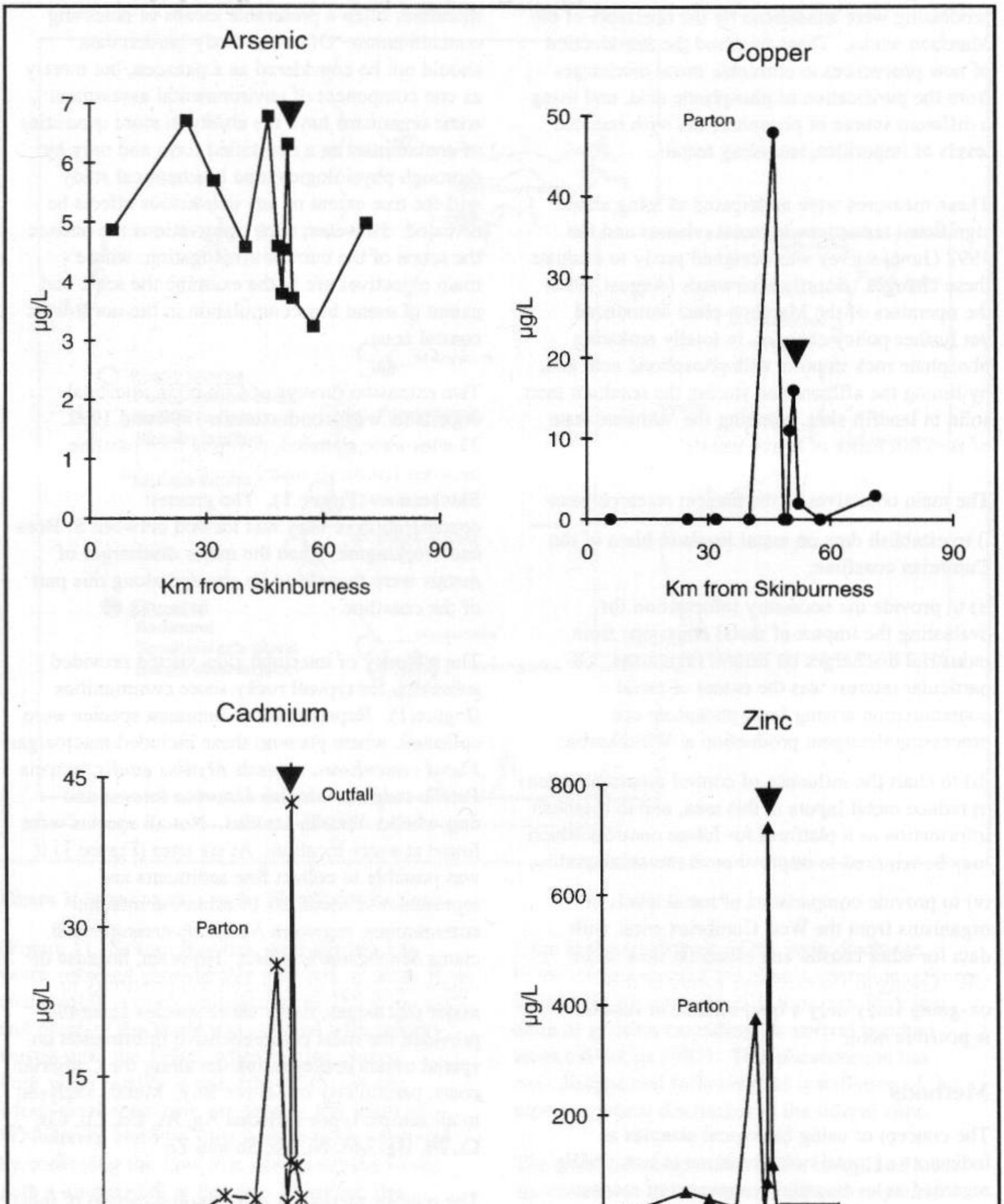


Figure 2 Metals in seawater (unfiltered), Cumbria 1992. Arrows indicate position of Marchon discharge, Saltom Bay.

samples examined. Any metal not removed by this treatment is unlikely to be bioavailable). After evaporating the acid, the residue was dissolved in concentrated hydrochloric acid and diluted to give 1M HCl prior to analysis. Most determinations for Ag, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb and Zn were carried out by flame atomic absorption using an air-acetylene flame (Perkin-Elmer 603 or Varian AA20). Background correction was employed for all metals except Cu, Fe, Mn and Zn. Low concentrations of metals such as Ag and Cd were determined by graphite furnace atomic absorption using standard addition methods (Perkin-Elmer 603 with 76B furnace or Varian 300 Zeeman).

Sediment samples for As and Hg analysis were refluxed with nitric acid in Kjeldahl flasks fitted with condensers and then diluted with distilled water. Tissue Hg was solubilised in a similar fashion using a mixture of nitric and sulphuric acids at 80°C followed by final oxidation with hydrogen peroxide. For analysis of Sn and As in biota, samples were dry ashed in a muffle furnace with a mixture of magnesium oxide and magnesium nitrate as an ashing aid. The residue was dissolved in 25% hydrochloric acid. Flameless AA was used in the measurement of this group of elements (Perkin-Elmer MHS-20 hydride system) using either stannous chloride (Hg) or sodium borohydride (As, Sn) as reducing agents. Concentrations of all elements are expressed on a dry weight basis throughout.

In addition to sediments and organisms, filtered (0.45 µm) and unfiltered water samples were collected for analysis from several Cumbrian sites, to assist in pin-pointing the sources and sizes of metal inputs. Phosphate, salinity, pH and various other determinants of water quality were measured in these samples, in addition to metals. However, since the object of this research was primarily to judge the impact of industrial discharges on residues accumulated in biota, the number of water samples taken was limited.

Although extensive monitoring was not a major objective from the outset, our laboratory has, in the course of its long-term research programme, amassed a considerable dataset for concentrations of metals in the above organisms and sediments, not only for Cumbria but encompassing more than 100 estuaries and coastal regions around the UK. These extensive data have been used to place the present observations from north-west England in a national context.

Results and discussion

Metals in water

Analysis of metals in water provides only a 'snapshot' of contaminant levels in the coastal aquatic environment at the time of sampling. Nevertheless, for the elements measured in unfiltered samples from the Cumbrian coast, elevated concentrations were found to occur consistently between Parton and St Bees, over a distance of 6.5 km, with highest levels predominantly centred around the Marchon outfall (Barrowmouth) in Saltom Bay, and also at Parton (see Figure 1 for locations and examples for As, Cd, Cu and Zn in Figure 2).

Confirmation of a common source of As, Cu, Cd and Zn (together with other metals such as Fe and Mn) in Saltom Bay - namely the effluent from the Marchon plant - was established from significant correlations with phosphate concentrations in water ($P<0.01$ for Cd and Zn; $P<0.05$ for Cu and As). The elevated metal concentrations measured at Parton, in unfiltered samples (Figure 2), were largely due to the significant contribution from particulate metals. This has been established by analysing a limited set of filtered samples which, by eliminating contributions from suspended solids, more clearly demonstrate the significance of dissolved, as opposed to particulate, metal loads. Thus, in contrast to samples from Parton, dissolved metals were the dominant fraction in seawater collected in the vicinity of the Marchon outfall in Saltom Bay, and in the 1992 survey included significantly elevated values of 6 µg (As) l^{-1}, 528 µg (Zn) l^{-1}, 65 µg (Mn) l^{-1} and 44 µg (Cd) l^{-1}.

The origin of the high particulate metal load in seawater at Parton is uncertain (possibilities include contributions from freshwater run-off from Distington Beck, and a subtidal long outfall from a nearby sewage treatment plant), but was particularly important for Fe and Mn (whose oxyhydroxide coatings on particulates may scavenge other metals). Fe and Mg were also enriched in unfiltered water samples from Maryport, and coincided with high concentrations of both of these metals in sediments and biota at this location.

Metal concentrations in (unfiltered) waters of Saltom Bay were, if anything, slightly higher in 1992, compared with the 1990 survey. However, since water concentrations are known to vary considerably over time in the vicinity of discharges, little should be drawn from these observations with regard to temporal trends in water quality.

Rocky shore species - coastal sites

Most organisms integrate contamination over a period of months, or longer, and are therefore more reliable indicators of long-term trends, compared with analyses of water samples. As a consequence, some consistent patterns emerge from biological monitoring which help to define the impact of industrial discharges on metal levels in Cumbrian biota. Only a summary of these patterns is reviewed here. More detailed information can be found in survey reports (Langston & Pope 1991; Langston *et al.* 1993) and a comprehensive description of trends is planned for publication in the near future.

As might be expected from the profiles of metals in water (Figure 2), the discharges into Saltom Bay were by far the most significant influence on metal burdens in rocky shore species from the Cumbrian coast, particularly for Ag, Cd, Cr, Cu, Ni and Zn.

Table 1a Metal contamination in rocky shore species, Saltom Bay 1992 (most contaminated sites).

	Ag	*As*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*Hg*	*Mn*	*Ni*	*Pb*	*Sn*	*Zn*
Patella vulgata	+++		+++	++	+++	+++		+		+	+		+
Littorina littorea	+	+	+++	+	+++	+++	+	+		+			++
Nucella lapillus	++		+++	++	+++	+++	+			+++			+++
Mytilus edulis	+++		+++		+++	+++	+++			+++			+
Fucus vesiculosus			+++	+	+++	+++	+			+++			+++

+++ = High; ++ = Moderate; + = Low. Blank values denote contamination not significantly above baseline.

Table 1b Metal contamination in sediments and infaunal species, Cumbria 1992 (most contaminated sites).

	Ag	*As*	*Cd*	*Co*	*Cr*	*Cu*	*Fe*	*Hg*	*Mn*	*Ni*	*Pb*	*Sn*	*Zn*
Sediment	+		+++	++	++		++		+++	++	+		+
Nereis diversicolor	+	+	++		+++		+++		++	+		+	+
Scrobicularia plana	+++		++		+++	+	++	+	+++	+++			+

+++ = High; ++ = Moderate; + = Low. Blank values denote contamination not significantly above baseline.

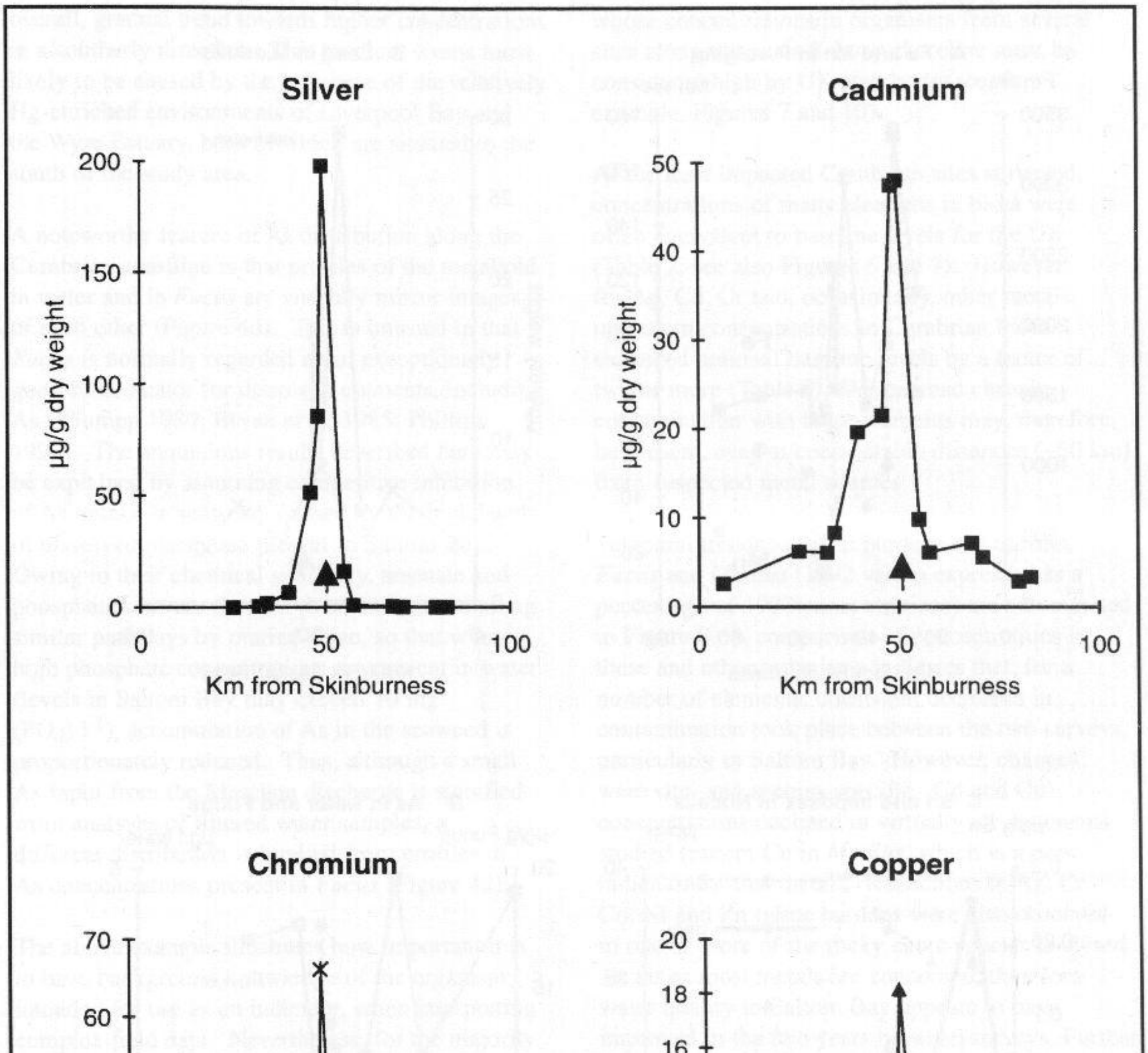
A summary of the relative degree of contamination in Saltom Bay samples is presented in Table 1a. The fact that not all species indicate the same degree of enrichment for certain metals is not surprising. The ability to regulate Zn, for example, is known to be highly species-specific, whilst Ag bioavailability is modified by both the physico-chemical form of the element and competitive interactions with other metals for uptake sites (both of which may be highly species-dependent).

Specific examples of profiles indicating the degree and extent of Ag, Cd, Cr and Cu contamination in mussels *M. edulis*, collected over the entire survey range in 1992, are shown in Figure 3. These unequivocally depict the magnitude of the effect of the Marchon discharge (arrowed) on metal accumulation and also its wider impact over at least several kilometres of shoreline.

There is clear evidence, from biomonitoring, of inputs of a number of other metals into Saltom Bay, notably Fe and Co (Table 1a) though for these metals (in contrast to Ag, Cd, Cr, Cu, Ni and Zn) overall profiles along the Cumbrian coastline were not so clearly dominated by the Marchon outfall.

Figures 4a, b and c illustrate examples where metal contamination was highest outside Saltom Bay. Thus, Fe and Mn concentrations in biota were usually most enriched at some of the more northerly sites, especially between Maryport and Workington (shown in Figure 4a for *Patella*) and probably signified the extensive influence of previous ore-processing activity which was once a major feature along this stretch of shoreline. Elevated Pb (and occasionally As, Mn and Ag) concentrations were prominent at Harrington (shown in Figure 4b for *Mytilus*). Sn contamination was usually highest near harbours, situated largely in the northern half of the survey area (Figure 4c), suggesting that tributyltin (from antifouling paints) was the major bioavailable source of this element along the Cumbrian coast.

Tributyltin (TBT) was widely used in antifouling paints on all types of vessel until 1987, when restrictions on usage (on boats smaller than 25 m) were introduced by the UK government following concern over toxicity of the compound to non-target organisms. TBT-induced reproductive abnormalities in female *Nucella lapillus* (notably imposex - the imposition of secondary male sexual characteristics, including penis development) provide an extremely specific and sensitive means of monitoring the biological impact of this contaminant in coastal waters (Bryan *et al.* 1986; Langston *et al.* 1990). The intensity of imposex, expressed as the Relative Penis Size Index (RPSI = [mean female penis length]^3/[mean male penis length]^3 x 100), was measured in most of the *Nucella* populations collected in the 1990 Cumbrian survey. Results clearly indicate that dog-whelks were affected at a number of sites (Figure 4c), predominantly those close to harbours and estuaries in the north of the study area. The similarity in profiles of the imposex index and Sn body burdens confirms that TBT from antifouling paint was most probably the major source of bioavailable Sn. Put in perspective, however, the RPSI values determined in *Nucella* populations from the



Arrow indicates location of Marchon outfall

Figure 3 Metals in *Mytilus edulis*, Cumbria 1992.

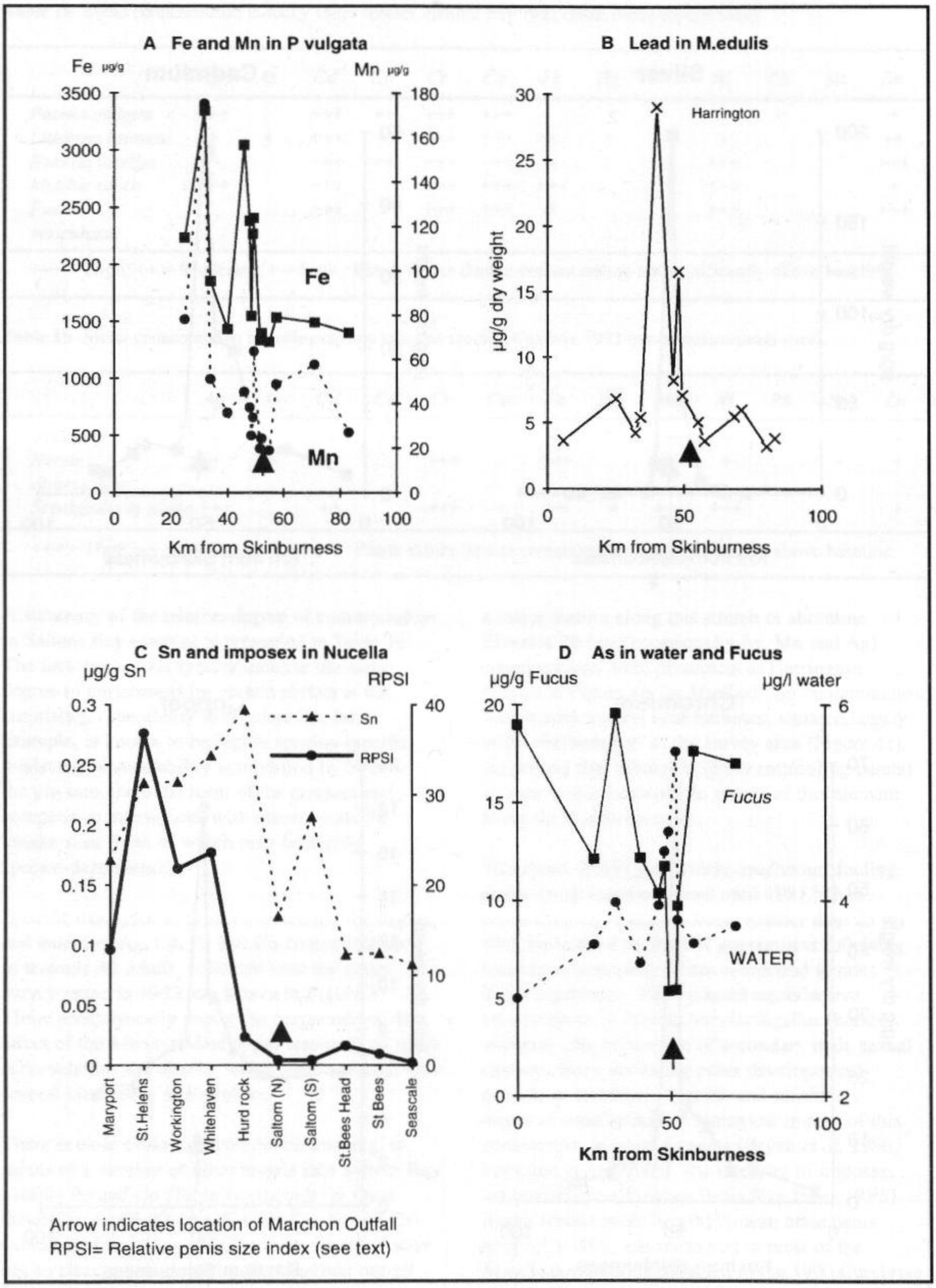


Figure 4 Examples of metal profiles in biota from the Cumbrian coast (not dominated by Marchon discharge).

Cumbrian coast, even at worst (37%), were much lower than at sites elsewhere in the UK which were heavily influenced by TBT antifouling, for example Yarmouth on the Isle of Wight (91%). Consequently, whilst dog-whelks have been eliminated from much of the Solent by TBT contamination (Langston *et al.* 1990), there was little evidence of any widespread decline in Cumbrian populations, based on current results.

There was a small degree of Hg enrichment in biota from Saltom Bay, though for most species surveyed along the Cumbrian coastline this localised enrichment was superimposed on an overall, gradual trend towards higher concentrations in a southerly direction. This gradient seems most likely to be caused by the influence of the relatively Hg-enriched environments of Liverpool Bay and the Wyre Estuary, both of which are situated to the south of the study area.

A noteworthy feature of As distribution along the Cumbrian coastline is that profiles of the metalloid in water and in *Fucus* are virtually mirror images of each other (Figure 4d). This is unusual in that *Fucus* is normally regarded as an exceptionally good bioindicator for dissolved elements, including As (Klumpp 1980; Bryan *et al.* 1985; Phillips 1990). The anomalous results described here may be explained by assuming competitive inhibition of As uptake in seaweed, caused by the high levels of dissolved phosphate present in Saltom Bay. Owing to their chemical similarity, arsenate and phosphate ions are thought to be assimilated along similar pathways by marine algae, so that where high phosphate concentrations are present in water (levels in Saltom Bay may exceed 10 mg $(PO_4)\ l^{-1}$), accumulation of As in the seaweed is proportionately reduced. Thus, although a small As input from the Marchon discharge is signified from analyses of filtered water samples, a different distribution is implied from profiles of As concentrations present in *Fucus* (Figure 4d).

The above example illustrates how important it is to have background knowledge of the organism intended for use as an indicator, when interpreting complex field data. Nevertheless, for the majority of species studied here, the impact of discharges along the Cumbrian coastline, as reflected by body burdens of metals including Ag, Cd, Cr, Cu, Ni and Zn, were unambiguously dominated by inputs to Saltom Bay (summarised in Table 1a).

Ag, Cd, Cr and Ni concentrations in organisms from the most contaminated Cumbrian rocky-shore sites (usually in Saltom Bay) were consistently comparable to some of the uppermost values encountered in the UK, as illustrated by examples for *Patella, Nucella* and *Mytilus* in Figures 5, 6 and 7, respectively. This was also true for Cu and Zn in the stenohaline species such as *Nucella* (Figure 6) and *Patella* which are restricted to open coast sites exhibiting fully marine, and usually unpolluted, conditions. However, in *Mytilus, Littorina* and *Fucus* (species which can tolerate lower salinities and therefore also inhabit estuaries), the highest concentrations of these latter two metals were encountered in specimens from some of the more heavily contaminated tidal creeks in metal-rich parts of south-west England.

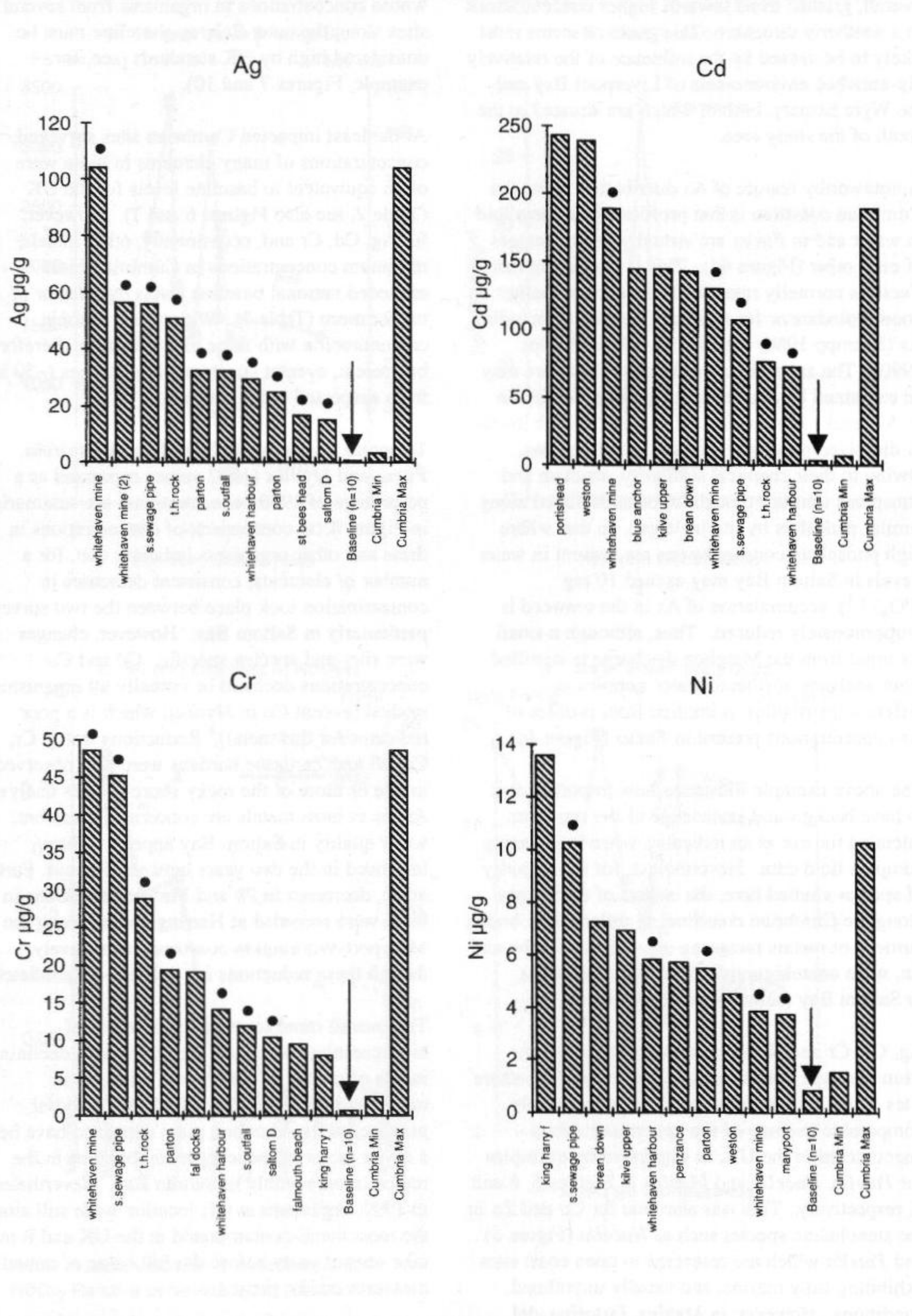
Other examples of significant metal accumulations in Cumbrian biota included those of Fe and Mn, whose concentrations in organisms from several sites along the outer Solway shoreline must be considered high by UK standards (see, for example, Figures 7 and 10).

At the least impacted Cumbrian sites surveyed, concentrations of many elements in biota were often equivalent to baseline levels for the UK (Table 2, see also Figures 6 and 7). However, for Ag, Cd, Cr and, occasionally, other metals, minimum concentrations in Cumbrian biota exceeded national baseline levels by a factor of two or more (Table 2). Widespread chronic contamination with these elements may, therefore, be present, even at considerable distances (~50 km) from suspected metal sources.

Temporal trends in metal burdens in *Littorina, Fucus* and *Mytilus* (1992 values expressed as a percentage of 1990 concentrations) are summarised in Figure 8. A comparison of concentrations in these and other organisms indicates that, for a number of elements, consistent decreases in contamination took place between the two surveys, particularly in Saltom Bay. However, changes were site- and species-specific. Cd and Cu concentrations declined in virtually all organisms studied (except Cu in *Mytilus*, which is a poor indicator for this metal). Reductions in Ag, Cr, Co, Ni and Zn tissue burdens were also observed in one or more of the rocky shore species analysed. As far as most metals are concerned, therefore, water quality in Saltom Bay appears to have improved in the two years between surveys. Further north, decreases in Pb and Mn concentrations in biota were recorded at Harrington and along the Maryport-Workington coastline, respectively, though these reductions are unlikely to be related.

The overall trend towards lower levels of bioaccumulation reflects the anticipated declining inputs of metals in the region. Changes in manufacturing operations and waste disposal practices at the Marchon plant appear to have been a major factor in reducing metal burdens in the region, most notably in Saltom Bay. Nevertheless, in 1992, organisms at this location were still among the most metal-contaminated in the UK and it may take several years before the full value of remedial measures can be judged.

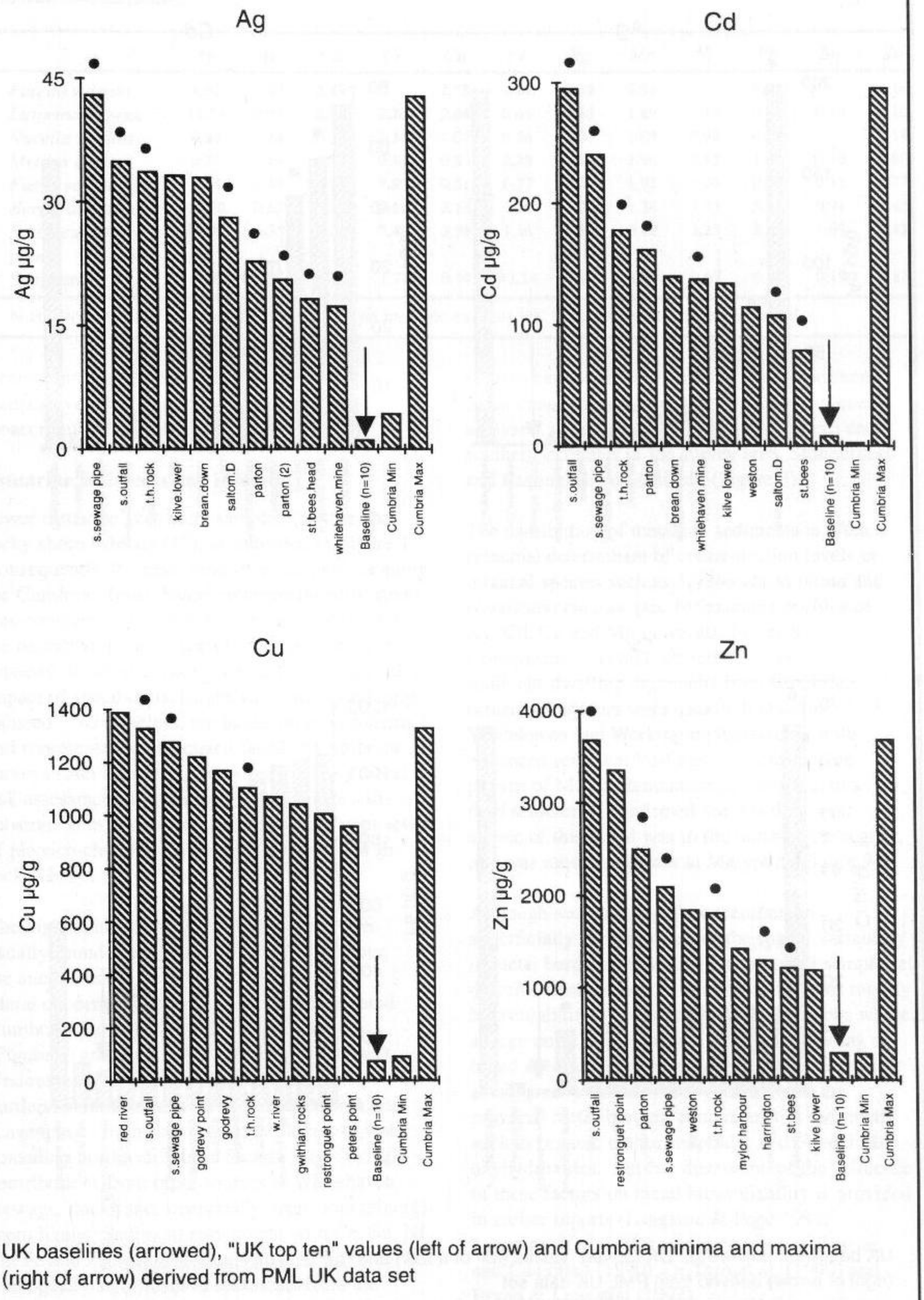
A few examples of temporal increases in metal burdens in biota were observed - most consistently for As (see examples for *Fucus* and *Mytilus*, Figure 8). Since dissolved As concentrations have changed very little between surveys, one possible explanation for the more recent increases in As tissue burdens may be that effluent treatment, and improvement to water quality in Saltom Bay, has resulted in a reduction of phosphate levels in water.



UK Baselines (arrowed), "UK Top ten" values(left of arrow) and Cumbrian minima and maxima (right of arrow) derived from PML UK data set.

● indicates occurence of Cumbrian site in UK top ten

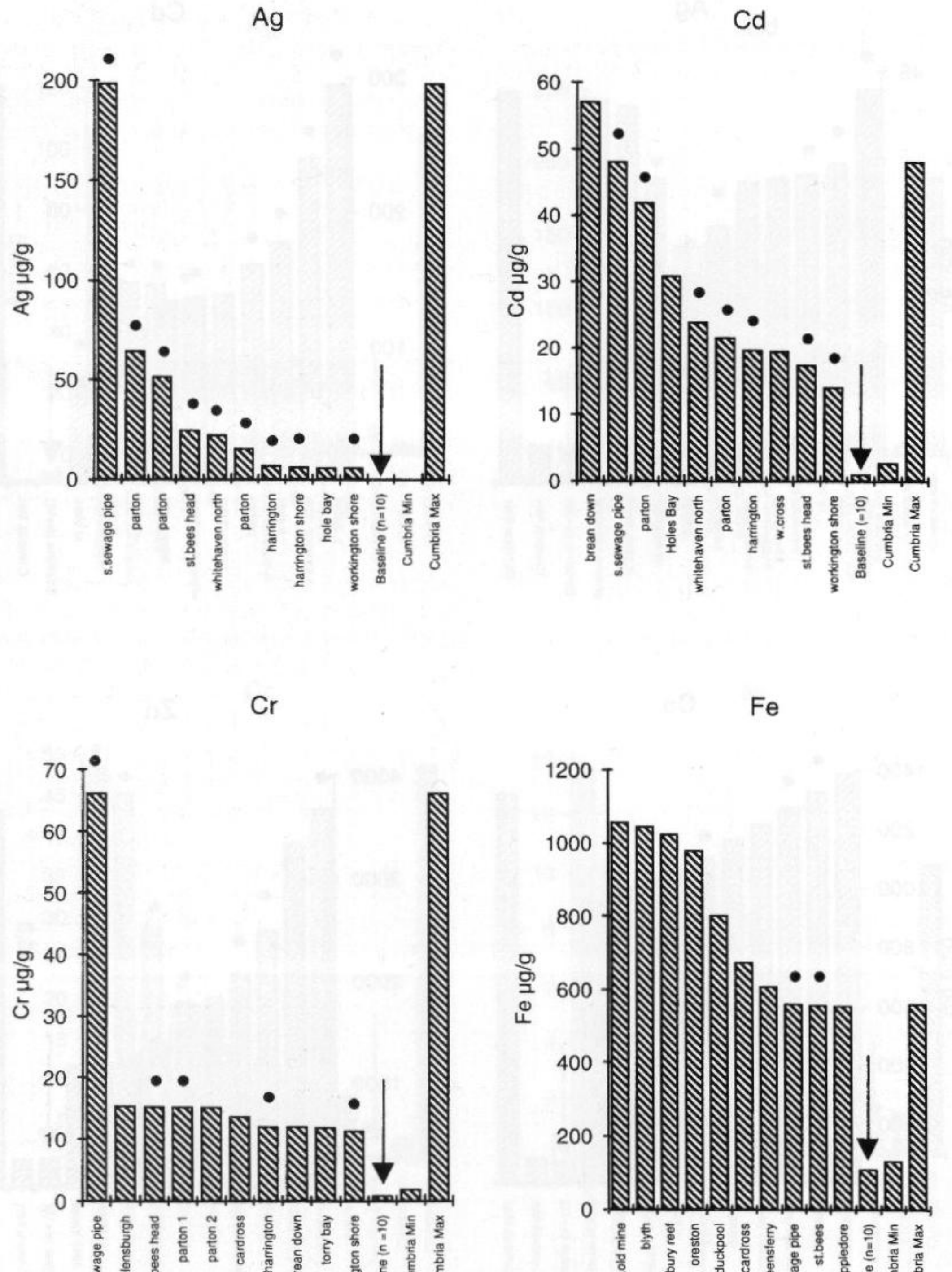
Figure 5 Metal concentration ranges in *Patella vulgata*, UK and Cumbria.



UK baselines (arrowed), "UK top ten" values (left of arrow) and Cumbria minima and maxima (right of arrow) derived from PML UK data set

● - indicates Cumbrian sites

Figure 6 Metal concentration ranges in *Nucella lapillus*, UK and Cumbria.



UK baselines (arrowed), "UK top ten" values (left of arrow) and Cumbria minima and maxima (right of arrow) derived from PML UK data set

● - indicates Cumbrian sites

Figure 7 Metal concentration ranges in *Mytilus edulis*, UK and Cumbria.

Table 2 Comparison of baseline metal concentrations, Cumbria and UK (values are ratios of Cumbrian minimum/UK minimum concentrations).

	Ag	*As*	*Cd*	*Cr*	*Cu*	*Fe*	*Hg*	*Mn*	*Ni*	*Pb*	*Sn*	*Zn*
Patella vulgata	**4.02**	0.50	**2.49**		**2.75**	1.14	1.39	**5.51**		**5.56**		1.16
Littorina littorea	**11.53**	0.94	**2.24**	**2.20**	**2.04**	0.65	0.45	1.89	1.19	0.81	0.50	1.10
Nucella lapillus	**3.30**	0.28	0.32	**2.36**	1.07	0.56	1.05	1.09	0.98	0.61		1.19
Mytilus edulis	0.30	1.19	**6.53**	**9.13**	0.85	**2.20**	1.83	1.96	**2.15**	1.90	0.30	1.80
Fucus vesiculosus	1.04	0.49	1.32	**7.87**	0.51	0.77	0.03	1.92	1.06	0.59	0.12	0.77
Nereis diversicolor	**12.70**	0.62	**13.83**	**3.06**	**2.14**	1.24	1.20	1.36	1.33	**5.33**	0.91	1.43
Scrobicularia plana	**68.97**	4.35	**4.36**	**7.41**	**3.90**	1.16	**8.10**	0.16	**3.23**	**3.23**	1.69	**2.42**
Sediment	1.30	1.95	1.95	1.71	0.39	**12.24**	0.92	**6.90**	0.67	0.56	0.19	0.83

N.B. Figures in bold denote that the Cumbrian baseline exceeds UK baseline by more than two-fold.

Hence, this may have lowered the effect of competitive inhibition, by PO_4, on arsenate bioaccumulation (described above).

Estuarine sediments and infauna

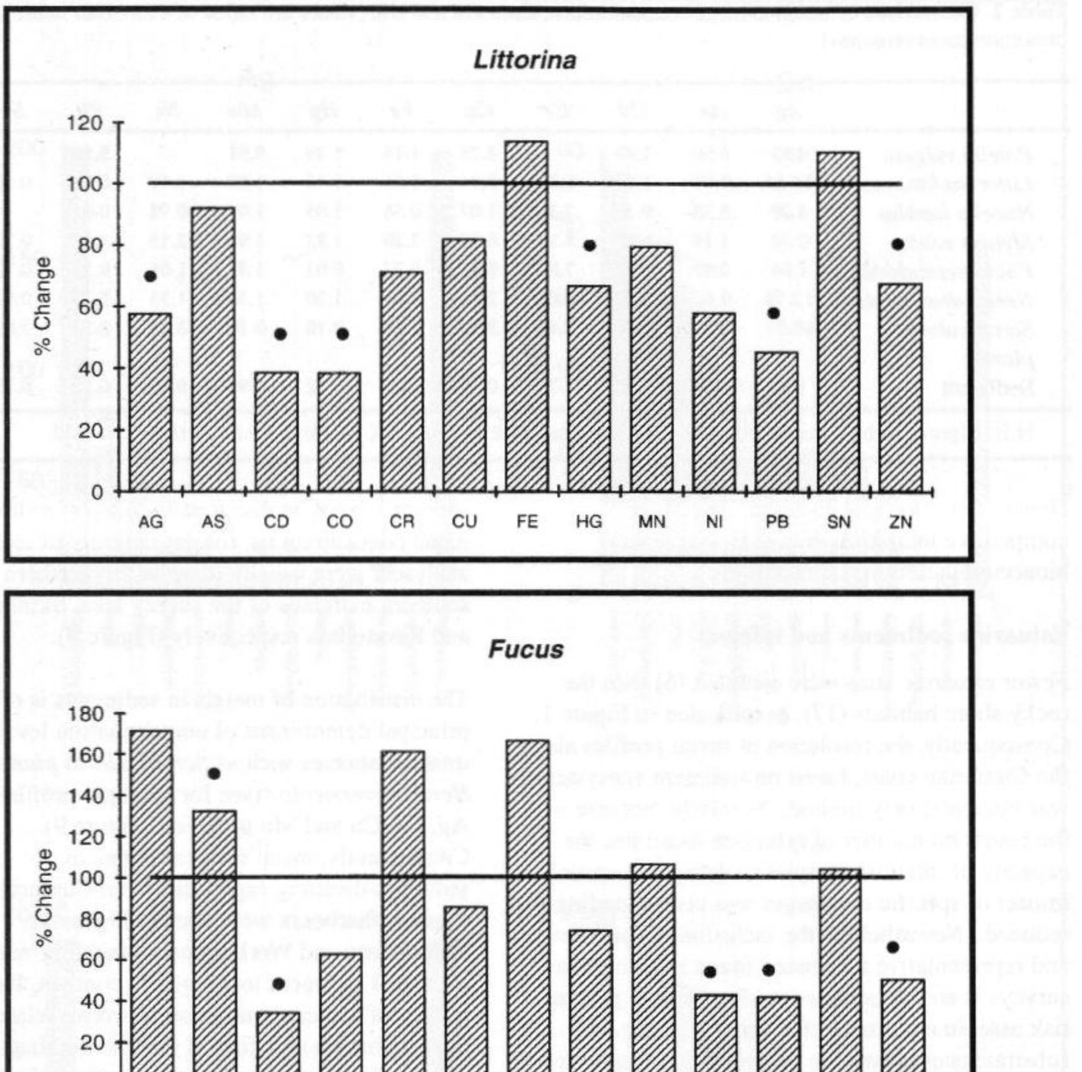
Fewer estuarine sites were sampled (6) than the rocky shore habitats (17), as indicated in Figure 1. Consequently, the resolution of metal profiles along the Cumbrian coast, based on sediment ecosystems, was comparatively limited. Similarly, because of the restricted number of estuarine locations, the capacity of infaunal samples to define the spatial impact of specific discharges was correspondingly reduced. Nevertheless, the inclusion of sediments and representative associated fauna in Cumbrian surveys is an important component in the general risk assessment process for the area, since soft-substrate ecosystems are subject to a different set of physico-chemical challenges, compared with rocky shores.

The highest metal loadings in sediments were usually found to occur at Whitehaven Harbour, the site closest to the Saltom Bay outfall. Metal concentrations at this location dominated Cumbrian sediment profiles for Ag, Cd, Cu (Figure 9) and As, Cr and Hg (data not shown). Undoubtedly, some of this particulate metal burden resulted from solid-phase adsorption and scavenging - from the metal-rich plumes of water spreading northwards from Saltom Bay - though contributions from other sources at Whitehaven (sewage, docks and, historically, from coal mining) seem likely. Sediment enrichment with Co, Sn, Ni, Pb, Fe and Zn was also observed at Whitehaven but was equally significant in sediments from the Derwent Estuary at Workington. Sediment Mn concentrations were highest at Maryport (Figure 9). The association of Mn, Fe, and presumably certain other metals, with previous ore shipment and processing at Maryport and Workington probably accounts for a significant proportion of the elevated sediment metal burden observed at these sites, though other industrial and geological sources cannot be discounted. Lowest sediment metal concentrations, for the majority of elements analysed, were usually those at the northern and southern extremes of the survey area, Skinburness and Ravenglass respectively (Figure 9).

The distribution of metals in sediments is often a principal determinant of contamination levels in infaunal species such as *Scrobicularia plana* and *Nereis diversicolor* (see for example profiles of Ag, Cd, Cu and Mn in *Nereis*, Figure 9). Consequently, metal concentrations in sediment-dwelling organisms from Cumbrian estuaries/harbours were usually highest at Whitehaven and Workington, coinciding with enhanced sediment loadings. In contrast, the pattern of Mn contamination in worms, clams (and sediments) confirmed that the dominant source of this metal was to the north of the region, and was most significant at Maryport (Figure 9).

Although sediment metal concentrations superficially explain much of the spatial variability in metal burdens in infauna for the small sample set described here, other factors can sometimes modify bioavailability. These become more obvious where a large range of estuaries is sampled, covering a broad spectrum of physico-chemical conditions, and typically include redox, salinity and the principal metal-binding components in sediments such as organic matter, sulphides and Fe and Mn oxyhydroxides. Further discussion of the influence of these factors on metal bioavailability is provided in earlier reports (Langston & Pope 1991; Langston *et al.* 1993) and in reviews by Tessier and Campbell (1990), Di Toro *et al.* (1990) and Bryan & Langston (1992).

Sediment metal loadings in Cumbrian estuaries have been assessed alongside data for other UK estuaries, which included some very highly polluted sites in south-west England associated with metal mining. Not surprisingly, relative to the latter, contamination of Cumbrian sediments was not



Histograms represent % change in 1992 samples relative to 1990 (Horizontal line -100%)

● Denotes significant change, ($P<0.05$)

Figure 8 Changes in metals in Cumbrian samples 1990 -1992.

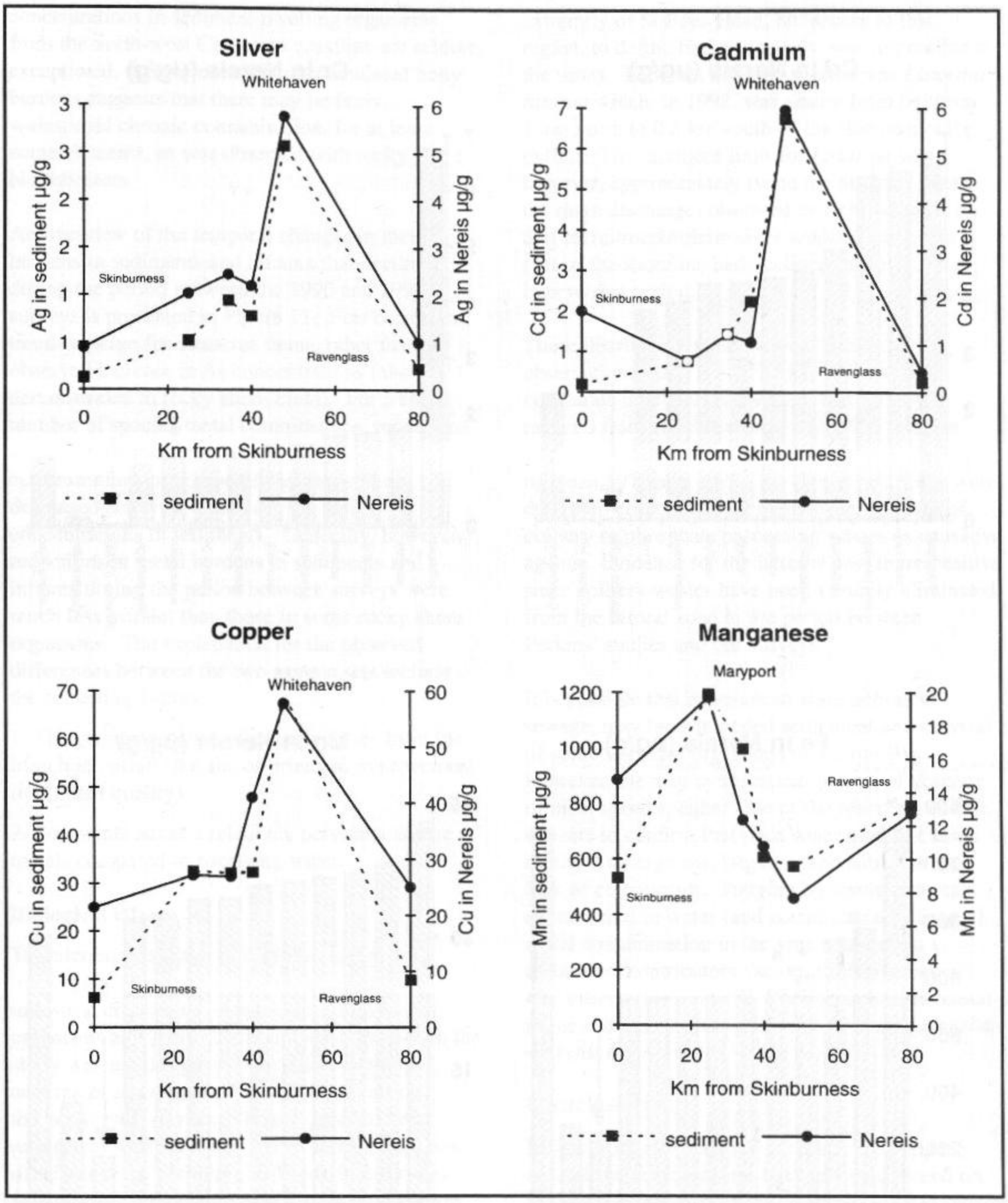
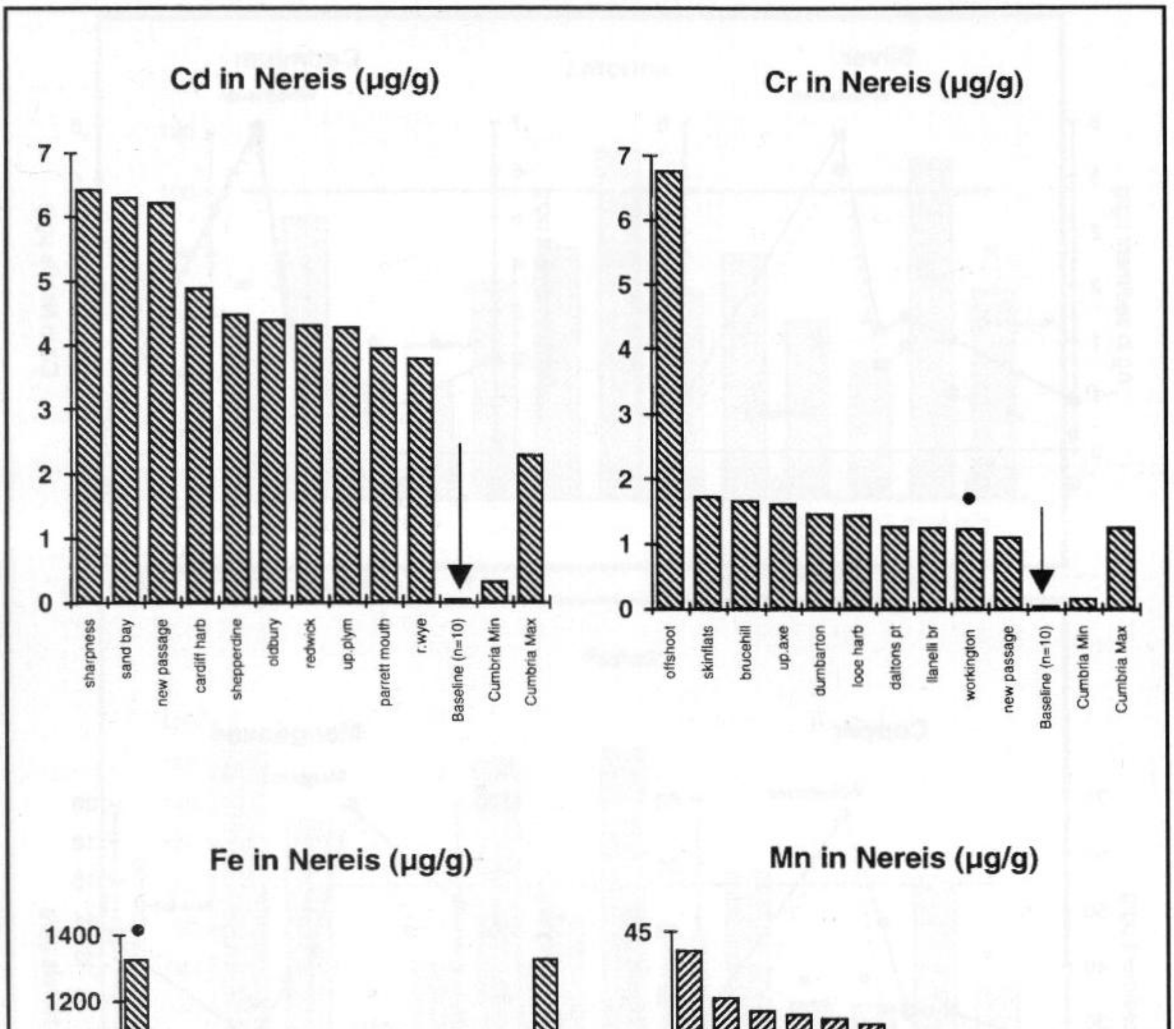


Figure 9 Metal in sediments and *Nereis*, Cumbria 1992.

exceptional, other than for Cd at Whitehaven and Mn at Maryport. Comparisons indicated that there was a moderate degree of enrichment with Ag, Co, Cr, Fe, Ni, Pb and Zn, principally at Whitehaven and Workington, as summarised in Table 1b. This scale of sediment contamination was generally reflected in the tissue burdens measured in infaunal organisms, *S. plana* and *N. diversicolor* (Table 1b), as might be expected from the relationships described in the previous paragraphs.

Estuarine infaunal sampling did not include sites in the immediate vicinity of the Saltom Bay outfall and, therefore, levels of metal enhancement in *S. plana* and *N. diversicolor* did not match the exceptional enrichment found in some of the rocky shore fauna most severely impacted by the Marchon discharge. Nevertheless Ag, Cd, Cr, Fe, Mn, and Ni concentrations in *Nereis* and *Scrobicularia* from the most contaminated Cumbrian sediments were, as indicated above, often of significance in terms of UK ranges (Table 1b and, for Cd, Cr Fe and Mn in *Nereis*, Figure 10). Furthermore, for most of these metals (and also Cu), minimum values in Cumbrian estuarine infauna exceeded baseline levels for the UK by at least a factor of two and sometimes considerably more (Table 2 and, for *Nereis*, Figure 10). Therefore, even though metal



UK baselines (arrowed), "UK top ten" values (left of arrow) and Cumbria minima and maxima (right of arrow) derived from PML UK data set

● indicates occurence of Cumbrian site in UK top ten

Figure 10 Metal concentration ranges in *Nereis diversicolor*, UK and Cumbria.

concentrations in sediment-dwelling organisms from the north-west Cumbrian coastline are seldom exceptional, the evidence from accumulated body burdens suggests that there may be fairly widespread chronic contamination, for at least some elements, as was observed with rocky shore bioindicators.

An overview of the temporal changes in metal burdens in sediments and infauna that occurred during the period between the 1990 and 1992 surveys is presented in Figure 11. Few consistent trends emerge for estuarine fauna, other than an observed increase in As concentrations (also demonstrated in rocky shore biota). For a small number of species-metal combinations, reductions were significant: for example, Mn and Pb concentrations in *Scrobicularia plana* have decreased since 1990, as have Co and Ni concentrations in sediments. Generally, however, reductions in metal burdens in sediments and infauna during the period between surveys were much less evident than those in some rocky shore organisms. The explanation for the observed differences between the two sample sets include the following factors:

1. The greater distance of estuarine sites from the Marchon outfall (the site of principal improvement in effluent quality).

2. Sediments act as a relatively persistent source of metals compared to overlying water.

Biological effects

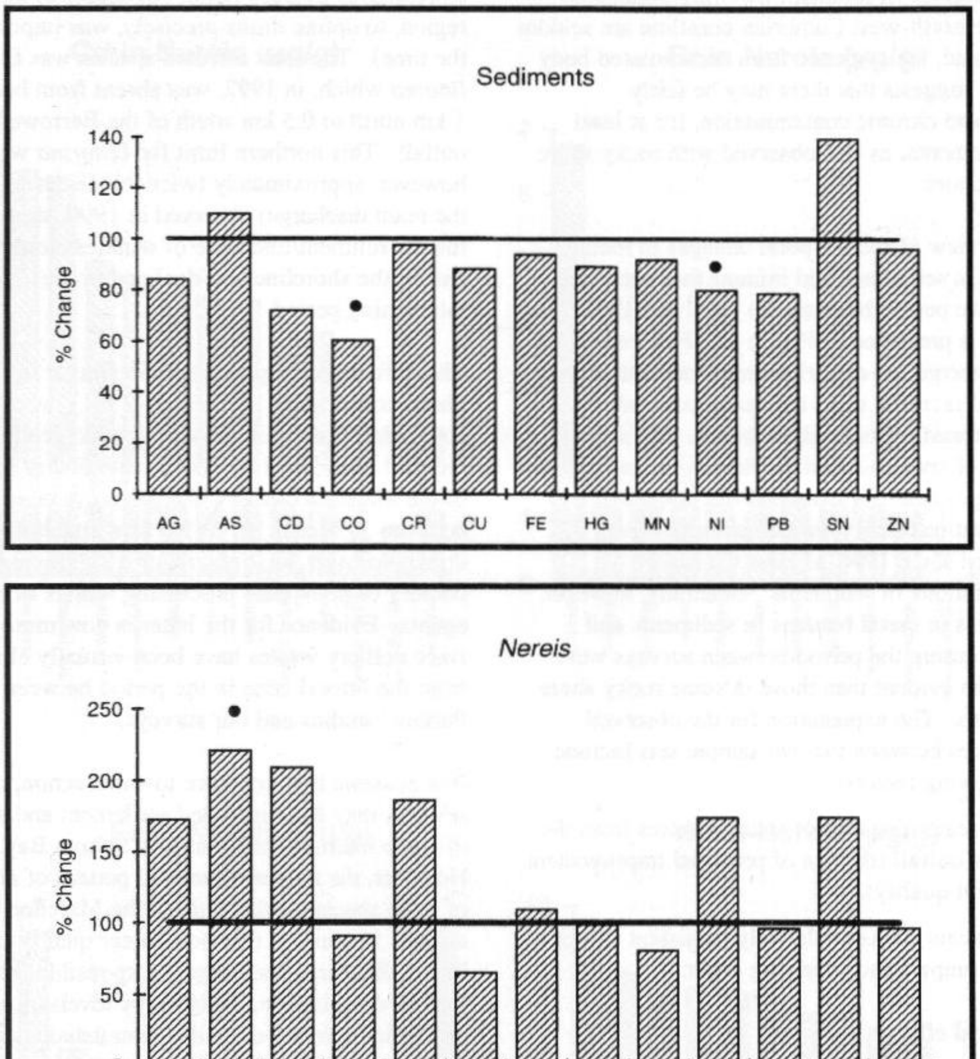
To reiterate, the major aim of the current investigation was to determine the impact of industrial discharges on metal accumulation in organisms along the Cumbrian coast. Although the study was not designed to include a thorough ecological assessment, some observations on the occurrence of rocky shore organisms are, nevertheless, of relevance, particularly as species distributions in both the 1990 and 1992 surveys were conspicuously influenced by contamination along the shoreline in Saltom Bay. Damage to intertidal communities caused by the discharges in this area, was, if anything, slightly more extensive in the later study, despite some improvement in water quality, though the pattern of impact was consistent throughout the two-year period. Thus, in 1992, *Fucus* spp. were absent from almost 2 km north of the Barrowmouth outfall (Figure 1) to 0.75 km to the south, while *Patella vulgata* and *Nucella lapillus* were eliminated over similar ranges (1.5 km N, 0.75 km S and 1.7 km N, 0.75 km S respectively). Of all the species studied, the distribution of *Mytilus edulis* was most impacted, with individuals absent from 1.7 km north of the outfall to some 4 km to the south. (This species may have been present towards the western extremity of St Bees Head, but access to this region, to define limits precisely, was impossible at the time). The least affected species was *Littorina littorea* which, in 1992, was absent from between 1 km north to 0.5 km south of the Barrowmouth outfall. This northern limit for *Littorina* was, however, approximately twice the distance (from the main discharge) observed in 1990, suggesting that recruitment/tolerance of winkles along this part of the shoreline had declined in the intervening period.

These distribution patterns were similar to observations made by Perkins (1981), who concluded that species diversity was greatly reduced from Hurd Rocks to a site 500 m south of the Marchon outfall during surveys conducted between 1970 and 1977. No firm conclusions were drawn however, as to the relative significance of colliery or phosphate processing wastes as causative agents. Evidence for the latter is now more positive since colliery wastes have been virtually eliminated from the littoral zone in the period between Perkins' studies and our surveys.

It is possible that exposure to wave action, or sewage, may have impeded settlement and survival of some intertidal organisms in Saltom Bay. However, the near symmetrical pattern of absence of most species, either side of the Marchon outfall, appears to confirm that poor water quality caused by the discharge was largely responsible for the lack of colonisation. Judging by levels of metals encountered in water (and accumulated in tissues), metal contamination in the area was almost certainly a contributory factor in this process. Our observations indicate that sensitivity increased in the order: *Littorina* < *Patella* < *Fucus* < *Nucella* < *Mytilus.*

Conclusions

Bioaccumulation data for metals in Cumbrian coastal environments has been assessed, based on surveys carried out in 1990 and 1992. It has proved essential to utilise several bioindicator species in order to gain a comprehensive understanding of bioavailability for the suite of elements studied (Ag, As, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Sn and Zn). Cumbrian rocky shore biota contained some exceptional concentrations of Ag, Cd and Cr (and a number of other metals). Highest body burdens were principally restricted to the shoreline of Saltom Bay and were thought to originate from the Marchon outfall at Barrowmouth, though the presence of sewage discharging onto the shore in Saltom Bay may have enhanced the bioavailability of certain metals, particularly Ag. Significant metal contamination was observed at other sites along this stretch of coast, for example Mn at Maryport and Pb at Harrington.



Histograms represent % change in 1992 samples relative to 1990 (Horizontal line -100%)

● Denotes significant change ,P<0.05

Figure 11 Changes in metals in Cumbrian sediment and in fauna, 1990-1992.

As recently as 1990, the discharge of Cd and other elements into Saltom Bay represented a major input to the sea, even on a national scale. This was reflected not only in exceptionally high concentrations of metals in biota from that location but also by widespread, low-level contamination, detectable as far away as 50 km from the source. Subsequent reductions in metal discharges from the Marchon plant, brought about by operational changes and the introduction of new waste treatment policies between 1990 and 1992, have resulted in significant local reductions in metal concentrations in organisms, though at the time of the later survey Saltom Bay body burdens were still considerably elevated in comparison to most UK sites.

Recent chemical and biological evidence suggests that impact from metals and other discharges along this coastline is diminishing, though still significant (unpublished data from a survey conducted in 1994). Further surveillance of biota will be necessary to determine the long-term effectiveness of measures taken to improve water quality, and to follow the progress, interactions and consequences of contaminant levels. In particular, sublethal effects caused by pollutants may be much more widespread than the observed acute impact (absence of species) described here. There is clearly a need for further research into these more subtle, biological indices of damage and for their application to gradients of chemical contamination present along the Cumbrian coastline.

Acknowledgements

Support for this work from the NRA(NW) and in particular the encouragement of Dr J. McEvoy, is gratefully acknowledged. Thanks are due to Dr P. Head and Dr G. Millward for their constructive reviews of the paper.

References

Bryan, G.W., & Langston, W.J. 1992. Bioavailability, accumulation and effects of heavy metals in sediments with special reference to United Kingdom estuaries: a review. *Environmental Pollution, 76:* 89-131.

Bryan, G.W., Langston, W.J., Hummerstone, L.G., & Burt, G.R. 1985. A guide to the assessment of heavy metal contamination in estuaries using biological indicators. *Marine Biological Association of the UK, Occasional Publication,* No. 4.

Bryan, G.W., Gibbs, P.E., Burt, G.R., & Hummerstone, L.G. 1986. The decline of the gastropod *Nucella lapillus* around south-west England: evidence for the effects of tributyltin from antifouling paints. *Journal of the Marine Biological Association of the UK, 66:* 611-640.

Di Toro, D.M., Mahony, J.D., Hansen, D.J., Scott, K.J., Hicks, M.B., Mayr, S.M., & Redmond, M.S. 1990. Toxicity of cadmium in sediments: the role of acid volatile sulphide. *Environmental Toxicology and Chemistry, 9:* 1,487-1,502.

Klumpp, D.W. 1980. Characteristics of arsenic accumulation by the seaweeds *Fucus spiralis* and *Ascophyllum nodosum. Marine Biology, 58:* 257-264.

Langston, W.J. 1986. Metals in sediments and benthic organisms in the Mersey Estuary. *Estuarine and Coastal Shelf Science, 23:* 239-261.

Langston, W.J., & Pope, N.D. 1991. *The impact of industrial discharges on metal levels in biota of the west Cumbrian coast - 1990.* Plymouth, Plymouth Marine Laboratory.

Langston, W.J., Pope, N.D., & Burt, G.R. 1993. *The impact of industrial discharges on metal levels in biota of the west Cumbrian coast - 1992.* Plymouth, Plymouth Marine Laboratory.

Langston, W.J., Bryan, G.W., Burt, G.R., & Gibbs, P.E. 1990. Assessing the impact of tin and TBT in estuaries and coastal regions. *Functional Ecology, 4:* 433-443.

Perkins, E.J. 1977. The Solway Firth. *In: Problems of a small estuary,* ed. by A. Nelson Smith & E.M. Bridges, 1/1-1/6.

Perkins, E.J. 1981. *Studies in the distribution and biological impact of the effluent released by Albright and Wilson, Marchon Division, Whitehaven, Cumbria. 2. Water quality and shoreline biota 1970-1977.* Whitehaven, Cumbria Sea Fisheries Committee. (Scientific Report 78/1.)

Phillips, D.J.H. 1980. *Quantitative aquatic biological indicators.* London, Applied Science Publishers Ltd.

Phillips, D.J.H. 1990. The use of macroalgae and invertebrates as monitors of metal levels in estuaries and coastal waters. *In: Heavy metals in the marine environment,* ed. by R.W. Furness & P.S. Rainbow, 81-99. Boca Raton, Florida, CRC Press Inc.

Rainbow, P.S. 1995. Biomonitoring of heavy metal availability in the marine environment. *Marine Pollution Bulletin, 31:* 183-192.

Tessier, A., & Campbell, P.G.C. 1990. Partitioning of trace metals in sediments and its relationship to their accumulation in benthic organisms. *In: Metal speciation in the environment,* ed. by J.A.C. Brockaert, S. Gucer & F. Adams, 545-569. Berlin, Springer-Verlag. (NATO ASI Series, Volume G23.)

Coastal Zone Topics, 2: 90-98

Changes in the intertidal fauna of the north bank of the Inner Solway Firth, 1975-1992

N.C.D. Craig & C.M. Ashman

The Scottish shore of the inner Solway Firth is largely backed by agricultural land and there are high quality salmon rivers draining into the Firth between Torduff Point in the east and Southerness Point in the west. This stretch of coast receives two significant industrial discharges. These two tidal discharges have a potential effect on the intertidal fauna of the area and, following baseline studies, regular monitoring of the fauna has been sponsored by the dischargers since the 1970s. The results of this programme have shown that numbers and diversity of the fauna appear largely dependent on the physical and climatic changes in the area. Throughout the period of study no evidence of effects from the industrial discharges has been found.

N.C.D. Craig & C.M. Ashman, Brixham Environmental Laboratory, ZENECA Limited, Brixham, Devon TQ5 8BA

Introduction

The major part of the Scottish coast of inner Solway is bounded by agricultural land. The area is drained by two substantial rivers, the Nith and the Annan, and a smaller stream, the Lochar Water. The Nith and the Annan are good salmon waters. The Caerlaverock reserve, an extensive area of merse important for wildfowl, lies between the Nith Estuary and the Lochar Water (Figure 1).

In the early 1970s two major industrial developments took place in the area. Firstly the ICI works at Dumfries developed a joint disposal system with the Dumfries and Galloway Regional Council to bring liquid effluent to Airds Point at

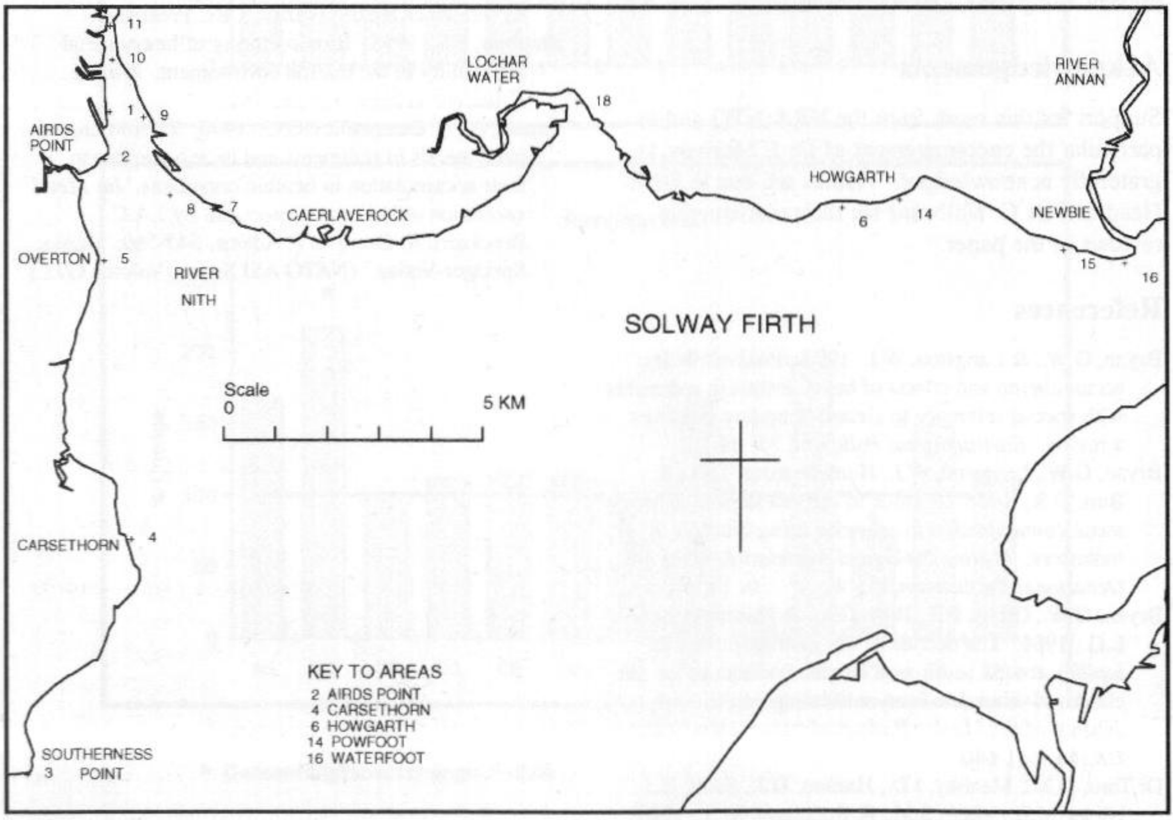


Figure 1 Monitoring areas in the Inner Solway 1975-1992.

the mouth of the Nith Estuary. The second development was the commissioning of a new works at Newbie by Glaxochem (now Glaxo Wellcome) which discharged effluent just west of the mouth of the River Annan.

Both of these discharge systems employ tidal retention tanks which hold effluent prior to discharge shortly after the commencement of the ebb tide. The unspoiled nature of the area and the concern over possible effects of these discharges necessitated extensive investigation of water movement and quality before construction began. There was also a biological baseline survey in spring and autumn to determine the nature and extent of the intertidal populations.

The consents to discharge from the two sites that were granted by the Solway River Purification Board were combined with an understanding that a biological monitoring programme would be put in place. Initially monitoring surveys were made three times per year, in spring and autumn by the Brixham Environmental Laboratory, and in summer by the Solway River Purification Board. Subsequently the spring survey was discontinued.

Methods and procedures

Figure 1 shows the area and the positions of the beaches that are studied. Since the monitoring programme began in 1975, a small number of areas have been discarded and one area (18, Stanhope) has been added.

At each sampling position a 0.0625 m^2 quadrat has been excavated to a depth of 15 cm and the sediment washed through a 0.5 mm mesh sieve. The retained material has been preserved with formalin containing rose bengal dye to assist in the subsequent laboratory sorting of the samples. Each fauna sample has been accompanied by a sample of undisturbed sediment for determination of particle size distribution. The number of sampling stations on each beach varies between one and six, with duplicate quadrats excavated at each station. The distance between stations varies between beaches, dependent on their normal intertidal length, but sample points remain constant from year to year. If physical change to any beach prevents access to a sample point it is omitted altogether.

Identification of the fauna has been as far as possible to species level. A large body of fauna data has been accumulated since monitoring commenced (Brixham Environmental Laboratory 1976 *et seq.*, 1975 *et seq*; SRPB 1976 *et seq.*).

Characteristics and changes

To look at changes in the fauna over time, a proportion of the data has been selected and examined. The five selected beaches are Airds Point (2) and Waterfoot (16), adjacent to the two effluent discharges, Powfoot (15) and Carsethorn (4) close to Waterfoot and Airds Point respectively, and finally Howgarth (6), considered to be unaffected by discharges.

Table 1 lists the ten most dominant species at these five beaches. The table is derived from the assembled data from all the surveys made between 1975 and 1992.

All five beaches are dominated by common estuarine invertebrates, particularly the bivalve mollusc *Macoma balthica* and the amphipod *Corophium volutator.* The table shows that just 18 species are found amongst the ten dominants of these five beaches. At Airds Point oligochaetes and the nematode *Adoncholaimus fuscus* are dominant, as they are at Carsethorn, where *Tubificoides benedeni* has the highest ranking. The three more eastern beaches are characterised by *Bathyporeia* sp. and *Hydrobia ulvae.*

Variation within beaches

The different sampling patterns on these five beaches may give rise to significant variability within individual beaches. As a check, data from these beaches for five separate years were subjected to classification analysis. This analysis showed that the variability between the five beaches was greater than variability within any beach. Consequently it was possible to analyse the data using the overall average of all the stations on each beach.

Airds Point and Carsethorn

Figure 2 shows the mean number of species per sample and Figure 3 the total number of individuals recorded each year at these two beaches.

At Airds Point there has been an overall rise in mean number of species, particularly between 1989-92; there was a noticeable decrease in 1976, shortly after the discharge system was commissioned. The total number of individuals rose slightly between 1975 and 1980. There was a generally rising trend in numbers between 1983 and 1989, linked with increases in *Corophium*, nematodes, *Manayunkia* and oligochaetes.

At Carsethorn mean number of species per sample was greater than at Airds Point throughout the 1980s. Total numbers of individuals have generally been higher, with particular peaks in 1977 and 1978. No animals at all were found at Carsethorn

Table 1 Ten most dominant species in each area.

Years & area	*1975-1992 Airds point (2)*	*1975-1992 Carsethorn (4)*	*1975-1992 Howgarth (14)*	*1976-1992 Powfoot (14)*	*1976-1992 Waterfoot (16)*
	Corophium volutator	*Tubificoides benedeni*	*Hydrobia ulvae*	*Hydrobia ulvae*	*Macoma balthica*
	Oligochaete unident.	*Corophium volutator*	*Macoma balthica*	*Macoma balthica*	*Hydrobia ulvae*
	Macoma balthica	*Macoma balthica*	*Pygospio elegans*	*Pygospio elegans*	*Bathyporeia sp.*
	Adoncholaimus fuscus	*Oligochaete* unident.	*Bathyporeia* sp.	*Eteone* sp.	*Capitella capitata*
	Neanthes diversicolor	*Hydrobia ulvae*	*Corophium volutator*	*Corophium volutator*	*Eteone* sp.
	Pygospio elegans	*Neanthes diversicolor*	*Adoncholaimus fuscus*	*Adoncholaimus fuscus*	*Corophium volutator*
	Eteone sp.	*Cerastoderma edule*	*Capitella capitata*	*Capitella capitata*	*Oligochaete* unident.
	Manayunkia aestuarina	*Adoncholaimus fuscus*	*Cerastoderma edule*	*Cerastoderma edule*	*Pygospio elegans*
	Nemertine unident.	*Eteone* sp.	*Neanthes diversicolor*	*Neanthes diversicolor*	*Neomysis integer*
	Enoplus brevis	*Mytilus edulis*	*Mya arenaria*	*Mya arenaria*	*Mytilus edulis*
Sediment type	High proportion of silt/clay	High proportion of silt/clay	Very fine sand and silt/clay	Very fine sand and silt/clay	Medium to very fine sand

in 1976 due to the inundation of the beach with a thick layer of plant fibre. This material disappeared during the winter of 1976-7.

Howgarth, Powfoot and Waterfoot

Figure 4 shows the mean number of species per sample and Figure 5 the total number of individuals at these three beaches.

Howgarth beach appears to be most stable, with relatively narrow fluctuations in mean number of species and of total numbers of individuals. These statistics support the visual observation that this beach is the most physically stable of all those studied.

Powfoot is also quite stable in terms of mean number of species and generally of numbers of individuals. There was a sharp increase in numbers of individuals in 1990; no samples were taken at this beach in 1991 but by 1992 individual numbers had returned to pre-1990 levels.

Waterfoot is more variable in mean species number. This beach is physically variable from year to year, with some stations being lost in some years. The low numbers reflect the instability of the sediments. The peaks registered in 1979 and 1986 are theresult of heavy settlement of the polychaete *Pygospio elegans.*

Changes in community structure

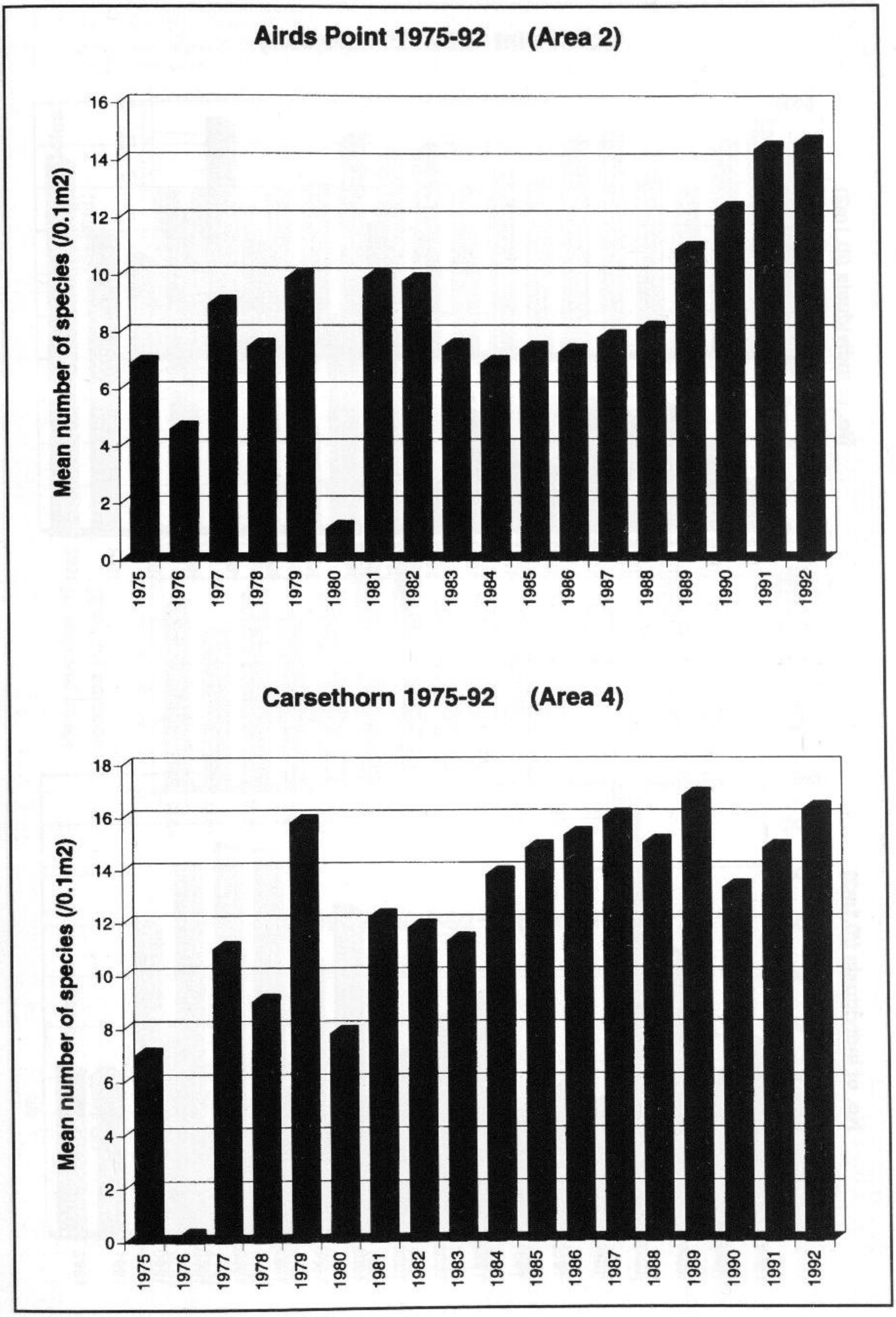
The data from group-averaged fauna statistics have been used to compare the five beaches (Airds Point, Carsethorn, Howgarth, Powfoot and Waterfoot) between two years (1983 and 1992) considered typical of the main body of data.

Table 2 shows data for 1983 and Table 3 for 1992. The tables clearly show that the 1992 fauna at Airds Point and at Carsethorn is both more diverse and numerous than in 1983. The numbers of individuals present are an order of magnitude greater in both cases.

Howgarth and Powfoot have barely changed in mean number of species between 1983 and 1992, but numbers of individuals have tripled. At Waterfoot, however, the fauna in 1992 is less diverse and less abundant than in 1983.

Discussion

Over the whole of the area studied, the basic characteristics of the fauna are apparently determined by three main factors. Two of these are the nature of the sediments and the water salinity. The most westerly beach included in the full survey, at Southerness Point (area 3 on Figure 1) is exposed, sandy and has salinity approaching full seawater. This is reflected in the presence of marine species such as *Nephtys hombergi* and *Spio martinensis.* By contrast the beaches on the east side of the Nith Estuary such as Kenneth Bank (9) and Lower Glencaple (10) (see Figure 1) are of very fine sand/silt, well sheltered and populated by a small range of estuarine species such as *Corophium volutator* and *Macoma balthica* that tolerate the non-saline water present for part of the tidal cycle.



Airds Point 1975-92 (Area 2)

Carsethorn 1975-92 (Area 4)

Figure 2 Mean number of species recorded per sample 1975-1992.

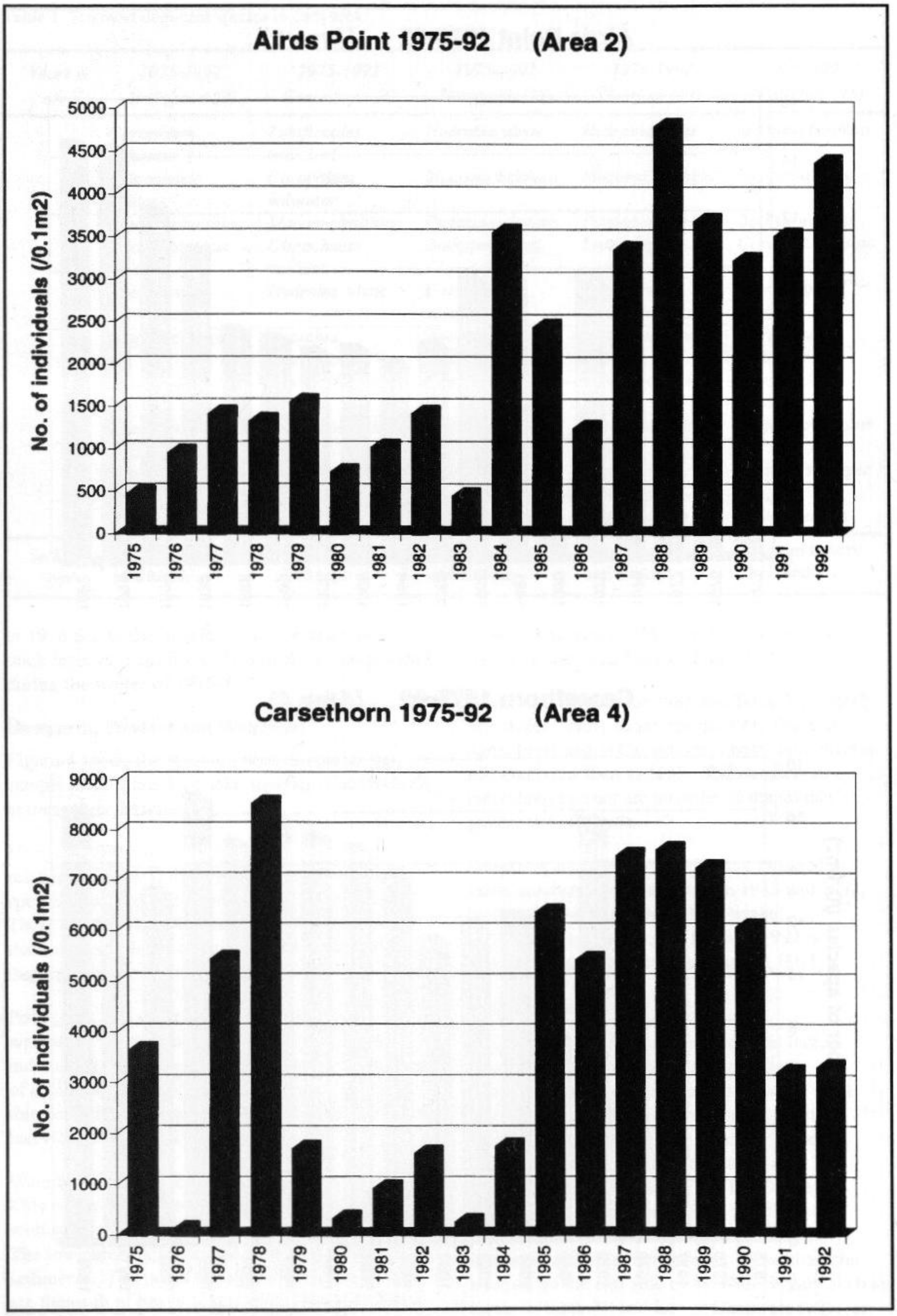


Figure 3 Total number of individuals recorded per sample at Airds Point and Carsethorne 1975-1992.

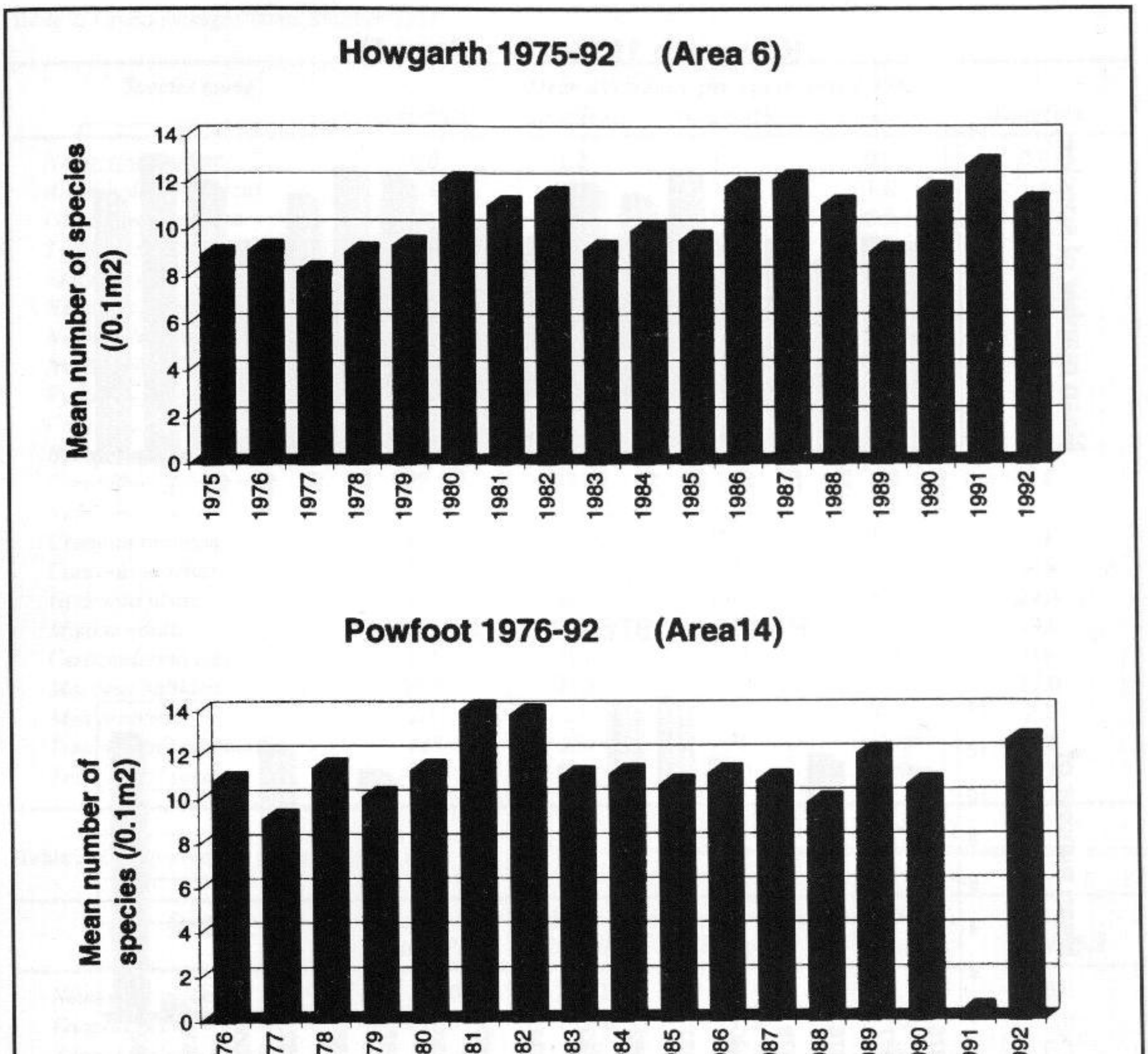
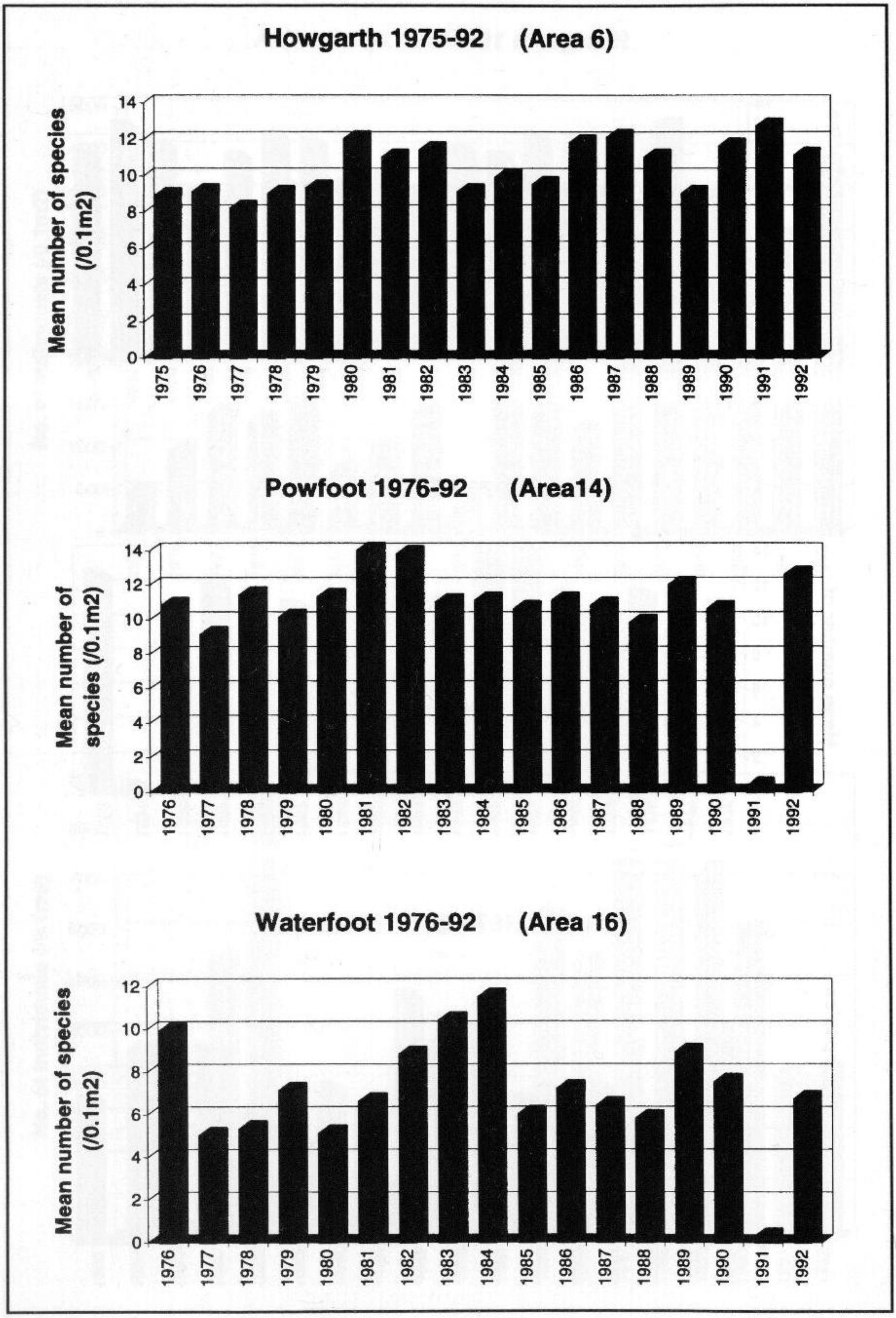


Figure 4 Mean number of species recorded per sample 1975-1992.



Howgarth 1975-92 (Area 6)

Powfoot 1976-92 (Area14)

Waterfoot 1976-92 (Area 16)

Figure 5 Total number of individuals recorded per sample at Howgarth, Powfoot and Waterfoot 1975-1992.

Table 2 Group-averaged fauna statistics 1983.

Species name	*Mean abundance per square metre 1983*				
	Airds Point	*Carsethorn*	*Howgarth*	*Powfoot*	*Waterfoot*
Nemertine unident.	14.0	1.2	1.6	0.8	0.8
Adoncholaimus fuscus	21.8	10.4	1.3	1.6	1.1
Oligochaeta unident.	1.0	4.8	0.0	0.2	7.8
Tubificoides benedeni	0.2	82.0	0.0	0.0	4.5
Eteone sp.	0.6	1.6	2.7	32.2	10.4
Neanthes diversicolor	26.0	10.0	9.3	12.4	16.8
Nephtys hombergi	0.0	0.4	9.3	5.8	0.0
Nephtys sp.	0.0	0.4	0.6	1.0	0.0
Pygospio elegans	8.2	0.4	47.4	294.8	3.0
Capitella capitata	0.0	0.8	0.3	5.8	6.2
Bathyporeia sp.	0.0	0.0	4.2	0.4	0.5
Corophium volutator	337.0	58.4	1.8	1.2	1.4
Neomysis integer	0.0	2.0	2.9	11.2	3.5
Crangon crangon	0.2	0.0	12.6	3.0	5.1
Carcinus maenas	0.6	1.6	0.3	0.6	0.5
Hydrobia ulvae	0.0	20.8	336.6	497.6	24.3
Mytilus edulis	0.0	2.4	0.0	0.0	19.0
Cerastoderma edule	0.0	30.8	17.3	13.4	0.8
Macoma balthica	31.2	24.8	107.5	265.2	17.0
Mya arenaria	2.8	2.0	0.5	30.8	2.1
Total no. of individuals	*445*	*256*	*556*	*1,180*	*126*
Total no. of species	*9.5*	*14.5*	*11.0*	*12.8*	*13.8*

Table 3 Group-averaged fauna statistics 1992.

Species	*Mean abundance per square metre 1992*				
	Airds Point	*Carsethorn*	*Howgarth*	*Powfoot*	*Waterfoot*
Nemertine unident.	13.0	9.2	1.4	1.8	0.0
Enoplus brevis	14.4	26.8	0.0	0.0	0.0
Adoncholalmns fuscus	122.4	169.2	77.8	14.0	0.8
Sphaerolaimus hirsutus	0.2	4.4	0.0	0.0	0.0
Oligochaeta unident.	336.6	60.8	0.3	10.0	0.6
Tubificoides benedeni	4.6	2,107.2	0.0	0.2	0.1
Anaitides sp.	0.0	0.4	0.0	7.8	0.0
Eteone sp.	25.4	73.2	74.1	35.4	2.5
Neanthes diversicolor	144.0	14.4	2.9	41.2	1.5
Nephtys hombergi	0.0	0.0	1.9	2.8	0.2
Nephtys sp. (juv.)	0.0	0.0	15.7	14.0	0.0
Pygospio elegans	135.4	10.4	27.7	99.8	0.3
Polydora ciliata	6.8	70.0	0.0	11.8	0.0
Capitellidae unident.	0.0	26.4	0.0	1.4	4.3
Capitella capitata	0.0	0.0	1.8	5.8	1.0
Manayunkia aestuarina	409.2	0.0	0.0	0.0	0.0
Bathyporeia sp.	0.0	0.0	212.3	23.6	13.0
Gammarus sp.	0.0	0.4	0.0	0.0	1.6
Corophium volutator	2,855.2	586.8	108.5	31.2	0.9
Neomysis integer	0.0	0.0	1.9	0.0	19.7
Decapoda unident.	2.6	0.4	0.0	0.0	0.0
Crangon crangon	1.0	0.4	0.8	0.8	0.3
Carcinus maenas	1.2	0.4	0.3	0.0	0.1
Hydrobia ulvae	198.6	90.4	1,037.8	2,568.8	10.5
Mytilus edulis	0.0	2.8	0.0	0.0	0.3
Cerastoderma edule	0.0	13.6	13.0	18.4	0.5
Macoma balthica	96.0	29.2	133.6	155.2	7.2
Mya arenaria	0.2	0.4	1.4	58.2	6.3
Total no. of individuals	*4,370*	*3,300*	*1,710*	*3,100*	*72*
Total no. of species	*14.6*	*16.3*	*11.1*	*12.6*	*6.71*

The third factor in the make-up of the fauna of the area is the physical nature of the Solway Firth. The tidal curve becomes progressively asymmetric from west to east and the tidal flow rates are very fast, particularly on spring tides. Very large amounts of sediment are resuspended by the tide and profiles of beaches and low water channels are subject to massive changes (Allen 1989). The position of the low water outflow from the Nith Estuary can vary by several kilometres. These extensive physical changes have major effects on fauna distribution.
The application of simple statistical analysis to part of the large data set available from the Solway beaches has shown up some changes. At Airds Point there has been a definite rise in abundance and diversity, particularly between 1989 and 1992. There are differences in community structure at Waterfoot over time and it is clearly different from the neighbouring beach at Powfoot and from Howgarth to the west.

Experience of the study area has shown that the physical factors such as tidal currents, exposure, possibly severe winters and dry summers have an effect on the intertidal fauna of the Solway. The use of standard statistical techniques can assist in understanding the changes that occur from year to year, but the determination of the impact of discharges to the area requires a combination of local knowledge and observation with mathematical handling of data.

Acknowledgement

The authors wish to thank ICI Dumfries Works and Glaxo Wellcome Newbie Works for permission to present this paper. We also thank Ross Brown for help in producing the figures.

References

Allen., J.R.L. 1989. Evolution of saltmarsh cliffs in muddy and sandy systems: a qualitative comparison of British west coast estuaries. *Earth Surface Processes and Landforms, 14:* 85-92.

Brixham Environmental Laboratory. 1976 *et seq. Fauna surveys for Glaxochem, Newbie 1976-92.* Unpublished reports from Brixham Environmental Laboratory.

Brixham Environmental Laboratory. 1975 *et seq. Annual fauna survey for ICI Dumfries.* Unpublished, Brixham Environmental Laboratory.

Solway River Purification Board. 1976 *et seq. Reports on fauna of the beaches of the Inner Solway.* Unpublished, Solway River Purification Board.

Benthic invertebrate studies in Loch Ryan in relation to effluent discharges

D.A. Rendall & A.A. Bell

D.A. Rendall & A.A. Bell, Solway River Purification Board, Irongay Road, Dumfries, DG2 0JE*

**Now part of Scottish Environment Protection Agency (SEPA)*

Introduction

The Solway River Purification Board (SRPB) is responsible for pollution control and the consenting and monitoring of all discharges to the aquatic environment in south-west Scotland. This area extends from the border between Scotland and England on the Inner Solway Firth to the West Galloway Coast north of Loch Ryan.

Loch Ryan lies on the West Galloway coast and is the most southerly of the Scottish sea lochs (see Figure 1). It opens to the north, is about 13 km long and 2-5 m deep at the head end. No major rivers discharge to the loch, so it is fully marine. There are two major discharges, the Galloway Creamery and Stranraer Sewage Works, both of which discharge at the southerly (head) end of the loch. The Galloway Creamery discharges approximately 1,000 cubic metres per day of partially screened milk waste and has a population equivalent of more than 60,000. The Stranraer Sewage Works effluent receives primary treatment only and has a population equivalent of around 12,000. Both discharges are now monitored (on an annual basis) by means of benthic invertebrate studies.

Biological monitoring plays a vital role in the assessment of the environmental effects of aquatic discharges because it measures effects directly in the receiving environment and thus demonstrates if consent conditions are adequate. If it is found that the receiving environment is suffering adverse effects then consent conditions will be reviewed and adjusted accordingly.

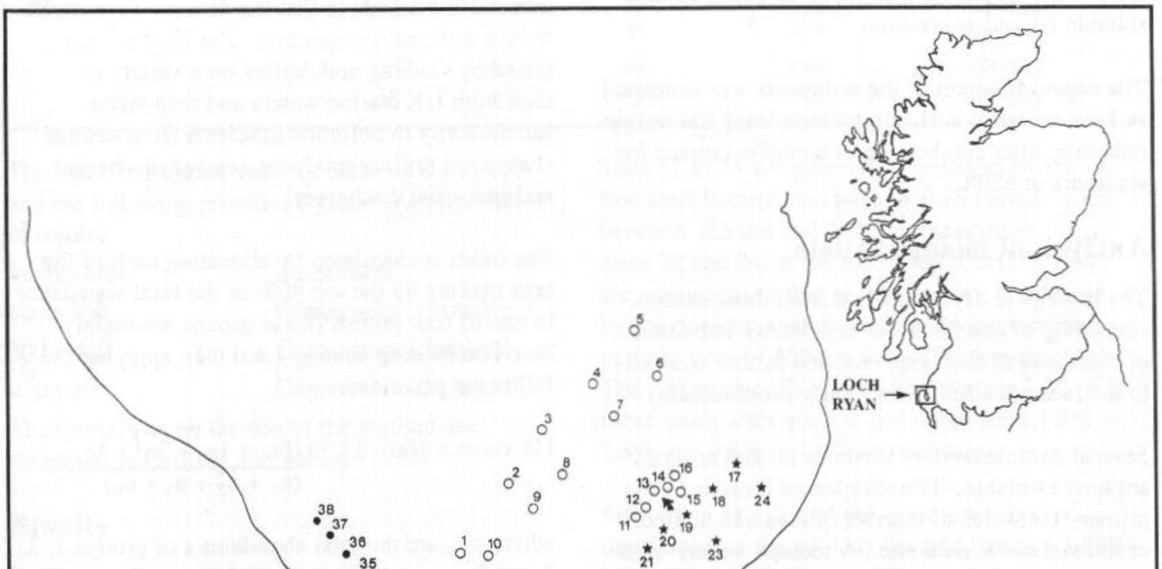


Figure 1 Location of sampling sites in Loch Ryan.

Methods

The sites sampled are shown on Figure 1. These comprise 16 subtidal and eight intertidal sites for the creamery discharge. Subtidal samples were collected using a mini-Van Veen grab of dimensions 12 cm by 15 cm. Ten replicate grabs were taken at each site, gently sieved through a 0.5 mm mesh and bulked. Samples were fixed and preserved using 8% buffered formalin and stained using rose bengal. Intertidal samples were taken with a 0.018 m^2 corer, to a depth of 15 cm. Five replicate samples were collected at each site, gently sieved through a 0.5 mm mesh, fixed and preserved using 8% buffered formalin and stained using rose bengal.

Samples were sorted after passage through a sieve stack, of mesh sizes 5.6 mm down to 0.5 mm. The fraction remaining on the 0.5 mm sieve was sorted, at x 7 magnification, using a stereoscopic microscope. All other fractions were sorted with the aid of an illuminated magnifier with x 1.75 magnification. All specimens were identified to species (where possible).

A separate sample was collected at each site for particle size analysis. This was carried out using the method described by Buchanan (1984). This involves splitting the wet sediment into a sand fraction and a silt-clay fraction (i.e. less than 63 μm). The sand fraction was further divided using a six sieve stack of sizes 2.0 mm, 1.0 mm, 0.5 mm, 0.125 mm and 0.063 mm. The results were analysed by the method of moments using a suitable computer program.

The organic content of the sediments was estimated as Loss on Ignition (LOI), by measuring the weight reduction after combustion in a muffle furnace for six hours at 550°C.

Analysis of biological data

The biological data generated from these studies, consisting of counts of the numbers of individuals of each taxa at each site, required further analysis to aid interpretation and simplify presentation.

Several complementary methods of data analysis are now available. The simplest of these is to use primary measures of number of taxa and number of individuals at each site. A second, widely-used method is the calculation of diversity indices. The use and limitations of these are discussed by Rees *et al.* (1990). The present study used the Shannon-Wiener Index (using $\log_2$) which was recommended by Pearson and Rosenberg (1978). This was complemented by the use of Sanders' rarefaction (Sanders 1968) as a measure of species richness and Pielou's (1975) measure of evenness. These indices were calculated using a modified version of the computer programme described in Moore (1983).

In recent years, due to the widespread availability of computers, the analysis of biological data using multivariate techniques has become practical. The development and application of the various techniques is discussed in Gauch (1982) and recommendations regarding which techniques to use are given in Rees *et al.* (1990). There are two main types of multivariate technique, ordination and classification. In this study the ordination technique used was Detrended Correspondence Analysis calculated using the Cornell Ecology programme DECORANA. Two classification techniques were used: (a) Two-way Indicator Species Analysis calculated using the Cornell Ecology Programme TWINSPAN and (b) Czekanowski's similarity coefficient with group average sorting. Czekanowski's coefficient is algebraically equivalent to the Bray-Curtis coefficient (Field *et al.* 1982). Before analysis, taxa counts were transformed using the $\log_{10}(N+1)$ transformation.

To these techniques a marine biotic index was added, namely the Infaunal Trophic Index (ITI) recently developed by Codling and Ashley (1992) from earlier work by Word (1978, 1980, 1990). Biotic indices differ from the preceding, essentially numerical, methods as knowledge of the ecology of the taxa involved is required for their formulation. Thus they form a useful complement to the numerical methods in that the data are considered from a different perspective. The ITI has been tested by Codling and Ashley on a variety of data from UK marine waters and responded satisfactorily to pollution gradients from sewage sludge, oil drilling products, sewage discharges and industrial discharges.

The index is calculated by allocating each of the taxa making up the top 80% of the total abundance to one of four groups (these groups are mainly based on feeding strategy) and then applying the following equation:

$$\text{ITI value} = 100 - 33.33\,\frac{(0n_1 + 1n_2 + 2n_3 + 3n_4)}{(n_1 + n_2 + n_3 + n_4)}$$

where n_{1-4} are the total abundances of groups 1, 2, 3 and 4.

The method of assignment of taxa to particular groups is outlined by Codling and Ashley (1992).

Table 1 Loch Ryan particle size summary.

	Site	*% LOI*	*% Silt-clay*	*Median particle size (μm)*	*Wentworth grade*
Creamery discharge					
Muddy subtidal	1	4.8	79	<63	Silt-clay
	2	6.6	84	<63	Silt-clay
	3	6.4	82	<63	Silt-clay
	4	9.9	81	<63	Silt-clay
	5	7.2	89	<63	Silt-clay
	6	4.7	55	<63	Silt-clay
	7	5.8	61	<63	Silt-clay
	8	6.9	73	<63	Silt-clay
	9	6.9	76	<63	Silt-clay
	10	5.6	77	<63	Silt-clay
Sandy subtidal	11	1.4	2.4	185	Fine sand
	12	1.2	2.2	186	Fine sand
	13	1.1	2.8	192	Fine sand
	14	1.2	1.9	198	Fine sand
	15	1.0	2.4	199	Fine sand
	16	1.2	2.5	196	Fine sand
Intertidal	17	0.9	1.3	229	Fine sand
	18	0.9	1.4	215	Fine sand
	19	1.0	2.1	200	Fine sand
	20	0.8	1.4	202	Fine sand
	21	1.0	2.1	186	Fine sand
	22	0.8	1.5	256	Medium sand
	23	0.9	2.2	243	Fine sand
	24	0.8	1.5	275	Medium sand
Sewage works discharge					
	31	5.1	79	<63	Silt-clay
	32	4.6	71	<63	Silt-clay
	33	5.3	75	<63	Silt-clay
	34	4.4	73	<63	Silt-clay
	35	4.2	67	<63	Silt-clay
	36	4.1	68	<63	Silt-clay
	38	4.4	75	<63	Silt-clay

The index has a final value of between 0 and 100 and the following provides a guide to interpretation of results:

Index value	*Assessment*
60 to 100	Community 'normal'
30 to <60	Community 'changed'
0 to <30	Community 'degraded'

The limitations on the use of the method are discussed in Codling and Ashley (1992).

Results

Sediment characteristics

Table 1 shows the percentage Loss on Ignition (LOI), the percentage silt-clay, the median particle size and the Wentworth grade for all sites. Sites 1 to 10 are dominated by the silt-clay fraction (range 55%-89%) and consequently all have median particle sizes less than 63 μm and relatively high LOIs of between 4.7 and 9.9% ($\chi = 6.5\%$).

Sites 11 to 24 are generally dominated by the fine sand fraction and have median particle sizes between 185 μm and 243 μm respectively. Sites 22 and 24, at the top of the intertidal zone, are exceptions to this in that they are dominated by the medium sand fraction and have median particle sizes of 265 μm and 275 μm respectively. The percentage silt-clay and percentage LOI of all these sandy sites are low and range from 1.3% to 2.8% and 0.8% to 1.4% respectively.

Sites 31 to 38 (around the sewage works) are dominated by the silt-clay fraction (range 67-79%) and consequently have median particle sizes below 63 μm and fairly high LOIs ranging from 4.1% to 5.3%.

Principal species

The principal species together with their mean occurrence, range and ITI group, for each type of site, are shown in Table 2.

Table 2 Principal species at sites in Loch Ryan (per 0.18 m^2).

Sites	*Taxa*	*Mean*	*Range*	*ITI Group*
1 to 10	*Melinna palmata*	283	105-633	3
	Ampelisca brevicornis	188	38-276	1
	Abra nitida	164	53-294	2
	Ampharete sp.	123	11-222	2
	Ampelisca tenuicornis	122	25-209	1
	Photis longicaudata	79	10-182	2
	Chaetozone gibber	68	13-102	2
	Corophium (crassicorne?)	63	1-255	1
	Nepthys hombergi	45	25-62	3
	Nucula turgida	43	1-68	3
	Eudorella truncatula	40	15-114	2
11 to 16	*Hydrobia ulvae*	404	76-948	2*
	Spio martinensis	170	65-392	1
	Capitella capitata	144	9-428	4
	Mya arenaria	37	8-86	1
	Polydora ligni	15	0-61	2
	Pygospio elegans	10	0-25	2
17 to 24	*Hydrobia ulvae*	4,983**	3,240-7,316	n/a
	Cardidae	189**	61-417	n/a
	Pygospio elegans	84**	14-199	n/a
	Spio martinensis	71**	28-136	n/a
	Capitella capitata	20**	1-76	n/a
	Angulus tenuis	16**	4-31	n/a
	Cerastoderma edule	13**	1-52	n/a
31 to 38	*Melinna palmata*	322	6-865	3
	Chaetozone gibber	206	2-660	2
	Nepthys sp.	204	97-303	3
	Ampharetinae	46	5-96	2
	Capitella capitata	42	2-161	4
	Edwardsia sp.	38	0-117	3
	Nepthys hombergi	33	14-50	3
	Tubificoides swirencoides	22	2-46	4
	Ampharete sp.	18	0-52	2
	Ampelisca brevicornis	17	2-51	1
	Philine sp.	17	2-35	3*

* = coded by the authors; ** = per 0.09 m^2; n/a = not applicable - intertidal sites

Sites 1 to 10 (the muddy sites near the creamery outfall) are dominated by a mixed principal species fauna consisting of four polychaete species, four amphipods, one cumacean and one bivalve. Sites 11 to 24 (the sandy sites near the creamery outfall) are generally dominated by the gastropod mollusc *Hydrobia ulvae*, although polychaete and bivalve mollusc species are also important.

Sites 31 to 38 (near the sewage outfall), although similar physically to sites 1 to 10 and having many taxa in common, have a different balance of principal species comprising seven polychaete species, one oligochaete, one amphipod and one mollusc species.

Univariate parameters

The univariate parameter data for all sites are shown in Table 3. Sites 1 to 10 are very rich with a mean number of taxa of 58 (range 45-72) and a mean number of individuals of around 17,000 per m^2. The Shannon-Wiener diversity index varied from 3.44 to 4.55, suggesting a healthy invertebrate community.

Sites 11 to 16 (sandy subtidal sites) are much less rich than the 'muddy' sites and have a mean taxa number of 14 and a Shannon-Wiener diversity range from 0.14 to 2.20. As well as being naturally less rich than muddy sites the value of all the diversity parameters are depressed due to the dominance of *Hydrobia ulvae.* This is particularly

Table 3 Univariate parameters and infaunal trophic index for sites in Loch Ryan.

Site	*No. of taxa ($0.18\ m^2$)*	*No. of individs. ($0.18\ m^2$)*	*H'*	*Spp richness (per 100 individs.)*	*Eveness*	*ITI Value*	*ITI Assessment*
1	45	2,639	3.44	23.6	0.63	66.9	Normal
2	58	1,855	4.28	28.5	0.73	69.3	Normal
3	49	1,113	4.20	27.2	0.75	65.2	Normal
4	66	1,446	4.55	32.5	0.75	66.5	Normal
5	55	1,267	4.55	30.0	0.79	66.9	Normal
6	72	1,373	4.52	34.4	0.73	76.6	Normal
7	62	1,482	4.35	30.8	0.73	71.4	Normal
8	56	2,286	4.22	28.4	0.73	69.1	Normal
9	60	2,074	4.18	29.2	0.71	68.1	Normal
10	58	2,243	4.14	29.3	0.71	65.0	Normal
11	13	882	1.55	7.4	0.42	75.4	Normal
12	22	863	2.17	7.1	0.49	77.8	Normal
13	15	785	1.94	7.2	0.50	39.1	Changed
14	14	569	2.20	8.6	0.58	49.0	Changed
15	10	9,456	0.14	2.4	0.04	67.0	Normal
16	13	1,196	1.15	6.3	0.31	62.0	Normal
17*	21	5,904	0.95	6.2	0.22	n/a	n/a
18*	18	8,127	0.54	5.0	0.13	n/a	n/a
19*	20	6,414	0.39	5.2	0.09	n/a	n/a
20*	14	8,428	0.32	4.5	0.09	n/a	n/a
21*	13	4,322	0.62	5.2	0.17	n/a	n/a
22*	17	6,938	0.68	5.4	0.17	n/a	n/a
23*	29	4,314	1.10	9.1	0.23	n/a	n/a
24*	18	4,010	0.75	6.7	0.18	n/a	n/a
31	19	542	2.46	13.1	0.58	25.7	Degraded
32	24	473	2.42	13.4	0.53	21.3	Degraded
33	35	1,078	2.78	15.9	0.54	50.2	Changed
34	39	955	3.11	19.0	0.59	42.2	Changed
35	40	1,804	2.85	16.9	0.54	49.3	Changed
36	39	1,717	2.85	19.2	0.54	44.7	Changed
38	34	1,520	3.28	19.0	0.65	50.9	Changed

* = per $0.09\ m^2$; n/a = not applicable - intertidal sites

the case at site 15 where *H. ulvae* comprised 98% of the individuals.

Sites 17 to 24 (sandy intertidal sites) are richer than the sandy subtidal sites and have a mean taxa of 19. The Shannon-Wiener diversity index ranges from 0.32 to 1.10 but once again the values of all the diversity indices are depressed due to the massive dominance of *H. ulvae* which generally comprised well over 90% of the individuals at all these sites.

Sites 31 and 32 (near the sewage discharge) show a distinct depression in the number of taxa, number of individuals, Shannon-Wiener diversity index and species richness but no lowering of evenness. Sites 33 to 38 have more normal values for these parameters although (with the exception of the number of individuals) they are distinctly lower than the values at sites 1 to 10. These results indicate a marked effect of the sewage effluent. However, this effect lessens considerably away from the discharge point.

Table 3 also shows the Infaunal Trophic Index results for each site. With regard to the creamery, the faunas at sites 1 to 10, 11, 12, 15 and 16 are categorised as 'normal'; while those at sites 13 (nearest the creamery discharge) and 14 are categorised as 'changed'. These results suggest slight effects immediately adjacent to the discharge.

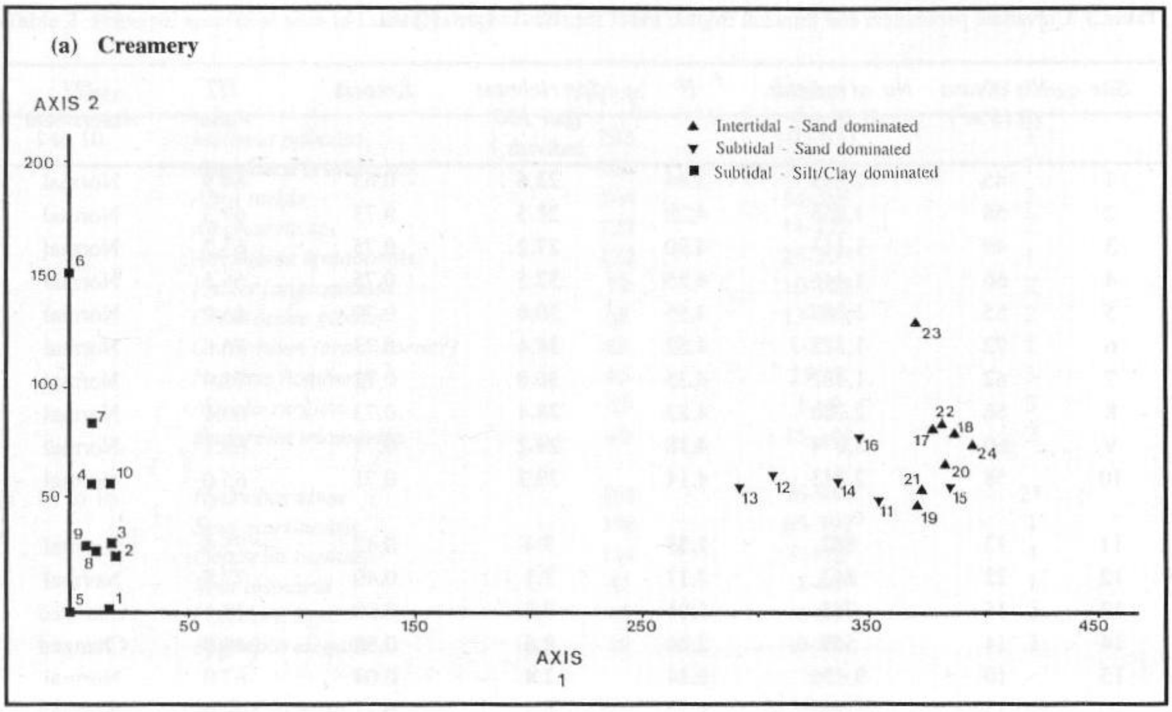


Figure 2a Ordination of sites: Creamery.

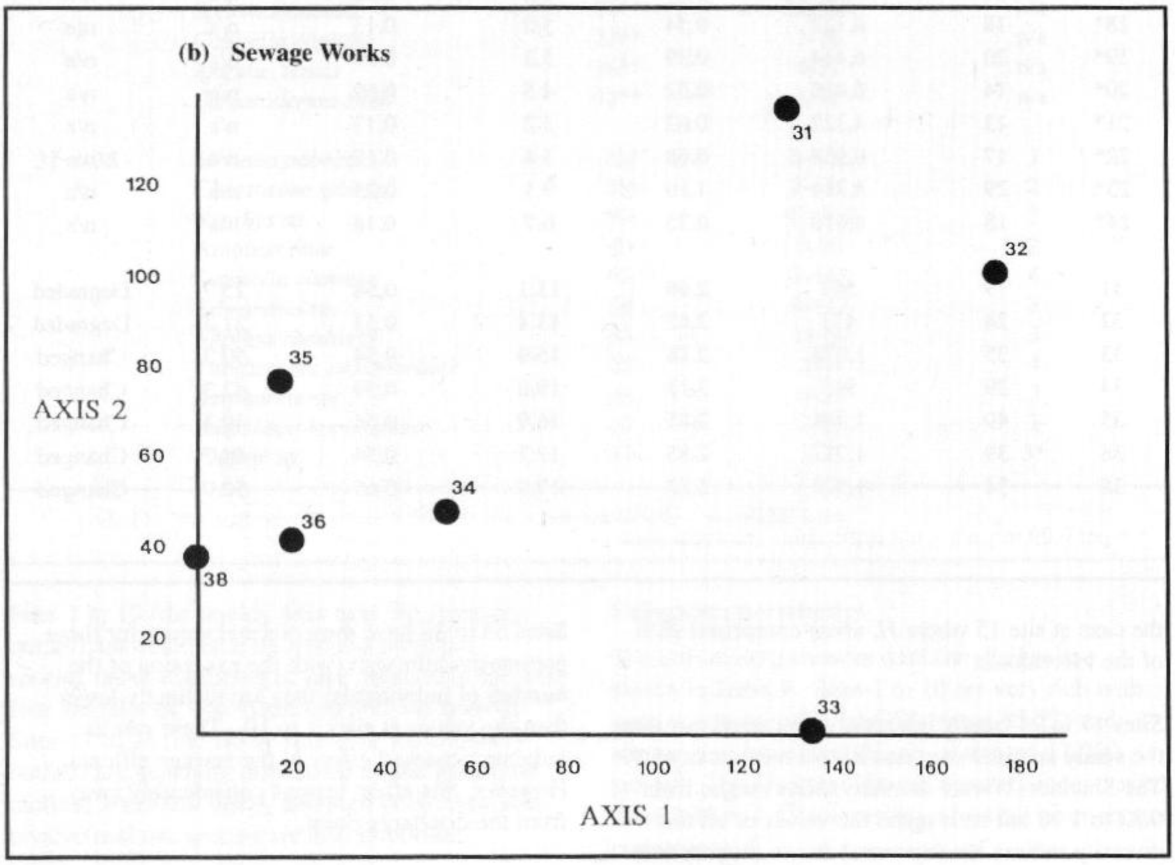


Figure 2b Ordination of sites: Sewage Works.

For the sewage works discharge the fauna at sites 31 and 32 are categorised as 'degraded', while sites 33 to 38 are categorised as 'changed'. These results suggest quite severe effects at the sites adjacent to the sewage discharge and a continuing slight influence at some distance from it.

Multivariate methods

The results of the ordination of sites around the creamery using DECORANA are shown in Figure 2. The more similar the faunas of sites are, the closer their DECORANA scores will be.

In Figure 2a the sites are clearly divided into two groups along axis 1 (eigenvalue 0.83). On the left are the muddy sites (1 to 10) and on the right are the sandy sites (11 to 24). This is a very strong trend in the data which highlights the very different invertebrate communities present at the sandy and muddy sites. Although all the sandy sites are placed fairly close together, the sandy subtidal sites are, in the main, separated from the intertidal sites. Site 13 (the site nearest the discharge) and site 12 are slightly separated from the other sandy sites, suggesting a small modification of the fauna at these sites, possibly due to the discharge.
Figure 3 shows the results obtained from both classification methods. The muddy-sandy division of sites shown by DECORANA is also shown by both classification methods. The weak division between the intertidal and subtidal sandy sites is also suggested although the split of sites by the two methods is not uniform. This implies a fairly weak trend in the data. Site 13 is not highlighted by either classification method.

Figure 2b shows the ordination of sites around the sewage discharge. Sites 31 and 32 are quite clearly separated from the other sites, indicating a strong influence from the sewage discharge. Site 33 is also set apart from all of the other sites, possibly because of its proximity to the harbour or perhaps due to some freshwater influence.

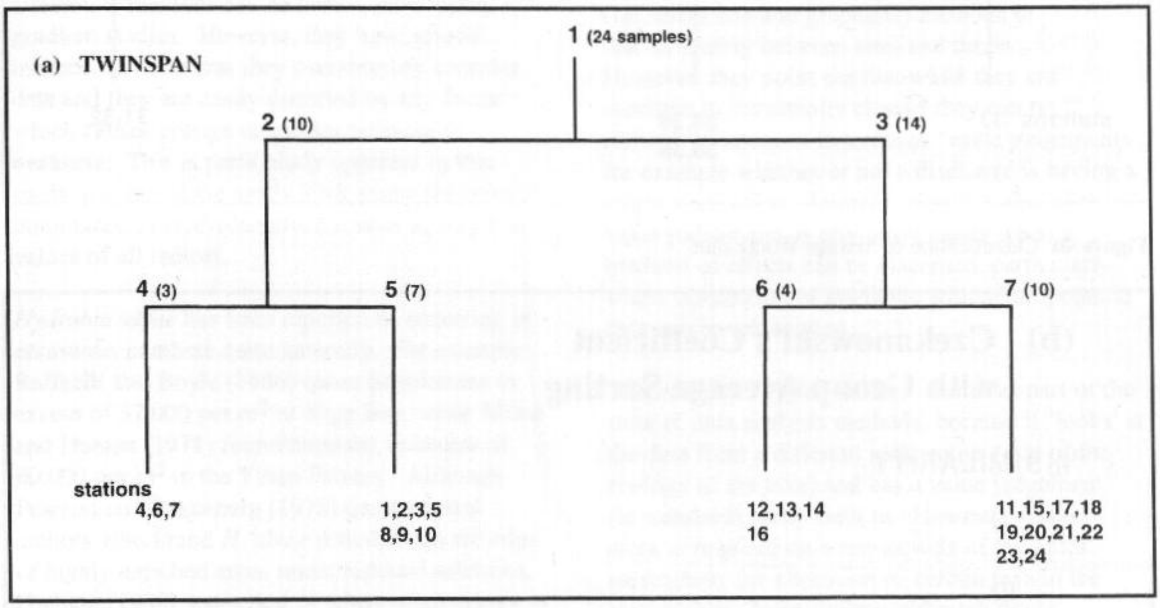


Figure 3a Classification of Creamery sites.

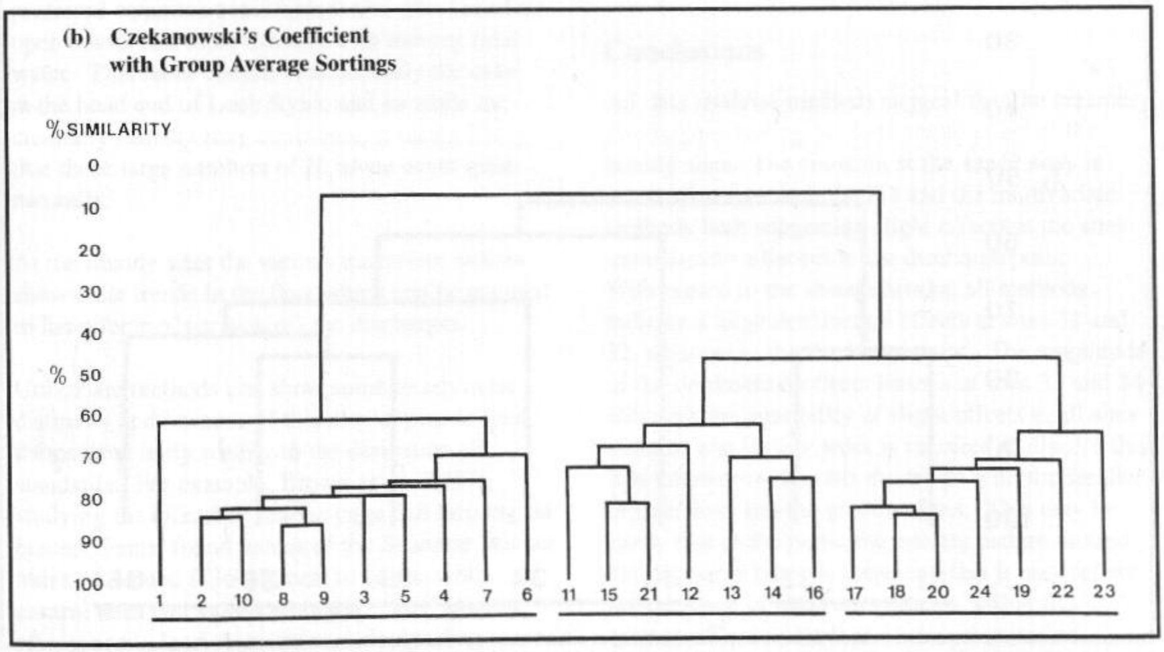


Figure 3b Czekanowski's Coefficient with Group Average Sorting.

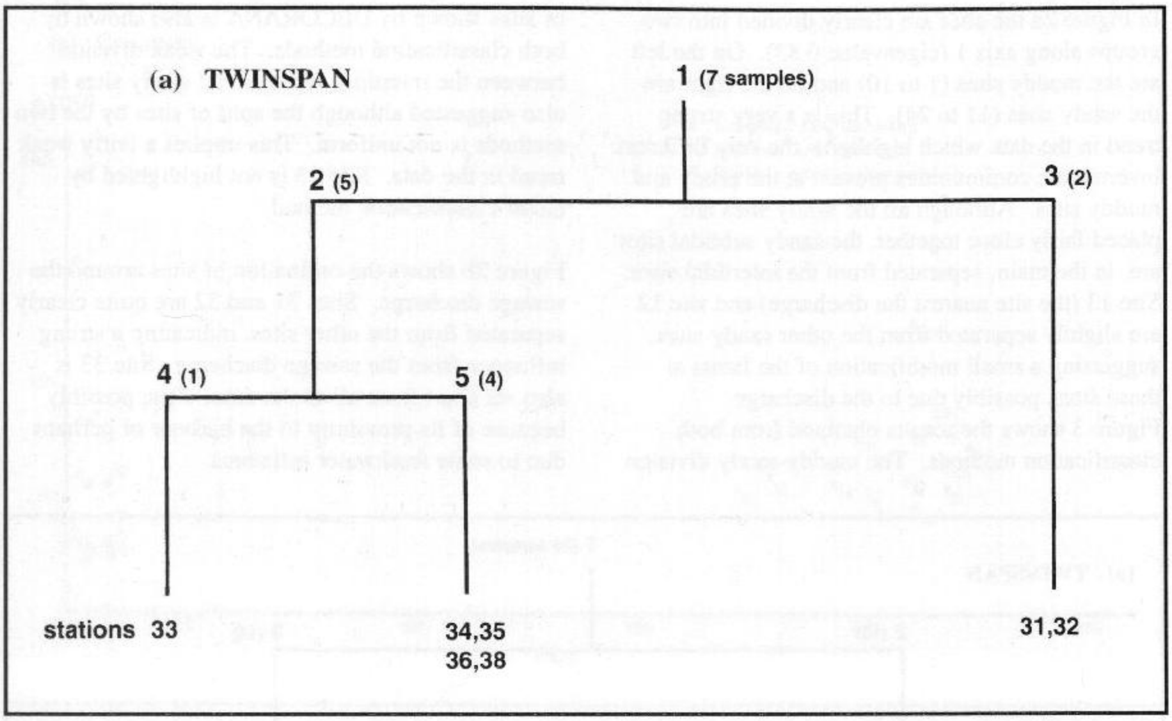


Figure 4a Classification of Sewage Works sites.

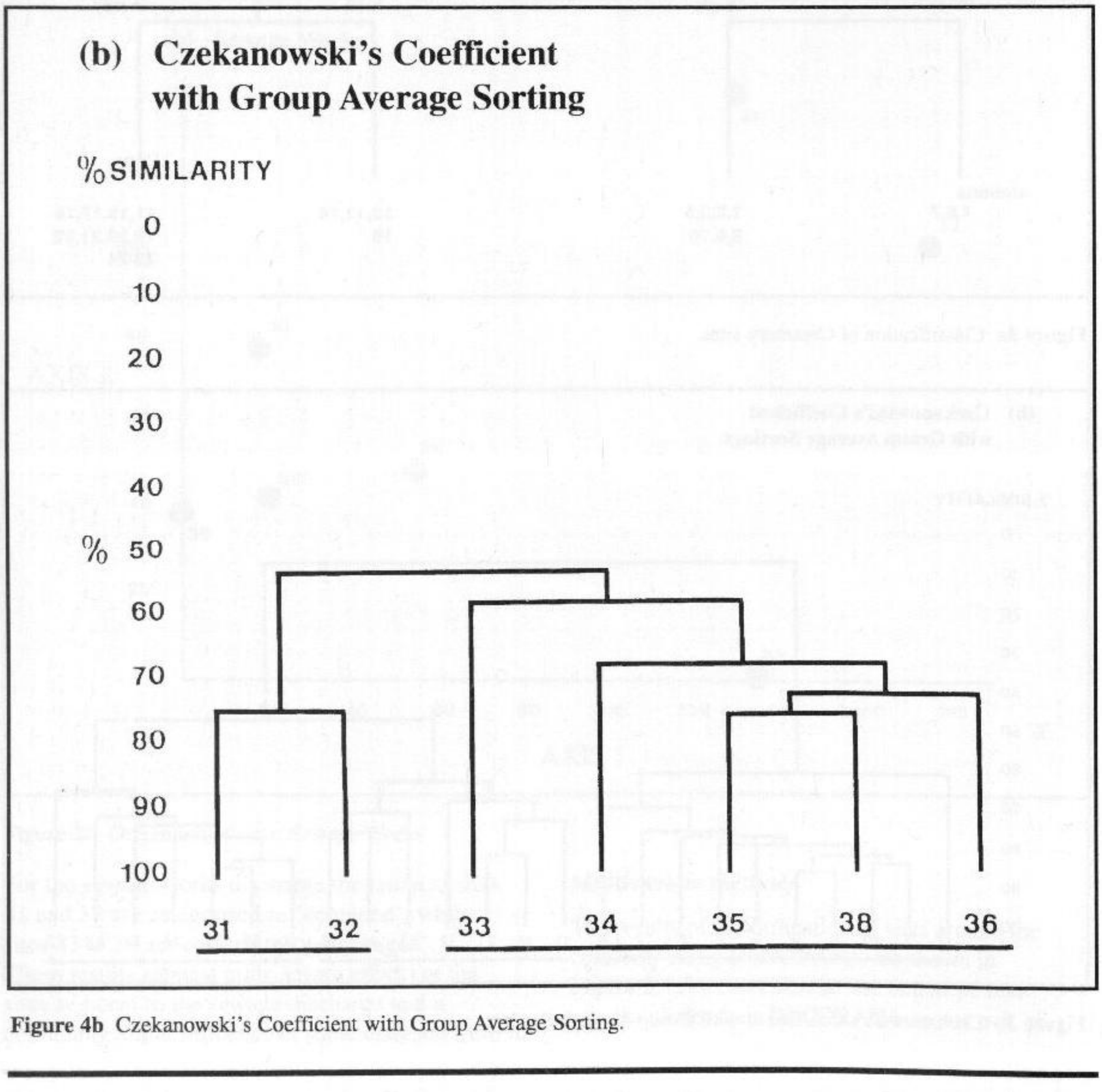


Figure 4b Czekanowski's Coefficient with Group Average Sorting.

Figure 4 shows the classification results from these sites. Once again both TWINSPAN and the Czekanowski's coefficient give a similar split in the data and reveal essentially the same pattern as found using the ordination.

Discussion

The approach to the analysis of data from marine benthic communities outlined by Rees *et al.* (1990) has been followed, as far as possible, in his study. These recommendations include univariate and multivariate numerical methods and to these has been added a biotic index, the Infaunal Trophic Index.

Univariate methods can be useful, particularly in gradient studies. However, they have several inherent flaws in that they oversimplify complex data and they are easily distorted by any factor which causes change in species richness or evenness. This is particularly apparent in this study at some of the sandy sites where the massive dominance of *Hydrobia ulvae* results in very low values of all indices.

Hydrobia ulvae has been reported as occurring in enormous numbers quite naturally. For example Raffaelli and Boyle (1986) quote populations in excess of 37,000 per m^2 in Nigg Bay, while Milne and Dunnet (1971) found numbers in excess of 80,000 per m^2 in the Ythan Estuary. Although Pearson and Rosenberg (1978) quote several authors who found *H. ulvae* abundant on the edge of highly enriched areas under reduced salinities, Graham (1988) states that *H. ulvae* often occurs in enormous numbers on wet banks of sand or mud. Graham goes on to say that although *H. ulvae* preferred estuarine conditions it was also found on open coasts and liked habitats with moving tidal water. This latter condition is certainly the case at the head end of Loch Ryan, and so while the creamery effluent may contribute, it seems likely that these large numbers of *H. ulvae* occur quite naturally.

At the muddy sites the various univariate indices show clear trends in the data which can be equated to the effects of (or lack of) the discharges.

Univariate methods can show some trends quite distinctly and because of this they appear to lend themselves fairly readily to the derivation of standards. For example, Brown *et al.* (1987), studying the effects of marine cage fish farming on benthic fauna, found values of the Shannon-Wiener index of around 0.36 adjacent to cages, while control sites had values around 4. Such marked effects easily lend themselves to designating some sites as unacceptable. Elliott and O'Reilly (1991) have taken this a stage further and looked at the variability of univariate parameters using data from the Firth of Forth. They found Shannon-Wiener diversity and number of species to be the most consistent, and they suggested a tentative standard of a change of plus or minus 40% as being outwith 'normal' variability. However they stressed that other data analysis methods (e.g. multivariate) must also be used.

Multivariate techniques incorporate the identity of each species within the analysis, maximising the amount of original information present, and are able to detect quite subtle changes. Warwick and Clarke (1991) found that multivariate methods were much more sensitive than 'species independent' (i.e. univariate and graphical) methods in discriminating between sites and times. However, they point out that while they are sensitive to community change they can be difficult to interpret in terms of 'value judgements', for example whether or not a discharge is having a detrimental effect. Interpretation in terms of these value judgements is obviously easier when a gradient of effects can be discerned, particularly where correlation of gradients with anthropogenic data can be established.

The Infaunal Trophic Index is useful as part of the suite of data analysis methods, because it 'looks' at the data from a different perspective (that of the ecology of the taxa) and has a value judgement (or standard) partly built in. However, further work is required on some aspects of the index, particularly the allocation of certain taxa to the four groups. Nevertheless, although future improvements can be anticipated the index is useful as it stands.

Conclusions

All data analysis methods suggest that the creamery discharge is having no detrimental effect at the muddy sites. The situation at the sandy sites is not so clear-cut with the ITI and the multivariate methods both suggesting slight effects at the sites immediately adjacent to the discharge point. With regard to the sewage works, all methods indicate a large detrimental effects at sites 31 and 32, adjacent to the discharge point. The magnitude of the detrimental effects lessens at sites 33 and 34 although the possibility of slight effects at all sites remains and further work is required to discern this. It is noteworthy that the discharge with the smaller organic load has the greater effect. This may be partly due to the particular mixing pattern around the discharge but it is suspected that it may reflect the presence of toxic components within the sewage effluent. Further work is required to resolve this issue.

References

Brown, J.J., Gowen, R.J., & McLusky, D.S. 1987. The effects of salmon farming on the benthos of a Scottish sea loch. *Journal of Experimental Marine Biology, 109:* 39-51.

Buchanan, J.B. 1984. Sediment analysis. *In: Methods of study of marine benthos*, ed. by N.A. Holme & A.D. McIntyre. Oxford, Blackwell Scientific Publications. (IBP Handbook No. 16. 2nd ed.)

Codling, I.D., & Ashley, S.J. 1992. *Development of a biotic index for the assessment of pollution status of marine benthic communities.* Scotland and Northern Ireland Forum For Environmental Research report by WRc. (Report No. NR 3102/1.)

Elliott, M., & O'Reilly, M.G. 1991. The variability and prediction of marine benthic community parameters. *In: Estuaries and coasts: spatial and temporal intercomparisons*, ed. by M. Elliott & J.P. Ducrotoy. Denmark, Olsen and Olsen. (ECSA 19 Symposium.)

Field, J.G., Clarke, K.R., & Warwick, R.M. 1982. A practical strategy for analysing multispecies distribution patterns. *Marine Ecology Progress Series, 8:* 37-52.

Gauch, H.G., Jr. 1982. *Multivariate analysis in community ecology.* Cambridge, Cambridge University Press.

Graham, A. 1988. *Molluscs: prosobranch and pyramidellid gastropods.* 2nd ed. Leiden, Linnean Society of London/Estuarine and Brackish Water Sciences Association.

Milne, H., & Dunnett, G.M. 1971. Standing crop, productivity and trophic relations of the fauna of the Ythan Estuary. *In: The estuarine environment*, ed. by R.S.K. Barnes & J. Green. London, Applied Science Publishers.

Moore, C.G. 1983. A BASIC program for the investigation of species diversity. *Water Pollution Control, 82:* 102-106.

Pearson, T.H., & Rosenberg, R. 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanography and Marine Biology Annual Review, 16:* 229-311.

Pielou, E.C. 1975. *Ecological diversity.* New York, Wiley.

Raffaelli, D., & Boyle, P.R. 1986. The intertidal macrofauna of Nigg Bay. *Proceedings of the Royal Society of Edinburgh, 91B:* 113-141.

Rees, H.L., Moore, D.C., Pearson, T.H., Elliott, M., Service, M., Pomfret, J., & Johnson, D. 1990. *Procedures for the monitoring of marine benthic communities at UK sewage sludge disposal sites.* Aberdeen, Dept. of Agriculture and Fisheries for Scotland. (Scottish Fisheries Information Pamphlet No. 18.)

Sanders, H.L. 1968. Marine benthic diversity: a comparative study. *American Naturalist, 102:* 243-283.

Warwick, R.M., & Clarke, K.R. 1991. A comparison of some methods for analysing changes in benthic community structure. *Journal of the Marine Biological Association of the United Kingdom, 71:* 225-244.

Word, J.Q. 1978. The Infaunal Trophic Index. *In: Coastal Water Research Project Annual Report*, 19-39. El Segundo, Southern California Coastal Water Research Project.

Word, J.Q. 1980. Classification of benthic invertebrates into infaunal trophic feeding groups. *In: Coastal Water Research Project Biennial Report 1979-80*, 103-121. El Segundo, South California Coastal Water Research Project.

Word, J.Q. 1990. *The Infaunal Trophic Index, a functional approach to benthic community analyses.* PhD Thesis, University of Washington.

The importance and distribution of waterfowl on the inner Solway Firth

J.L. Quinn, L. Still, M.F. Carrier & J.S. Kirby

The significance of waterfowl numbers on the Solway Firth was examined using primarily Wetland Bird Survey data collected from 1988-89 to 1992-93. The estuary was internationally important for 12 species during this period, including the entire winter population of the Svalbard barnacle goose, 8.8% of the international population of pink-footed goose and 4% of the international populations of oystercatcher and bar-tailed godwit. Estimates of population turnover from ringing studies suggest that 6-8% of the East-Atlantic Flyway population passed through in 1993.

The Solway supported nationally important numbers of nine other waterfowl species including 63% of the British wintering population of scaup. In winter the estuary was amongst the top five sites in Britain for oystercatcher, golden plover, bar-tailed godwit, curlew, cormorant and, in spring or summer, sanderling, ringed plover and shelduck. The Solway is one of the few British estuaries that holds large numbers of ringed plovers and sanderlings on passage to their Arctic breeding grounds in late spring.

Important feeding areas for waterfowl at low tide were determined. Outer parts of the estuary were the most important for diving species like scaup and grebes. Intertidally, the saltmarshes were the most important areas for terrestrial wildfowl (especially geese), although intertidal areas also provided important feeding areas for pintail and shelduck. The largest numbers of waders occurred on the extensive areas of sand in the outer parts of the estuary but highest densities occurred on the inner estuary, especially on the north shore.

The Solway's saltmarshes held 860 pairs of breeding waders in 1993 and a further 40-44 pairs of ringed plover bred on its stony beaches. The number of oystercatcher pairs on the Solway accounted for 0.7-0.9% of the British breeding population; here they occur in very high densities in comparison with other British saltmarshes. The Solway was also important for breeding shelduck and in 1992 was amongst the top five sites in Britain for this species. Other breeding species of significance on the Solway included the cormorant, with its two colonies together accounting for around 3.7% of the British breeding population.

Although the importance of the Solway for waterfowl is well recognised, its true status for some species, particularly inshore birds which are difficult to count and species during migration, has yet to be determined. The most significant areas for waterfowl during the day have been identified but it is not known to what extent these change at night. Much remains to be discovered about how waterfowl use one of Britain's most important wetlands for birds.

Correspondence: J.L Quinn, The Wildfowl & Wetlands Trust, Slimbridge, Gloucester, GL2 7BT

Introduction

The Solway Firth is not only Britain's third largest estuary (27,550 ha), surpassed in area by Morecambe Bay (33,749 ha) and the Wash (29,770 ha) (Davidson *et al.* 1991), it is also one of the most important for waterfowl (divers, grebes, cormorants *Phalacrocorax carbo*, wildfowl, waders and gulls). This is reflected in the designation of the entire Upper Solway Flats and Marshes Site of Special Scientific Interest (SSSI) as a Special Protection Area (SPA) under EC Directive (79/409/EEC) on the conservation of wild birds. Like much of western Europe, the Solway is important for waterfowl as it is located on the flyways used by migratory waterfowl, it has a climate that is relatively mild and its expansive intertidal area provides excellent feeding grounds. Population monitoring has long been recognised as an essential element of waterfowl conservation. Britain's monitoring scheme began in 1947 when a wildfowl count network was set up by the International Wildfowl Inquiry Committee (Atkinson-Willes 1963). Today it takes the form of the Wetland Bird Survey (WeBS), a joint initiative of the British Trust for Ornithology (BTO), the Wildfowl & Wetlands Trust (WWT), the Royal Society for the Protection of Birds (RSPB) and the

Joint Nature Conservation Committee (JNCC). WeBS is effective at monitoring populations of most species and allows important sites to be identified. Other studies are required, however, to collect more detailed information on individual sites. There have been three such studies on the Solway. Two of these were restricted to short periods or concentrated on one aspect of bird distribution (Mearns 1977; Moser 1984). The other, a two-year project, looked at waterfowl numbers and distribution throughout the year and at both low and high tide (Quinn *et al.* 1993).

This paper is based largely on WeBS data and the study of Quinn *et al.* (1993). It provides a summary of current knowledge on the distribution of waterfowl on the Solway Firth and the significance of their numbers during the late 1980s and early 1990s.

Study area

The inner Solway Firth, or the Solway Estuary, is defined here as the area stretching from Sandyhills at the western end of Mersehead Sands on the Scottish shore to Silloth on the Cumbrian shore (Figure 1). The boundaries of the SPA are similar but continue to Mawbray on the south shore. An indication of the main habitats and sediment types on the inner estuary is provided in Figure 1. The 'outer' Solway Firth refers to the area of sea enclosed by Maryport on the Cumbrian coast to the Mull of Galloway on the Scottish coast.

Information sources and analysis

Estimates of non-breeding waterfowl numbers

WeBS counts are undertaken monthly at high tide by volunteer observers (see Prater 1981, Owen *et al.* 1986 for full details). Counts are typically treated as minima because observers tend to underestimate numbers (Prater 1979). Present count coverage on the Solway is very good and most areas are counted every month of the year, but prior to 1992 the north Solway was not covered in spring or summer. Since geese and gulls occur on the Solway in much greater numbers when roosting at night than during the day, additional counts of these species, when leaving or flying to the roost along traditional flightlines, were undertaken.

In any given area there can be frequent 'turnover' in the individual species present, as some birds move into an area and others leave, and so the total number of birds using the area is greater than the maximum count indicates. On the Solway this is especially evident in spring and autumn. Turnover can be detected by monitoring the proportions of dye-marked birds in flocks. This was done on the Solway in spring 1992 and 1993 for ringed plover *Charadrius hiaticula* and sanderling *C. alba* (Quinn *et al.* 1993), following the methods of Kersten & Smit (1984).

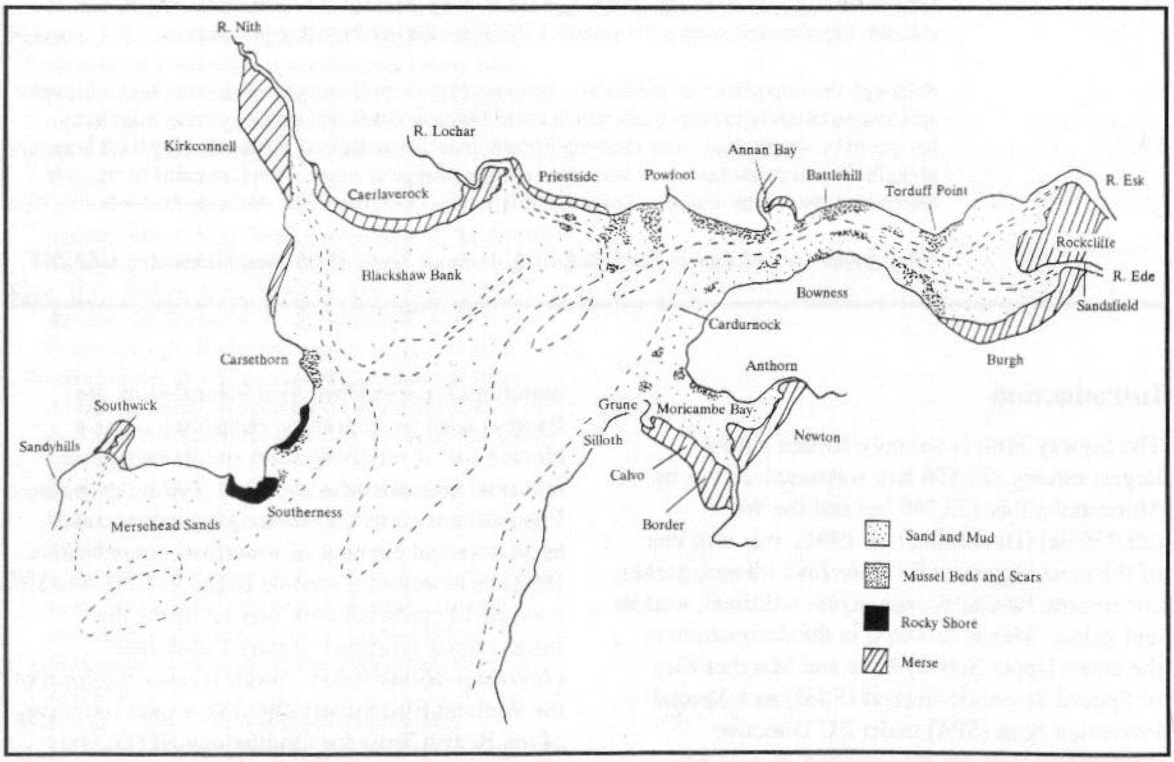


Figure 1 The Solway Firth showing principal habitat features and locations.

The significance of waterfowl numbers

Britain's wintering wildfowl belong to the north-west European international populations (Monval & Pirot 1989) whilst its waders belong to the East-Atlantic Flyway (Smit & Piersma 1989). A site is considered to be nationally or internationally important for a species, or sub-species, if maximum winter counts regularly (usually over five winters) exceed 1% of the national or international population of that species. 1% qualifying levels are fixed over several years and do not fluctuate with natural annual population changes, so they give an approximate but practical guide to the proportions of national and international populations that occur on individual sites. Average peak counts from 1988-89 to 1992-93 were used to estimate percentage of populations that occur on the Solway. As the north Solway has only recently been counted from April to August, spring estimates are given for 1992 and 1993 when coverage was good, as well as for the five-year period. Qualifying levels for importance are not officially set for many species (e.g. cormorant, divers, gulls) so percentage population estimates for these are based on population estimates given in Lack (1986).

Average peak counts were also compared with those of the other 2,173 wetland sites in the UK covered by WeBS in 1991-92 (of which 117 were estuarine). Rankings given are based on results in Cranswick *et al.* (1992) who used average winter maxima as the ranking criterion. It is stressed that these rankings are approximate and should not be interpreted as being rigid.

Distribution in the non-breeding season

For the majority of species, low tide distribution reflects their most important feeding areas. Quinn *et al.* (1993) counted the Solway over two years on a monthly basis and describe the distribution of 42 species in detail. Using the same data here, the overall importance of individual sections at low tide, in terms of species diversity, rarity and abundance, is examined using an index adapted from Williams (1980). This Site Value Index (SVI) is represented as:-

$$SVI = (D/s) \sum (d_i w_i)$$

where D is the average number of species present per visit, s is an arbitrary scaling factor, d_i is the average count per visit for species i, and w_i is a rarity weight for the ith species in the group. The rarity weight for a species was calculated by dividing its qualifying level for national importance in Britain into that of the species in the same group with the largest qualifying level. The SVI was calculated for 32 species, split into three different groups: diving species, non-diving wildfowl (i.e. all other wildfowl) and waders. In the map legends, ranges covered for each dot size are given and the cumulative summed percentages accounted for by each range are indicated. Note that different scaling factors were used in analyses and the magnitude of values should not be compared between analyses. A general description of roosting areas at high tide is given based on mapped information collected by observers during the WeBS counts from 1991-93. Detailed information is provided elsewhere (Mearns 1977; Moser 1984; Quinn *et al.* 1993).

Breeding waterfowl

The first complete surveys of waders nesting on the inner Solway were carried out in 1992 and 1993. Estimates of numbers of pairs were obtained from three visits undertaken between April and June, using methods described by Smith (1983). Breeding shelduck *Tadorna tadorna* were surveyed from 1991 to 1993, in the first two years as part of a national survey organised by WWT (Delany 1991). In each year, on a falling tide, pairs and territorial males were counted in late April or early May, and broods were counted in early to mid-July. Population estimates for other species are taken from published sources.

Results and discussion

Non-breeding waterfowl

Total numbers and seasonality

The total numbers of wildfowl, waders, gulls and waterfowl counted on the Solway from November 1991 to July 1993 are shown in Figure 2. Peak numbers of waterfowl occurred in December or January, lowest numbers in May and June. Waders were the most numerous and peak numbers were in excess of 70,000 birds, while wildfowl peaked just above 30,000. Gulls never exceeded 20,000 on WeBS counts but much larger numbers used the estuary at night as a roost (see below).

Seasonal patterns in abundance varied between species. Pink-footed geese *Anser brachyrhynchus* occurred in all months apart from June, July and August, but very high numbers occurred only in February and March (Figure 3). Shelduck numbers peaked twice in each year, in February or March and again in June or July. Pintail *Anas acuta* counts were highest in mid-winter but large numbers pass through the Solway in October, often undetected, and this is the true peak month (Cranswick *et al.* 1992). In Britain as a whole, peak numbers of pintail occur in December (Owen *et al.* 1986). Great crested grebes *Podiceps cristatus* peaked in November in 1991-92 but also in January in 1992-93. Grebes and divers are

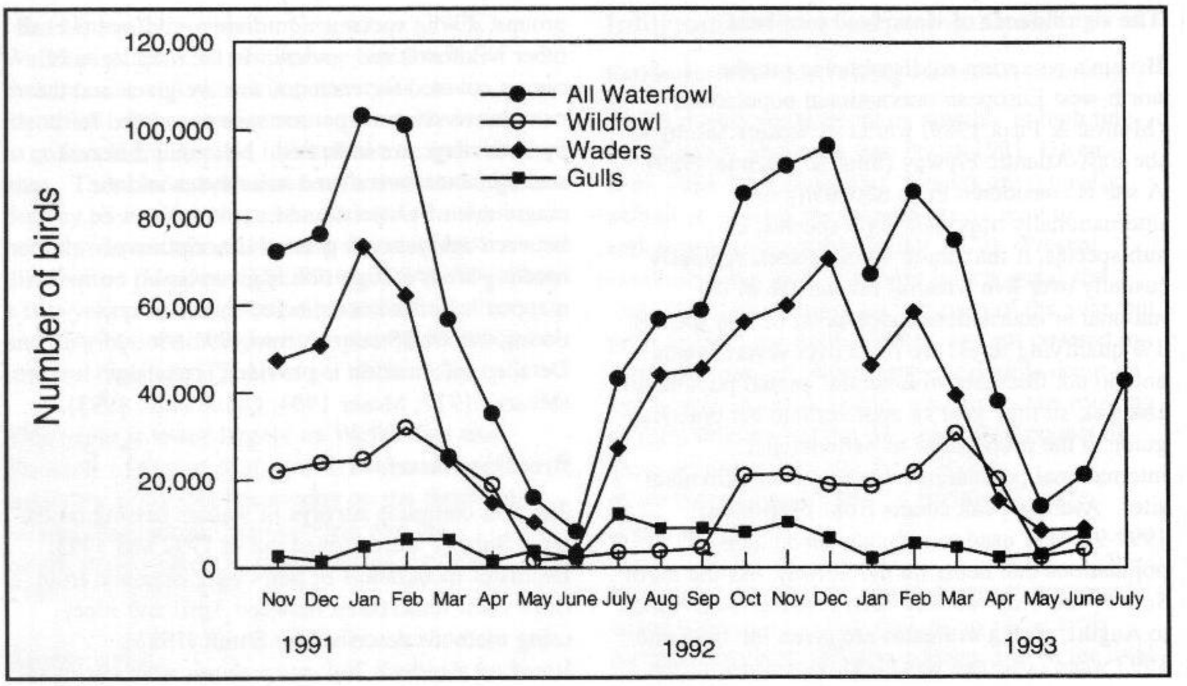


Figure 2 Seasonal variation in numbers of wildfowl, waders, gulls and waterfowl on the Solway Firth from November 1991 to July 1993.

consistently undercounted on the Solway because their detection is heavily reliant on calm conditions on the estuary. As these birds occur offshore, even moderate waves can make them impossible to see.

Oystercatcher *Haematopus ostralegus* numbers approached their maximum early in both seasons and were maintained until March. Knot *Calidris canutus* have a much shorter season and occurred in highest numbers from December to February. Ringed plover showed two seasonal peaks, in May and in September, both related to the passage of birds through the estuary.

Internationally important populations

The importance of the Solway to international populations of waterfowl is summarised in Tables 1 (autumn and winter) and 2 (spring). Internationally important numbers were recorded for 12 species during the 1988-89 to 1992-93 period. Of particular importance is the Svalbard barnacle goose *Branta leucopsis*, whose entire population winters exclusively around the Solway. Pink-footed goose numbers were also very important with the firth supporting 8.8% of the total Icelandic/Greenland population. The Solway used to hold a much higher proportion of the total goose population; Atkinson-Willes (1963) mentions that up to a quarter of the population have been recorded here, albeit at a time when the population was only a tenth of today's. Pink-footed geese are also thought to pass through the Solway in very large, but unknown, numbers in late autumn on route to wintering grounds in Lancashire and Norfolk (Fox *et al.* 1994). Pintail (2.1%) and scaup *Athya marila* (1.7%) numbers were not as significant, although the true importance of the Solway to these species is yet to be discovered because they are frequently undercounted by WeBS (Quinn *et al.* 1993).

Oystercatchers were the most abundant species on the Solway. Numbers exceeded 35,000 in both autumn and winter and represented 4.3% and 3.9% respectively of the East-Atlantic Flyway population. Bar-tailed godwit *Limosa lapponica* (4.2%) and knot (3.3%) occurred in much smaller, but equally significant, numbers in winter. Small numbers of ringed plover wintered on the Solway but, in spring and autumn, peak counts represented 3.7% and 2.3% of the international population. Estimates of turnover in 1993 suggested that 3,240-3,868 ringed plovers used the estuary, representing 6.5-7.7% of the flyway population in that year. Smaller numbers passed through in 1992 and a similar rate of turnover was estimated (Quinn *et al.* 1993). Moser & Carrier (1984) recorded similar turnover rates in the early 1980s, but only at one or two roosts and involving much smaller numbers of birds.

The Solway may be internationally important for two other species: dunlin *Calidris alpina* and shelduck. Between 1988-89 and 1992-93, wintering dunlin numbers were just below the level of international significance (0.9%). Low tide counts from 1991-1993 suggested they may have been consistently undercounted at high tide. During the 1991-92 season, numbers exceeded the 1% level only once on high tide counts but

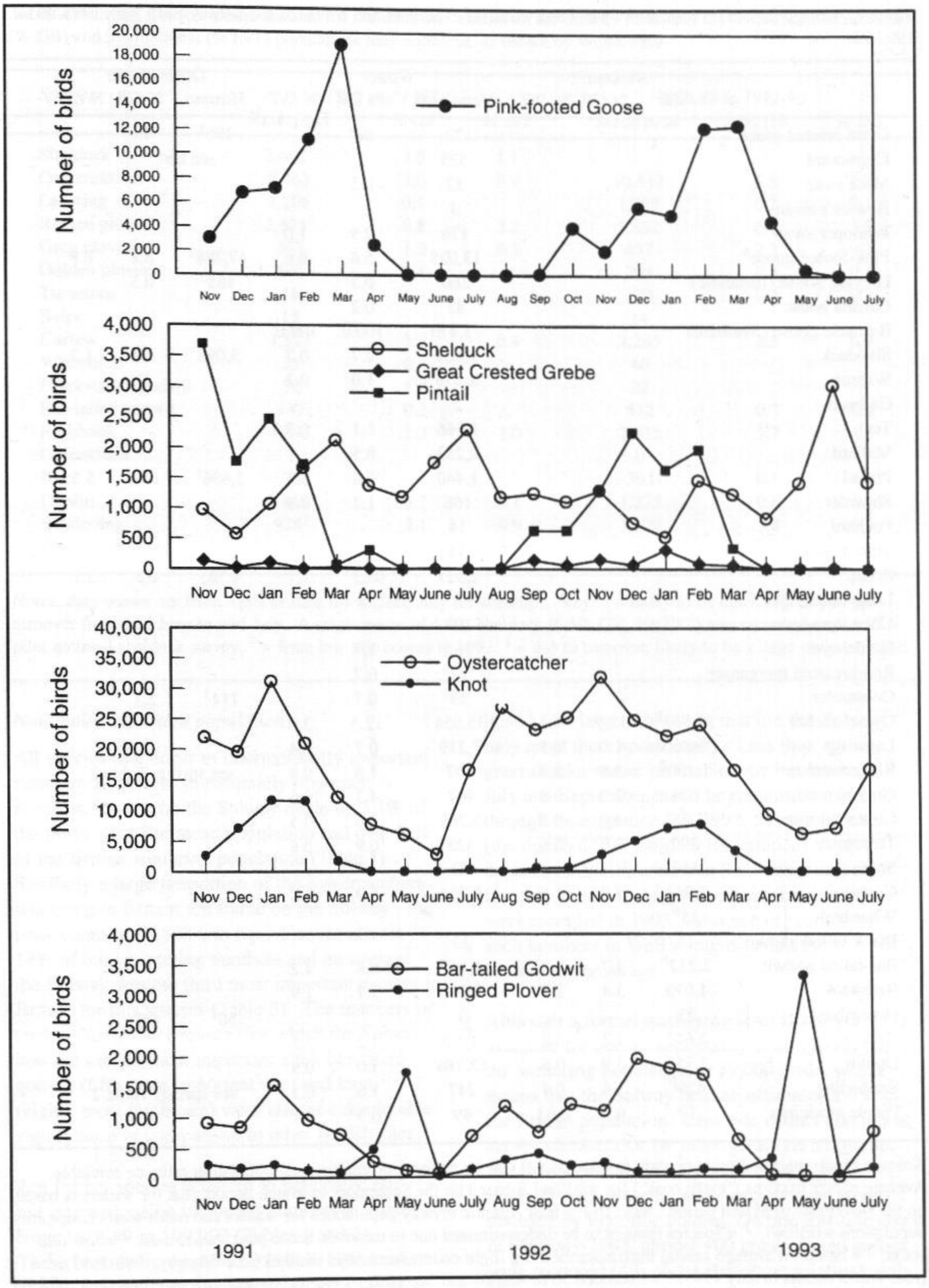


Figure 3 Seasonal variation in numbers of selected species of waterfowl on the Solway from November 1991 to July 1993.

five times on low tide counts (Quinn *et al.* 1993). The likely explanation for this discrepancy is that dunlin are difficult to see when roosting at high tide, particularly on Caerlaverock and Priestside merses (saltmarshes).

WeBS data suggested that the Solway held 0.7% of the north-west European population of shelduck in winter, but additional surveys undertaken in July 1991 and 1992 revealed maximum shelduck numbers equivalent to 1.3% and 2.0% of the north-west European populations (Quinn *et al.*

Table 1 Average maximum counts of waders and wildfowl in autumn and winter on the Solway Firth from 1988-89 to 1992-93.

	Autumn			*Winter*			*Other counts*		
	Peak	*% GB*	*% INT*	*Mean peak*	*% GB*	*% INT*	*Maxima*	*% GB*	*% INT*
Great crested grebe				72	0.7		396[1]	4.0	
Cormorant				525			see text		
Mute swan				53	0.3				
Bewick's swan				3					
Whooper swan				176	2.9	1.0			
Pink-footed goose[6]				13,035	6.6	6.6	17,288[2]	8.8	8.8
Greylag goose (Icelandic)				260	0.3		385[2]	0.5	
Canada goose				83	0.2				
Barnacle goose (Svalbard)				13,470	100.0	100.0			
Shelduck				1,804	2.7	0.7	3,093	4.1	1.2
Wigeon				2,476	1.0	0.3			
Gadwall				2					
Teal				1,066	1.1	0.3			
Mallard				2,263	0.5				
Pintail				1,440	5.8	2.1	3,696[1]	14.8	5.3
Shoveler				106	1.2	0.3			
Pochard				14					
Tufted duck				34					
Scaup				2,533	63.3[5]	1.7	4,595	62-	3.1
Long-tailed duck				2					
Common scoter				26					
Goldeneye				262	1.7				
Red-breasted merganser				72	0.7				
Goosander				33	0.7		114[3]	2.3	
Oystercatcher	38,863[P]	13.9	4.3	35,054	12.5	3.9			
Lapwing	9,860	1.0	0.5	7,219	0.7	0.4			
Ringed plover	1,130[P]	3.8	2.3	407	1.8	0.8	see spring, Table 2		
Grey plover	626	3.0	0.4	902	4.3	0.6			
Golden plover	7,923	4.0	0.8	5,243	2.6	0.5			
Turnstone	390	0.9	0.6	423	0.9	0.6			
Snipe	117			53					
Curlew	5,261	5.8	1.5	6,265	6.9	1.8			
Whimbrel	15[P]								
Black-tailed godwit	14			33					
Bar-tailed godwit	2,232[P]	3.7	2.2	4,167	6.8	4.2			
Redshank	4,070	3.4	2.7	2,789	3.7	1.9			
Greenshank	23			3			50[4]	1.0	
Knot	2,643	1.2	0.8	11,520	5.2	3.3			
Dunlin	7,753	3.9	0.6	12,786	3.0	0.9			
Sanderling	426[P]	1.4	0.4	247	1.8	0.3	see spring, Table 2		
Purple sandpiper	17	0.1	0.03	49	0.3	0.1			

Notes: a blank space indicates no data, a value of > 0.1 or no national or international population estimate available. Average winter maxima ('mean peak') for wildfowl is based on the September to March period; that for waders is based on the November to March period. Key: INT = East Atlantic Flyway populations for waders and north-west Europe for populations wildfowl. [P] = species thought to be underestimated due to turnover, hence peak values used; [1] = low tide count; [2] = based on average annual maximum morning flight counts from 1998 to 1993 (after Mawby 1988-1993); [3] = from WeBS counts in July 1993; [4] = exceeded 50 in August and September 1992 and in autumn 1993 (pers. obs.); [5] = the population is thought to be 6,000-7,500 (Salmon 1988) with large variations between years; [6] = international population estimated from annual WWT national goose counts.

1993). Due to poor summer coverage in the past, and the fact that this high concentration of birds is present for only a short period before migrating to moult in the Dutch Waddensea, the Solway is likely to be internationally important for shelduck. Golden plover *Pluvialis apricaria* occasionally exceed internationally important numbers on the Solway. As they feed primarily in agricultural fields, it is unlikely all birds using the Solway Estuary occur at the same time, and hence many remain uncounted.

Table 2 Average spring/summer maxima for shelduck and waders on the Solway Firth, and the proportions of national (% GB) and international (% INT) populations they represent, as shown by WeBS data.

Species	*1992 and 1993*			*1988-89 to 1992-93*		
	Mean peak	*% GB*	*% INT*	*Mean peak*	*% GB*	*% INT*
Shelduck	2,662[1]	3.5	1.1			
Oystercatcher	8,463	3.0	0.9	10,612	3.8	1.2
Lapwing	1,206	0.1		1,705	0.2	0.1
Ringed plover	2,625[2]	8.8	5.2	1,852	6.2	3.7
Grey plover	393	1.9	0.3	457	2.2	0.3
Golden plover	695	0.4		794	0.4	0.1
Turnstone	16			170	0.4	0.3
Snipe	15			14		
Curlew	1,527	1.7	0.4	2,265	2.5	0.7
Whimbrel	25	0.5		40		
Black-tailed godwit	52	1.0		22		
Bar-tailed godwit	147	0.2		412	0.7	0.4
Redshank	1,443	1.2	1.0	2,015	1.7	1.3
Greenshank	1			0		
Knot	78			303	0.1	0.1
Dunlin	1,441[3]	0.7	0.1	1,275	0.6	0.1
Sanderling	928[3]	3.1	0.9	1,129	3.8	1.1
Purple sandpiper	3			0		

Notes: data shown are from April to June for waders, July for shelduck. Key: [1] = likely to be much higher due to turnover from mid-June to mid-July. A single count of 4,894 shelduck (6.5% GB, 2% INT) was recorded on the 1991 pilot national shelduck survey; [2] = from low tide counts in 1993; [3] = due to turnover, likely to be a large underestimate.

Nationally important populations

All species that occur in internationally important numbers also occur in nationally important numbers. Scaup on the Solway made up 3.1% of the north-west European population and over half of the British wintering population (Table 1). Similarly a large proportion of the oystercatchers wintering in Britain are found on the Solway - the peak count of 38,863 was equivalent to almost 14% of total wintering numbers and on average the Solway was the third most important estuary in Britain for this species (Table 3). The numbers of curlew *Numenius arquata* (for which the Solway was the second most important site), bar-tailed godwit (fifth most important site) and knot (eighth most important) were also of considerable significance in comparison to other British sites.

Ten further species occurred in nationally, but not internationally, important numbers in winter from 1988-89 to 1992-93 (Tables 1 and 2). These included grey plover *Pluvialis squatarola* (4.3%), dunlin (3%) and golden plover (2.6%). Several other species also occasionally exceeded nationally important numbers but not often enough to be designated as nationally important. These included red-breasted merganser *Mergus serrator*, goosander *M. merganser*, lapwing *Vanellus vanellus*, black-tailed godwit *Limosa limosa* and greenshank *Tringa nebularia.* Lapwing, like golden plover, feed primarily inland so a large proportion that use the Solway only roost there sporadically. Less than six greenshanks winter on the Solway but between July and September much larger numbers pass through on migration. In 1992, 50 greenshanks (the threshold for national importance) were counted on WeBS counts in September and on low tide counts in August, and similar numbers were recorded in 1993. Absence of records of such numbers in WeBS counts is due to incomplete coverage.

Although a formal qualifying level is not yet available for cormorants, Kirby *et al.* (1995) put the wintering population at 19,000 birds, which means that the Solway held an estimated 2.7% of the British population. Low tide counts and a boat survey showed that far more great crested grebes and divers (mainly red-throated divers *Gavia stellata*) were present on the estuary than were revealed by high tide counts. On one low tide count in February 1993, almost 400 great crested grebes were recorded (4% of the British population); only three sites in Britain had higher numbers in 1991-92 (Table 3). Records of 100-200 divers on passage in April have been frequent in recent years, especially during adverse weather conditions (e.g. Carrier 1992; Watson pers. comm.). Webb *et al.* (1990) found highest densities of divers in the eastern Irish Sea in March and April. Danielsen *et al.* (1992) put the British wintering red-throated diver population at only 4,300 to 5,400 birds, which

Table 3 The approximate ranking of the inner Solway Firth amongst wetland sites in Britain for the main waterfowl species.

Species	*Ranking amongst British wetlands*
Great crested grebe	top 10*
Cormorant	4
Whooper swan	6
Pink-footed goose	9
Barnacle goose	1
Shelduck	probably 15-20 in winter, 1-3 in summer
Mallard	9
Pintail	10
Scaup	1
Common scoter	probably top 10*
Goldeneye	probably top 20*
Red-breasted merganser	probably top 30*
Oystercatcher	3
Ringed plover	top 3 in spring
Golden plover	5
Grey plover	probably 20-25
Lapwing	8
Sanderling	top 3 in spring
Knot	8
Dunlin	14
Bar-tailed godwit	5
Curlew	2
Redshank	14
Greenshank	top 10-15 in autumn**

Source: Cranswick *et al.* (1992). Key: *at least 17 sites had average maxima greater than that recorded from the Solway; **only nine sites recorded autumn peaks greater than 50 birds in 1991-92.

implies that the Solway undoubtedly holds numbers of national importance, at least in spring.

Common scoters *Melanitta nigra* were seen in nationally important numbers on the outer part of the north Solway on many other occasions in May and June 1993 (Quinn *et al.* 1993), and also in spring 1992 from Grune Point (Carrier 1992). Aerial surveys have identified the Solway Firth (including the far outer Solway) as being one of the four most important areas in the eastern Irish Sea for common scoter (Webb *et al.* 1990). The whole Solway Firth area holds nationally important numbers but these are recorded only sporadically on the inner estuary. The qualifying level for whimbrel *Numenius phaecopus* on passage is 50 birds. Records from low and high tide counts, and other casual records, suggest that the Solway exceeds this regularly.

Gulls occur on the Solway in very large numbers in winter when roosting at night. Results from four evening flight counts on the Solway are given in Table 4 (from Quinn *et al.* 1993). Black-headed gull *Larus ribundus*, common gull *L. canus* and herring gull *L. argentatus* all occurred on the Solway in numbers exceeding 1% of the best British wintering population estimates available. Of these, herring gull numbers were most significant and as much as 6% of the estimated British population roosted on the Solway in winter.

Important areas for non-breeding waterfowl

High tide

The locations of the main high tide roosting areas are shown in Figure 4. The extent to which these were used varied greatly between species. Some, such as oystercatcher and curlew, used many roosts while others, like knot and bar-tailed godwit, used very few. Most waders are forced to roost at high tide but many wildfowl can still feed on the flooded saltmarshes and diving species may increase their feeding activity. Geese are largely unaffected by the tide during the day but the most important feeding areas of most other species become available only once the tide begins to recede. The following sections concentrate on the distribution of waterfowl at low tide (Figures 5-8).

Low tide: diving species

Most of the Solway's diving birds were found almost exclusively on the shallow inshore waters and river channels. Blackshaw Bank was by far the most important area (Figure 5a), primarily due to the presence of most of the Solway's roosting scaup (Figure 5b). Here two sections on the bank alone

Table 4 Total numbers of gulls counted flying in to roost on the Solway Firth in 1992-1993 and % of British wintering populations for maximum and average counts.

Species	*2 Feb. 1992*	*15 Nov. 1992*	*20 Dec. 1992*	*24 Jan. 1993*	*Max. % GB*	*Average % GB*
Black-headed gull	32,131	28,551	22,512	23,169	1.28	1.06
Common gull	8,334	12,747	10,665	12,458	2.01	1.74
Herring gull	16,570	22,140	20,289	11,946	6.30	5.06
Lesser black-backed gull	138	725	119	88	0.14	-
Great black-backed gull	197	264	235	260	0.33-0.53	0.29
Unidentified	0	9,980	4,892	8,435		
Total	*57,370*	*74,407*	*58,712*	*56,356*		

Estimates of British wintering populations from Lack (1986) and Bowes *et al.* (1984).

accounted for 71% of the summed indices. West of the River Nith on the north shore and Cardurnock on the south shore were also important. Blackshaw Bank held on average three times as many scaup as any other area and several counts greater than 3,000 have been recorded here (Figure 5b). The relative importance of these areas apparently changed from year to year, and may well have been related to changes in cockle harvesting activities (Quinn *et al.* 1997). Grebes, divers and red-breasted mergansers all had a broadly similar distribution to that of scaup.

The distribution of goldeneye *Bucephala clangula* is not reflected in the index, largely because of the overshadowing effect of large scaup numbers. Like goosander, most are found around the mouths of the various rivers flowing into the estuary (Figure 5c).

Low tide: other wildfowl

Other species of wildfowl were distributed in four main areas at low tide: Rockcliffe and Burgh Marshes, between the River Lochar and the west bank of the River Nith, Moricambe Bay, and Mersehead (Figure 6a). Two sections on Rockcliffe Marsh alone accounted for 51% of the summed indices, largely because of the presence of large numbers of barnacle and pink-footed geese.

Pink-footed geese in the Solway basin feed on both agricultural land and on estuarine saltmarshes, especially on Rockcliffe Marsh, Newton and Border on Moricambe Bay, and Burgh Marsh (Figure 6b). The relative degree to which these areas are used during the winter is apparently affected by shooting pressure. Barnacle geese feed on the same saltmarshes with the exception of Moricambe Bay, while Rockcliffe Marsh generally became more important as the year advanced (Shimmings *et al.* 1993). Agricultural land is also used by barnacle geese, but only those areas close to the estuary, in contrast to pink-footed geese which feed over much larger distances. Some geese continue to graze at night, especially under moonlight. Geese were normally only found on intertidal areas when roosting.

Wigeon *Anas penelope* also grazed extensively at night, making it difficult to assess the relative importance of different feeding areas. During the

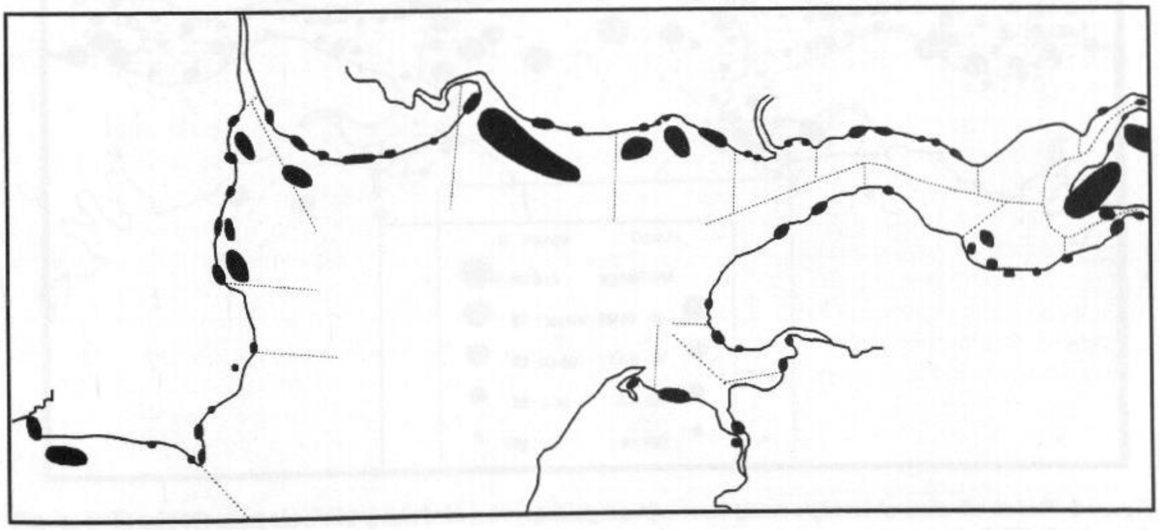
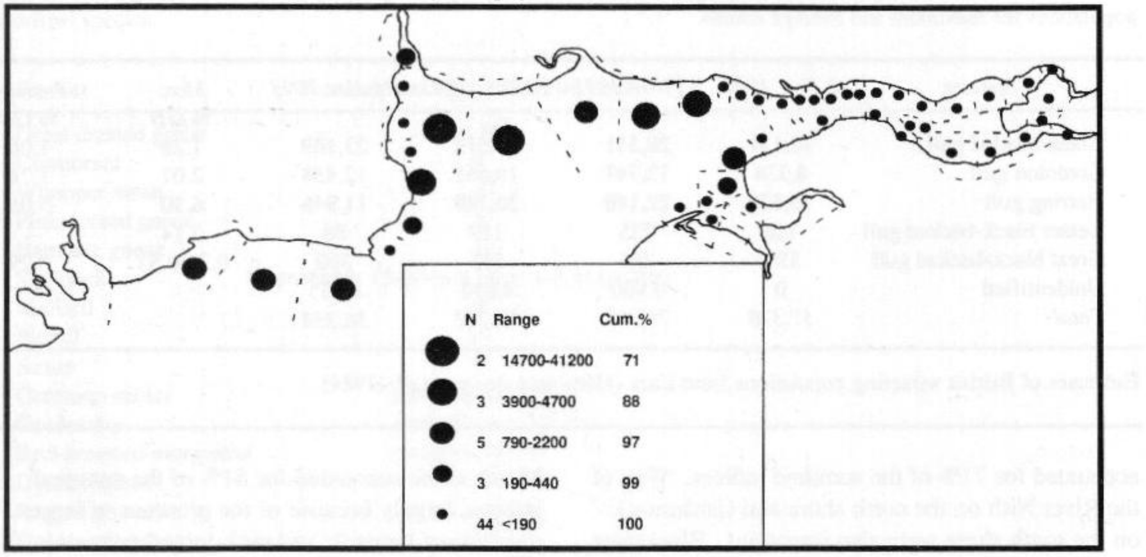
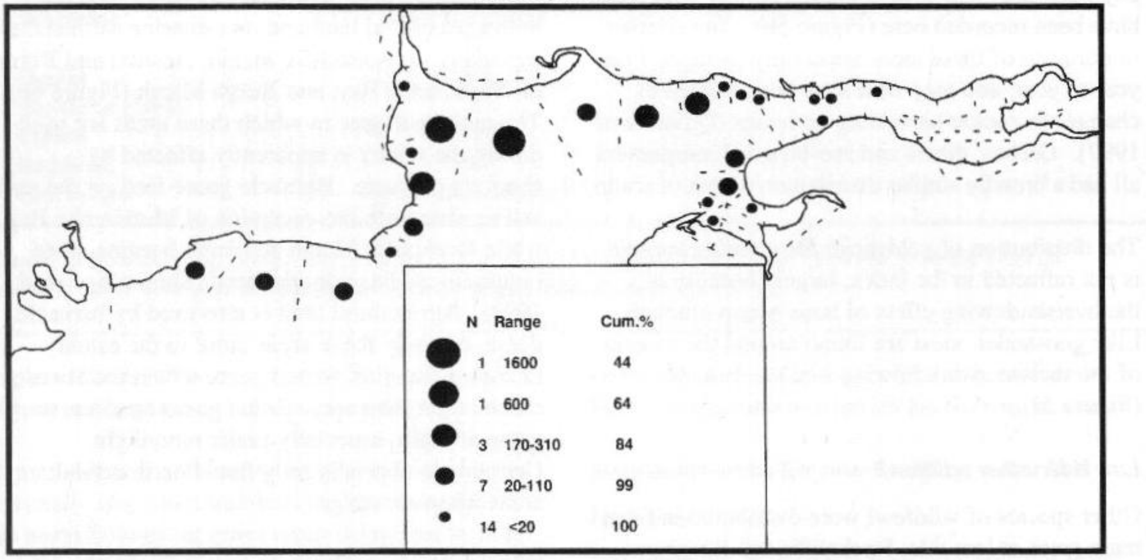


Figure 4 The main high tide roosting areas for waterfowl on the Solway in winter, 1991 to 1993.

a) Diving species (SVI winter)



b) Scaup (winter)



c) Goldeneye (winter

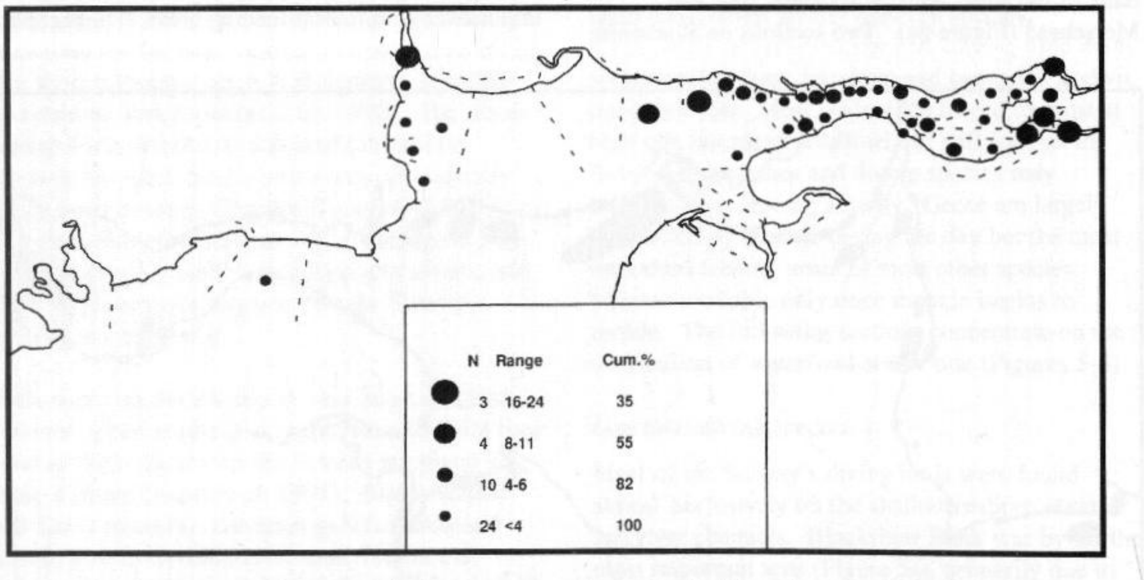
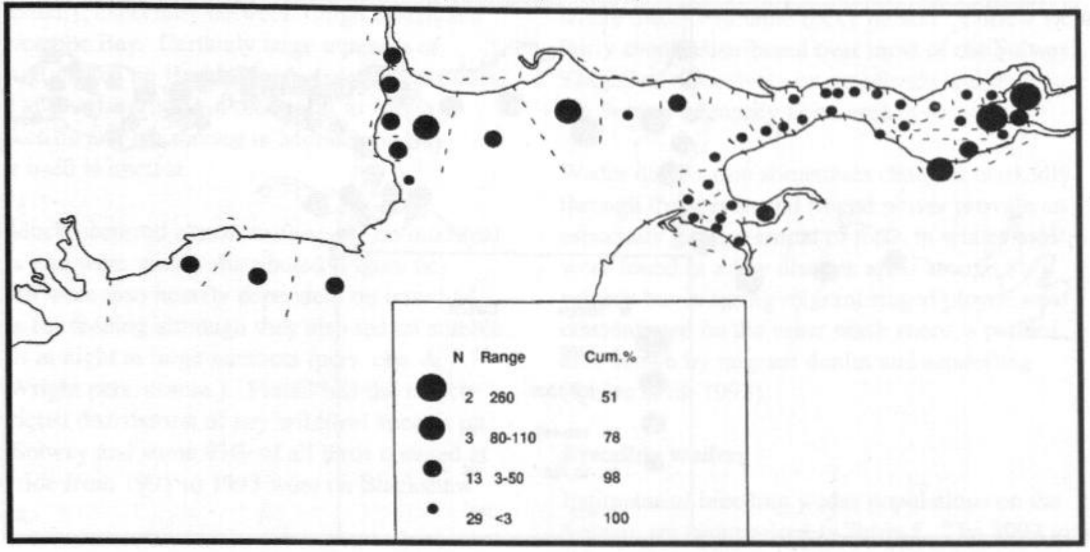
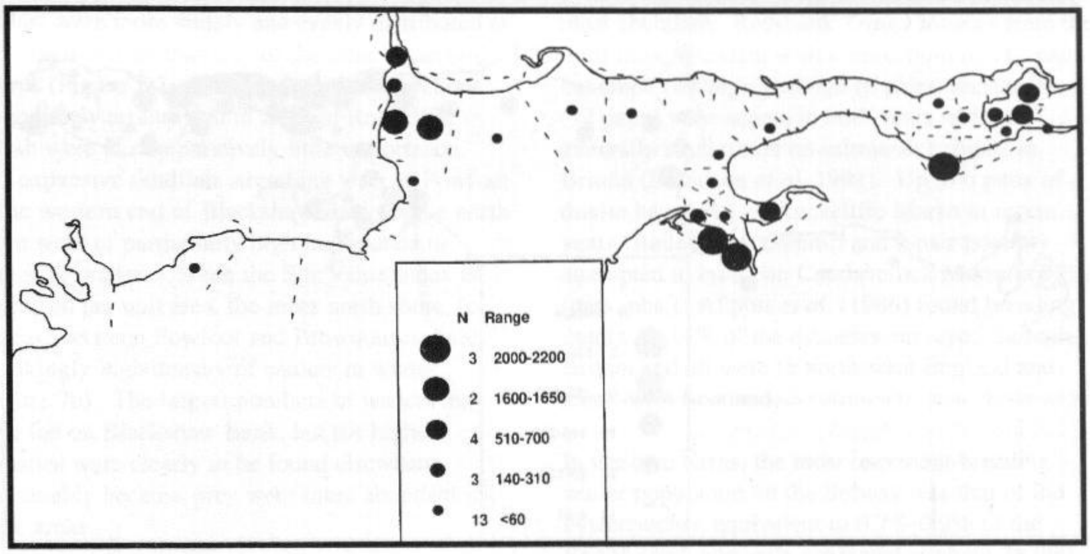


Figure 5 The distribution of diving waterfowl, scaup and goldeneye on the Solway in winter from 1991 to 1993 as shown by the SVI. Range gives maximum and minimum; cum. % shows cumulative summed percentages accounted for by each range, e.g. the two most important sections accounted for 71% of all SVIs.

a) Wildfowl (SVI winter)



b) Pink-footed Goose (winter maxima)



c) Shelduck (winter)

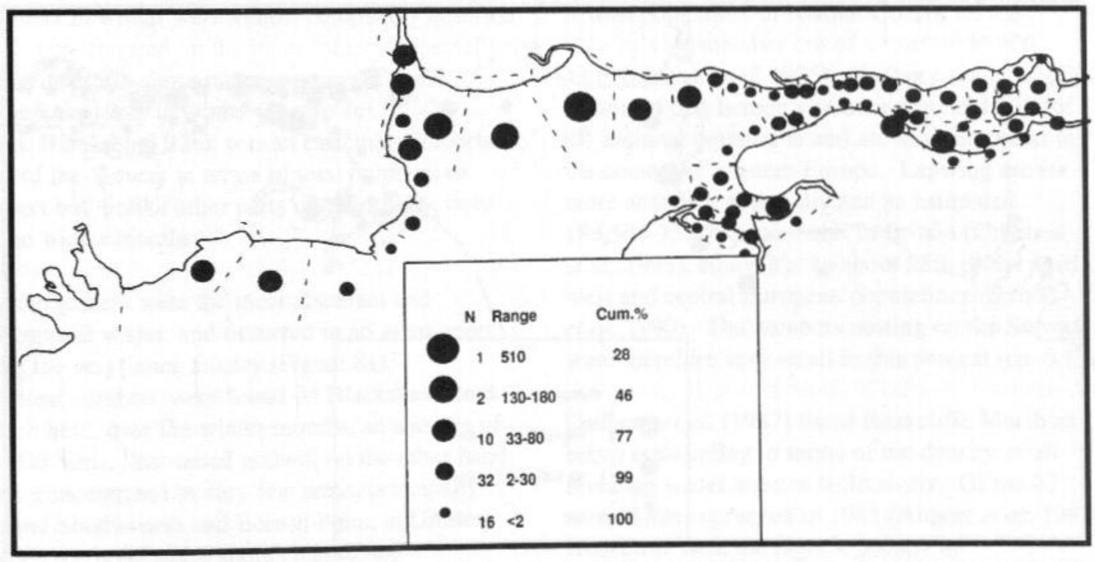
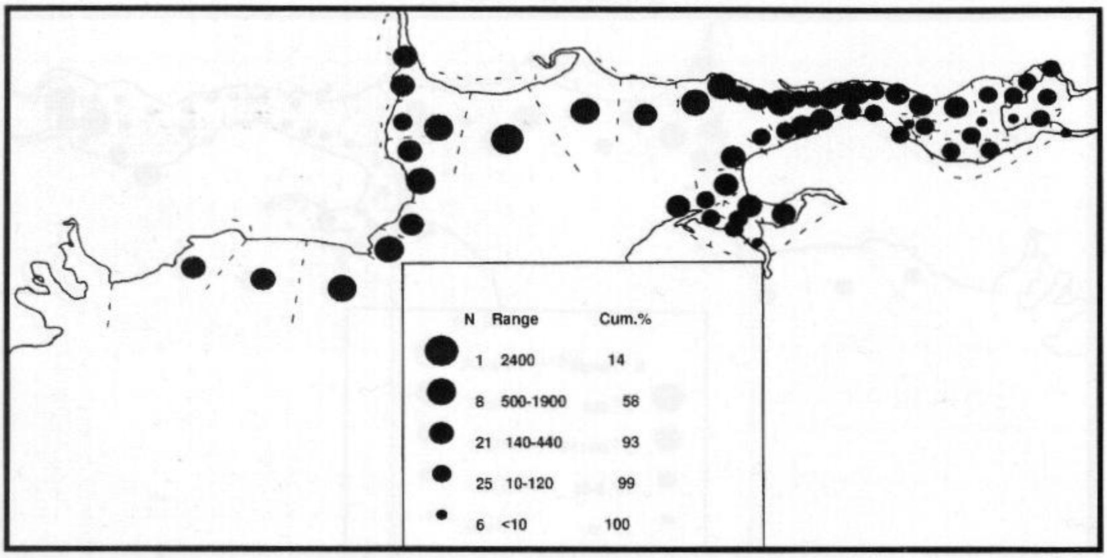
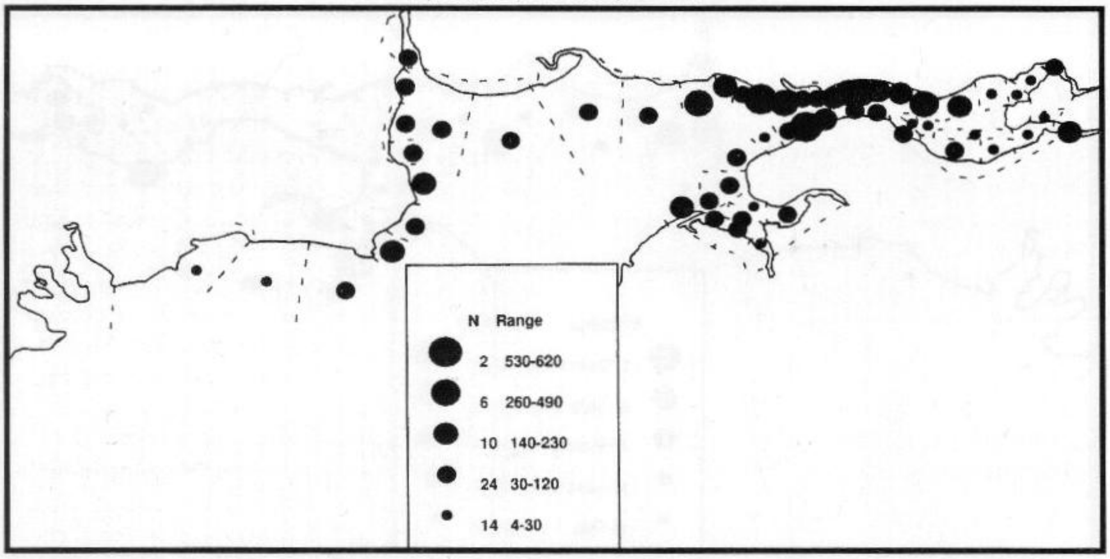


Figure 6 The distribution of wildfowl (excluding diving birds), pink-footed geese and shelduck on the Solway in winter from 1991 to 1993 as shown by the SVI (see Figure 5 for explanation).

a) Waders (SVI winter)



b) Waders (SVI density, winter)



c) Waders (SVI spring)

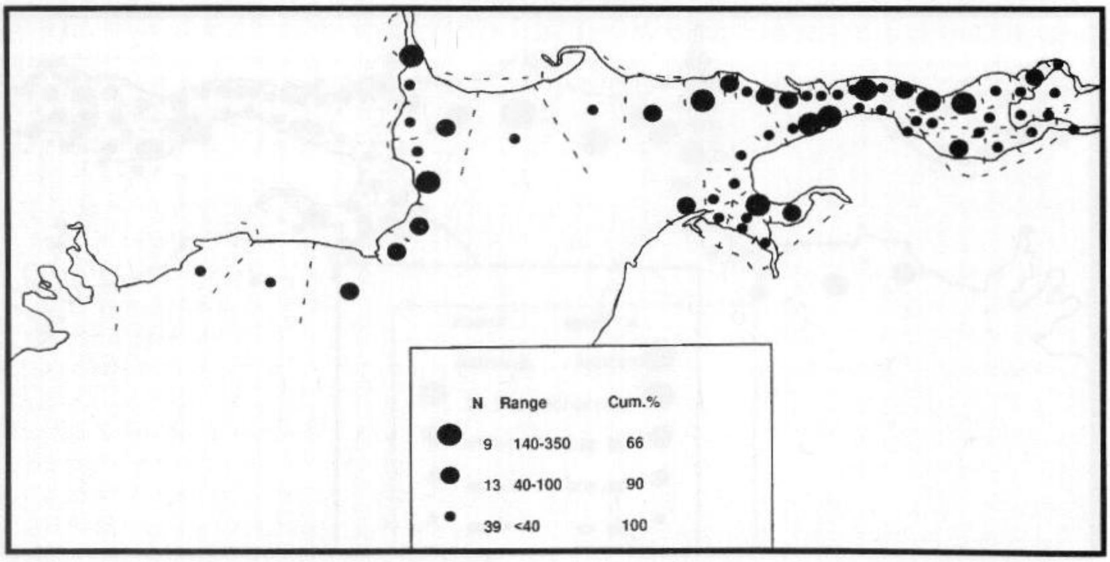


Figure 7 The distribution of waders on the Solway in winter from 1991 to 1993 as shown by the SVI and SVI per unit area (see Figure 5), and the distribution of waders in the spring.

day most loafed on the water on the inner part of the estuary, especially between Burgh Marsh and Moricambe Bay. Certainly large numbers of wigeon grazed on Burgh Marsh and on agricultural land at Caerlaverock but the extent to which Rockcliffe and the merses in Moricambe Bay were used is unclear.

Shelduck occurred almost exclusively on intertidal areas and were widely distributed (Figure 6c). Pintail were also heavily dependent on intertidal areas for feeding although they also fed on stubble fields at night in large numbers (pers. obs. & W. Wright pers. comm.). Pintail had the most restricted distribution of any wildfowl species on the Solway and some 93% of all birds counted at low tide from 1991 to 1993 were on Blackshaw Bank.

Low tide: waders

Waders were more widely and evenly distributed at low tide in winter than any of the other waterbird groups (Figure 7a). Only the very inner sections immediately around and in front of Rockcliffe Marsh were of comparatively little importance. The expansive sandflats stretching west of Powfoot to the western end of Blackshaw Bank on the north shore were of particularly high importance to wintering waders. When the Site Value Index is expressed per unit area, the inner north shore, to the east between Powfoot and Browhouses, held a strikingly high density of waders in winter (Figure 7b). The largest numbers of waders may have fed on Blackshaw Bank, but the highest densities were clearly to be found elsewhere, presumably because prey were more abundant in these areas.

In spring the vast sandy areas that held largest numbers in winter were almost completely deserted. Birds concentrated on the inner estuary, especially along the north shore in those areas that held highest densities in winter (Figure 7c). Thus, Blackshaw Bank was an extremely important part of the Solway in terms of total numbers of waders but, unlike other parts of the estuary, only in the winter months.

Oystercatchers were the most abundant and widespread wader, and occurred in all areas apart from the very inner estuary (Figure 8a). Greatest numbers were found on Blackshaw Bank which held, over the winter months, an average of 15,000 birds. Bar-tailed godwit, on the other hand, were concentrated in very few areas, principally around Southerness and Borron Point, at Grune and on the inner north shore (Figure 8b). Purple sandpipers *Calidris maritima* were the most restricted regularly-occurring species on the Solway and were found only at Southerness, the only place where there is suitable rocky habitat. Curlew were fairly evenly distributed over most of the Solway. They feed extensively on grasslands and many use the Solway primarily as an area to roost.

Wader distribution sometimes changed markedly through the season and ringed plover provide an especially good example of this. In winter most were found in a few discrete areas around the estuary but in spring migrant ringed plover were concentrated on the inner north shore, a pattern also shown by migrant dunlin and sanderling (Quinn *et al.* 1993).

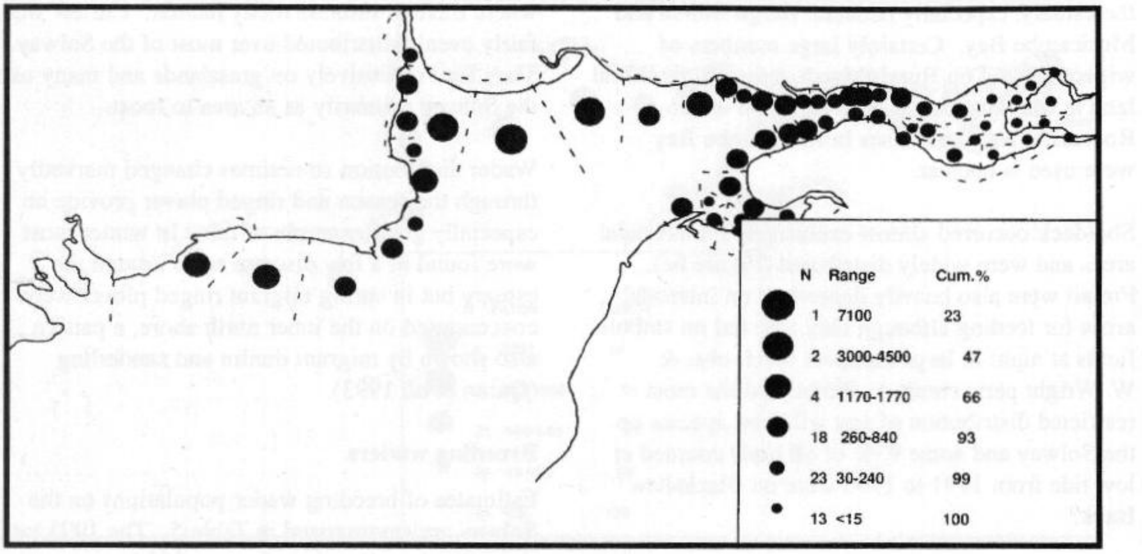
Breeding waders

Estimates of breeding wader populations on the Solway are summarised in Table 5. The 1993 totals show that lapwings (maximum of 374 pairs) and oystercatchers (maximum of 283 pairs) were the most abundant. Redshank *Tringa totanus* were the third most abundant with a maximum of 187 pairs but snipe *Gallingo gallingo* (6 pairs) and curlew (12 pairs) were scarce in both years and are generally uncommon on saltmarsh habitats in Britain (Davidson *et al.* 1991). Up to 6 pairs of dunlin have bred on Rockcliffe Marsh in recent years (Bailey pers. comm.) and 1 pair possibly attempted to breed on Caerlaverock Merse in 1992 (pers. obs.). Allport *et al.* (1986) found breeding dunlin on 14% of the estuaries surveyed throughout Britain and all were in north-west England and south-west Scotland.

In national terms, the most important breeding wader population on the Solway was that of the oystercatcher, equivalent to 0.7%-0.9% of the British total, currently estimated at about 38,000 pairs (Stroud *et al.* 1990). About 0.6% of the British population of redshank occur on the Solway's saltmarshes out of a total of 30,600-33,600 pairs (Reed 1985). Cadbury *et al.* (1987) estimated that Britain's saltmarshes hold 60% of the national population and are also important in the context of western Europe. Lapwing are far more abundant nationally and an estimated 183,500-238,500 pairs nest in Britain (Gibbons *et al.* 1993), equivalent to about 25% of the north-west and central European populations (Stroud *et al.* 1990). The numbers nesting on the Solway were therefore very small in this context (ca. 0.1%).

Cadbury *et al.* (1987) listed Rockcliffe Marsh as being outstanding in terms of the density of all breeding wader species collectively. Of the 77 sample sites surveyed in 1985 (Allport *et al.* 1986), Rockcliffe held the highest density of oystercatchers. Densities of redshank, however, were considered to be low in comparison to other

a) Oystercatcher (winter)



b) Bar-tailed Godwit (winter)

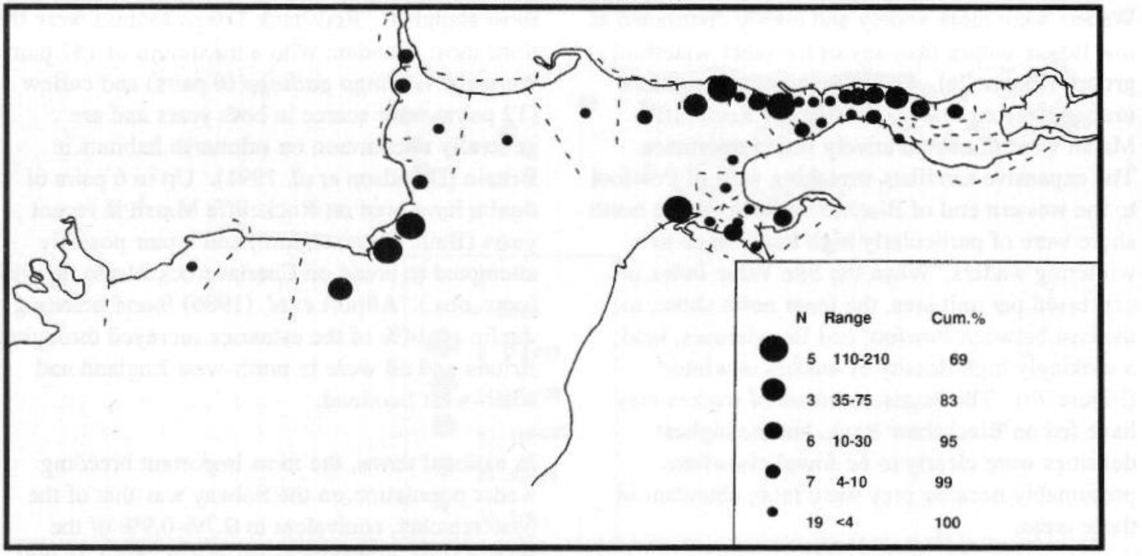


Figure 8 The distribution of oystercatchers and bar-tailed godwits on the Solway in winter from 1991 to 1993 as shown by the SVI.

key saltmarshes surveyed, primarily because much of the habitat on Rockcliffe was neutral grassland rather than saltmarsh, the preferred nesting habitat of redshanks.

The numbers of breeding pairs on some of the best lowland wet meadows in Britain are given in Smith (1983). The North Kent Marshes and the Ouse Washes held largest numbers of lapwing, 666 and 326 pairs respectively, compared with 374 pairs on the Solway in 1993. The same two sites held 446 and 203 pairs of redshank respectively compared with 187 on the Solway. Davidson *et al.* (1991) list the Solway as being one of the top grassland sites in Britain for breeding oystercatchers in terms of numbers of breeding pairs.

Prater (1989) states that the Solway was one of just ten areas in Britain where more than 50 pairs of ringed plover were recorded. Quinn *et al.* (1993) recorded considerably fewer - less than 44 pairs in 1992 but more than 41 pairs the following year - but the difference may be due to Prater's study area extending further onto the outer south Solway. British estuaries are of major international importance to the north-west and central European population of breeding ringed plover, holding about 19% of the total.

Rockcliffe Marsh was by far the most important area for breeding waders on the Solway (Table 5). In 1993, Rockcliffe held 426 pairs compared to 105 on Burgh Marsh, 91 on Caerlaverock, 79 on Border/Calvo and 60 on Kirkconnell. Ringed plover bred on Rockcliffe Marsh (5 pairs), most on gravelly areas at the northern end, but primarily nest on the shingle and stony beaches at Grune Point (9-11 pairs) and west of the mouth

Table 5 Estimated numbers of breeding pairs of waders on the Solway Firth's saltmarshes.

	Oystercatcher		*Lapwing*		*Redshank*		*Curlew*		*Snipe*	
	1992	*1993*	*1992*	*1993*	*1992*	*1993*	*1992*	*1993*	*1992*	*1993*
North Solway										
Southwick Merse	4	15	7	4[1]	0	0	2	0	1	0
Kirkconnell Merse	22	23	24	19	3	10	9	6	2	2
Caerlaverock Merse	11	17	30	46	17	25	0	0	1	3
Priestside Merse	ns	8	ns	23	ns	5	ns	0	ns	0
Annan Bay	0	4	ns	0	0	0	0	0	0	0
South Solway										
Rockcliffe Marsh[2]	93	155[3]	47	159[4]	42	112[5]	0	0	0	0
Burgh Marsh[6]	22	24	53	60	11	17	7	4	1-2	0
Newton Marsh	13	17	21	15	6	7	1	1	0	0
Border/Calvo Marshes	7	20	14	48	5	11	2	0	0	0
Total	*172*	*283*	*196*	*374*	*84*	*187*	*12*	*11*	*5-6*	*5*

Key: ns = not surveyed; [1] = apparently none bred successfully; [2] = provided by the Cumbria Wildlife Trust; [3] = comparable with 153 nests found by Rockcliffe warden; [4] = provided by Cumbria Wildlife Trust warden; [5] = comparable with Cumbria Wildlife Trust warden's count of 96 nests; [6] = estimates for western half provided by F. Mawby, based on several ringing expeditions.

of the River Annan to Powfoot (5-7 pairs). Oystercatchers also bred on shingle in a few areas but in small numbers.

Breeding shelduck

Apart from small numbers of mallard and the occasional red-breasted merganser or teal, the only other wildfowl found breeding on the Solway is shelduck. Estimates of the numbers of territorial pairs of breeding shelduck from 1990-93 were 267, 266, 285 and 121 pairs (Quinn *et al.* 1993). Most pairs were recorded on the south (average of 99 pairs) compared with the north shore (61 pairs), which is nearly twice as long. The British breeding population has been estimated at around 10,600 pairs (Gibbons *et al.* 1993) and accounts for approximately 11% of the north-west European population (Owen *et al.* 1986). Based on this figure, the inner Solway held 1.1-2.7% of the British total between 1990-93. From a national survey organised by WWT in 1992, it was found that the Solway was one of the five best sites in Britain for breeding shelduck (S. Delany pers. comm.), producing 363 young.

Other breeding species

The only cormorant colony in Cumbria is on an old Royal Air Force practice target on the south Solway which in 1990 had 69 successful nesting pairs (Carrier & Baker 1991). On the north shore just outside the study area, there is another colony of about 180 pairs (e.g. Watson 1988), many of which feed on the inner estuary. The latest estimate for the British population is 7,000 pairs (Gibbons *et al.* 1993), so these two colonies may account for up to 3.6% of the British total.

Other breeding seabirds found on the Solway include approximately 2,500 pairs of large gulls at Rockcliffe Marsh, consisting of lesser black-backed gulls *Larus fucus* and herring gulls in an approximate 3:1 ratio, and an estimated 8 pairs of great black-backed gulls *L. marinus* (Bailey & Bailey 1986-92). The lesser black-backed gulls are most significant in a national context and account for about 2.3% of the British population estimate given in Lloyd *et al.* (1991). The 600 pairs of herring gull make up 0.4% of the population (Gibbons *et al.* 1993). The small colony of black-headed gulls on Rockcliffe Marsh is in decline. Nest count estimates since 1986 are as follows: 594, 793, 893, 1,267, 1,007, 303 and 147 (Bailey & Bailey 1986-1992). This dramatic decline has also happened on other parts of the Solway in the past (K. Bruce pers. comm.) and is a common trait of this species which readily abandons the use of one colony in favour of another.

Estuaries support 37% of British common terns *Sterna hirundo* (Davidson *et al.* 1991) yet they occur on relatively few sites (Prater 1981). Rockcliffe is one such site and held on average over 100 pairs of common terns (and a few Arctic terns *Sterna paradisaea*) from 1986 to 1990 although numbers since then have been much lower and breeding success extremely poor. No young fledged in 1993 making it the fifth consecutive year when breeding was unsuccessful. Historical records show that common terns once bred on Kirkconnell and Southwick merses (K. Bruce pers. comm.) but these colonies have also disappeared, in line with this species' downward national trend (Lloyd *et al.* 1991). Historically little terns *S. albifrons* nested at Grune Point and Mersehead Sands but no longer do so regularly.

Conclusions

Large numbers of waterfowl occur on the Solway throughout the year. WeBS counts have shown that the Solway is a key site for waterfowl in Britain and north-west Europe. Summing species maxima in a single year, and taking into account high, low and roost counts, Quinn *et al.* (1993) suggest that a minimum of 230,000 individual waterfowl use the Solway in 12 months. With population turnover, the figure is probably nearer 400,000.

The distribution of birds during the day is reasonably well known. Diving birds occur in shallow waters on the outer parts of the estuary while waders and wildfowl are more evenly distributed. Blackshaw Bank was especially important for waterfowl in terms of numbers but parts of the inner estuary held highest densities. Practically nothing is known about the nocturnal distribution of waterfowl, but the available evidence suggests that this may differ markedly from that observed during the day (Quinn *et al.* 1993).

Although the numbers of many waterfowl species on the Solway have been well established, particularly in winter, there remain considerable practical difficulties in acquiring similar levels of information about others, notably seaducks and grebes. Acquiring such information in a large estuary like the Solway needs substantial input of additional resources. It is important to consider the limitations of conventional monitoring procedures when assessing the significance of an estuary to waterfowl.

Acknowledgements

Special thanks are due to the WeBS volunteers who count the Solway every month: J. Skilling, J. Barclay, C. Mitchell, C. Rolie (RSPB), E. Fellowes, J. Randell, W. Wright (Scottish Natural Heritage), V. Fleming (SNH), K. Bruce, R. Smith, J. Kirkwood, D. Hodgson, D. Bailey (Cumbria Trust for Nature Conservation), C. Wilson, E. Rhone, J. Brown, R. Atkins, J. Ryden, R. Hancock, V. Stanger, M. Tullock, N. Holton (RSPB), F. Mawby (English Nature), J. Hamer, R. Mearns, B. Mearns and Fraser Patterson. Thanks to P. Cranswick and M. Pollitt for supplying WeBS wildfowl data, and Ray Waters from the BTO for supplying the WeBS wader data. The following helped with low tide counts: N. Holton, D. Bailey, C. Wilson, K. Bruce, J. Shotton, J. Drew, T. Drew and D. Parish. A special thanks to J. Stenning for fieldwork undertaken in the first six months of the project, to P. Cranswick who also helped in the early stages and P. Lambdon who played a major role in the second year's fieldwork. Frank Mawby (EN) organised the goose roost counts and G. Baker provided information on breeding ringed plover at Grune. Thanks also to Jack Sheldon, the Wash Wader Ringing Group and the North Solway Ringing Group, who undertook the wader catches. Thanks to British Nuclear Fuels Ltd who commissioned the 1991-1993 WAS project. Thanks also to R. Warren (OVE ARUP), D. Price (WAS) and C. Menendez.

References

Allport, G., O'Brien, M., & Cadbury, C.J. 1986. Survey of redshank and other breeding birds on saltmarshes in Britain in 1985. *Nature Conservancy Council, CSD Report,* No. 649.

Atkinson-Willes, G.L. 1963. *Wildfowl in Great Britain.* London, HMSO.

Bailey, D., & Bailey, J. 1986 *et seq. Reports to the Reserves Committee on the management of the Rockcliffe Marsh Reserve during the 1986 season.* Unpublished, Cumbria Trust for Nature Conservation.

Bowes, A., Lack, P.C., & Fletcher, M.R. 1984. Wintering gulls in Britain, January 1983. *Bird Study, 31:* 161-170.

Cadbury, C.J., Green, R.E., & Allport, G. 1987. Redshanks and other breeding waders of British saltmarshes. *RSPB Conservation Review, 1:* 37-40.

Carrier, M., *ed.* 1992. *Birds in Cumbria. A county natural history report for 1992.* Cumbria Naturalists Union.

Carrier, M., & Baker, G. 1991. Breeding cormorants in the Solway. *In: Birds in Cumbria,* ed. by M. Carrier, 76-78. Cumbria Naturalists Union.

Cranswick, P.A., Kirby, J.S., & Waters, R.J. 1992. *Wildfowl and wader counts 1991-92.* Slimbridge, The Wildfowl & Wetlands Trust.

Danielsen, F., Skov, H., & Durinck, J. 1992. Estimates of the wintering population of red-throated diver *Gavia stellata* and black-throated diver *Gavia arctica* in north-west Europe. *Proceedings of the Seventh Nordic Congress of Ornithology.*

Davidson, N.C., Laffoley, D. d'A., Doody, J.P., Way, L.S., Gordon, J., Key, R., Drake, C.M., Pienkowski, M.W., Mitchell, R., & Duff, K.L. 1991. *Nature conservation and estuaries in Great Britain.* Peterborough, Nature Conservancy Council.

Delaney, S. 1991. *Pilot survey of breeding shelduck in Great Britain and Northern Ireland, April to July 1990.* Report to the Nature Conservancy Council by the Wildfowl and Wetlands Trust.

Fox, A.D., Mitchell, C., Stewart, A., Fletcher, J.D., Turner, J.V.N., Boyd, H., Shimmings, P., Salmon, D.G., Haines, W.G., & Tomlinson, C. 1994. Winter movements and site fidelity of pink-footed geese *Anser brachyrhynchus* ringed in Britain, with particular emphasis on those marked in Lancashire. *Bird Study, 41(3):* 221-234.

Gibbons, D.W., Reid, J.B., & Chapman, R.A., *eds.* 1993. *The new atlas of breeding birds in Britain and Ireland: 1988-1991.* London, Poyser.

Kersten, M., & Smit, C.J. 1984. The Atlantic coast of Morocco. *In: Coastal waders and wildfowl in winter,* ed. by P.R. Evans, J.D. Goss-Custard & W.G. Hale, 276-292. Cambridge, Cambridge University Press.

Kirby, J.S., Gilburn, A.S., & Sellers, R.M. 1995. Status, distribution and habitat use by cormorants *Phalacrocorax carbo* wintering in Great Britain. *Ardea, 83(1):* 93-102.

Lack, P.C. 1986. *The atlas of wintering birds in Britain and Ireland.* Calton, Poyser.

Lloyd, C., Tasker, M.L., & Partridge, K. 1991. *The status of seabirds in Britain and Ireland.* London, Poyser.

Mawby, F. 1988-93. *Reports on the results of the pink-footed goose counts on the Solway Firth.* (Unpublished reports.)

Mearns, R.J. 1977. *Roosting and feeding waders on the north shore of the Inner Solway.* Unpublished report to the Nature Conservancy Council.

Monval, J.-Y., & Pirot, J.-Y. 1989. *Results of the IWRB International Waterfowl Census 1967-86.* Slimbridge, IWRB. (IWRB Special Publication No. 8.)

Moser, M.E. 1984. *Solway winter shorebird survey 1982-84.* Report to the Nature Conservancy Council and the Royal Society for the Protection of Birds. Tring, British Trust for Ornithology.

Moser, M.E., & Carrier, M.F. 1984. Patterns of population turnover in ringed plovers and turnstones during their spring passage through the Solway Firth in 1983. *Wader Study Group Bulletin, 39:* 37-41.

Owen, M., Atkinson-Willes, G.L., & Salmon, D.G. 1986. *Wildfowl in Great Britain.* 2nd ed. Cambridge, Cambridge University Press.

Prater, A.J. 1979. Trends in accuracy of counting birds. *Bird Study, 26:* 198-200.

Prater, A.J. 1981. *Estuary birds of Britain and Ireland.* Calton, Poyser.

Prater, A.J. 1989. Ringed plover *Charadrius hiaticula* breeding population of the United Kingdom in 1984. *Bird Study, 36:* 154-159.

Quinn, J.L., Still, L., Carrier, M.F., & Lambdon, P. 1993. *The distribution of waterfowl and other bird species on the Solway Firth, at Chapelcross, and in the Annan catchment: October 1991-July 1993.* Final report prepared by the Wetlands Advisory Service for British Nuclear Fuels Ltd. (3 Volumes.)

Quinn, J.L., Still, L., Kirby, J.S., Carrier, M.F., & Lambdon, P. 1997. The effects of cockling on the numbers and distribution of scaup *Athya marila* on the Solway Firth. *Wildfowl, 47.*

Reed, T. 1985. Estimates of British breeding wader populations. *Wader Study Group Bulletin, 45:* 11-12.

Shimmings, P., Choudhury, S., Owen, M., & Black, J.M. 1993. *Wintering barnacle geese on the Solway Firth. Report to Scottish Natural Heritage on the 1992-93 season.* Slimbridge, The Wildfowl & Wetlands Trust.

Smith, K.W. 1983. The status and distribution of waders breeding on wet lowland grasslands in England and Wales. *Bird Study, 30:* 177-192.

Smit, C., & Piersma, T. 1989. Numbers, midwinter distribution, and migration of wader populations using the East Atlantic Flyway. *In: Flyways and reserve networks for water birds,* ed. by H. Boyd & J-Y. Pirot, 24-63. Slimbridge, IWRB. (IWRB Special Publication No. 9.)

Stroud, D.A., Mudge, G.P., & Pienkowski, M.W. 1990. *Protecting internationally important bird sites - A review of the EEC Special Protection Area network in Great Britain.* Peterborough, Nature Conservancy Council.

Watson, A.D., *ed.* 1988. *Dumfries and Galloway Region Bird Report.* Dumfries, Scottish Ornithologists' Club.

Webb, A., Harrison, N.M., Leaper, G.M., Steele, R.D., Tasker, M.L., & Pienkowski, M.W. 1990. *Seabird distribution west of Britain.* Peterborough, Nature Conservancy Council.

Williams, G. 1980. An index for the ranking of wildfowl habitats, as applied to eleven sites in West Surrey, England. *Biological Conservation, 18:* 93-99.

Coastal Zone Topics, 2: 126-129

The Solway Firth Partnership: a Coastal Zone Management initiative

S.M. Atkins

S.M. Atkins, Scottish Natural Heritage, 2 Anderson Place, Edinburgh EH6 5NP

Background

The Solway Firth is a largely unchanged environment crucial to the lives of the whole population inhabiting its shores. It includes some of the largest expanses of tidal mudflats in the UK, which provide feeding grounds for a high density and diversity of wildlife. The coastal waters and rivers of the Solway support important salmon and sea trout fisheries. The peace, tranquillity and scenic beauty of the Solway is perhaps its greatest attraction and the landscapes are world renowned for their high quality and variety.

The range and levels of human activities around the Solway are continually increasing. In recent years cockle fishing has arrived on a commercial scale, inshore exploration for oil and gas has commenced, gas and electricity infrastructure has been constructed, more facilities for the tourist and recreation industries have been established as demand continues to increase and there are currently plans for a new nuclear reactor development at Chapelcross.

These increasing demands on the firth have provoked a raised awareness and concern that some activities may conflict with other interests. This creates a challenge for the whole population to manage the use and development of the resources of the Solway in a sustainable manner.

The Solway Firth Partnership represents a major step towards addressing this challenge by promoting co-operation and consensus between users, managers and planners from both the Scottish and English sides of the firth. The partnership, which is supported by all the statutory agencies in the region, was launched in Dumfries by Magnus Magnusson in June 1994. The overall aim of the Solway Partnership is:-

To develop in partnership with others, a management strategy which promotes the current and future uses of the Solway Firth for the purpose of achieving a level of social, economic and ecological development for the region that is compatible with the principles of the sustainable use of the natural resources.

The Solway project receives strong financial support from the Scottish Natural Heritage 'Focus on Firths' and English Nature's 'Estuaries' Initiatives. Both of these are national programmes to raise awareness of the environmental importance of firths and estuaries, promoting their wise and sustainable use and development through the approach of voluntary integrated coastal zone management (ICZM). The Solway is also referred to in the UK Biodiversity Action Plan where an objective is included to put in place a management strategy for the firth by 1998. The work of the Solway Partnership is expected to lead to the achievement of this objective.

Structure of the Solway Partnership

The steering group of the partnership comprises representatives of all organisations that hold statutory powers and responsibility in and around the firth (Figure 1). The steering group meets at approximately quarterly intervals to review progress and determine the overall direction of the project. The day to day management and administration of the work programme is overseen by a smaller working group, comprising members of the steering group. The working group meets at approximately six-weekly intervals. The secretariat for the partnership is provided by a Project Officer, managed by SNH with co-funding from EN. Substantial resources of Officer time and funds are being made available by steering group partners. In particular, Dumfries and Galloway Regional Council have provided significant public relations input which has raised the profile of the project. The Solway Partnership is currently in receipt of funding from the EU in accordance with the Objective 5b structure fund status of the area.

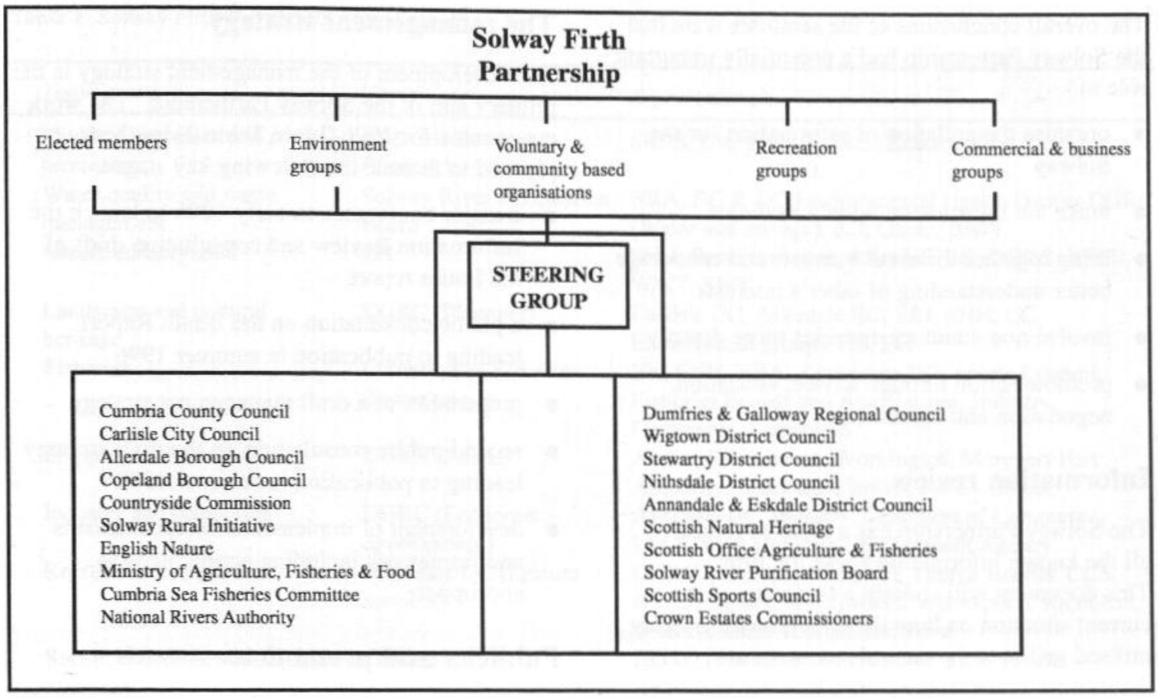


Figure 1 The Steering Group of the Solway Firth Partnership.

Detailed objectives of the Solway Firth partnership

These are to:-

- identify sustainable management principles for the Solway which have wide acceptance and support
- establish a mechanism or structure within which a strategy for the integrated and sustainable management of the Solway can be developed and implemented
- produce a management strategy containing policy and management guidelines covering all aspects of estuary use that can be implemented by all interests
- implement a management strategy agreed by all interested parties so that future management plans for particular localities and sectors are fully integrated with other interests and are sustainable
- promote participation of, and partnership between all managers, users, interest groups and local community members to ensure broad support and ownership of the process and decisions leading towards the sustainable management of the Solway.

The long-term goal is to assist the management structures already in place to deliver policies and management plans which are informed by a set of principles for the sustainable management of the estuarine resources and agreed to by all firth users.

Community seminars

An early task of the partnership was to survey the opinions, concerns, values and aspirations of all inhabitants and interest groups on the constraints and potential for management in the Solway. If the aims of the partnership are to be achieved it is essential that wide ownership and a shared vision of how the firth should develop in the future should be developed. To address this need, a series of seminars were held in July 1994 to which a wide range of over 500 organisations, societies and individuals were invited and approximately 100 people contributed.

Themes which characterised the discussions included:-

- the special nature of the Solway in relation to wildlife, landscapes, peace and tranquillity and the characteristics of a working estuary with many unspoiled features
- sustainability and the balance between prosperity and natural resources
- legislation, particularly cross-border differences with respect to fisheries and wildfowling
- concern over pollution such as sewage, industrial, oil, radioactivity and litter
- the need for information
- the economy and employment prospects
- the need for local community involvement and ownership.

The overall conclusions of the seminars were that the Solway Partnership had a potentially important role to:-

- organise the collation of information for the Solway
- make the information widely available
- bring together different interests and encourage better understanding of other's interests
- involve non-statutory agencies more directly
- promote action through advice, education, negotiation and agreement.

Information review

The Solway Partnership has a remit to review all the known information about the firth. This document will contain a summary of the current situation on how the environment is being utilised and how the natural resources are distributed. This 'Information Review' will help the Partnership identify where different interests overlap, and what the key issues and development opportunities are. It will also list the main sources and identify the existence of more detailed information. The Solway Firth Information Review should be an easy to read document with data and information presented mainly in a graphical format using maps.

It is further intended that the Information Review will inform the most important phase of the project, namely seeking consensus over the various components of a management strategy.

Topic groups

The Information Review is being written by a wide range of organisations and individuals contributing to the partnership. A series of ten specialist sub-groups or 'topic groups' have been set up to prepare appropriate chapters of the review. Each group is led by a chairman, usually a member of the Partnership management group, and between five and ten core members who meet regularly during the period of work and carry out the bulk of the task. The review will be further informed by a wide range of individuals and organisations representing the wider partnership of interests. The list of topic groups, chairmen and key participants are shown in Table 1.

Following their review of information, topic groups will continue working towards the identification of the key issues which are indicated by the Information Review. These will be collated into an 'Issues Report' which will be circulated widely as a draft for consultation at the same time as the Information Review is published.

The management strategy

The development of the management strategy is the primary aim of the Solway Partnership. The work programme for 1996-7 (see Table 2) has been planned to include the following key stages:-

- a major conference in early 1996 to launch the Information Review and consultation draft of the Issues report
- a public consultation on the Issues Report leading to publication in summer 1996
- preparation of a draft management strategy
- second public consultation on the draft strategy leading to publication in summer 1997
- development of implementation mechanisms and framework including action plans as appropriate.

Publicity and promotion

In order to be effective, the Partnership must generate a high profile throughout the Solway Firth area. Towards this aim, a newsletter *Tidelines* is published several times a year which is received by the full mailing list of over 600 addressees. Anyone who has useful material or information can contribute to this bulletin. An exhibition has toured libraries, agricultural shows and other venues throughout the Solway and a programme of seminars and approximately annual conferences is planned. For more details of any of this information please contact the Solway Firth Project Officer, Scottish Natural Heritage, Dumfries.

Table 1 Solway Firth Partnership - topic groups.

Topic group	*Chair*	*Representation*
Physical processes and coastal protection	Allerdale Borough Council	SRPB, EN, SNH, DGRC (Roads), NRA
Water quality and waste management	Solway River Purification Board	NRA, BC & DC Environmental Health Depts., DGRC (Water and sewage), ICI, Glaxo, BNFL
Nature conservation	EN	SNH, Rural Initiative, Allerdale BC, DGRC, RSPB, WWT, SWT
Landscape and cultural heritage	DGRC (Planning)	Carlisle CC, Allerdale BC, SRI, SNH, CC, Environment groups, HS, EH
Fisheries	Cumbria Sea Fisheries Committee	EN, SNH, NRA, Annandale DC, Sports Council, Fisheries Boards and Associations, Industry, Commerce, Recreation
Shipping and navigation	DGRC (Roads)	Annan, Whitehaven, Workington, Maryport Port Authority, Associated British Ports - Silloth
Industry and commerce	DGRC (Economic development)	Allerdale BC, Industry, Chambers of Commerce, LECs, West Cumbria Development Agency
Recreation and tourism	Nithsdale DC (Leisure services)	DGRC, Allerdale BC, SNH, Tourist Boards, CCS, RYA, Anglers, Wildfowlers, Watersports, Ramblers, West Cumbria Tourism Initiative
Social, economic and physical planning	Carlisle CC	DGRC (Planning), Allerdale BC, SW Forum, Voluntary Action Cumbria, LECs
Land use/ownership	Scottish Landowners Federation/Lord Annandale	Landowners & organisations, Farmers Union, SNH

Table 2 Work programme.

Expected output		*Date*
Publication Information Review.	Prepared by topic groups comprising the key statutory and non-statutory organisations.	March 1996
Publication of Issues Discussion Paper.	Prepared by topic groups and with wider involvement.	March 1996
Conference.	To launch the Information Review and the Issues Document.	March 1996
Consultation of Issues.	Public Consultation to involve as wide range of interest groups as possible.	June 1996
Publication of Issues Report.	Based on work of topic groups and feedback from consultations. This will focus on key strategic issues on Solway and development.	July 1996
Development of management principles.	Topic groups will be cross-sectoral and develop management principles in the context of key issues in Issues Report.	October 1996
Preparation of draft management strategy and consultation.	Topic groups prepare draft management strategy containing management principles and actions required.	October 1997
Publication of Management Strategy.	Based on work of topic groups and feedback from consultation.	January 1998
Establish Implementation Framework.		April 1998
Public Awareness and understanding of the Partnership.	The process of issues resolution, consensus, building, developing management principles will be open to public involvement. This will consist of newsletters, seminars, talks, leaflets, displays, public consultations, conferences.	April 1998

Coastal Zone Topics, 2: 130-136

Marine Nature Conservation Review studies in the eastern basin of the Irish Sea - the Solway in a regional context

R. Covey

As part of the Joint Nature Conservation Committee's Marine Nature Conservation Review (formerly carried out within the Nature Conservancy Council) littoral and sublittoral marine biological surveys have been undertaken in the eastern basin of the Irish Sea (from Colwyn Bay to the Mull of Galloway). Information gathering and field survey has been completed and data from these two sources have been analysed to produce descriptions of the biotopes (i.e. habitats and their associated communities) present. The results from this exercise will enable comparison and evaluation of sites including identification of the best examples of each biotope present. The biotopes described will also contribute to a national classification being developed within the MNCR.

In this paper the Solway has been defined as extending east of a line between St Bees Head and the Mull of Galloway. Littoral sediment habitats show a clear zonation from relatively clean tide-swept or mobile sand in the west, through muddier fine sand in areas such as Wigtown Bay and Auchencairn Bay, to mud with very fine sand at the head of many of the feeder estuaries in the east.

Rocky littoral biota show a slight gradation with decreasing salinity up the firth from the Mull of Galloway, though few rocky shores occur towards the head of the Solway where salinity is consistently reduced.

Rocky sublittoral biota also show a gradation from west to east, allied to the scouring effect of suspended sediment in the water column, which increases eastwards from Burrow Head. Tide-swept rock occurs around the Mull of Galloway and Burrow Head, with rich communities dominated by filter feeders, typical of tide-swept rock. Further east, bedrock becomes more limited in extent, and communities become characterised by scour-resistant species such as the bryozoan *Flustra foliacea*.

R. Covey, (formerly) Joint Nature Conservation Committee, Department of Biological and Molecular Sciences, University of Stirling, Stirling FK9 4LA, United Kingdom

Introduction

The Solway is the largest estuary in the eastern basin of the Irish Sea, that part of the coastline between Colwyn Bay in the south and the Mull of Galloway in the north. Covering an area of over 2,400 km^2 the Solway forms a substantial portion of this section of coast. Many workers have placed differing boundaries on the Solway Firth, but for the purpose of this paper, the Solway is taken to include all of the area east of a line from Mull of Galloway to St Bees Head, extending into the firth to the limits of saline influence (Figure 1). This area includes a diverse range of habitats, from the wave- and tide-swept rocky headland of the Mull of Galloway to the sheltered muddy backwaters at the head of the firth.

The surveys described here have been undertaken as part of the Marine Nature Conservation Review, which was initiated in 1987 under the auspices of the Nature Conservancy Council, later transferring in 1991 to the Joint Nature Conservation Committee. The aims of the MNCR are to:

- extend the knowledge of benthic marine habitats, communities and species in Great Britain, particularly through description of their characteristics, distribution and extent;
- identify sites of nature conservation importance. MNCR data also support more general measures opposing the adverse effects of development and pollution.

Charged with these responsibilities, survey work commenced on the Irish Sea coasts in 1989 continuing until 1991. During this period 12 surveys were carried out, describing much of the coastline of the eastern basin of the Irish Sea. These surveys resulted in the description of 213

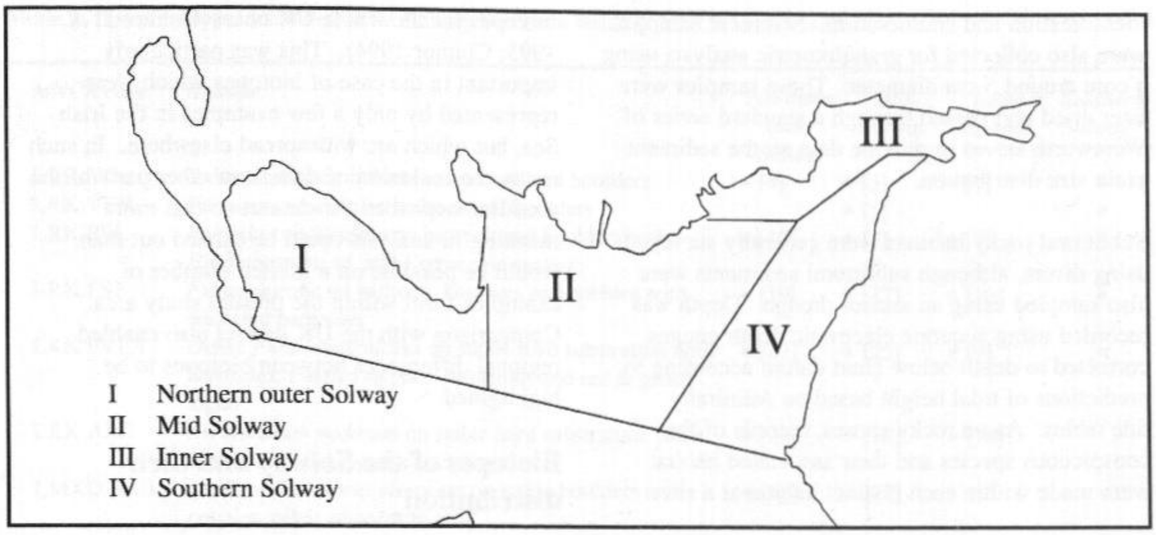


Figure 1 Boundaries of outer, mid and inner Solway areas.

sites, with further subdivision resulting in records describing 652 separate habitats from these sites. Surveys were carried out by MNCR staff, augmented by contract field staff.

MNCR data presented in this paper are for all littoral sediments, and for littoral and sublittoral rock.

Methodology and MNCR surveys

There are six main elements to the MNCR's work:

- collation and assessment of existing information;
- commissioning new field surveys to fill in gaps in our knowledge;
- classifying marine ecosystems;
- comparing and evaluating sites;
- identifying sites and species of nature conservation importance;
- publishing results.

Data used to describe biotopes in the eastern basin of the Irish Sea have come largely from MNCR surveys, with additional information from surveys carried out by other organisations such as North West Water and National Rivers Authority North West Region. Any additional data used were checked to ensure compatibility of data collection with MNCR methods, and to ensure the data were of suitable quality.

MNCR survey methodology is described fully by Hiscock (1990). In summary, for each length of coast, field surveyors identified the range of different habitats present and, within each habitat, described the communities present by their conspicuous species. Sediment core samples were taken where appropriate to describe the infauna. Survey sites were selected after consulting available information to avoid resurveying sites for which adequate data existed, and to ensure the complete range of physiographic and habitat types within the survey area were sampled.

Rocky shores were surveyed from the lowest level of terrestrial plants, down to the lowest level of tide that day (surveying on spring tides). After an initial inspection, the shore was divided into a number of zones or habitats where distinctly different assemblages of plants and animals were present. Detailed records were made from each of these habitats, recording both physical data such as substratum and angle of slope, and noting conspicuous species of plants and animals using a six-point abundance scale.

On sediment shores, both descriptive and quantitative sampling were carried out. Sampling stations were usually located in the upper, mid- and lower shore levels, but on extensive shores more samples were taken over the length of the shore. In addition to taking samples down the length of the shore, samples were also taken from locations where different sediment types occur, or on less uniform shores where the biota was different. Descriptive survey was carried out at each station to describe the physical features, including sediment type, firmness, stability, draining, and surface features such as ripples, holes, casts and tubes. An area of around 1 m^2 was dug over to a depth of around 30 cm to identify conspicuous, widely-dispersed infauna which was then assessed for abundance. More detailed samples for smaller infauna were taken by collecting four cores of 0.01 m^2, sieving these over a 0.5 mm mesh sieve and preserving the remaining material in eosin formalin for later sorting, identification and enumeration. Sediment samples were also collected for granulometric analysis using a core around 5 cm diameter. These samples were later dried and passed through a standard series of Wentworth sieves to provide data on the sediment grain size distribution.

Sublittoral rocky habitats were generally surveyed using divers, although sublittoral sediments were also sampled using an anchor dredge. Depth was recorded using accurate electronic depth gauges, corrected to depth below chart datum according to predictions of tidal height based on Admiralty tide tables. As on rocky shores, records of the conspicuous species and their associated habitat were made within each distinct habitat at a site.

Data analysis and interpretation

Field data collected during MNCR surveys were entered into a purpose-built computer database which allows storage, fast access and manipulation of the data. Also interfaced with the database are analytical packages, including TWINSPAN (Two-Way Indicator Species Analysis) (Hill 1979a) and DECORANA (Detrended Correspondence Analysis) (Hill 1979b). Further details of the MNCR database can be found in Mills (1991), and further information on the analysis of MNCR data can be found in Mills (1994).

Data analysis consists of identifying groups of similar field habitat records to produce a catalogue of 'biotopes' present in the eastern basin of the Irish Sea, a biotope being the combination of habitat and its associated community (Connor *et al.* 1995). To produce biotope descriptions, groups of habitat records are analysed using TWINSPAN to identify similarities and differences between records on the basis of their species composition. Initial manual selection of broad groups of habitat records is carried out to prevent too many variables masking changes due to smaller variations of a single variable. For example, all records of rocky habitats were initially split manually from those of sediment. The groupings suggested by TWINSPAN on the basis of species differences were then assessed to determine whether valid differences in the habitat were present, or whether variation may be due to chance factors such as recruitment. If valid differences in the habitat matched the differences in the species present, then the grouping was considered to represent a valid biotope. A listing of all the rock and littoral sediment biotopes identified for the Solway Firth is given in Table 1.

In drawing together biotope descriptions for the Irish Sea it was important to take into account the parallel development of a classification of marine biotopes for the whole UK coast (Connor *et al.* 1995; Connor 1994). This was particularly important in the case of biotopes which were represented by only a few examples in the Irish Sea, but which are widespread elsewhere. In such cases, the inclusion of data from other parts of the coastline expanded the dataset so that more meaningful analysis could be carried out than would be possible on a limited number of examples from within the present study area. Comparison with the UK dataset also enabled regional differences between biotopes to be highlighted.

Biotopes of the Solway and their distribution

For comparative purposes the Solway has been divided into four areas shown in Figure 1: the northern outer Solway, from the Mull of Galloway to the Isle of Whithorn; the mid-Solway, from the Isle of Whithorn to Balcary Point; the inner Solway, east of a line from Balcary point to Grune Point; and the southern Solway, from Grune Point to St Bees. These divisions largely follow those suggested by Perkins (1978) on the basis of hydrographic differences. The distribution of biotopes within these areas is given in Table 1, and portrayed graphically in Figure 2. Codes given in brackets in the text refer to the biotope types. Further information and descriptions of these biotopes can be found in Covey (in prep).

The Solway Firth has a diverse range of biotopes, being situated at an area of transition between the enclosed turbid waters of the eastern Irish Sea, and the more wave-exposed, clear waters of south-west Scotland. Sediment shores show a marked gradient of change from wave-exposed coarse sands in the outer Solway to sheltered low salinity muddy fine sands at the head of the firth. In very few areas of the Solway does 'pure' mud occur, finer sediments being composed generally of a large proportion of very fine sand, with a maximum of around 50% silt/clay fraction. It is worth noting that the Solway is unusual since the sediments are largely of marine rather than fluvial origin (Perkins 1978). This causes differences in the biotopes when compared with other estuaries, where similar salinity regimes coincide with muddier conditions (for example Hill & Emblow in prep).

Outer Solway sediment shores are characterised by a suite of biotopes typical of mobile, fully-saline clean sands. In the most mobile sediments, typically only sparse populations of burrowing amphipods are present with the isopod *Eurydice pulchra* and very few polychaetes (LSND.AE). This biotope was only recorded from the outer Solway, where suitable wave-exposed conditions

Table 1 List of biotopes identified in the Solway Firth as a result of MNCR survey work.

*MNCR code**	*Biotope*	*Northern outer Solway*	*Mid-Solway*	*Inner Solway*	*Southern Solway*[a]
LRK.YG	Yellow and grey lichens on bedrock and boulders	• [4]	• [5]	• [7]	•
LRK.VER	*Verrucaria maura* on bedrock and boulders		• [5]		•
LRK.PEL	*Pelvetia canaliculata* on bedrock and boulders with *Hildenbrandia* sp. and *Verrucaria maura*	• [10]	• [7]	• [7]	•
LRK.FSP	*Fucus spiralis* on bedrock, boulders and cobbles with scattered barnacles	• [19]	• [17]	• [10]	•
LRK.FVES	Dense *Fucus vesiculosus* on stable hard substratum with barnacles, *Patella vulgata*, littorinids and red & green algae	• [27]	• [25]	• [9]	•
LRK.ASC	*Ascophyllum nodosum* on stable hard substratum, often with associated *Fucus vesiculosus*	• [25]	• [18]	• [18]	
LMXD.SAB	Reefs of *Sabellaria alveolata* on stable boulders and cobbles, often adjacent to sand	• [13]	• [23]		•
LRK.MYT	Dense beds of *Mytilus edulis* on stable hard substratum	• [16]	• [15]	• [14]	•
LMXD.MYT	Dense beds of *Mytilus edulis* on sediment mixture with associated infauna			• [11]	•
LMXD.SB	Mobile and scoured boulders on sediment with abraded barnacles.	• [8]	• [4]	• [7]	•
LRK.BP	Open coast wave-exposed bedrock with *Patella vulgata* and barnacles (predominantly *Semibalanus balanoides* and *Elminius modestus*)	• [17]	• [20]	• [17]	•
LRK.P	Rockpools	• [37]	• [23]		•
LMXD.BLIT	Upper and midshore barnacle dominated scar grounds	• [9]	• [13]		•
LMXD.BLE	Boulders cobbles and pebbles subject to low salinity, with barnacles, littorinids and *Enteromorpha* sp.			• [3]	
LRK.FSE	*Fucus serratus* dominated lower shore hard substratum	• [30]	• [28]		•
LMXD.SAR	Species rich lower eulittoral mixed cobbles pebbles and sediment with sponges and ascidians	• [29]	• [30]		•
LRK.LDIG	Sublittoral fringe bedrock and boulders with *Laminaria digitata*	• [31]	• [37]		•
LSND.AE	Burrowing amphipods with *Eurydice pulchra* and few polychaetes	• [6]			
LSND.AP.S	Burrowing amphipods with polychaetes	• [2]	• [2]		•
LSND.AP.AR	Burrowing amphipods with *Arenicola marina*	• [5]	• [5]		•
LSND.AP.A	Amphipods with bivalves *Angulus tenuis*, *Donax vittatus* and *Fabulina fabula*	• [14]	• [21]		•
LMSND.PC	Clean sands with polychaetes and *Cerastoderma edule*		• [12]	• [8]	•
LMSND.LAN	Dense *Lanice conchilega*		• [6]		
LMUD.HM	*Hediste diversicolor* with *Macoma balthica* but without *Scrobicularia plana*			• [10]	•
LMUD.HS	*Hediste diversicolor* with *Scrobicularia plana*		• [9]	• [14]	
LMUD.HC	*Hediste diversicolor* with *Corophium volutator* without bivalves		• [7]	• [5]	
LMUD.HO	*Hediste diversicolor* with oligochaetes				•
SRK.SC	Sand scoured sublittoral fringe bedrock				•
SRK.LHYP	Dense forest of *Laminaria hyperborea*	• [78]			
SMXD.UR	Mixed rocks and sand with *Urticina felina* and red algal turf	• [36]			
SMXD.RB	Lower infralittoral algal dominated bedrock, boulders and cobbles	• [10]	• [45]		
SMXD.SSP	Reefs of *Sabellaria spinulosa* on boulders and cobbles	• [76]			
SMXD.SHA	Current-swept silted bedrock, boulders and cobbles with a rich turf of sponges, hydroids and ascidians		• [43]		
SRK.STA	Tide-swept circalittoral bedrock and boulders with sponges, *Tubularia* and *Alcyonium digitatum*	• [49]			

[ ] = mean number of species per biotope example in each area. [a] Data for the Southern Outer Solway have not been quantified; as non-MNCR data have been included, the methodology is not directly comparable. Note: since the time of writing, the MNCR codes have been modified as part of the national classification of biotopes.

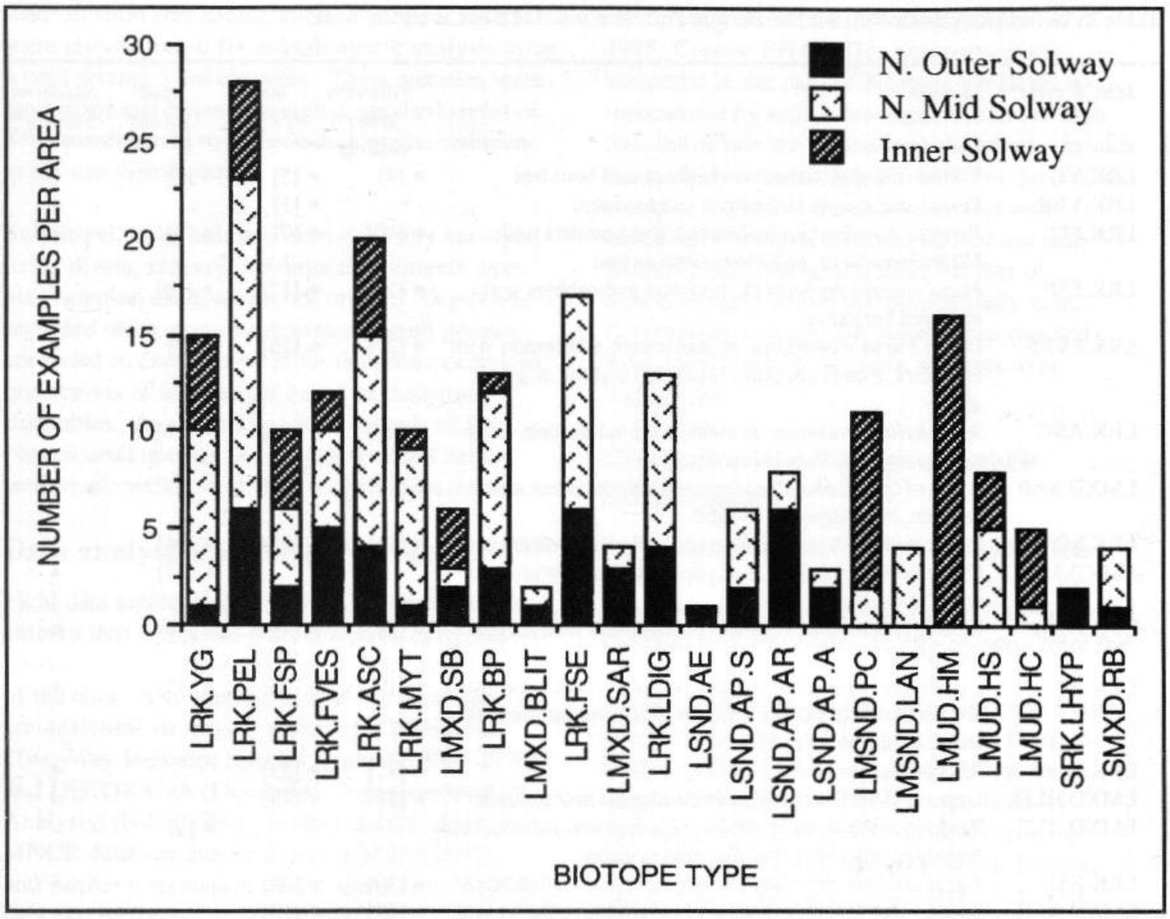


Figure 2 Distribution of selected biotopes in the Solway Firth.

occurred. Reduced wave exposure, in embayments or in the shelter of headlands, allows a greater range of polychaetes together with burrowing amphipods (LSND.AP.S) to colonise the sand. Further reduction in wave exposure allows the colonisation by dense populations of *Arenicola marina* (LSND.AP.AR), then by populations of robust bivalves such as *Angulus tenuis, Donax vittatus* and *Fabulina fabula* (LSND.AP.A). All of these biotopes are present only in the outer and mid-Solway, being absent from the more wave-sheltered inner Solway.

Absent from the outer Solway, but widespread in the mid- and inner Solway, are biotopes of more sheltered and estuarine conditions. The change in these conditions is demonstrated initially by the presence of the cockle *Cerastoderma edule* in cleaner sands with polychaetes such as *Arenicola marina* (LMSND.PC). There is a trend towards the head of the firth of increasing silt content in the sediment and decreasing salinity. This leads initially to communities of *Hediste diversicolor* with *Macoma balthica* (LMUD.HM), then to *H. diversicolor* with *Scrobicularia plana* (LMUD.HS) and finally to *H. diversicolor* and *Corophium volutator* with no bivalves, but a range of oligochaetes present (LMUD.HC).

Intertidal rock communities show a limited change in character up the firth, with changes in siltation and turbidity apparently having a limited effect on the intertidal biota. The main variation in the intertidal communities is due to changes in wave exposure and salinity, with examples of similar biotopes showing a reduction in the average number of species recorded from west to east (Table 1). Most of the rocky littoral biotopes were present throughout the Solway, since suitable hard substratum occurs in all areas, although it is more limited in the inner Solway. Lower shore communities show the greatest change, being absent from the inner Solway due to a lack of suitable lower shore rock. For example, *Fucus serratus*-dominated rock (LRK.FSE), lower eulittoral cobbles with sponges and ascidians (LMXD.SAR) and sublittoral fringe bedrock with *Laminaria digitata* (LRK.LDIG) are all absent from the inner Solway. In contrast to the absence of lower shore rock communities, those that occur owing to reduced salinity are present only in the inner Solway area. These biotopes are boulders and cobbles with barnacles, littorinids and *Enteromorpha* sp. (LMXD.BLE) and beds of *Mytilus edulis* on muddy mixed substrata (LMXD.MYT).

Subtidal rock communities are predominantly affected by water turbidity. Clear waters sweep into the northern section of the Irish Sea through the North Channel, past the Mull of Galloway and the Scars, leading to the development of extremely rich sponge- and hydroid-dominated communities in the circalittoral zone (SRK.STA). Above this, in the infralittoral zone, dense forests of *Laminaria hyperborea* occur, extending to depths of around 12 m below chart datum. This contrasts markedly with the rocky substrata east of Burrow Head, where turbidity reduces light penetration such that kelps are limited to a maximum depth of 1 or 2 m below chart datum and fail to reach high densities. Burrow Head represents an area of sharp change, where the clear waters from the North Channel meet the silt-laden waters of the Solway Firth. Turbidity increases markedly east of this point. At Burrow Head, dense populations of the tube-building polychaete *Sabellaria spinulosa* occur, thriving in the tide-swept waters. Associated with the *S. spinulosa* is a rich community of hydroids and ascidians (SMXD.SSP). This particular biotope has not yet been recorded at any other site in Great Britain. Although dense colonies of *S. spinulosa* are known from a wide variety of other locations, none is associated with such a rich biota. The three examples of this biotope surveyed had a mean of 76 species recorded.

East of Burrow Head, increasing turbidity leads to decreasing species richness, and a change to species which are tolerant of the scouring effect of tide-swept, silt-laden water. The infralittoral zone is dominated by foliose and filamentous red algae (SMXD.RB), with kelps sparse, or in extreme turbidity limited by light intensity to the sublittoral fringe. Below the infralittoral, the circalittoral zone gradually extends into shallower water with increasing turbidity. Here communities are dominated by the scour-tolerant bryozoans *Flustra foliacea* and *Alcyonidium diaphanum* (SMXD.SHA). Associated with the strong tides is a diverse ascidian fauna. Algae are limited both by light intensity and by extensive silt deposition on upward-facing surfaces which would otherwise be suitable for algal colonisation.

East of Auchencairn Bay, sublittoral rock is absent, except for localised areas of boulders and cobbles which are covered and uncovered periodically by the shifting sandbanks of the inner Solway. In the southern outer Solway, the sublittoral zone consists mostly of sediment. Even at the southern boundary at St Bees Head, where substantial sandstone cliffs plunge around 50 m to the sea, the bedrock ends at a sand-scoured sublittoral fringe (SRK.SC) on the edge of a wave-cut platform adjacent to a plain of shallow sand.

Discussion

Data on habitats and species (biotopes) show a marked transition from the outer to the inner Solway, predominantly owing to changes in wave exposure, salinity and turbidity. Some of the changes also occur due to geological factors affecting the availability of hard substratum, and thus the distribution of biotopes. This transition is punctuated by major boundaries where distinct changes occur, such as the change from clear water to turbid around Burrow Head. These boundaries are reflected in the distribution of biotopes and support the division of the Solway into the four areas suggested earlier in accordance with those suggested by Perkins (1978) on the basis of hydrography. Perkins suggested further subdivisions, generally into open coast and each of the feeder estuaries, which are again reflected by the distribution of the mud biotopes in the estuaries, the muddy sand in the more open sections of the inner Solway, and the clean sands of the open coast.

There is also a gradient of change from north to south, due to changes in water quality and geology. Rocky biotopes are not well represented in the eastern basin of the Irish Sea, and those recorded in the Solway are among the best examples in the area. In particular the clear-water biotopes from around the Mull of Galloway are not present elsewhere in the eastern basin of the Irish Sea, and lower shore rocky biotopes are very poorly represented on the English coast of the Irish Sea.

Many of the sediment biotopes described from the Solway are found throughout the eastern basin of the Irish Sea. For example, large areas of Morecambe Bay consist of clean sands with *Cerastoderma edule* and polychaetes, whilst more sheltered estuarine areas such as the Duddon, Ribble and Dee Estuaries contain muddy fine sands with *Hediste diversicolor* and *Macoma balthica.*

Biotopes of particular note are those of tide-swept rock around the Mull of Galloway and boulders around Burrow Head. The clear-water, sponge- and hydroid-dominated sublittoral rock around the Mull of Galloway is not present in the rest of the eastern basin of the Irish Sea. However, good examples of this biotope are present in a number of locations around other parts of the western Scotland coast. The *Sabellaria spinulosa*-dominated boulders and cobbles of Burrow Head are not, however, known from any other sites around Britain. This limited distribution, along with the high species richness of the Burrow Head example, makes it of conservation importance.

The classification of habitats and communities into biotopes, where environmental and habitat factors are linked to characterising groups of species, provides a useful means of describing the marine environment in common 'units'. Using these biotopes as standard units, comparison can be made between adjacent areas of coast (providing data collection and analysis is compatible) to assess the conservation value in a structured fashion. Biotopes can be compared, and the best example of each selected for conservation.

References

Connor, D.W. 1994. *Marine biotopes. A working manual of biotopes from UK coastal waters. Version 11.94.* Unpublished, Joint Nature Conservation Committee.

Connor, D.W., Hiscock, K., Foster-Smith, R.L., & Covey, R. 1995. A classification system for benthic marine biotopes. *In: Proceedings of 28th European Marine Biology Symposium, Crete.* Olsen & Olsen.

Covey, R. In prep. *The eastern basin of the Irish Sea, benthic marine biotopes.* Peterborough, Joint Nature Conservation Committee.

Hill, M.O. 1979a. *TWINSPAN - a FORTRAN program for arranging multivariate data in an ordered two-way table by classification of the individuals and attributes.* Ithaca, New York, Cornell University.

Hill, M.O. 1979b. *DECORANA - a FORTRAN program for detrended correspondence analysis and reciprocal averaging.* Ithaca, New York, Cornell University.

Hill, T.O., & Emblow, C.S. In prep. Marine biological surveys of estuaries from Norfolk to the Swale (MNCR Sector 6): Classification of benthic marine biotopes. *Joint Nature Conservation Committee Report*, No. 149. (Marine Nature Conservation Review Report, No. MNCR/SR/23.)

Hiscock, K. 1990. Marine Nature Conservation Review: methods. *Nature Conservancy Council, CSD Report*, No. 1,072. (Marine Nature Conservation Review Report, No. MNCR/OR/5.)

Mills, D.J.L. 1991. Marine Nature Conservation Review: data handling systems. *Nature Conservancy Council, CSD Report*, No. 1,192. (Marine Nature Conservation Review Report, No. MNCR/OR/12.)

Mills, D.J.L. 1994. A manual for the analysis of marine field survey data held on the Marine Nature Conservation Review database. *Joint Nature Conservation Committee Report*, No. 173. (Marine Nature Conservation Review Report, No. MNCR/OR/18.)

Perkins, E.J. 1978. *The Solway Firth - its hydrology and biology.* Unpublished, Nature Conservancy Council, Scotland, South-west Region. (Internal report, No. NC 178 J).

Broad-scale biotope mapping survey of the Solway Firth

N. Cutts and K. Hemingway

This study was commissioned to map the intertidal and subtidal habitats of the Solway Firth, utilising the Marine Nature Conservation Review's methodology of defining and assigning marine biotopes. An intertidal survey covered the Scottish shoreline from Gretna to Balcary and recorded in detail the physical and biological parameters. The subtidal survey used the RoxAnn® ground discriminator system, with associated ground-truthing carried out using a Remote Operated Vehicle (ROV) and conventional sea-bed grab sampling.

Within the intertidal area, species diversity increased with distance downstream from the head of the estuary. The inner Firth was dominated by muddy sandflats backed by saltmarsh, and the outer Firth by a hard substratum with associated sandbanks. The saltmarsh of the inner Firth was dominated by common saltmarsh-grass *Puccinellia maritima*, with the muddy sandflats characterised by an abundance of the amphipod *Corophium volutator*, the polychaete *Nereis diversicolor* and the bivalve *Macoma balthica*. A more diverse fauna, including the reef-building polychaete *Sabellaria alveolata* was recorded from the scar grounds of the inner Firth. The hard substratum within the outer Firth supported lichens in the supralittoral zone, with fucoid algae in the littoral. Sandbanks were dominated by *N. diversicolor*, the lugworm *Arenicola marina*, *M. balthica* and the cockle *Cerastoderma edule*.

The subtidal survey showed shallow sandflats dominating the area, characterised by the polychaetes *Nephtys cirrosa* and *Magelona mirabilis*, although species richness was low. The RoxAnn® output showed that sediment became coarser with increased depth, with the channel beds containing coarse sand and gravel with patches of cobbles and rock and a more varied fauna. A large, shallow area of hard substratum was recorded off Dubmill Point; this scar area comprised patches of pebbles, cobbles and rock with interstitial sandy mud and a variable fauna.

Correspondence: K. Hemingway, Institute of Estuarine and Coastal Studies, University of Hull, Hull, HU6 7RX

Introduction

The Scottish Natural Heritage 'Focus on Firths' initiative aims to promote greater awareness of the importance of the natural heritage of estuaries and to facilitate integrated management strategies to safeguard their future. The development of such a management strategy requires comprehensive data on the habitats present and their significance in a wider geographical context. Often this requires the collation of existing and new information and its presentation in a form suitable for communication to environmental managers and other users of the system.

This present study was commissioned by Scottish Natural Heritage, Edinburgh, to provide broad-scale habitat mapping of the Solway Firth, together with a review of all previous ecological survey work in the area. It aimed to quantify the biotopes present, determine their relative importance both in a local and national context, and provide information for implementing European Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora (the 'Habitats and Species Directive').

Existing information about the distribution of marine intertidal and subtidal habitat types in the Solway Firth was both limited and fragmented. Therefore, in order to provide an integrated description of the habitats present, it was necessary to carry out a habitat survey of the Solway Firth. The survey area comprised all intertidal and subtidal areas below the High Water spring tide, to the east of a line joining Balcary Point on the Scottish shore and Dubmill Point on the southern shore of the Firth (see Figure 1). The project specification excluded the intertidal areas of the English coast from the survey area.

One approach to describing the various habitats present within an area is by assigning biotopes, distinguishable communities based on a series of biological and physical parameters (Hiscock 1996; Connor *et al.* 1996). This methodology has been developed through the collaborative work of the Joint Nature Conservation Committee's Marine

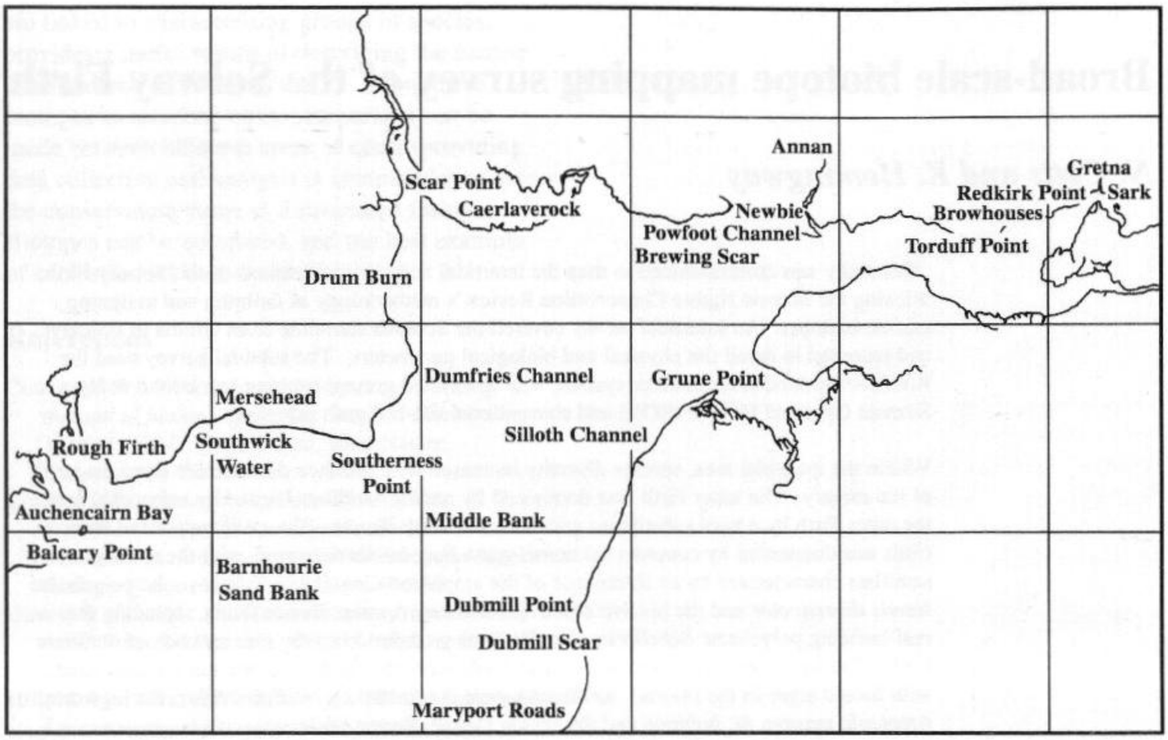


Figure 1 Location of sites cited in text.

Nature Conservation Review (MNCR) and Biomar (University of Newcastle). In the case of offshore uniform substratum, single biotopes may cover many square kilometres, whilst for distinctive features such as rock pools a biotope may be only a few square metres in area.

Although the main basis for classification of biotopes is primarily biological, i.e. based on species assemblage, most communities within the marine environment are initially produced by a particular physical environment (Hiscock 1996). As many marine areas and thus their communities are highly dynamic and may not be dominated by any single organism, it is often of value to use physical attributes as a basis for biotope classification. The physical attributes which appear to strongly influence community composition within the intertidal zone include underlying geology and substratum, exposure to air and thus desiccation. In the sublittoral, in addition to substratum type, attenuation of light with depth, wave exposure, tidal stream strength, salinity and temperature are important factors.

This paper summarises the findings of the habitat mapping survey. A more detailed textual and graphical descriptions of the habitats within the Solway has been published by Scottish Natural Heritage (Cutts & Hemingway 1996).

Methods

The field survey comprised two phases, a shore-based intertidal survey and a boat-based subtidal survey. The majority of intertidal survey work was undertaken between 20th and 30th September 1994, with additional work between 31st October and 2nd November 1994. The subtidal survey was undertaken between 23rd September and 6th October 1994.

The intertidal survey utilised teams of field workers visiting sites along the shoreline, recording in detail the geology, coastal processes and flora and fauna at each distinct habitat following the MNCR methodology, assigning biotopes to the differing habitats (Hiscock 1996). Given the extensive nature of the intertidal flats it was not possible to cover the entire area, and therefore brief visits were made to areas adjacent to the major sites. If the general geomorphological and biological components were similar to the major study area, then similar biotopes were assigned. On some of the extensive sandflats where it was unsafe to survey to the low water mark, binoculars were used to check for apparent changes in sediment type. If no obvious change was visible, then the area of the known biotope was extended to low water.

The subtidal survey utilised the RoxAnn® ground discriminator system with echosounder set-up for use in shallow water conditions. As each sea-bed material type has a unique signature which is a combination of roughness and hardness, these characteristics are returned to RoxAnn® and displayed on a Cartesian graph on screen. Boxes are drawn to encompass ranges of values according to the requirements of the project, and hence the data are divided into material types which are then assigned unique colours.

As the vessel proceeds, information is obtained on the acoustic properties of the sea bed and a map built up from parallel tracks. Position-fixing of the survey vessel (the *Hydrotech*) was achieved using a Sercel NR51 DGPS. These data were stored on disk together with the results of the associated ground-truth sampling. Ground-truthing was achieved using a remotely-operated colour video camera and 0.1m^2 van Veen grab. Material in each grab was sieved through a 1 mm mesh and the sieve residue retained for sorting and the identification and enumeration of the benthic fauna. A sediment subsample was additionally taken for subsequent analysis by Malvern laser particle sizer.

The study also utilised existing sources of information on habitats within the Solway Firth, including data from published works and privately commissioned surveys where possible.

Once collated, the data from both intertidal and subtidal surveys were input into an Intergraph Geographical Information System (GIS), creating an easily interrogated dataset on the geomorphological, hydrological and biological parameters.

Results

Intertidal

The supralittoral fringe of the Scottish coastline from Gretna to Torduff Point (Figure 2) was dominated by a narrow band of *Puccinellia* saltmarsh above muddy sandflats characterised by the amphipod *Corophium volutator* and the bivalve mollusc *Macoma balthica.* Between Torduff Point and Annan the coastline comprised a mosaic of cobble, pebble and sand with a slightly more diverse fauna including the mussel *Mytilus edulis*, the gastropod *Littorina littorea* and the lugworm *Arenicola marina.* To the west of Annan fucoid algae were recorded on the more stable areas of scar ground (areas of glacially-derived boulders and cobbles), with the sandflats featuring a more diverse fauna including the polychaetes *Nereis diversicolor* and *Capitella capitata*, the bivalves *Mya arenaria* and *Cerastoderma edule* and the amphipod *Bathyporeia* spp. Map 2 illustrates the location and extent of the intertidal biotopes present. As this output has been taken from an original series of larger scale full colour maps, the complexity of the biotope distribution cannot be fully illustrated here, but is available in Cutts & Hemingway (1996).

The extensive muddy sandflats and saltmarsh around the Caerlaverock nature reserve featured an abundant fauna including *C. volutator, A. marina* and *M. balthica*, this area being of international importance for wildfowl and waders which feed and roost on the mudflats (Barne *et al.* 1996). To the west of Caerlaverock in the Nith estuary, species richness was reduced although *C. volutator* was extremely abundant in some areas of the lower estuary.

The area around Drum Burn featured *Salicornia* saltmarsh fronted by extensive fine sandflats characterised by abundant *C. volutator.* Southerness Point featured exposed bedrock and sandflats with increased species richness, including the sand-mason *Lanice conchilega* in the sandier substratum of the lower shore.

West of Southerness Point and occupying the area to Southwick Water are the extensive sandflats of Mersehead, backed by a narrow dune system, the flats being characterised by *A. marina, N. diversicolor, M. balthica* and *C. volutator.*

Southwick Water marks a change in geology, with the coastline between Southwick and Balcary Point dominated by exposed bedrock in the form of steep cliffs with yellow and grey lichens in the supralittoral zone. These were replaced by *Pelvetia canaliculata* and, in turn, fucoids. *Patella vulgata, Littorina saxatilis* complex, *L. littorea* and barnacles also characterised this latter zone. At the base of the cliffs the extensive sandflats were dominated by *A. marina* and *M. balthica*, together with the bivalves *C. edule* and *Scrobicularia plana.* The habitats in the Rough Firth/Auchencairn Bay complex were widely different from these. Here, the sediment type was finer and biotopes were similar to those found upstream towards the head of the Solway Firth, being dominated by *C. volutator, M. balthica* and *Puccinellia* saltmarsh flora towards the rear of the sites. Previous surveys by Perkins (1973) and Covey & Emblow (1991) have shown the presence of seagrass *Zostera* beds within the Rough Firth/Auchencairn Bay complex although the present survey found only very sparse patches of *Zostera* spp. It is considered that the present very low coverage by seagrasses may be the result of the recent manual collection of cockles through the raking of the flats.

Subtidal

The data from RoxAnn® highlights several broad trends, with the subtidal survey having recorded distinct habitats, shown through colour differences on the RoxAnn® output. For the requirements of this paper, these habitat types have been broadly grouped into five colour bands (see Figure 2). The red areas of the output (Figure 2) indicate a predominantly rocky or boulder substratum with small areas of gravel, shell debris and coarse sand. These areas were generally restricted to the southern areas of the Solway, close to the English shore, although other rocky areas were located within the bed of the main channels (Figure 2).

The pink and dark blue shading in Figure 2 represents medium-coarse sand with gravel and shell debris, and medium sand with gravel respectively. Both of these tones appear to indicate the main channels, i.e. areas of higher energy, and therefore coarser material.

Fine-medium sand with shell debris (represented by green in Figure 2) occurred in areas just outside the main channels, whilst yellow, which appears to be the dominant output throughout the majority of the survey area, indicates well-sorted fine muddy sands. This corresponds to the extensive sandflats outside the main channels.

The area off Balcary/Auchencairn Bay, including parts of the intertidal Barnhourie sandbank, was characterised by fine to medium sands with an average median grain size of between 100 and 200 µm. In this area the dominant species included the polychaetes *Nephtys cirrosa* and *Magelona mirabilis*, amphipods and bivalves, organisms adapted to mobile medium sands.

Towards the middle of the Solway (Scotch Deep and Middle Channel), the area was characterised by sediments which differed from those to the west, with coarser sand and areas of pebble and rock. The sandier areas were dominated by *N. cirrosa*, but featured low species abundance and very low values of species richness. In contrast, the gravel and pebble areas appeared to have an abundant fauna with large numbers of *Microthalamus similis* and juvenile *M. edulis* recorded in the grab, although species richness was low. The video images showed a rich epifauna with a number of crabs and fish visible, taxa unlikely to be taken during ground-truthing using solely grab samplers. In the Dumfries Channel off Southerness Point, areas of fine muddy sand were found adjacent to coarse sand and gravel. On either side of the channel, areas of fine to medium sand were apparently dominated by the polychaetes *N. cirrosa, M. mirabilis* and *B. elegans*, whilst the channel areas featured a coarser sediment type with a fauna similar to that of the Middle Channel.

Fine to medium sands dominated the extensive area known as Middle Bank, with an impoverished fauna within the areas of fine sediment (*N. cirrosa* most abundant), and a diverse fauna featuring *M. mirabilis* and *N. cirrosa* within the coarser sediment.

Around Maryport Roads, Dubmill Scar and Silloth Channel (Figure 3) the sea bed was characterised by a hard, rocky substratum. Ground-truthing reflected this, as a series of grabs failed due to the hard nature of the substratum. Although successful grab samples showed the sea bed to be characterised by pebbles and gravel with interstitial sand and mud. These areas had a variable fauna (depending on substratum), with the fauna of a single grab varying from a single *N. cirrosa* to 20 species including abundant juvenile mussels, polychaetes and crustacea. The video image for the area showed a variable substratum of sand with pebbles and rock.

The upper reaches of the Silloth Channel leading into the Powfoot Channel were dominated by a finer sediment type. However, due to high current velocities and turbidity levels within the area, grab and video ground-truthing could not be carried out effectively. Therefore, any indication of habitat for the area must be extrapolated from similar sonar outputs in the middle Firth where physical parameters may differ.

Discussion

The Solway Firth is one of the largest tidal embayments in the Irish Sea. The estuary, in comparison to the adjacent coastline, contains unique biotopes including large expanses of intertidal sand/mudflats, together with extensive areas of fringing saltmarsh. North of the Solway Firth, the coastline is predominantly rocky with a large proportion of intertidal flats in the Clyde reclaimed for industry, and many of the remaining areas affected by pollution (Allen *et al.* 1986). To the south of the Solway, the Esk and Duddon estuaries have small areas of intertidal flats with some saltmarsh, however the only significant areas of sandflat and saltmarsh occur at Morecambe Bay and within the Ribble Estuary (Barne *et al.* 1996). Thus the geographical position of the Solway indicates its importance in supporting habitats necessary for maintaining wading bird and fish populations (Davidson *et al.* 1991).

As shown by the present survey and previous studies, the Solway Firth is a dynamic area of mobile sediment, with regularly migrating river channels. Within the Solway, spring-neap and winter-summer erosion-deposition processes continually rework the sediments, thus creating the community dominated by amphipod crustaceans, polychaetes and bivalve molluscs tolerant of mobile sediments. Accretion occurs in sheltered areas which are mostly characterised by advancing saltmarsh, for example areas found towards the head of the Rough Firth/Auchencairn Bay complex, along the tidal tributaries and towards the estuary.

These areas were found to be characterised by very fine sands and muds.

This pattern of deposition is not uniform across the estuary, as several saltmarsh sites towards the head of the Firth were observed to be undergoing erosion with sheer, often unstable, cliffed edges. Much of this erosion appeared to be due to channel migration in the area between Redkirk Point and Browhouses. Similarly, the saltmarsh at Scar Point towards the mouth of the River Nith also appeared to be eroding.

The Central Northern shore has been surveyed regularly over a number of years by Perkins & Williams (1966), Williams (1977-1990), Rendall (1990) and Ove Arup & Partners (1993a, 1993b) and indicates that patterns of accretion and erosion are subject to frequent change. A comparison of conditions over this period shows physical and biological parameters to have altered considerably both seasonally and inter-annually. This degree of variability was most evident when regular studies of the shore were undertaken by Williams (1977-1990) which showed that the fauna of the site fluctuated between barren and abundant.

In general, the intertidal habitats exhibited a similar division with fine muddy sand and scar grounds backed by saltmarsh dominating the inner Firth, whilst the outer Firth areas were dominated by medium sand backed by bedrock. The exception to the latter was the Rough Firth/Auchencairn Bay complex which comprised fine muddy sand backed by saltmarsh.

The present survey showed that species diversity conformed to the classical pattern of decreasing diversity as one enters the estuary from both the seaward and freshwater reaches, with salinity determining the distance that a species is capable of penetrating into the estuary (McLusky 1989). The species diversity minimum was found at the 'Freshwater-Seawater Interface' which occurs between Sark and Annan.

Perkins (1986) described the ecology of scar grounds in the Solway Firth as being characterised by rapid stages of settlement and community development, with the frequency of inundation by sand often influencing the development of stable communities on more permanent features. In both the present and previous surveys, the scar grounds were shown to be a very rich habitat with the biota inhabiting them comprising a large number of species drawn from many phyla. For example, species richness at scar grounds to the south of Priestside Bank, together with those at Powfoot, was found to be high.

Large reefs made by the polychaete *Sabellaria alveolata*, together with *Mytilus*, were found around Brewing Scar to the south of Priestside Bank. Perkins (1986) does not mention these particular reefs in his studies of the Solway, but suggests that a very successful *Mytilus* spat settlement at Siddick in 1986 may have the long-term effect of out-competing the *Sabellaria* found there for food, and thus may lead to a fundamental change in the species composition of the area. Therefore it appears that since the last study by Perkins, *Sabellaria* has been able to colonise a previously unsuitable area. This increase/or recolonisation is of conservation importance for the creation of biogenic reefs.

The results of the RoxAnn® survey showed fine to medium sands dominating the subtidal zone of the survey area (generally around 5 m below Chart Datum). Large areas of sandflat were located around the Barnhourie Bank and Middle Bank, and these areas were dominated by *N. cirrosa, M. mirabilis* and occasional amphipods, although in general, both species richness and levels of abundance were poor, possibly due to the high mobility of the sediment creating conditions suitable for only a few species.

The main channels within the survey area exhibit different characteristics to the shallow subtidal sandflats, with sediment gradually coarsening with increased depth. The bed of the Middle Channel and Scotch Deep were characterised by a gradual change from fine sand to gravel and rock on the channel bed. The sandy areas were seen to be species-poor, with ROV and grab data for the coarser sediment showing abundant fauna dominated by *M. similis* and *M. edulis*, although with a lower richness.

The Dumfries Channel which passes near to Southerness Point and joins the Middle Channel (with channel depths ranging from 5 to 15 metres below Chart Datum) exhibited differing habitats with the RoxAnn® and ground-truthing revealing a mixed substratum of sand and mud close to areas of gravel, pebble and cobble. Similarly, the Silloth channel adjacent to the English shore was shown to have a coarse substratum similar to that of the Middle Channel. The channel decreases in depth northwards until it becomes unclear off Grune Point, with a ground signature similar to that of the adjacent banks and a depth of less than 5 m below Chart Datum.

The survey output from the area of Maryport Roads and Dubmill/Catherine Scars shows features of particular note. Here, the RoxAnn® indicated an extensive area of predominantly 'hard' substratum in shallow water (less than 5 m below Chart

Datum), with ground-truthing showing the bed to be characterised by a rocky substratum of boulders, cobbles and pebbles with interstitial sands and mud. These areas had a variable fauna with grab contents varying in species number depending on substratum and community characteristic of the Solway 'scar grounds'.

Previous studies of the Solway have indicated the general features of the estuary and have contributed to an understanding of its biological functioning. However, the present study and its methods have allowed a more comprehensive spatial coverage. It also indicated that the survey techniques required to ground-truth the remote sensing by RoxAnn®, using both conventional grab sampling with subsequent laboratory analysis and the operation of an ROV, were required to give an overall and sufficiently detailed mapping of the habitats present. At the time of survey, a series of biotopes were indicated which had not been delimited for estuarine areas in the form present in the Solway. However, the Solway, as with many estuaries, has an importance dictated more by its overall functioning and support for wading bird and juvenile fish predators than for the rarity of its habitats (Davidson *et al.* 1991).

Such an indication of the number and importance of the biotopes and habitats has acquired an additional importance through the implementation of the EC Habitats and Species Directive (CEC 1992; Earll 1993). The Solway Firth has been proposed as a Special Area of Conservation (SAC) as an estuary, for its subtidal sandbanks and for its intertidal mud and sandflats, habitats of high conservation and commercial value in supporting overwintering wading birds and juvenile flatfishes (Davidson *et al.* 1991). The Solway has also been proposed as a Special Protection Area under the EU Wild Birds Directive (CEC 1979).

The UK Regulations for the implementation of the EU Habitats and Species Directive indicate that there must be registration and notification of the SACs, followed by management agreements for the site in order to control potentially damaging operations (HMSO 1994). In the case of the Solway, Scottish Natural Heritage is required to determine conservation objectives for the protection of the designated habitats and species. This requires the features of the area to be catalogued and such data provide the basis for determining change as the result of human activities. Hence, the present survey has produced baseline information against which the importance and cause of any future change is measured.

Acknowledgements

We wish to thank Dr Timothy Hill of the Marine Nature Conservation Review (JNCC) for his constructive comments on an earlier draft of this paper. This work was commissioned and fully funded by Scottish Natural Heritage as part of their Focus on Firths initiative (Contract Number SNH/069A/95 HS).

References

Allen, J.A., Barnett, P.R.O., Boyd, J.M., Kirkwood, R.C., McKay, D.W., & Smyth, J.C., *eds.* 1986. *Environment of the estuary and firth of Clyde. Proceedings of the Royal Society of Edinburgh, 90B.*

Barne, J.H., Robson, C.F., Kaznowska, S.S., Doody, J.P., & Davidson, N.C., *eds.* 1996. *Coasts and seas of the United Kingdom: Region 13 Northern Irish Sea, Colwyn Bay to Stranraer, including the Isle of Man.* Peterborough, Joint Nature Conservation Committee.

CEC. 1979. Council Directive 79/409/EEC on the conservation of wild birds. *Official Journal of the European Communities, Series L 103:* 1-6.

CEC. 1992. Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora. *Official Journal of the European Communities, Series L 206:* 7-50.

Connor, D.W., Brazier, D.P., Hill, T.O., Holt, R.H.F., Northen, K., & Sanderson, W.G. 1996. *Marine Nature Conservation Review: marine biotopes. A working classification for the British Isles, Version 96.7.* Peterborough, Joint Nature Conservation Committee.

Covey, R., & Emblow, C.S. 1992. Littoral survey of the Inner Solway Firth and additional sites in Dumfries and Galloway. *Joint Nature Conservation Committee Report,* No. 33.

Cutts, N., & Hemingway, K. 1996. The Solway Firth: broad-scale habitat mapping. *SNH Research, Survey & Monitoring Report,* No. 46.

Davidson, N.C., Laffoley, D.dfA., Doody, J.P., Way, L.S., Gordon, J., Key, R., Drake, C.M., Pienkowski, M.W., Mitchell, R., & Duff, K.L. 1991. *Nature conservation and estuaries in Great Britain.* Peterborough, Nature Conservancy Council.

Earll, R. 1993. EC Habitats Directive: marine protected areas in the UK. *Marine Pollution Bulletin, 26(12):* 661-662.

Hiscock, K., *ed.* 1996. *Marine Nature Conservation Review: rationale and methods.* Peterborough, Joint Nature Conservation Committee.

HMSO. 1994. *Conservation (Natural Habitats & etc.) Regulations.* London, HMSO. (Statutory Instrument 2176).

McLusky, D.S. 1989. *The estuarine ecosystem.* 2nd ed. Glasgow, Blackie.

Ove Arup & Partners. 1993a. *Marine ecology (Chapelcross & Sellafield).* Draft final report. (Contractor: Applied Environmental Research Centre Ltd). Internal report.

Ove Arup & Partners. 1993b. *Ecosystem assessment (Chapelcross Site and Estuary).* Draft final report. (Contractor: Bioscan (UK) Limited). Internal report.

Perkins, E.J. 1973. *The marine fauna and flora of the Solway Firth.* Dumfries, Dumfriesshire and Galloway Nature History Antiquarian Society.

Perkins, E.J. 1977. *The quality and biology of the environment adjacent to the Workington Works of the British Steel Corporation.* Carlisle, Cumbrian Sea Fisheries Committee. (Scientific Report No. 77/1.)

Perkins, E.J. 1986. The ecology of Scar Grounds in the Solway Firth. *Transactions of Dumfriesshire and Galloway Natural History and Antiquarian Society, 61:* 4-19.

Perkins, E.J., & Williams, B.R.H. 1966. *The biology of the Solway Firth in relation to the movement and accumulation of radioactive materials. II. The distribution of sediments and benthos.* United Kingdom Atomic Energy Authority. (PG Report 587 (CC).)

Rendall, D. 1987 *et seq. Biological and trace metal survey of the inner Solway Firth beaches.* Dumfries, Solway River Purification Board.

Williams. 1977-1990. *In: ICI Group Environmental Laboratory, Brixham. 1980-1990. Glaxo, Newbie: Monitoring surveys carried out in the Solway Firth.* Yearly reports between 1980 and 1990. Unpublished, ICI.

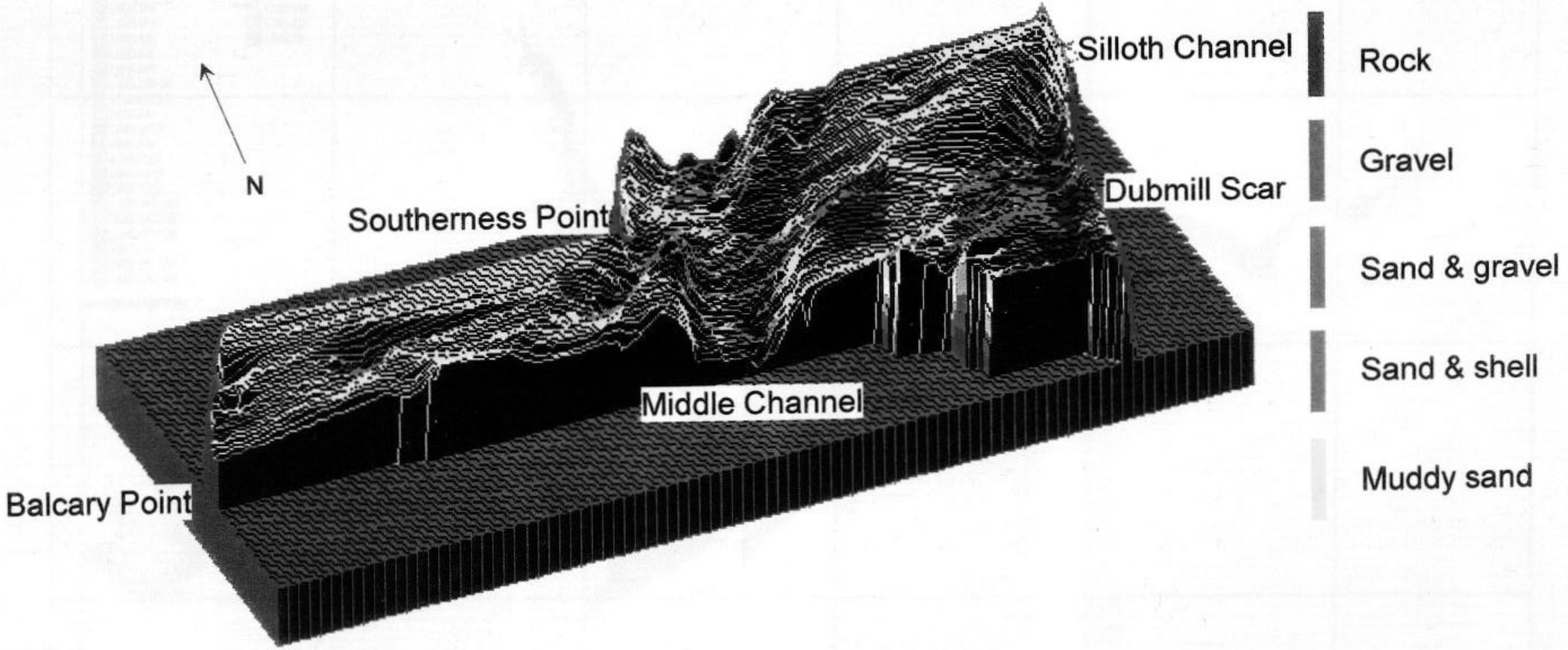


Figure 2. 3-D subtidal RoxAnn output.

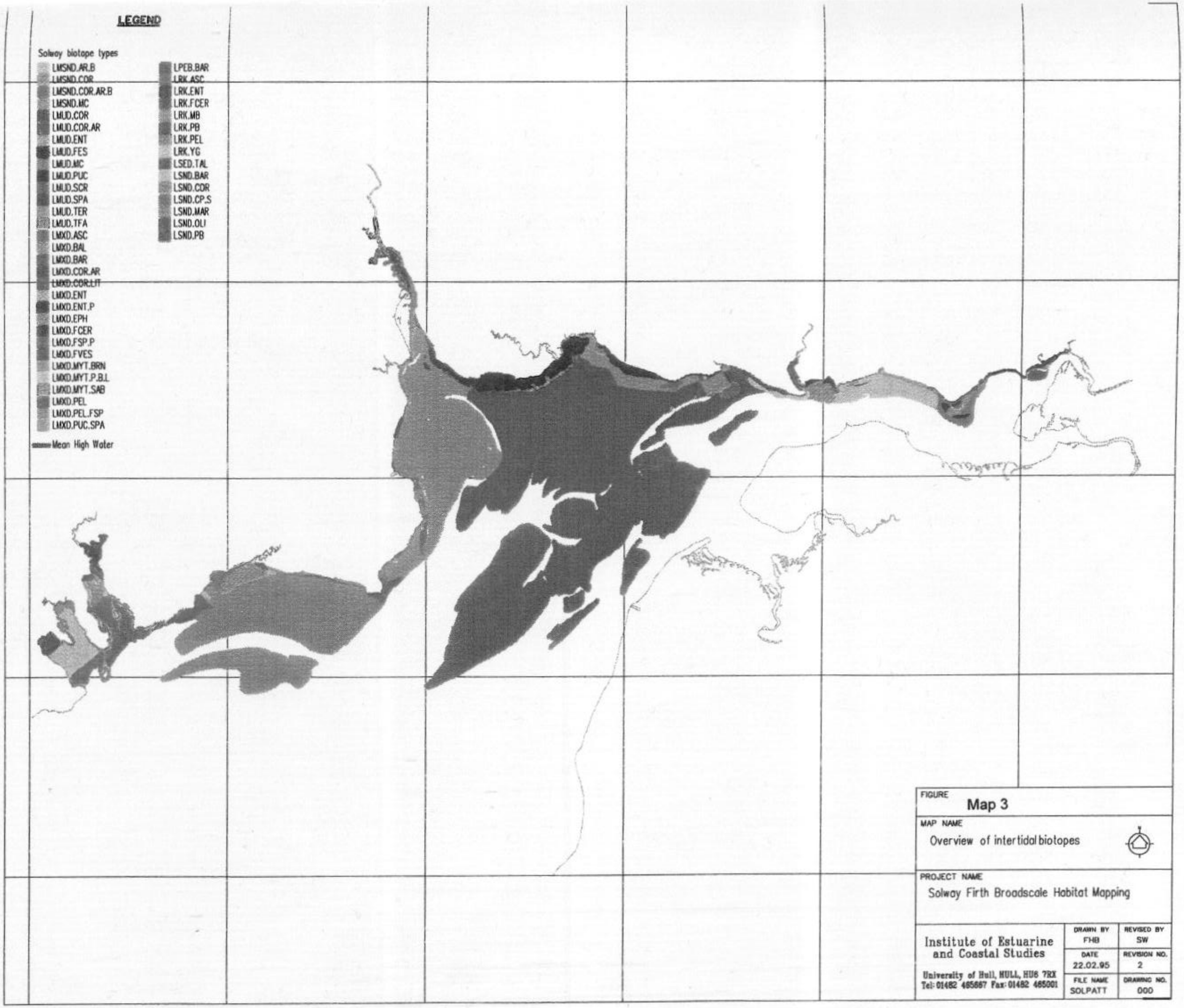


FIGURE
Map 3

MAP NAME
Overview of intertidal biotopes

PROJECT NAME
Solway Firth Broadscale Habitat Mapping

Institute of Estuarine and Coastal Studies University of Hull, HULL, HU6 7RX Tel: 01482 465667 Fax: 01482 465001	DRAWN BY FHB	REVISED BY SW
	DATE 22.02.95	REVISION NO. 2
	FILE NAME SOLPATT	DRAWING NO. 000