“Modelling the behaviour of nutrients in the coastal waters of Scotland”

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Summary

The overall goal of this project was to provide Scotland with a strategic ecosystem simulation tool for identifying maritime areas which could be at risk of eutrophication. The tool should provide spatially resolved output, and be capable of discriminating between different types and locations of nutrient inputs, so as to enable scenario analyses of different reduction options. The specific aims of the project were firstly to simulate the annual cycles of nutrients and ecological properties of Scottish waters and advise on areas which might suffer from eutrophication, and secondly, to determine the contribution of Scottish nutrient discharges to eutrophication in the OSPAR maritime area as a whole.

The European Regional Seas Ecosystem Model (ERSEM) was chosen as the basis for the project. ERSEM had previously been implemented at 60 x 60 km spatial resolution for the North Sea and this project extended the coverage to the entire Northwest European shelf from Brittany northwards. This was necessary in order to simulate the environment on the west coast of Scotland, and required the assembly of new ocean boundary, internal, initial and forcing data sets needed to run the model. Forcing data were assembled for three years (1984, 1987 and 1990) as examples of the range of climatic conditions experienced in the last few decades.

One of the major forcing data sets was the nutrient input from land sources to all of the coastal grid cells of the model. For Scotland, the OSPAR Harmonised Quantification and Reporting Procedures for Nutrients (HARP-NUT guidelines) were followed to calculate daily inputs of both inorganic and organic forms of nitrogen, phosphorus, carbon and silicon from riverine and direct discharges to the sea. The inputs were further resolved by source (urban waste water and industrial for 1999, aquaculture for 2001, and agriculture plus geological for each of the three climate years). Equivalent data were compiled at monthly resolution for England, Wales, Northern Ireland, the Republic of Ireland and Norway. Continental European riverine inputs were available at daily resolution from the earlier North Sea implementation of ERSEM.

Although Scotland represents 25% of the land area of the British Isles (including the Republic of Ireland), it contributes 42% of the freshwater runoff (averaged over 1984, 1987 and 1990). However, the nitrogen and phosphorus load from Scotland is only around 15% of the British Isles total (approximately 140,000 tonnes nitrogen and 14,000 tonnes phosphorus). Scotland contributes a disproportionate amount of silicon to the British Isles total loading, presumably due to the terrain and geology. On a Europe-wide basis, Scotland contributes less than 10% of the total nitrogen and phosphorus loading, but 26% of the silicon loading.

Urban waste water was found to account for approximately 12% of Scotland's nitrogen load, but 36% of the phosphorus load. Around 80% of the urban waste water load resulted from direct-to-sea discharges in 1999. The remaining 20% was discharged to river catchments. Salmon farming contributed approximately 6% of Scotland's nitrogen input and 13% of phosphorus (based on 2001 production figures). However, in some areas of the west of Scotland with small catchment areas and low levels of human habitation, aquaculture inputs represented greater than 80% of the total.

Reference runs of the ERSEM were carried out using 1984, 1987 and 1990 meteorological forcing (transport, irradiance and agricultural plus geological nutrient inputs) together with nutrient inputs from urban waste and industrial sources set at the levels estimated for 1999, and from aquaculture in 2001. The model was then run for three nutrient load reduction scenarios and the results compared to those from the reference runs. The three scenarios

were a) 75% reduction in Scottish urban waste water, b) 50% (OSPAR defined) reduction in all Scottish inputs, and c) 50% reduction in Scottish aquaculture inputs.

The impacts of nutrient load reductions were largely confined to the immediate locality of the inputs (at least on the scales resolved by the model). The wider Scottish east coast area was the only one of a number of larger regional areas examined which exhibited impacts in excess of the natural climate-driven variability exhibited by the reference run results. At a local scale, the model identified the Clyde Sea, and especially the Forth/Tay river plume as areas which should be examined in more detail and at a finer spatial scale for evidence of eutrophication, since the simulated impact of the nutrient load reductions was in excess of the natural climatological variability.

The model indicated that the impact of a 50% reduction in nutrient discharges from Scottish salmon farming was likely to be small (3% or less change in assessment criteria) both locally at the scale of the model, and regionally. This was below the natural variability in the system in the affected areas.

The impact of Scotland's nutrients on coastal waters appears to be considerably less than that of some other nations. In this project, a 50% reduction in Scottish nutrients produced a 5% or less mean change in overall water quality in Scottish east coast waters (equivalent to 0.2-10gC/m^2/year change in net primary production). Previous simulations of a European-wide 50% reduction in nutrient inputs, using the North Sea version of ERSEM, produced a similar change in Scottish waters, but around a 15% or greater change in Belgian, Dutch and German coastal waters (equivalent to 39-77gC/m^2/year net primary production).

Acknowledgements

The assembly of anthropogenic and riverine nutrient data for this project would not have been possible without the help and co-operation of staff from the Scottish Environment Protection Agency, in particular B Cowan, J Dobson, A Edwards, T Inglis, T Leatherland, B Miller, W Proctor and P Singleton. We extend our thanks to them.

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At IfM, G Radach acted as project leader, whilst W. Kuehn, H Lenhart and A Moll worked on various aspects of the data and model set-up.

Finally, we thank D Stevens at the Sir Alister Hardy Foundation for Ocean Science for carrying out extractions of zooplankton data from the Continuous Plankton recorder database, and staff at the International Council for the Exploration of the Sea in Copenhagen for extracting data from their hydro-chemical database.

1. Purpose and specific objectives of the project

The project has two purposes. Firstly, to establish whether Scottish waters suffer from eutrophication as defined by the UWWT and Nitrate Directive. Secondly, to determine the fate of nutrients emanating from Scottish sources, and in particular to determine whether they make a significant contribution to eutrophication in the waters of Scottish or other Member States.

The specific objectives of the project are structured according to 4 tasks:

Task 1. *Review the criteria for assessing eutrophication*.

The modelling aspects of the project must produce outputs which conform exactly with the criteria set out in the Urban Waste Water Treatment Directive (91/271/EEC) and the Nitrates Directive (91/676/EEC).

Task 2. *Review existing data on nutrient inputs from Scottish mainland and islands, England, Wales and Ireland.*

The project will identify areas of uncertainty and advise on future reporting requirements.

Task 3. *Implementation of an ecosystem model for Scottish waters.*

The European Regional Seas Ecosystem Model (ERSEM) will be implemented to simulate the transport and nutrient-algal-benthic cycling processes in shelf seas, for the European shelf seas, with particular attention to Scottish and European coastal waters.

Task 4. *Risk assessment of the areas affected by anthropogenic nutrients.*

The model results will be used to assess areas which are sensitive to anthropogenic nutrients in a way that will inform the review of nitrate sensitive areas as required by Article 5 of Directive 91/271/EEC.

Timetable for the project

Month →	Oct 2000	Nov	Dec	Jan 2001	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Task 1	■	■	■	■	■	■								
Task 2	■	■	■	■	■	■	■	■	■					
Task 3	■	■	■	■	■	■	■	■	■	■	■	■	■	
Task 4									■	■	■	■	■	
Interim reports					■				■					
Draft area designations											■			
Final report														■

The various stages of the project were completed on time, and final assessments of the simulated consequences of nutrient reduction scenarios delivered to the Scottish Executive in December 2001. Finalisation of the written final report was delayed until June 2002.

2. Results from each task

2.1 Task 1. Review of the criteria for assessing eutrophication

Deliverables from Task 1.

Month 6: Report summarising relevant criteria, and posing these in quantifiable terms of relevance to the ecosystem model.

Results from Task 1

The ecosystem model produces output on a wide range of aspects of the system which are relevant to assessing eutrophication status. The requirement is to reduce these to a sub-set of criteria which deliver a concise summary of the status of given regions under different enrichment scenarios.

The criteria adopted in this project were those recommended in the Report of the ASMO Modelling Workshop on Eutrophication Issues, 1996 (OSPAR 1998). The same criteria were amongst those subsequently adopted by ASMO (ASMO, 2002) as harmonised common assessment criteria for use by OSPAR Contracting Parties in preparing their comprehensive assessments of the eutrophication status of their parts of the OSPAR maritime area.

The central purpose of the criteria was to summarise:

- Where, and to what extent, do elevated nutrient loadings cause an impact on the ecosystem?
- What are the impacts to the different managment strategy aiming to reduce eutrophication symptoms?

Following these principles, we defined a set of criteria in the model output for which we compared data from a reference run with data from a range of reduction scenario runs:

- Criterion 1: mean winter dissolved inorganic phophorus (DIP)
- Criterion 2: mean winter dissolved inorganic nitrogen (DIN)
- Criterion 3: March – September average chlorophyll concentration
- Criterion 4: maximum weekly average chlorophyll
- Criterion 5: annual net primary production
- Criterion 6: maximum weekly net primary production
- Criterion 7: March – September ratio diatom chlorophyll : non diatom chlorophyll

Criteria 1 and 2: Because the winter nutrient concentrations are primarily a function of loadings and abiotic processes, changes in winter concentrations gives a good indication of the importance of loads in a geographic region.

Criteria 3 and 4: Chlorophyll concentrations are partly governed by the availability of nutrients. In oligotrophic areas, chlorophyll concentrations are typically very low throughout the summer. Areas supplied by enhanced nutrient input throughout the year exhibit relatively high chlorophyll concentrations with additionally temporally appearing blooms in summer and autumn. Chlorophyll concentration is also an index of phytoplankton biomass, and hence has an impact on zooplankton communities and export of organic material. For these reasons, the average concentration of chlorophyll during the spring-autumn period reflects the scale of nutrient loading and indicates the condition of the ecosystem.

Criteria 5 and 6: Net primary production gives a more direct indication for nutrient availability than chlorophyll concentration because zooplankton grazing may deplete phytoplankton abundance but only weakly influences primary production. In particular, the component of primary production which is supported by nitrate uptake as opposed to recycled ammonia (referred to as new production) is an important ecosystem indicator since it dictates the amount of carbon available to support higher trophic levels in the water column and in the sediments. For these reasons, the timing and magnitude of maximum production during the year is also a useful indicator of the condition of an ecosystem.

Criterion 7: Changes in nutrient supply may cause changes in phytoplankton species composition and, it has been suggested, a possible increase of toxic/nuisance phytoplankton blooms. Most areas identified as having eutrophication problems exhibit low values of the ratio of diatom : non diatom biomass because diatom abundance is usually limited by silicate concentrations, whilst an excess of nitrogen and phosphorus allows non-diatom to flourish. Silicate loadings are generally not controlled by anthropogenic input, being derived from natural land erosion.

The harmonised common assessment criteria adopted by ASMO (ASMO, 2002) were as shown in Table 1.1. The winter nutrient criteria (1 and 2) used in the modelling assessment reported here conform with the ASMO Category I, whilst the chlorophyll and diatom/flagellate criteria (3, 4 and 7) conform with Category II.

***Table 1.1**. The agreed harmonised assessment criteria adopted by ASMO.*

Category I. *Degree of nutrient enrichment*	Riverine total N and P inputs and direct discharges
	Winter DIN and DIP concentrations
	Winter N/P ratio
Category II. *Direct effects of nutrient enrichment*	Mean and maximum chlorophyll *a* concentration
	Region/area specific phytoplankton indicator species (*e.g.* diatom/flagellate biomass ratio)
	Macrophytes including macroalgae
Category III. *Indirect effects of nutrient enrichment*	Degree of oxygen deficiency
	Changes/kills in zoobenthos and fish
	Organic carbon/organic matter ratio
Category IV. *Other possible effects of nutrient enrichment*	Algal toxins

2.2 Task 2. Review of existing data on nutrient inputs from the Scottish mainland and islands, England, Wales and Ireland

Deliverables from Task 2

Month 6: A database in spreadsheet form of daily Scottish nutrient loadings accompanied by a brief report including tabulated summaries of the data.
Month 6: Updated monthly nutrient inputs from English sources to the North Sea, together with inputs from the west of the UK.
Month 9: Results from extrapolation of HMS data to include small rivers on the Scottish mainland and islands.

Results from Task 2

Introduction

Coastal waters receive the nutrients nitrogen, phosphorus and silicon via river outflow and direct anthropogenic discharges. Nitrogen is additionally deposited from the atmosphere. The river discharges themselves are a mixture of the products of natural land erosion and anthropogenic discharges. Task 2 involved the assembly and consolidation into a common format of riverine and direct to sea nutrient loadings for the whole of the British Isles, resolved by space and time. Apart from the bureaucratic problems associated with locating and accessing the required data, the major scientific problem arose from the fact that the network of river monitoring sites around the UK which provides regular data on river flows and nutrient concentrations, measure the runoff from substantially less that 100% of the total land area. Futher scientific problems arose from the need to disaggregate the Scottish riverine inputs into urban waste water and other components, in order to undertake the risk assessments with the ERSEM model detailed in task 4.

There have been a number of previous assessments of nutrient inputs to European waters, mainly undertaken for the North Sea Task Force Quality Status Report and by OSPAR working groups. Detailed assemblies of data for the UK, and Scotland in particular, are available from Turrell (2000), and in the Assessments of Eutrophication Status prepared by SEPA as part of the OSPAR Comprehensive Procedures (seen in draft, November 2001). However, none of these sources provide data on Scottish or other nations' nutrient inputs at sufficiently detailed chemical, spatial or temporal resolution to meet the demands of this modelling project. Hence, we undertook a new compilation of the available data at a higher level of detail than has been carried out previously.

The spatial, temporal and chemical resolutions applied to the nutrient input data which were compiled for the project, were dictated by the ERSEM marine ecosystem model. Full details of the configuration of ERSEM are given in Task 3. In summary, with regard to spatial resolution, the European shelf seas were represented by a network of boxes with typical surface dimensions of 60km x 60km. Nutrient inputs were estimated for each of these boxes which adjoined the land. In addition, model results were summarised in Task 4 according to a smaller number of coarser spatial resolution regions each composed of a number of basic ERSEM boxes. These were referred to as eutrophication assessment areas.

With regard to temporal resolution, ERSEM outputs data at daily time intervals over a year, and this is the ideal resolution and duration of any forcing data such as external nutrient inputs. Scottish inputs, which were to be subject to scenario analysis with the model, were therefore provided at daily resolution where possible (all river-borne nutrients), monthly averages (aquaculture inputs), or annual averages (direct to sea anthropogenic inputs), these being the finest resolutions achievable. River-borne inputs from England, Wales and Ireland were derived as monthly averages due to lack of ready access to daily resolved monitoring data.

The chemical species resolved in the nutrient input data had to correspond with those expected by the ERSEM ecosystem model. These were nitrate, nitrite, ammonium, phosphate, silicate, particulate organic phosphorus (POP), particulate organic nitrogen (PON), particulate organic silicon (POS), and particulate organic carbon (POC). In reality, this resolution exceeded that which was universally available for all river monitoring sites or discharge monitoring locations, so some parameters had to be estimated by assuming fixed proportional relationships with the measured nutrients.

Finally, the total loads of nutrient from rivers vary significantly from year to year depending on climate conditions. The same climate conditions also affect the physical oceanographic variables which are included in the ERSEM ecosystem model. Three years (1984, 1987 and 1990), representing contrasting scenarios of rainfall and ocean climate were chosen as described in Task 3. River loads were compiled for each of these years. However, the stipulated requirement of the eutrophication assessments in Task 4 was that the anthropogenic inputs should be based on the most recently available data. Hence, data from 1999 were assembled to represent urban waste water and industrial inputs to the ERSEM model, whilst production data from 2001 were used to estimate loadings from aquaculture. Aquaculture production in 1999 was around 80% of that in 2001, and in terms of nutrient loading this discrepancy amounted to only a small fraction of the total loadings to the system.

Estimation of daily riverine loads for Scotland

Delineation of drainage area boundaries for each ERSEM coastal box

Apportioning the land area draining into each ERSEM coastal box was achieved by using a combination of visual interpretation of OS maps and a Digital Elevation Model. The final designations for the UK as a whole, which for the purpose of this report are identified as basins. are shown in Figure 2.1.

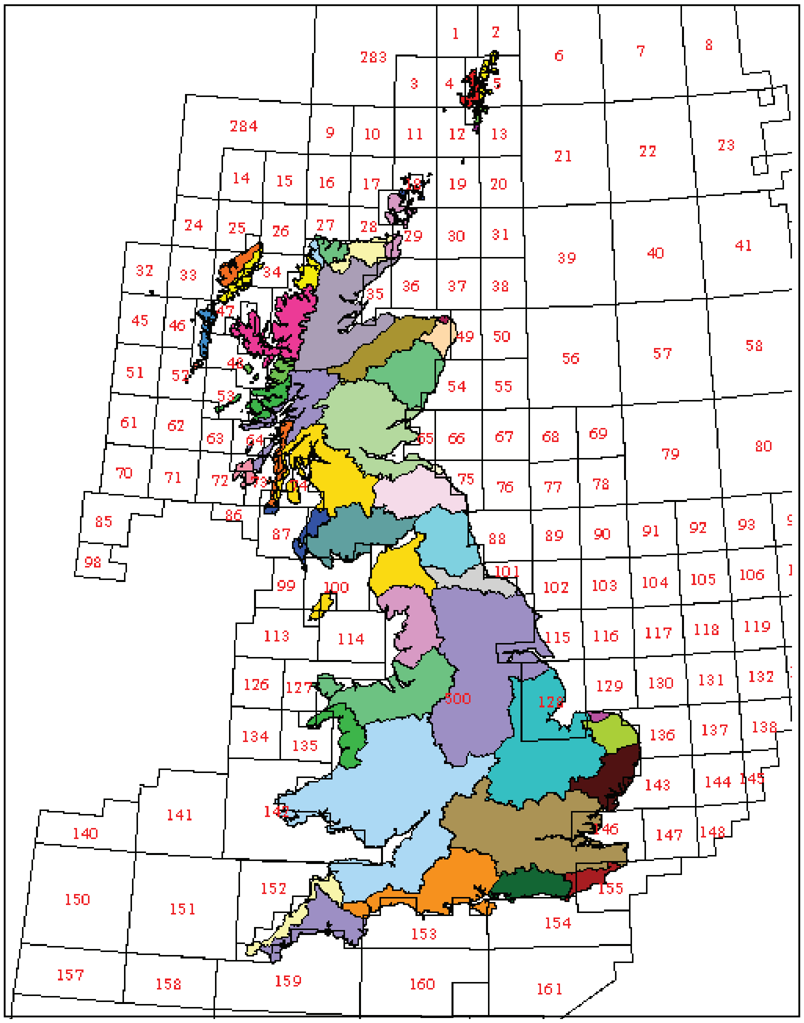

Figure 2.1 *Land area of the UK (excluding Northern Ireland) divided into the drainage basins corresponding to each of the coastal boxes of the ERSEM model.*

Some of the physical attributes of the Scottish basins have been summarised in Table 2.1. Land cover statistics (LCS, 1988) were ascribed to each ERSEM basin broadly defining the proportions of agricultural (arable and improved grassland) and non-agricultural (including moorland, urban, forestry and rough grass) land. Twelve basins areas are solely located on the mainland a further 8 consist of combined mainland/island while 10 consist of only islands, these account for 63 %, 28 % and 9 % of the total land area respectively. These basins have also been summed to coarser eutrophication assessment zones (as described in Task 4) (Table 2.1).

Table 2.1 *Estimated land areas draining into individual ERSEM boxes and the proportion of agricultural land (arable and improved grazing). ERSEM basins have also been grouped according to assessment zones described under Task 4.*

ERSEM box ID associated with land drainage basin	Area (km^2)	Percentage Agricultural	Eutrophication assessment area	Area (km^2)	Percentage Agricultural
74	8166.8	32.0	10a	9474.7	33.4
87	1308.0	41.9			
100	6753.0	33.4	10b	6753.0	33.4
49	1301.7	86.5	8a	23076.7	43.2
54	5411.3	39.5			
65	11860.3	38.6			
75	4503.4	47.3			
35	10739.2	12.0	8b	15403.7	17.8
36	4548.9	29.8			
37	115.6	85.0			
18	269.2	61.9	8c	4353.2	23.1
27	953.9	1.4			
28	1882.5	12.3			
29	1247.6	47.6			
4	655.8	13.6	8d	1459.7	15.6
5	587.2	14.7			
12	74.3	33.9			
13	142.4	18.7			
34	2033.4	3.3	9a	9467.9	3.2
47	4894.0	3.4			
48	904.4	1.6			
53	1636.1	3.6			
25	300	4.7	9b	2318.9	8.6
26	366.6	0.8			
33	802.1	4.7			
46	758.6	17.5			
52	91.6	12.9			
64	4810.6	2.4	9c	6514.0	5.5
72	621.1	16.4			
73	1082.3	13.0			
19	7.9	20.8	Offshore islands	16.5	10.0
32	8.6	0.0			
Total	**78838.2**	**25.7**			

Estimation of daily discharge for each ERSEM box

Daily and monthly flows (m^3s^{-1}) for rivers represented in the National Flow Archives (NRFA - Yearbooks, 1984, 1987 and 1990) were compiled and each catchment ascribed to the appropriate ERSEM basin. Where more than one gauged catchment area was represented in an individual basin then a combined total daily flow was produced and converted to mm of runoff using the total gauged land area. The distribution of available flow data was better in the East than the North West where some extrapolation between basins was necessary. The measured daily runoff value was applied across the remaining non-gauged area of each basin and converted to litres of flow for each ERSEM box. In Figure 2.2 the averaged annual rainfall for each test year and ERSEM box are shown and highlight the spatial variability in runoff.

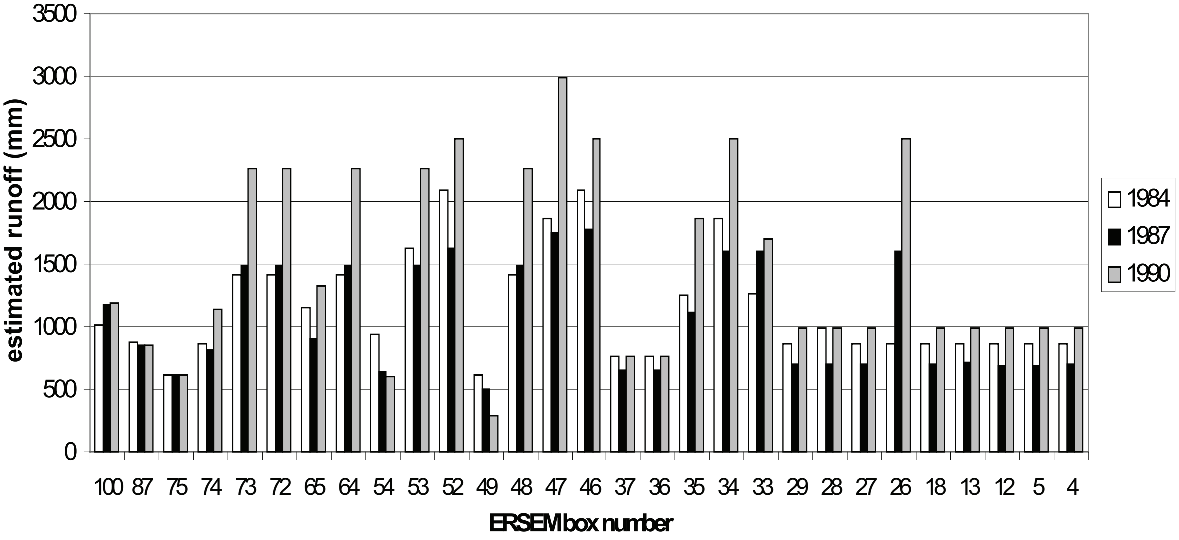

Figure 2.2 *Comparison of annual runoff from Scotland to each ERSEM coastal box for the three climate years (1984, 1987, 1990). For locations of ERSEM boxes, refer to the description of Task 3 later in this report.*

Estimation of daily elemental fluxes from each ERSEM box

The only, nationally available, river compositional data set is the Harmonised Monitoring Scheme (HMS), which consists of approximately monthly samples per year for some 58 catchments. In general the HMS sites are located at the lowest non-tidal points *Note not all HMS sites and NRFA are common.* In the majority of cases flow at the time of sampling or a daily average flow is included for each water sample. Not all elements are of equal reliability (see Ferrier *et al*., 2001 for a recent review of the data)

Calculation of flow weighted concentrations (FWC)

All available data for the individual years 1984, 1987 and 1990 were collated and flow weighted average annual concentrations calculated (sum of instantaneous loads/total flow) for Suspended solids, Nitrate+nitrite, Ammonium, orthophosphate, Silicate and Dissolved organic carbon (not available for all sites). *Note – the choice was made to treat the years separately because they were selected to be 'extreme' cases and it was considered that this may affect the subsequent relationships with land cover. One important limitation is that spot samples tend to be biased to lower flow conditions, but this is compensated to some degree by using daily flows and a flow weighted mean concentration.*

Relationships between land cover and FWC

Land cover attributes were ascribed to each HMS catchment area and the proportions of 'Agricultural', 'Non-agricultural' and 'Forestry/rough grass' for all HMS catchments are shown in Figure 2.3. The HMS catchments as a whole account for approximately 50% of the total Scottish land area (Figure 2.4) although importantly they do cover a wide range of land use conditions (ranging from 0 – 95% agriculture). The relationships between FWC and proportion of agricultural land (Edwards *et al*., 2000) were found to be statistically significant (Figure 2.5). Using these regression equations and the proportion of agricultural land in the catchment of each ERSEM box (Table 2.1), individual average FWC were produced. These FWC were used in combination with daily river flows to produce a daily elemental load for each box.

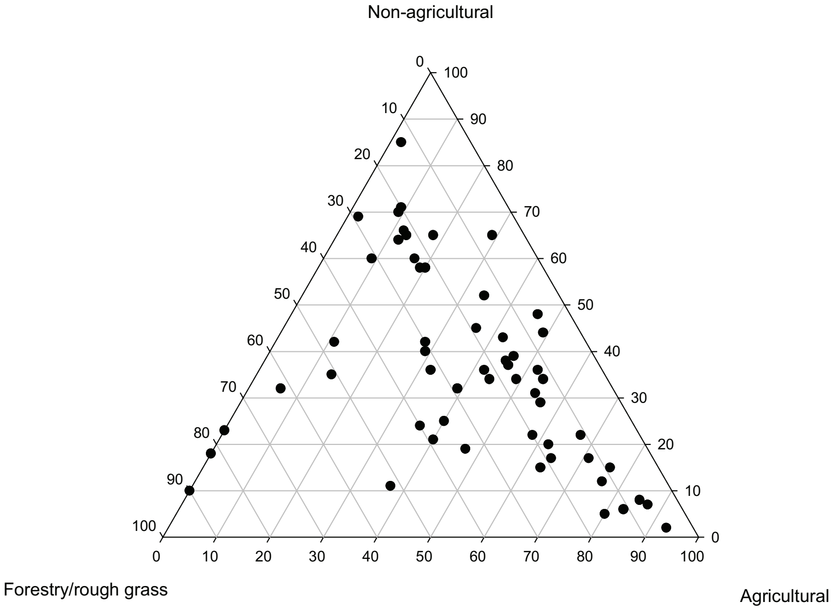

Figure 2.3 *Comparison of main land cover attributes for the Scottish Harmonised Monitoring Scheme (HMS) sites. The catchments shown in Figure 2.4 (each represented by circular symbol in the triangular diagram) were characterised by the percentage contributions of agricultural, non-agricultural, and forestry/rough grass land usage*

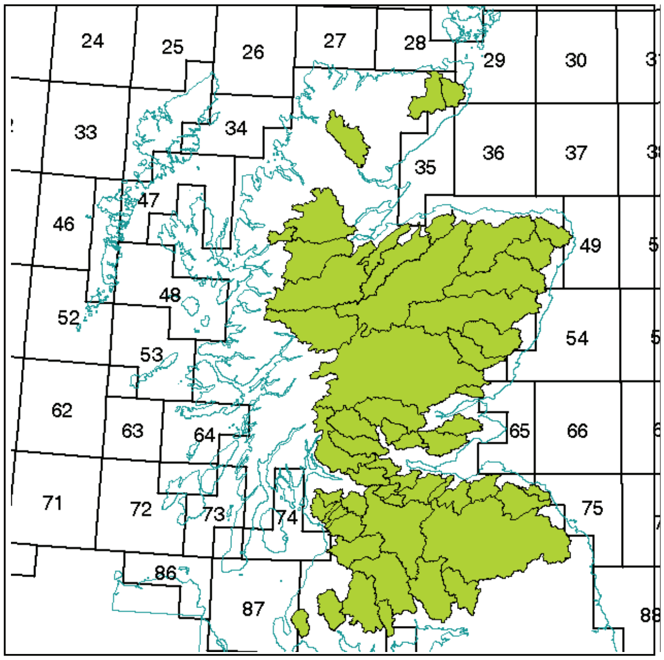

Figure 2.4 *Extent of Scottish Harmonised Monitoring Scheme catchments (in green) in relation to the land area of Scotland.*

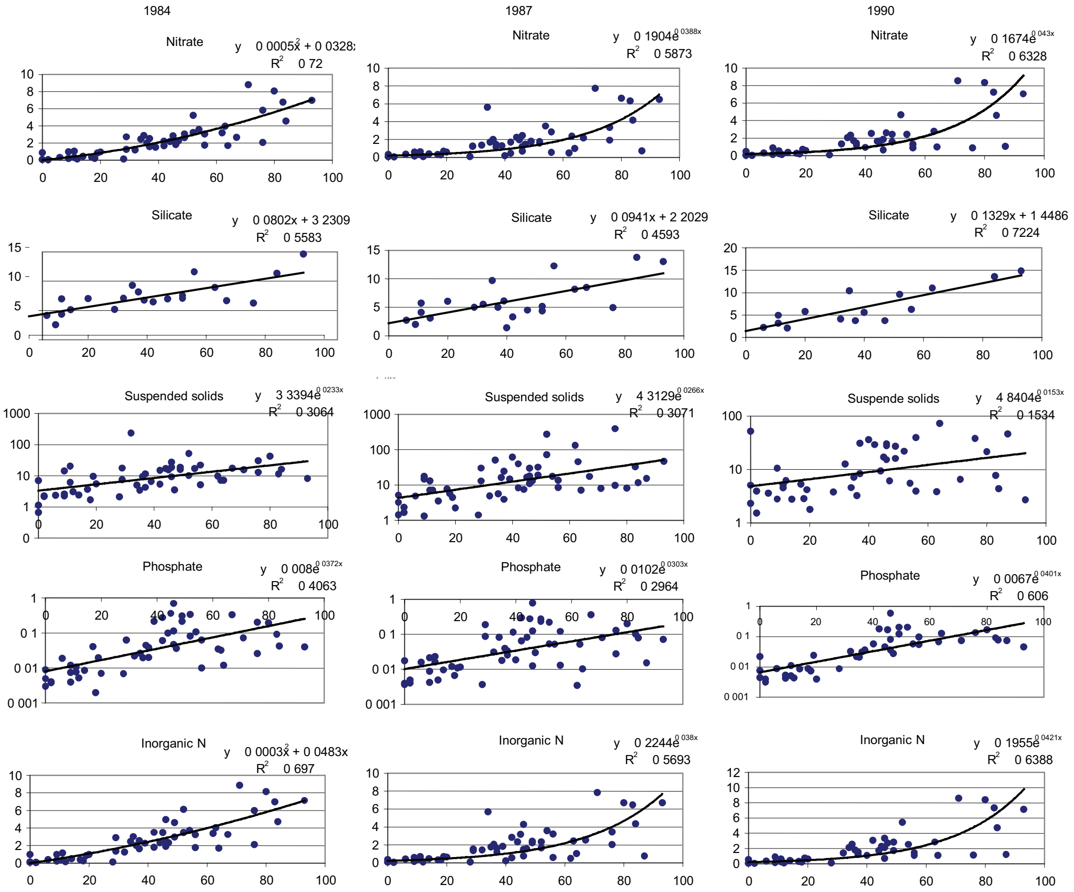

Figure 2.5 *Relationships between flow weighted concentrations (mg m^{-3}) of nitrate, silicate, suspended solids, phosphate and inorganic nitrogen (y-axes), and the proportion of agricultural land (x-axes) for the Scottish Harmonised Monitoring Scheme catchments. Left column, 1984; centre column, 1987; right column, 1990. Coefficients of the fitted relationships and r^2 values are shown for each graph*

Extrapolating from the chemical species measured in the HMS to those required by the ERSEM model

There was a considerable discrepancy between the range of variables measured by the HMS and those expected as loading inputs by the ERSEM ecosystem model. The HMS data routinely included nitrate+nitrite combined, ammonium, orthophosphate, silicate, dissolved organic carbon (not available for all sites) and a relatively small number of total nitrogen and total phosphorus measurements. In addition, data were available on the suspended solids concentration. In contrast, the ERSEM model expected data on nitrate, nitrite, ammonium, phosphate, silicate, particulate organic phosphorus (POP), particulate organic nitrogen (PON), particulate organic silicon (POS), and particulate organic carbon (POC). Various strategies were employed to estimate the unmeasured variables from those reliably included in the HMS data.

Since they were not routinely measured, particulate carbon and nitrogen were estimated from the suspended solids data using in most cases the values of 30% and 3% (an average taken from four surveys of seven East coast rivers; Ernstberger, 1999). Little information exists for concentrations of dissolved organic nitrogen (although its significance for drainage from unmanaged land has been reported by Chapman *et al*., 2001) so it had to be estimated using a relationship with nitrate that was apparent from unpublished work for rivers in the NE of Scotland. Dissolved organic carbon concentrations, where not measured, were estimated from the particulate carbon concentration using a mean ratio of 1.94, established from the few measurements available.

Obtaining estimates of the organic phosphorus concentration was especially difficult. A high proportion of phosphorus in river outflows is adsorbed onto particulate and colloidal material and is therefore difficult to both sample and measure. Measurements referred to as "total phosphorus" are likely to be an underestimate of true total averaged over the water volume passing the monitoring site, due partly to sampling methods which will tend to underestimate the total particulate material. In an effort to produce a realistic estimate of the organic phosphorus load, it was assumed that the measured "total phosphorus" concentration less the inorganic ortho-phosphate provides an underestimate of the dissolved plus particulate organic fractions. A realistic value for the total organic fraction was then assumed to be 2.17 times the estimated total, based on a comparison of organic:inorganic ratios in the data for nitrogen. Finally, 54% of the total organic phosphorus was assumed to be dissolved and 46% associated with particulate material, again based on ratios of dissolved:particulate fractions of organic nitrogen. Where "total phosphorus" was not directly measured, this was also estimated from the suspended solids data using a ratio of either 0.1% or 0.4% for predominantly unmanaged and managed catchments respectively.

The Scotland-wide averaged loss coefficients for each of the three years are summarised in Table 2.2. *Note – there is an obvious potential for errors in the loading estimates, however it was considered of greater value to include best estimates at this stage rather than not include certain flux values. These loss estimates can be improved as better information becomes available.*

Table 2.2 *A comparison of the averaged loss coefficients calculated for different substances for Scotland. All figures are as kg ha^{-1}*

Year	Ammonium-N	Nitrate-N	DON	Part-N	Ssolids	Ortho-P	Part -P	DOC	Part-C	Silica (SiO_2)
1984	2.1	12.4	4.1	1.8	68.2	0.3	0.2	46.1	17.6	56.3
1987	0.8	5.6	2.0	2.2	85.9	0.2	0.2	46.1	22.0	44.9
1990	1.0	7.2	2.6	2.6	97.6	0.3	0.2	46.1	26.1	58.2

For the purposes of compiling the data for inclusion in the ERSEM model, dissolved and particulate carbon concentrations were combined into a single value. The rationale for this was that a significant proportion of river-borne dissolved organic carbon is converted to particulate forms on contact with seawater. For consistency, the same approach was taken for organic nitrogen and phosphorus.

Two parameters required by the ERSEM model remained unmeasured in Scottish river waters. Firstly nitrate and nitrite were combined as total oxidised inorganic nitrogen in the HMS sample data. Secondly, no data were available on organic silicon.

Data from the England and Wales Environment Agency indicated that in English and Welsh rivers the ratio nitrite:total oxidised inorganic nitrogen varied seasonally between 3% in late summer and 0.6% in late winter. Given this small contribution, nitrite concentrations were set to zero for Scottish loadings, and the nitrate concentration in river waters assumed to be given by the total oxidised inorganic nitrogen.

Measurements of organic silicon in continental European rivers (Pätsch, 1997) showed no significant relationship to inorganic silicate or any of the other measured variables. However, Pätsch estimated the total load of organic silicon to the North Sea to be around 7% of the silicate load, and on this basis the organic component was set to zero for Scottish rivers. Cursory checks of the model results indicated that the discrepancy incurred by these assumptions was likely to be negligible.

Separation of urban waste water, industrial and terrestrial components of riverine loads

Estimates of the direct industrial/domestic discharges into rivers that occur above the HMS sampling points were provided by SEPA for 1999 as an annual load. After conversion into a daily value (assuming a constant daily load) these were subtracted from the appropriate total riverine load to ERSEM boxes. In this way, the total riverine load was divided into that due to urban waste water, and that due to the combination of agricultural activity and geology (natural erosion). *Note - the 1999 data was the only year that data was available so this was common to all years. This approach appeared to be reasonable for most rivers, except the Clyde when summer combined loads were below the daily industrial/domestic contribution. If more detailed loadings to specific areas such as ERSEM box 74 (Clyde) then it is recommended that a more detailed breakdown be made.*

Estimation of direct to sea discharges of urban waste and industrial nutrients

Data on direct-to-sea discharges (*i.e.* those downstream of HMS sites) in 1999 were obtained from SEPA. These discharges included urban waste treatment plants and various industrial units (*e.g.* distilleries and chemical plants). The data were available for each individual discharge site, and the monitored variables (kt/year) were total nitrogen, total organic nitrogen, ammonia, total phosphorus, and phosphate.

Individual discharges were assigned to ERSEM boxes and summed accordingly. The range of chemical species measured was extrapolated to that required for compatibility with the ERSEM model in the same fashion as for the river discharges, except that carbon loads (for which there were no measured data) were estimated from nitrogen loads assuming a C/N ratio of 10.

Finally, the annual discharges were converted to daily values assuming a constant rate of input over the year.

Estimation of aquaculture loads

Estimation of nutrient loads due to aquaculture involved two steps. The first was to calculate the monthly discharge of nutrients per annual tonne of salmonid production, and the second was to assemble the data on consented annual production for each of the ERSEM coastal boxes.

The calculation of discharge rates per tonne of production followed the guidelines set out by the OSPAR Framework and Approach of the Harmonised Quantification and Reporting Procedures for Nutrients (HARP-NUT), Guideline 2 (OSPAR, 2000). This deals only with the estimation of nitrogen and phosphorus losses from aquaculture plants, but the procedure was easily adapted to accommodate carbon losses.

Discharges of nutrients from aquaculture units are derived from uneaten feed, undigested material (faeces) and excretion via the gills and the urine. There are several approved methods of determining these losses, and one adopted here involved calculations based on the chemical composition of the feed material and of the harvested fish, and feed conversion ratios.

Input parameters to the calculations are given in Table 2.3, and the outputs in Table 2.4. The only modification to the OSPAR HARP-NUT guidelines was the assumption of an assimilation efficiency for each element, thereby allowing the discrimination of dissolved organic (faeces) and dissolved inorganic outputs. This was necessary because the distinction was required for the ERSEM model, and also because of the inclusion of carbon in the calculations. In contrast to excreted ammonia and phosphate, respired carbon dioxide does not contribute to the total nutrient loading.

Table 2.3 *Input parameters to the calculation of nutrient losses from salmon aquaculture units. Feed composition and from latest manufacturers data sheets. Feed conversion ratio is the operational value currently used in the industry.*

	Carbon	**Nitrogen**	**Phosphorus**
Feed % composition	57.8	7.2	1.46
Salmon % dry weight	40.0	15.0	2.5
Assimilation efficiency	0.85	0.85	0.85
Feed conversion ratio	1.2		
% food not eaten	5		
Salmon % water content	78		

Table 2.4 *Derived outputs from the calculations of losses from salmon aquaculture units.*

	Carbon	**Nitrogen**	**Phosphorus**
Feed input (kg/t wet production)	693.6	86.4	17.6
Harvested fish (kg/t wet production)	88	33	5.5
Uneaten food (particulate organic matter, kg/t wet production)	34.7	4.3	0.88
Faeces (dissolved organic matter, kg/t wet production)	98.8	12.3	2.50
Dissolved inorganic matter (kg/t wet production)	472.1 as CO_2	36.8 as NH_3	8.67 as PO_4
Total losses to the environment (kg/t wet production)	605.6	53.4	12.05

Data on the consented tonnages of salmon production for each sea loch in Scotland were available from records held at FRS. The most recently available year of data was 2001 for which the Scottish annual total was 162,904 tonnes. For comparison, the production in 1999, being the year for which urban waste water and industrial loadings were compiled, was 126,686 tonnes.

Each sea loch was assigned to an ERSEM box, and the tonnages summed over each box. It was then a straightforward matter to apply the loss rates calculated above to the tonnages in each ERSEM box. Finally, the annual discharge rates of nutrient species to each box were converted to daily rates averaged over each month of the year, using month-specific values of the ratio of monthly/annual average rate which take into account the seasonally varying size composition of fish on a typical multi-year class farm and the seasonal cycle of temperature.

Using this model, the estimated total annual discharges in 2001 of nitrogen, phosphorus and carbon from Scottish aquaculture were 8,699, 1,962 and 21,751 tonnes respectively. The resulting seasonal and spatial patterns in Scottish aquaculture nutrient loads to coastal waters (illustrated by the nitrogen loading) are shown in Figures 2.6 and 2.7.

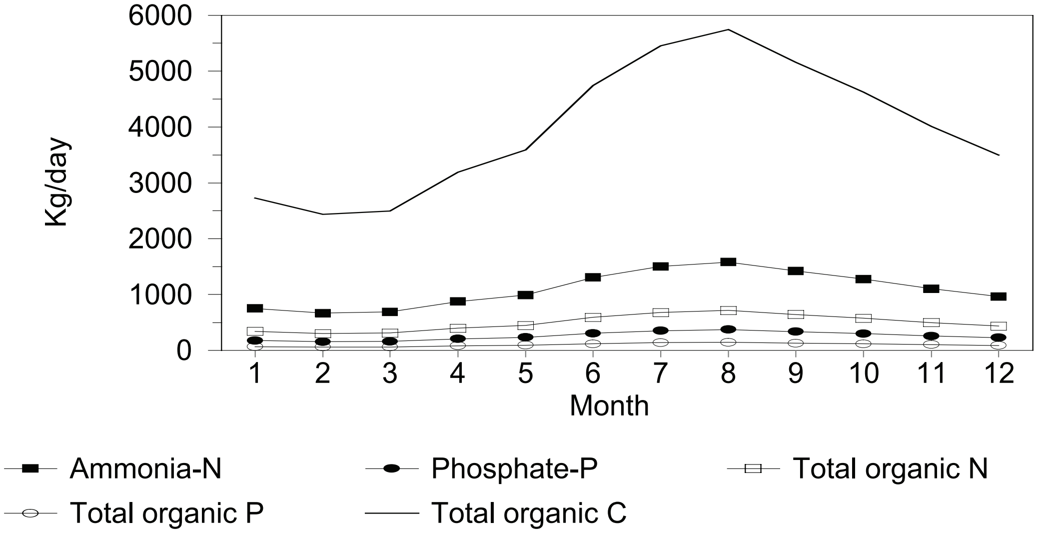

Figure 2.6 *Seasonal changes in the loss rates of organic and inorganic nutrients from salmon farms, summed over all farms in Scotland in 2001.*

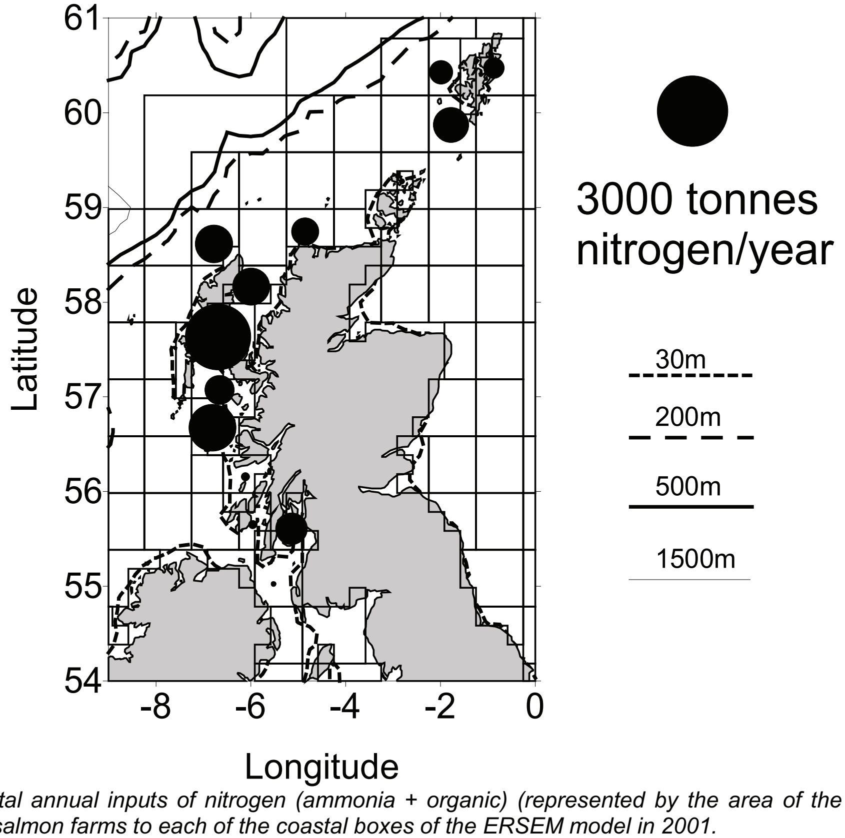

Figure 2.7 *Total annual inputs of nitrogen (ammonia + organic) (represented by the area of the filled circles), from Scottish salmon farms to each of the coastal boxes of the ERSEM model in 2001.*

Summary of loading contributions from Scotland

Summing over all sources and all the different inorganic and organic forms of each of the nutrient elements for the whole of Scotland, the total annual elemental loads are shown in

Table 2.5. It is clear that carbon and silicon form by far the largest component of the bio-reactive nutrient load to Scottish coastal waters. However, compared to the Redfield Ratio (106 carbon : 16 nitrogen : 1 phosphorus, molar ratio), which is taken to be typical of the average composition of living biological material, the total annual load appears to be depleted in phosphorus and rich in nitrogen relative to the carbon content (average year, 106 carbon : 20.4 nitrogen : 0.91 phosphorus, molar ratio).

Table 2.5 *Total annual loads of nitrogen, phosphorus, carbon and silicon due to Scottish runoff and discharges (all sources, and all forms of each nutrient element combined). Data for each of the three climate years 1984, 1987 and 1990, together with the average of these three years.*

	Total nitrogen load (kt/year)	**Total phosphorus load (kt/year)**	**Total carbon load (kt/year)**	**Total silicon load (kt/year)**
1984	186.0	13.6	597.4	444.0
1987	108.1	14.2	631.7	346.5
1990	130.7	14.4	664.3	459.3
Average	141.6	14.0	631.1	416.6

Table 2.6 *Composition of nutrient loads from Scotland as a whole. Agricultural and natural erosion inputs are given for each of the three climate years 1984, 1987 and 1990 and for the average of these three years; urban waste water and industrial inputs for 1999; and aquaculture inputs for 2001. Aquaculture inputs estimated for 1999 are also shown for comparison. Figures in brackets are percentages of the average year total loading from all sources.*

	Annual flow ($x10^6$ m^3)	**Total nitrogen load (kt/year)**	**Total phosphorus load (kt/year)**	**Total carbon load (kt/year)**	**Total silicon load (kt/year)**
1984 agri.+erosion	89.00	158.29	5.76	484.67	443.96
1987 agri.+erosion	81.43	80.45	6.36	519.01	346.49
1990 agri.+erosion	115.11	103.03	6.58	551.63	459.27
Avg. agri.+erosion	95.18	113.92 (80.5%)	6.23 (44.4%)	518.44 (82.1%)	416.57 (100%)
1999 Urban waste		17.82 (12.6%)	5.14 (36.6%)	82.81 (13.1%)	0
1999 Industry		1.16 (0.8%)	0.71 (5.1%)	8.15 (1.3%)	0
2001 Aquaculture		8.70 (6.1%)	1.96 (13.9%)	21.75 (3.5%)	0
1999 Aquaculture		6.76 (4.8%)	1.50 (11.2%)	16.91 (2.7%)	0

Table 2.7 *Proportions of annual Scottish urban waste water discharges originating from direct to sea discharges as opposed to discharge to the river catchments.*

	Nitrogen	**Phosphorus**	**Carbon**	**Silicon**
Proportion of UWW load from direct-to-sea discharges	0.80	0.76	0.56	n/a

All of the silicon in the annual load was estimated to derive from the agricultural and geological (natural erosion) runoff in rivers (Figure 2.8, Table 2.6). The distribution of carbon and nitrogen across the various sources (agriculture+erosion, urban waste water, aquaculture and industrial) was approximately the same with around 80% originating from agriculture and erosion. In contrast, aquaculture and especially urban waste water inputs were relatively enriched in phosphorus.

Inputs of nitrogen from aquaculture were approximately equivalent to half of the total urban waste water load from Scotland. Phosphorus inputs from aquaculture were approximately one-third of those from urban waste water. The calculated inputs from aquaculture were similar to those estimated by other investigations. For example, MacGarvin (2000) estimated that the 1998 annual salmonid production of 115,000 tonnes would release 6,900 tonnes of nitrogen and 1,140 tonnes of phosphorus, representing 0.0600 tonnes nitrogen and 0.0099 tonnes phosphorus/tonne production. The equivalent rates from the model presented in this report are 0.0534 tonnes nitrogen and 0.0121 tonnes phosphorus/tonne production.

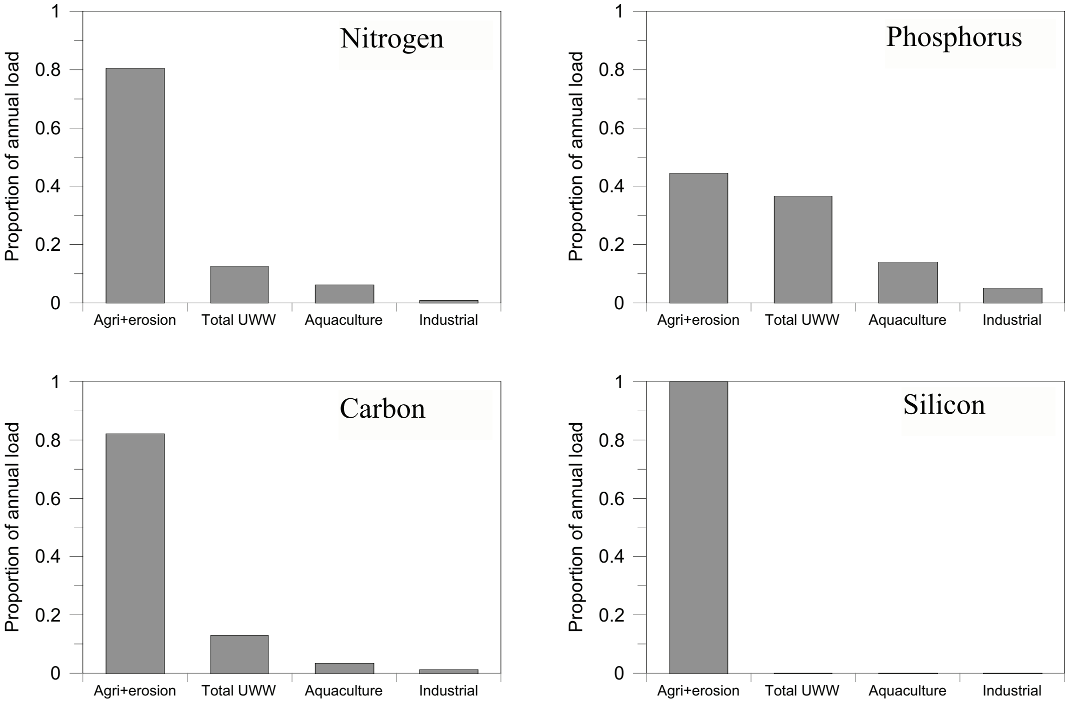

Figure 2.8 *Relative contributions of different sources of nutrient (agriculture and natural erosion, urban waste water (discharge to river catchment plus direct to sea discharges), aquaculture, and industrial) to the total annual nitrogen, phosphorus, carbon and silicon loads from Scotland in the average climate year.*

The majority of urban waste water discharges from Scotland enter the coastal water environment (Table 2.7). These are either direct from cities and towns on the coast or via valley sewer systems which collect wastes waters from inland towns and transport this to the coast for treatment and discharge in the marine environment. It should be noted that up until 1999 the majority of urban waste water discharges were subject to preliminary (or primary) treatment prior to discharge in marine waters, where natural dispersion, dilution and disinfection were considered to be appropriate treatments. Secondary treatment was the norm for inland discharges to freshwaters. Since 1999, a number of towns, cities and valley sewer systems have had secondary (biological) treatment systems provided in line with the requirements of the Urban Waste Water Treatment Directive.

Nitrate Vulnerable Zones have been designated along most parts of the East coast of Scotland. This designation covers most of the land in arable production from North East Scotland to the English Border. Nitrate reduction strategies are now being implemented in the majority of these catchments in the form of statutory Action Programme regulations.

Considering differences between the three climate years examined, the freshwater runoff averaged over the entire land area of Scotland was greatest in 1990 and least in 1987 (Figure 2.9). Inter-annual differences in the elemental nutrient load from river borne agricultural and erosion are shown in Figure 2.10, where the data are presented as standardised annual anomalies for each element,

$$\frac{\left(N-\overline{N}\right)}{\overline{N}}$$

where N is the annual load of a particular element. The results suggest that climate affects the load of carbon and phosphorus in a similar way, and quite differently to nitrogen and silicon. Nitrogen and silicon varied more in line with runoff. It is possible that the similarity between the inter-annual response of carbon and phosphorus is due to the linkage between these elements and the suspended sediment load which was used in the estimation of organic components, but this remains to be investigated.

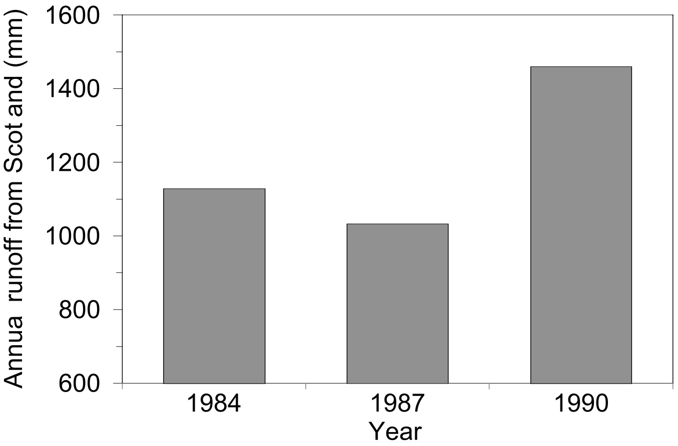

__Figure 2.9__ Differences between climate years in the annual runoff (mm) from the total land area of Scotland.

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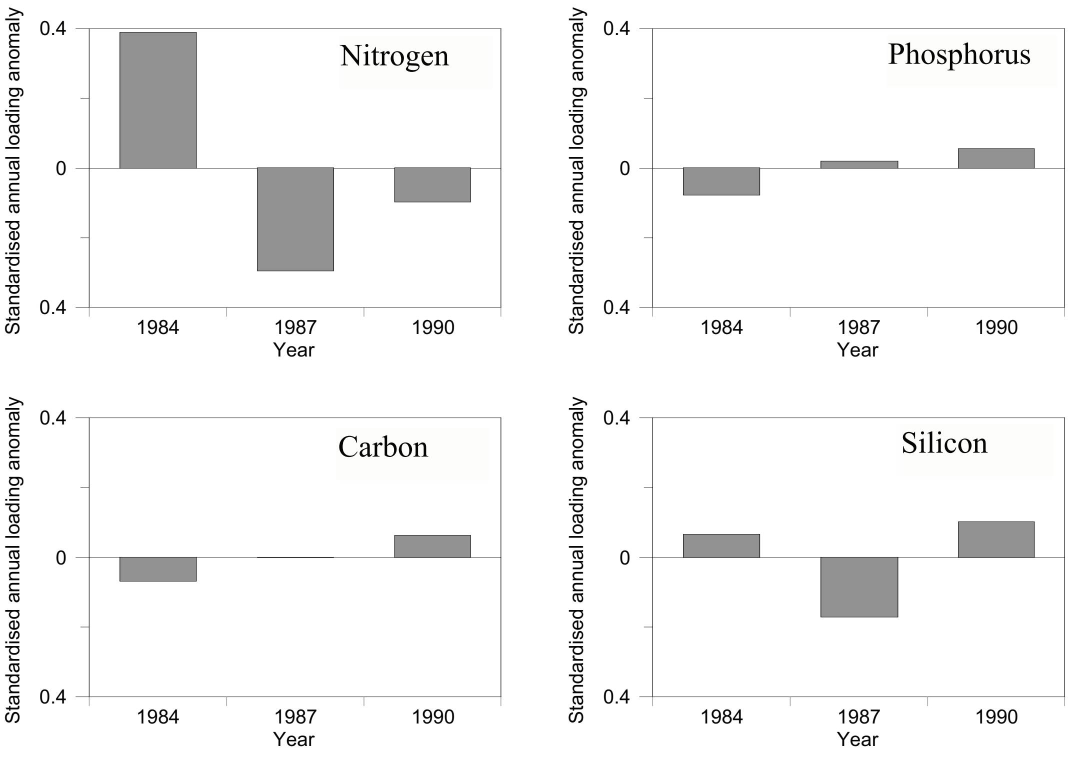


__Figure 2.10__ Differences between climate years in the total annual nutrient load due to agricultural runoff and natural erosion (all forms of each nutrient element combined). Data expressed as a standardised anomaly for each year.

The spatial distribution of the annual Scottish nutrient load, illustrated by the annual nitrogen load, is shown in Figure 2.11. Taken overall, the main centres of nutrient loading were associated with the major freshwater inputs (Forth, Clyde, Solway, Inverness Firth and the Inner Hebrides. Urban waste water loads (direct to sea and upstream discharges combined) were greatest in the vicinity of the major population centres of Glasgow and Edinburgh and northwards between Aberdeen and Inverness. However, only in the Firth of Clyde was the urban waste water load of similar magnitude to the river-borne agricultural and natural erosion load. In the Northern and Western Isles, aquaculture inputs formed that major part of the total load, but in the area of most intense aquaculture input (around Skye), river-borne natural erosion formed most of the total load.

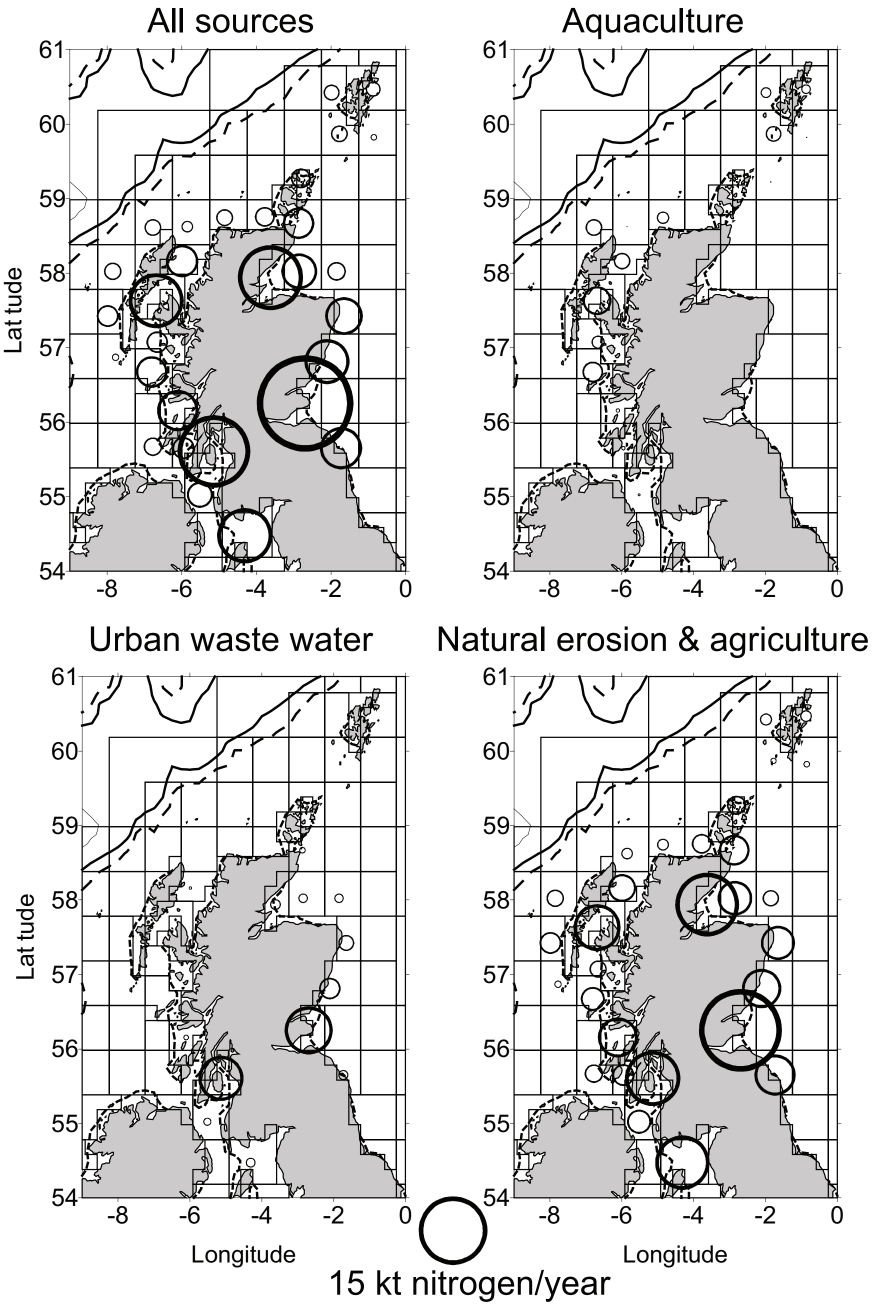


Figure 2.11 *Spatial variation in nitrogen load as expressed by the input to each coastal box of the ERSEM model adjoining the Scottish coastline. Data broken down by source (excluding industrial which was too small to display) and represented by circles of area scaled to the magnitude of the input.*

Estimation of nutrient loads for England and Wales

The approach adopted for England and Wales was similar to that outlined for Scotland with a digital terrain model and OS maps being used initially to estimate land draining each ERSEM box area and thus the runoff. In this case, only a total monthly loading was required but the series of calculations and assumptions were similar. The same combination of NRFA and HMS data (supplied by the Environment Agency, EA) was used to calculate monthly runoff (summarised as annual data in Figure 2.12) and loading for HMS rivers. Individual loss coefficients were extrapolated to non-gauged areas for each ERSEM box (Figure 2.13). No disaggregation of the total river load into terrestrial and industrial/domestic loads was necessary as there were no plans for model sensitivity analyses involving manipulation of England and Wales loads. However, the EA did supply data on the nutrient loads due to direct-to-sea discharges of urban waste water and from industrial sources (for 1999). Each source was allocated to an ERSEM box and the summed annual loading was divided by 12 to provide an estimated monthly load. No data were available on aquaculture loads for England and Wales, though these are extremely small.

Particulate C, N and P were estimated from the load of suspended solids as for Scotland. Dissolved organic carbon data were infrequent and where no data were available then a single value of 5 mg C l^{-1} was assumed.

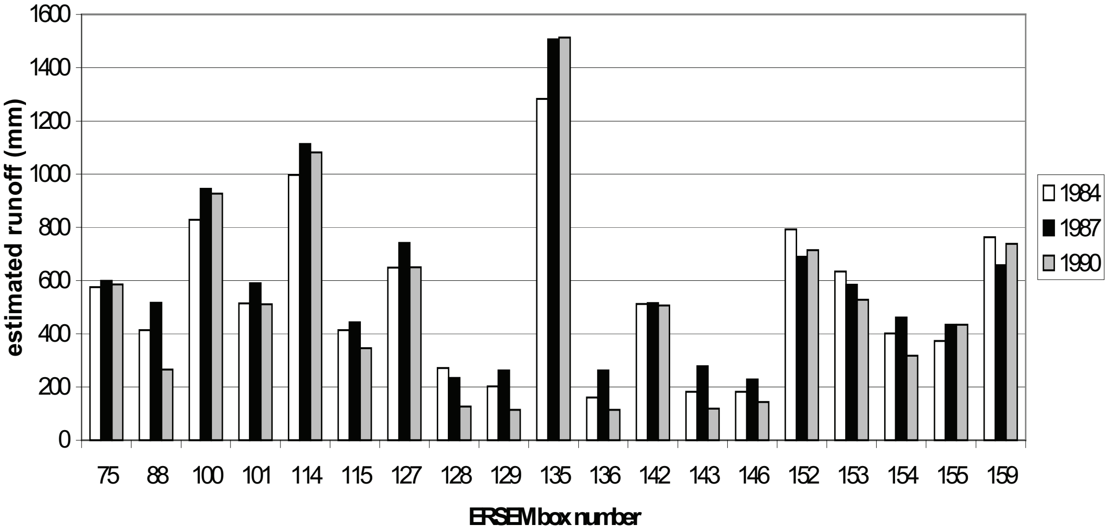


Figure 2.12 *Annual runoff (mm) from England and Wales to each of the ERSEM boxes adjoining the coastline. Note that boxes 75 and 100 also receive runoff from Scotland. For locations of ERSEM boxes, refer to the description of Task 3 later in this report.*

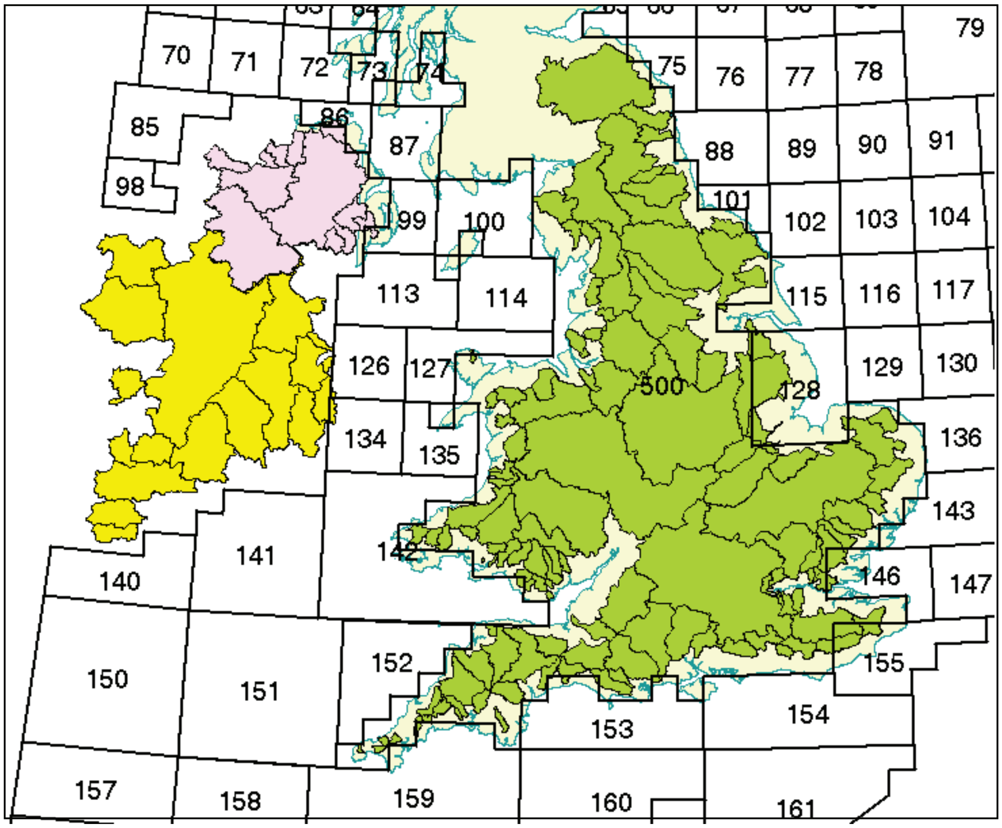


Figure 2.13 *Extent of Harmonised Monitoring Scheme catchments for England, Wales and Ireland (in green) in relation to the total land area.*

Estimation of Irish nutrient loads

The drainage areas for each ERSEM box adjoining the Irish coastline were estimated from ordinance survey maps. For the Irish Republic, long-term annual flows for the largest rivers and compositional data were obtained from the Irish EPA (http://www.epa.ie/rivermap/data-all/national.html and http://www.epa.ie/soe/soemain.html). Flow data, but no detailed compositional data, for Northern Ireland rivers were obtained from NRFA annual reports. No data on direct-to-sea discharges could be obtained for either the Irish Republic of Northern Ireland, nor any data to calculate aquaculture loads at the required resolution.

In the absence of nutrient concentration data for Northern Ireland rivers, these were assumed to be the same as for Irish Republic rivers flowing into nearby ERSEM boxes.

Of the three climate years under investigation, data for calculating monthly nutrient loads were available only for 1990. Hence a crude extrapolation was required to estimate the loads for 1984 and 1987. Loads for 1984 were estimating by applying the month-specific ratio of 1984:1990 runoff to coastal ERSEM boxes adjoining the western seaboard of England, Wales and Scotland. The equivalent procedure was employed to estimate 1987 loads.

Estimation of Norwegian nutrient loads

Annual loading data from industrial/domestic and agricultural sources were taken from the following sources (Natural Resources and the Environment 1999 (http://www.ssb.no/english/subjects/01/sa_nrm/nrm1999/) and these were divided by 12 to give equal monthly loads.

For Norwegian only annual estimates for P and N loadings were available for the years 1985, 1990 and 1998. For our simulation year 1984 we used the 1985-data, for 1987 we averaged 1985 and 1990-data, for 1990 we used the 1990-data. We assumed that 50% of the loadings were inorganic matter and 50% organic matter. For nitrogen additionally a subdivision of the inorganic pool into ammonium (17%) and nitrate (83%) was necessary. We equally distributed the Norwegian loadings among the Norwegian coastal boxes.

Estimation of Continental European nutrient loads

Daily nutrient loads from the continental rivers from Belgium, the Netherlands, Germany and Danmark entering the North Sea have been estimated in general accordance with the OSPAR HARP-NUT guidelines for the years 1977 to 1998 (Lenhart and Pätsch, 2001). The data are available at:

‘ftp.ifm.uni-hamburg.de‘ under the directory ‘pub/data/riverload‘.

The parameters available are:

- total nitrogen
- nitrate (+eventually nitrite)
- ammonium
- total phosphorus
- phosphate
- silicate

These variables were extrapolated to the range required by the ERSEM model along similar lines to those adopted for Scottish data.

- nitrite loadings were set to to zero (mostly they are implicitly include in the nitrate loadings)
- calculated particulate organic nitrogen = total nitrogen – nitrate - ammonium
- calculated particulate organic phosphorus = total phosphorus – phosphate
- applied particulate organic silicon values as calculated by the North Sea Task Force
- applied particulate organic carbon values as calculated by the North Sea Task Force

Danish nutrient loadings appear to be grossly underestimated by the above data as compared to recent estimates (OSPAR, 1999). This is because there are no major rivers enter the North Sea via Denmark and a major part of the loading from the region enters the North Sea by diffuse runoff.

No data could be obtained for French nutrient loadings to the southernmost boxes of the ERSEM model.

Summary of European-wide nutrient loading patterns

Scotland contributes around 15% of the total nitrogen and phosphorus loads from the British Isles (Scotland, England, Wales and Ireland) (Table 2.8), which is disproportionately small compared to both the Scottish land area and the freshwater input (runoff x land area) to coastal waters (Table 2.9). England and Wales contribute a disproportionately large amount of nitrogen and phosphorus. In contrast, carbon loads seem to scale roughly in proportion to land area, and silicon loads to freshwater input.

Table 2.8 *Nutrient element loads (kt/year, all forms combined) and percentages of the British Isles total for Scotland, England and Wales, and Ireland. In this context, Ireland refers to the Irish Republic + Northern Ireland. Data refer to the average of 1984, 1987 and 1990.*

	Scotland	**England and Wales**	**Ireland**	**British Isles total**
Nitrogen load (kt/year)	141.6	506.8	270.8	919.2
Phosphorus load (kt/year)	14.0	67.6	15.6	97.2
Carbon load (kt/year)	631.1	1359.0	439.5	2429.6
Silicon load (kt/year)	416.6	354.8	387.2	1158.6
Nitrogen load (% Brit.Is. total)	***15.4***	***55.1***	***29.5***	
Phosphorus load (% Brit.Is. total)	***14.4***	***69.5***	***16.0***	
Carbon load (% Brit.Is. total)	***26.0***	***55.9***	***18.1***	
Silicon load (% Brit.Is. total)	***36.0***	***30.6***	***33.4***	

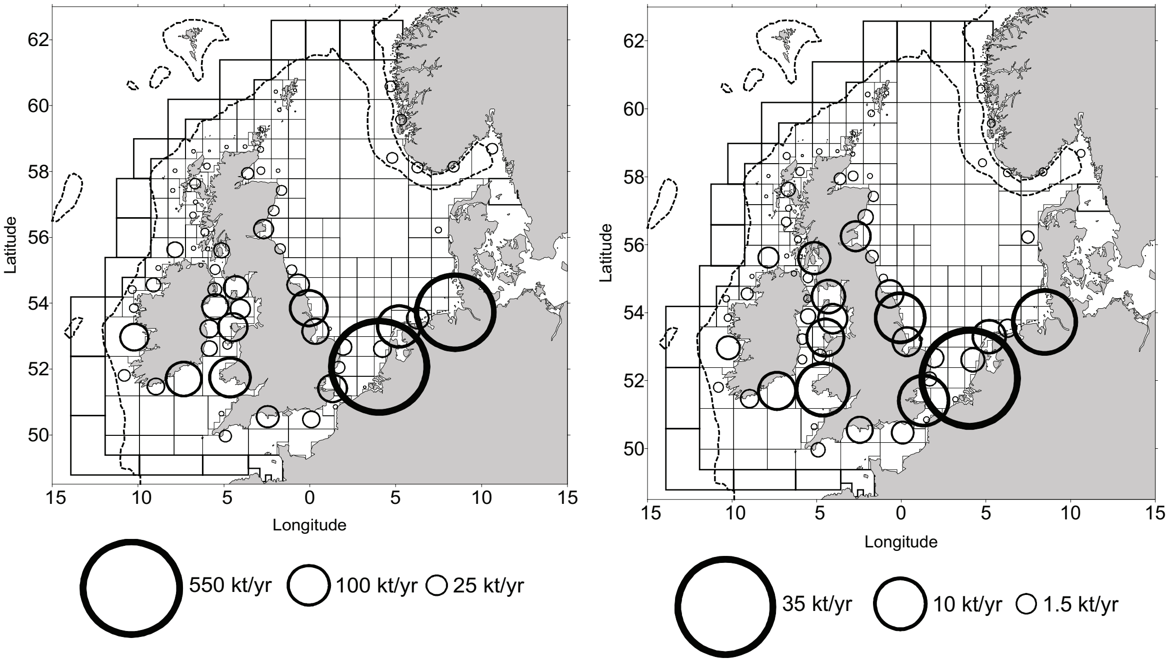
Table 2.9 *Regional contributions to the total land area and freshwater input to coastal waters for the British Isles (average of 1984, 1987 and 1990). Freshwater input is the runoff x land area.*

	Scotland	**England and Wales**	**Ireland**	**British Isles total**
Land area (km^2)	78838	151137	81464	311439
Average runoff (mm)	1207	459	607	711
% total land area	***25.3***	***48.5***	***26.2***	
Average % total freshwater input	***42.9***	***31.4***	***25.7***	

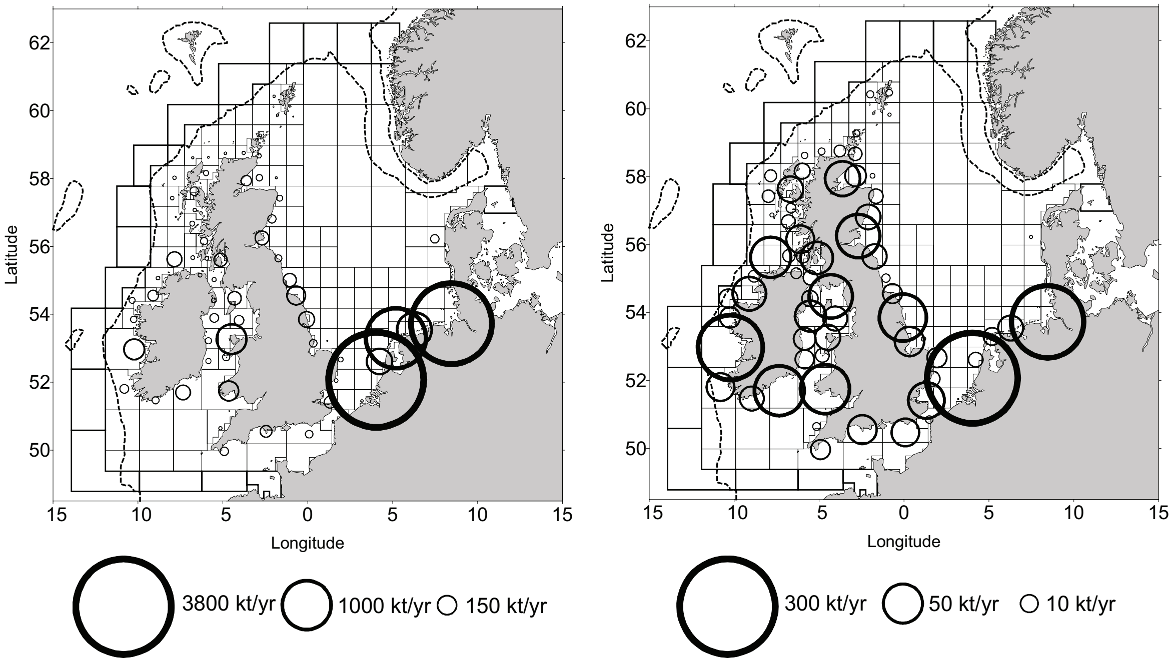
When the loadings due to the British Isles are compared with those from Continental Europe, it is clear that Scotland's contribution to the European nitrogen and phosphorus load is very small (<10%) (Table 2.10). Continental rivers are the major source of nitrogen loading (approximately 50%) (Table 2.10, Figure 2.14), but England and Wales are the major source of phosphorus. Carbon input is dominated by the large European rivers, but the pattern of silicon loading is quite different. Scotland makes a disproportionately large contribution to the total silicon loading. This presumably reflects the geology and topography of Scotland. However, it should be noted that the total carbon and silicon loadings do not include any data from Norway, which might also be a major contributor of silicon having similar terrain and geology to much of Scotland.

Table 2.10 *Percentages of the total nutrient element loads (all forms combined) to the entire ERSEM model domain (i.e. British Isles plus Continental Europe and Norway). Data refer to the average of loads in 1984, 1987 and 1990. Note that no carbon or silicon loading data were available for Norway, and only rudimentary data were available for Denmark.*

	Scotland	**England and Wales**	**Ireland**	**Continental Europe and Norway**
Nitrogen	***7.9***	***28.5***	***15.2***	***48.3***
Phosphorus	***9.4***	***45.1***	***10.4***	***35.1***
Carbon	***5.6***	***12.1***	***3.9***	***78.4***
Silicon	***26.4***	***22.5***	***24.6***	***26.5***


a) Nitrogen

b) Phosphorus


c) Carbon

d) Silicon

Figure 2.14 *Summary of annual loadings for the whole of the ERSEM model area based on 1987 river inputs. Dashed line denotes the 200m depth contour. Thin outlined boxes are the interior boxes of the model. Thicker outline boxes are boundary cells (see Task 3 for more details). The area of the circular symbols is directly scaled to the load (kt/year, all forms of each element) to each of the coastal boxes. Danish inputs were underestimated in each case, and no data on carbon or silicon were available for Norway.*

Comparison with other estimates of European nutrient loadings

Turrell (2000) compiled 1995 annual nitrogen and phosphorus loads from rivers and direct discharges to the North Sea Quality Status Report (QSR) Riverine Input and Direct Discharge (RID) regions. There are somewhat larger than the ERSEM assessment areas for Scottish waters, but coincide closely with the ERSEM areas for English and continental waters. Comparisons of Turrell's results with those obtained in this project are given in Table 2.11. In general, both total nitrogen and total phosphorus loadings used in the ERSEM project are around 50% higher than Turrell's for UK waters, and around 5-10% lower for continental waters. Inputs from the Atlantic coast of Scotland are almost certainly underestimated by Turrell's analysis due mainly to the poor river gauge cover in that region. Inputs to Danish coastal waters, and especially the Skagerrak, are certainly underestimated in the ERSEM loadings.

In general, the UK urban waste and industrial discharge loading estimates are similar from both the ERSEM loading analyses and those of Turrell (2000). The discrepancies arise mainly in the river loadings. This may be partly because of the different years for which the analyses were carried out, and partly because Turrell's analysis does not take account of runoff which is not monitored by the HMS gauges.

Table 2.11 *Comparison of total nitrogen and total phosphorus loads (excluding atmospheric inputs) to QSR regions as assessed by Turrell (2000), and as loadings for the ERSEM. Turrell's estimates are for 1995, whilst the ERSEM estimates are for a composite of 1999 urban waste and the average of 1984, 1987 and 1990 rivers.*

QSR RID regions	ERSEM regions	Total nitrogen kt/year, excluding atmospheric inputs			Total phosphorus kt/year, excluding atmospheric inputs		
		Turrell	ERSEM	ERSEM/Turrell	Turrell	ERSEM	ERSEM/Turrell
Atlantic Scotland	9a+9b+ 9c+10a	12.6	48.7	3.87	3.2	6.6	2.06
Scottish east coast	8a+8b+ 8c	57.0	83.6	1.47	3.8	6.5	1.72
English east coast	7	128.0	209.6	1.64	14.6	23.7	1.62
Irish Sea UK only	10b	72.9	104.4	1.43	13.2	11.6	0.88
Celtic Sea UK only	11	81.3	106.2	1.31	4.8	11.5	2.39
Belgian/Dutch coast	1+2	639.0	575.2	0.90	41.1	39.2	0.95
Danish/ German coast	3+4	302.2	241.3	0.80	12.1	11.9	0.99
Skagerrak	5	117.5	14.2	0.12	3.7	0.5	0.12

More recently, SEPA have produced assessments of the eutrophication status of each of the Scottish coastal water regions. Data for 1999 from the draft assessment report on the Scottish east coast (seen in draft, 8 November 2001; SEPA East, pers. comm.), are compared with loads calculated for the ERSEM model in Table 2.12. The total loads of nitrogen and phosphorus to the region from urban waste water and industry are in close agreement in the two analyses. 1999 river loads of nitrogen estimated by SEPA are of the same order but 12% higher than the 1984, 1987 and 1990 average estimated for the ERSEM project, whilst riverine phosphorus loads are 50% lower. As with the Turrell (2000) comparison, it is not clear to what extent these discrepancies reflect genuine hydrological variations between the years analysed, or differences in the methodology for assessing the total runoff from the land.

Table 2.12 *Comparison of total nitrogen and total phosphorus loads (excluding atmospheric inputs) to Scottish east coast regions. SEPA estimates are for 1999 compiled from the draft Comprehensive Procedures assessment. ERSEM model river loads are the average of 1984, 1987 and 1990, and ERSEM urban waste water (UWW) and industry inputs are for 1999.*

SEPA region	ERSEM boxes	Total nitrogen kt/year				Total phosphorus kt/year			
		Rivers		UWW+industry		Rivers		UWW+industry	
		SEPA	ERSEM	SEPA	ERSEM	SEPA	ERSEM	SEPA	ERSEM
Peterhead-StCyrus	49+54	8.17	10.93	1.85	2.29	0.16	0.77	0.30	0.52
St Cyrus-FirthofForth	65	20.46	14.80	8.93	7.83	1.19	1.29	2.22	2.12
Berwick coast	75	6.78	5.24	n/a	0.30	0.23	0.43	n/a	0.10
TOTAL		**35.42**	**30.97**	**10.78**	**10.42**	**1.58**	**2.49**	**2.51**	**2.75**

2.3 *Task 3. Implementation of an ecosystem model for Scottish waters*

Deliverables from Task 3

For the first report after 5 months:
Month 3: Configuration of ERSEM for extended area.
Month 5: Provision of irradiance and boundary conditions.

For the second report after 9 months:
Month 7: Provision of current fields.
Month 9: Test of new configuration with adapted forcing.
Month 9: Detailed outline of nutrient input scenarios to be simulated.

For the draft area designations after 11 months:
Month 11: Preparation and draft simulation of scenarios.

For the final report after 14 months:
Month 12: Evaluation of the model and comparison with seasonal time series data.
Month 13: Finalised scenario simulations.

Results from Task 3

The model set-up.

The starting point for this project was the “nd130” North Sea version of the ERSEM model inherited from the ERSEM project (Baretta-Bekker, 1995; Baretta-Bekker and Baretta, 1997). To address the issues of interest to the Scottish Executive, the model needed to be extended to cover the waters west of the UK.

The first, and most fundamental consequence of the westward extension of the model was that a new set of water circulation data were required to force the ecosystem model. These take the form of daily exchange coefficients between each neighbouring pair of spatial locations in the model domain. Such data can only be obtained as output from a hydrodynamic model of the region. Many different hydrodynamic models of the European shelf seas are in existence, and there are a range of archived results from such models. An assessment of the various options was undertaken early in the project, taking into account the time available to complete the work, the spatial resolution of the various models and accessibility of the archived data. Finally it was decided to use archived results from the LTT (long-term trend) 1955-1993 application of the HAMSOM (Hamburg Shelf-Ocean Model; Backhaus, 1985), which provides a reasonable representation of the flows to the west of Scotland and was well tried and tested as a source of circulation data for ERSEM applications (Pätsch and Radach, 1997). Figure 3.1 shows the model grid for the hydrodynamical simulations together with the box set-up of the so called “nd130” North Sea version of ERSEM.

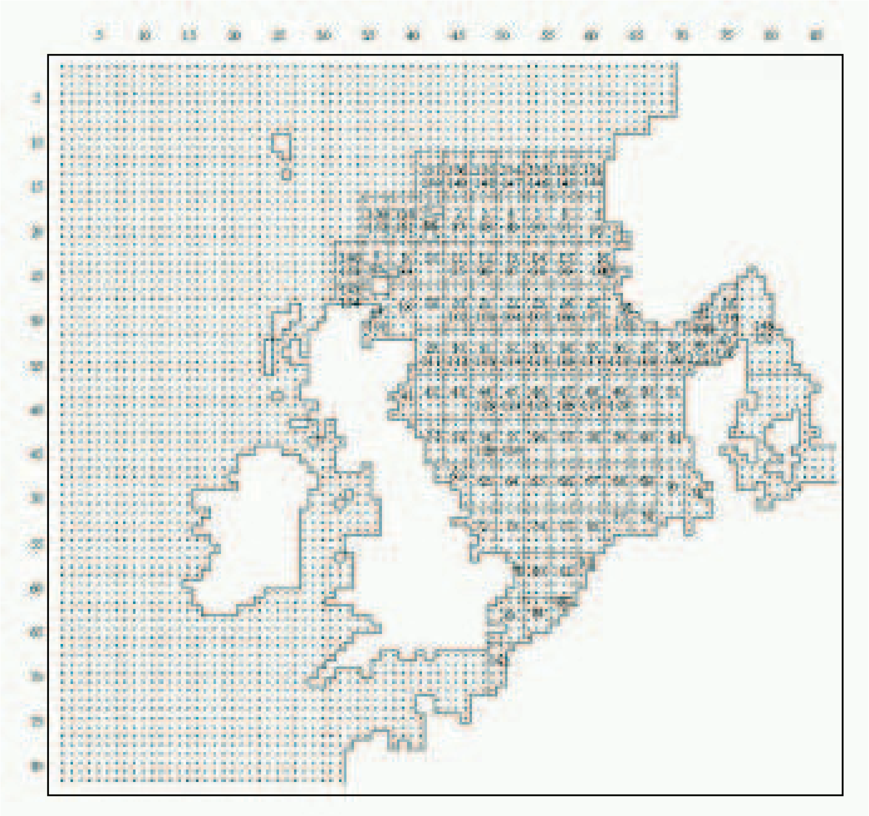
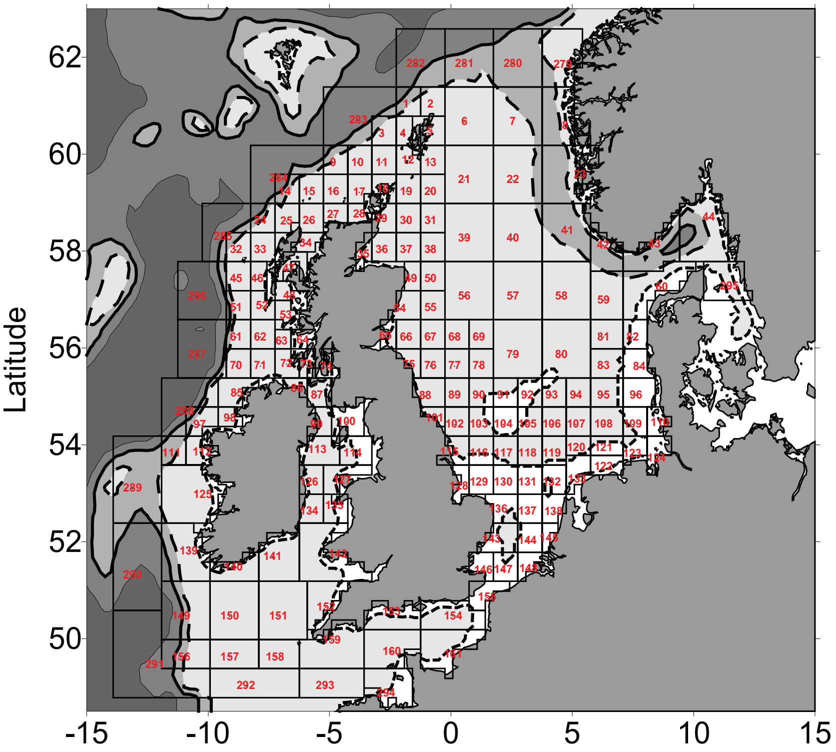


Figure 3.1 *Grid nodes of the LTT application of the HAMSOM hydrodynamic model, overlaid with the box structure of the nd130 North Sea version of ERSEM. X-axis and y-axis values refer to HAMSOM grid node numbers rather than longitude and latitude.*

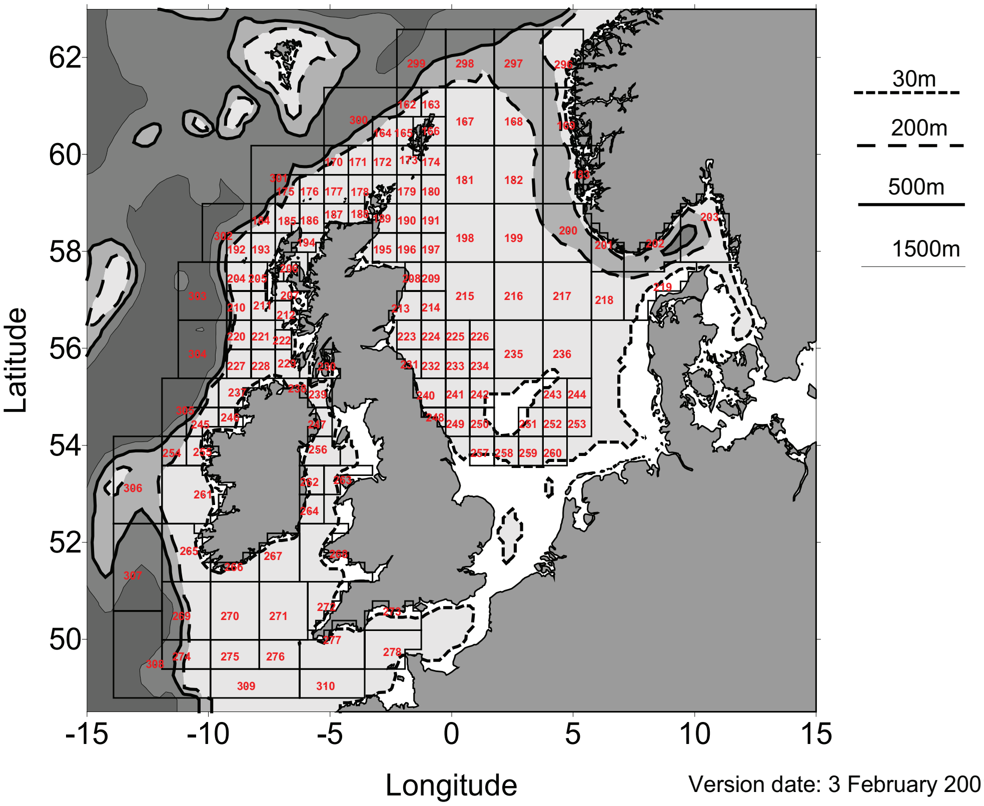
Having selected a source of hydrodynamic data, the next task was to establish the co-ordinates of the spatial compartments of the ecosystem model. ERSEM is a so-called “box model” in which the dynamic changes in the constituents of the system are simulated for each of an interconnected set of boxes, each representing a volume of water which is considered to be homogeneous. The choice of box configuration is therefore important for describing the topographic structure of the ecosystem. The box structure established for this project is shown for the entire model region (Figure 3.2) and for Scottish waters (Figure 3.3). The structure consists of 310 boxes in two layers, comprising 278 inner boxes and 32 boundary boxes. Time integration of model state variables operates only for the inner boxes. This version of the ERSEM model is hereafter referred to as “sc278”. The upper layer of boxes covers the top 30m of the water column, and the lower layer from 30m to the seabed. In some locations, where the total water depth was between 30 and 40m, a single layer of boxes extending to the seabed was used. In this way, 161 of the inner boxes have contact with the atmosphere, and 117 are isolated from the atmosphere. Appendix 1 gives depth, area and volume of each box.

Boxes in contact with the seabed generate and receive fluxes of material to/from the benthic module of the ERSEM model, which simulates the annual cycles of seabed chemical and biological variables. Two alternative benthic modules are available within ERSEM – the “Oldenburg” and “NIOZ” modules. The former was designed to minimise the run-time of the model at the expense of chemical and biological resolution, whilst the latter contains great detail of benthic chemistry processes but at a high computational cost. Due to the number of runs expected in this project, the Oldenburg benthic module was used throughout. For further switch definitions that turn on/off the submodules of ERSEM see Appendix 2.

Upper layer boxes (0-30m or total water column in areas of permanently mixed water)

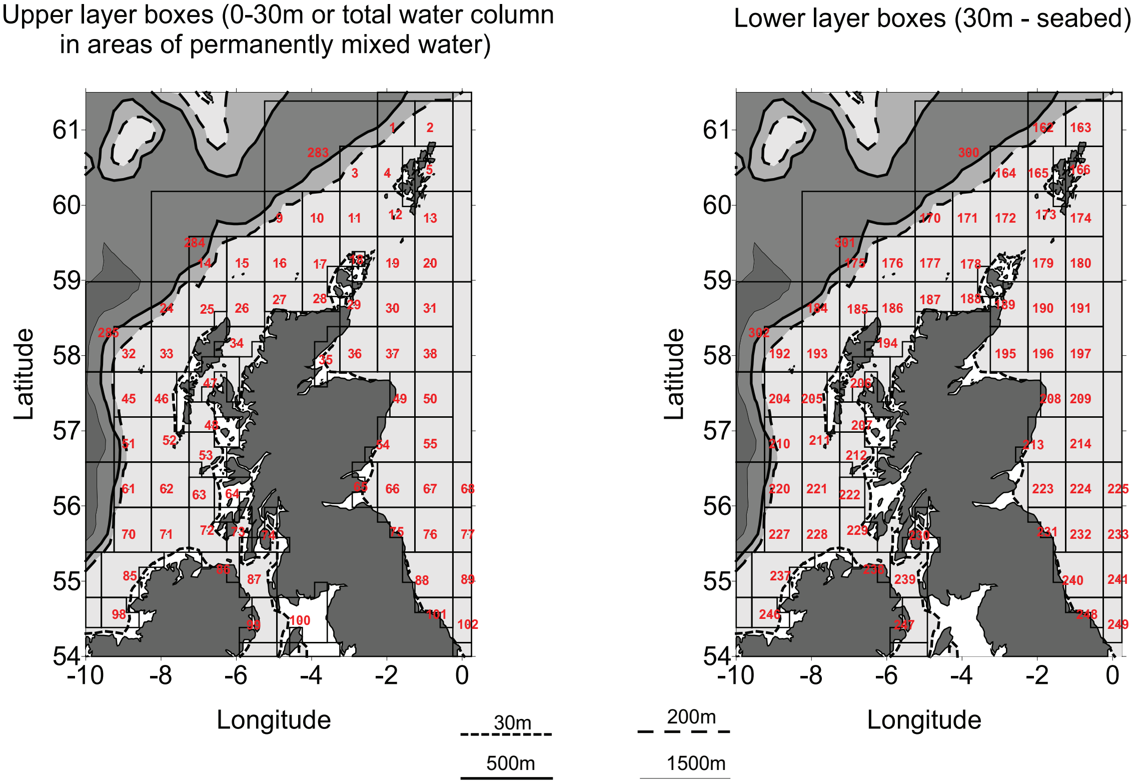


Lower layer boxes (30m - seabed)



Version date: 3 February 2001

Figure 3.2 *Configuration of upper and lower layer boxes in the “sc278” ERSEM model.*


Upper layer boxes (0-30m or total water column in areas of permanently mixed water)

Lower layer boxes (30m - seabed)

Figure 3.3 *Configuration of upper and lower layer boxes in the Scottish area of the "sc278" version of the ERSEM model.*

Which years to simulate with the ERSEM?

The LTT application of the HAMSOM hydrodynamic model provides daily advective transport and diffusion coefficients for the period 1 January 1955 – 31 December 1993, with which to drive the ERSEM. The temporal variability in the output data reflects variability in the 6-hourly weather data which are used to drive the HAMSOM. In this project, our aim was not to faithfully simulate the changes in ecological conditions which occurred over the period 1955-1993, but rather to select a few years out of the 39 available as representative of the range of climate conditions that may influence the fate of nutrients discharged into coastal waters.

Five data sets were analysed in order to determine which years of LTT application should be selected for driving ERSEM. The data were:

- Simulated annual volume inflow to the North Sea through the a transect at 59°N, 3°W-1°W. This was taken as an index of the shelf transport in the model.
- Annual rainfall anomalies at 7 locations in Scotland (3 on the western side – Dumfries, Paisley and Auchincruvie; and 4 on the east – Dunbar, Haddington, Dyce and Wick). The anomalies were averaged for the east and west of Scotland locations. The balance of rainfall between western and eastern Scotland was given by difference between the western anomaly and the eastern anomaly.
- Frequency of winds from the southwesterly quadrant in each year.
- 0-30m annual average sea temperature anomalies in the northern North Sea (57° 30'N–62°N, 1°W-6°E).

- The winter anomalies of the North Atlantic Oscillation index (NAO) which is a holistic indicator of climate conditions over the whole of the NE Atlantic region.

Details of the analysis are given in Appendix 3 to this report. In summary, the outcome was that:

- Sea temperature, SW winds and the NAO are all strongly inter-related,
- Inflow to the North Sea is positively related to the NAO, but only weakly to the SW wind frequency,
- West of Scotland rainfall is positively related to the North Sea inflow,
- East and west of Scotland rainfall are positively related,
- East of Scotland rainfall is inversely related to sea temperature and SW winds, but shows no or possibly a very weak inverse relationship with North Sea inflow (see time series plots).
- North Sea inflow is strongly correlated to the balance of rainfall between western and eastern Scotland.
- The balance of rainfall between western and eastern Scotland is correlated with western rainfall since this has double the variance of eastern rainfall. (Mean rainfall on western Scotland is also higher than to the east).

Taking all factors into consideration, the final choice of simulation years was:

- ***1984** as representative of weak transport, predominance of eastern rainfall and low NAO state*
- ***1990** as representative of strong transport, predominance of western rainfall and high NAO state*
- ***1987** as representative of an average year..*

Nutrient loading from the land (see Task 2), and irradiance forcing data for the ERSEM were therefore prepared for these selected years. For validation purposes, since these years represent the extreme range of variation in climate and input, we expect all observations of the marine conditions to fall within the range of values predicted by the simulations of these three years.

Forcing data

The model needs several driving data sets. These data are described in the following sections.

Transport

The transport data were calculated using output from the LTT version of the Hamburg Shelf Ocean Model (HAMSOM). The procedure for aggregating data for each of the boxes was the same as for the “nd130“ set-up. It resulted in daily values of net water exchange between the boxes (advection), vertical diffusion coefficients and horizontal diffusion coefficients. The raw (advective) transport values were smoothed by a running average procedure with 30 days bandwidth and Gaussian weights. Finally, small values of mass imbalance, introduced by the surface elevation of the hydrodynamical model HAMSOM, were reduced to zero. This procedure was described in detail by Lenhart *et al*. (1995).

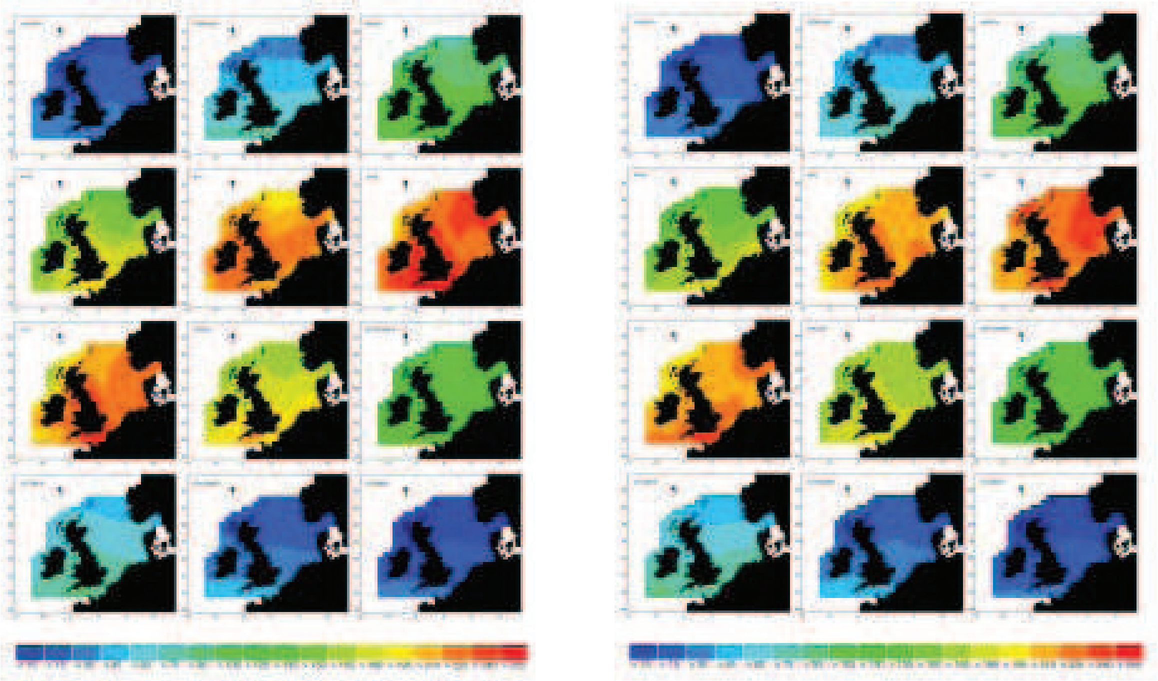
Values of the annual mean flushing times for each box for the years of interest are given in Appendix 4. The flushing time [d] is defined as the ratio of volume [m^3] and outflux [m^3 d^{-1}]. The data clearly identify areas with high exchange rates (low flushing times) west of UK and areas with low exchange rates in the eastern part of the North Sea and in the Irish Sea.

Irradiance

Daily values of net short wave irradiance were derived from the reanalysed data (“nswrs.sfc“) from NCEP/NCAR. These data were spatially interpolated to represent the centres of the “sc278“ boxes. Figures 3.4a-c illustrate monthly means of these data for the years of interest. The power per square meter [kW h m^{-2}] derived for the different years were: 1090 (1984), 1062 (1987) and 1082 (1990). The values differ by less than 3%.

a) Irradiance in 1984

b) Irradiance in 1987



c) Irradiance in 1990

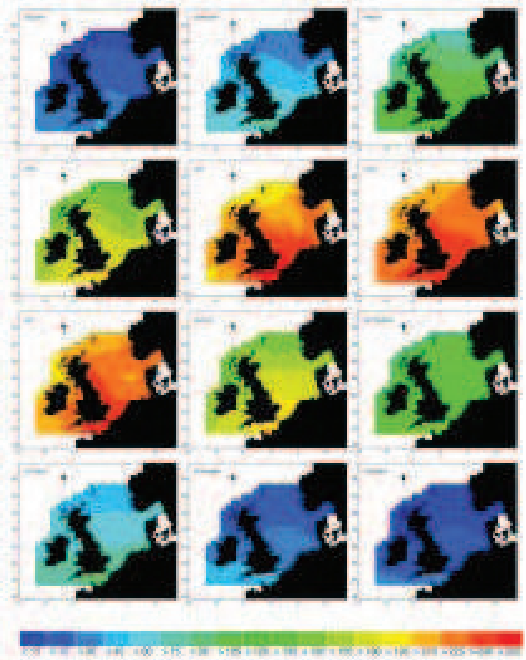


Figure 3.4 *Monthly mean irradiance [W m^{-2}] for a) 1984, b) 1987 and c) 1990.*

Silt concentrations

Concentrations of suspended particulate matter (SPM) in the water column are required by ERSEM as forcing data for each of the interior boxes of the model domain. The SPM load plays a major role in attenuating surface irradiance and controlling the light environment for the autotrophic plankton in the system. Field observations indicate strong spatial and temporal variability in SPM loads related particularly to freshwater fluxes from the land, tidal erosion and storm surges. Thus, spatial and temporal variability in SPM are important driving data for the model.

In the original nd130 North Sea version of ERSEM, 1988 and 1989 average daily time resolution SPM data were supplied for each of the interior boxes. These were derived from an independent model of suspended matter (Puls and Sundermann, 1990; Pohlmann and Puls 1994), calibrated using archived observational data as described by Lenhart *et al.*, 1997. However, neither modelled nor sufficient observational data exist to repeat this procedure for the regions west of the UK and Ireland. Hence, in this project the North Sea data were extrapolated using a statistical model based on topographic and hydrographic covariates.

We assumed an underlying model in which SPM originates from freshwater runoff draining into the sea, and from tidal scouring and resuspension. Hence we hypothesised that SPM concentrations might be inversely related to salinity and seabed depth, and directly related to maximum seabed tidal current speed at a given location. The applicability of this model was established using the SPM forcing data from the nd130 North Sea ERSEM model, topographic data, tidal current speed from an M_2 tidally forced hydrodynamic model of the region (Figure 3.5), and annual average salinity data assembled from archived records.

Salinity data were obtained from the ICES hydrographic data centre for the region (15°W – 14°E, 47° 30’N – 64°N). Even when all observations for the period 1970-1999 were combined, there were insufficient data to produce comprehensive climatological coverage of the entire model region at 3-monthly time resolution and LTT spatial resolution. However, by binning all of the available data to the LTT spatial resolution, it was possible to produce a gridded annual average climatological salinity data set for each of the required depth levels, which resolved the major freshwater input zones to the European shelf seas (Figure 3.6).

The subset of topography, tidal speed and salinity data corresponding to the area covered by the North Sea daily SPM values was used to develop a multiple regression model. For each day of the year, multiple regression parameters were calculated for the equation:

$\log((\text{SPM})_{i,j}) = c_j + (a_1)_j(\log(\text{seabed depth})_i) + (a_2)_j\,(\text{salinity})_i + (a_3)_j\,(\text{tidal current speed})_i$
where i = location, and j=julian day

The daily correlation coefficient (r^2) of fitted values and nd130 values in the North Sea are shown in Figure 3.7. The correlation was mostly higher than 0.5 throughout the year exhibiting a strong seasonal pattern. The statistical model was then used to extrapolate daily SPM concentrations over the entire LTT grid from the depth, salinity and tidal current speed data. Examples of the predicted seasonal cycles of SPM concentration at two locations in the North Sea are shown in Figure 3.8.

Monthly averages of the extrapolated SPM concentrations in each of the nd278 ERSEM boxes are shown in Figure 3.9, and compared to the original nd130 North Sea data.

The regression model adequately regenerated the original North Sea SPM data. Comparison with very limited beam attenuation data, indicated that the approach produced credible predictions of SPM loads to the west of the UK.

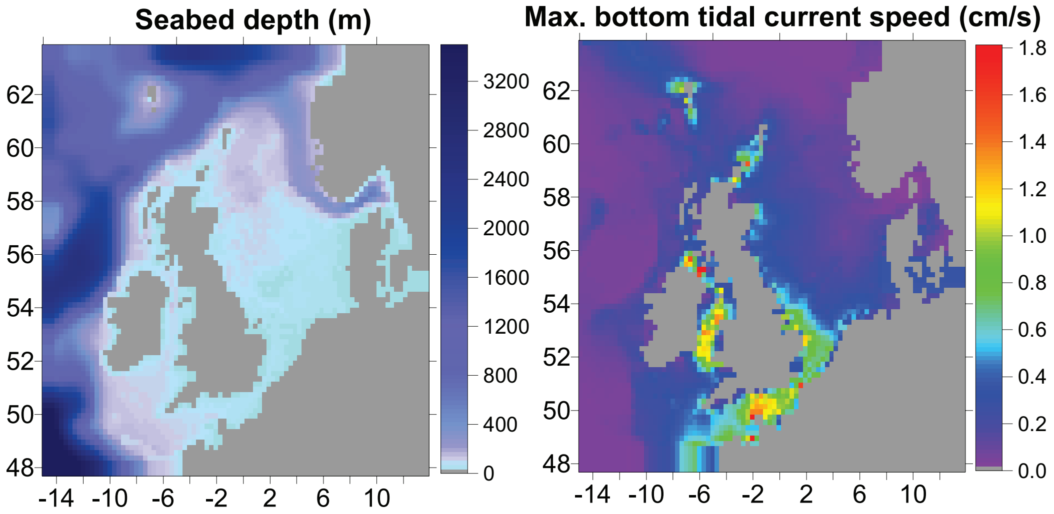


Figure 3.5 *Seabed depth and maximum bottom tidal current speed over the LTT model domain.*

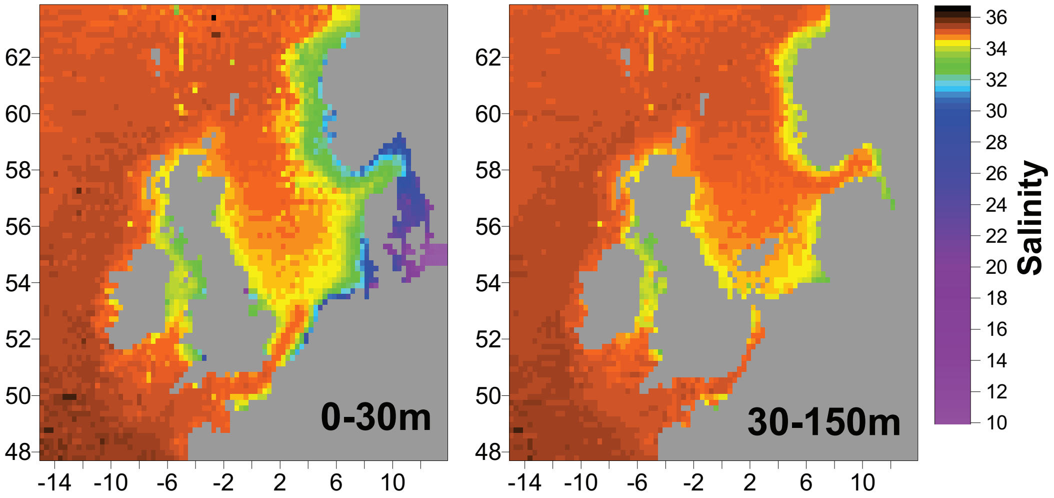


Figure 3.6 *Annual average salinity in two depth layers, binned to LTT grid resolution from1970-1999 data archived at the ICES hydrographic data centre.*

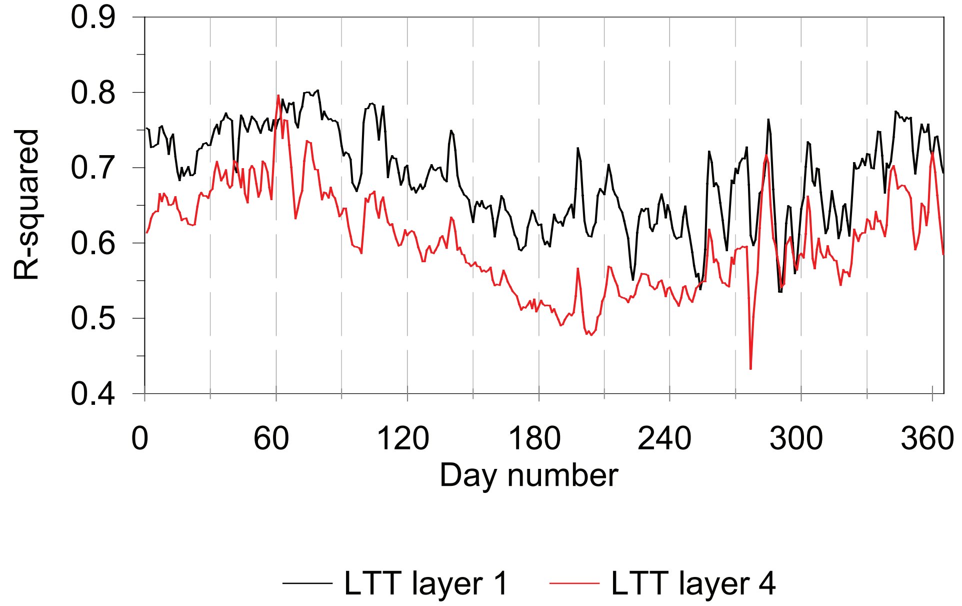


Figure 3.7 *Daily correlation coefficients (r^2) between the multiple regression derived SPM data and the SPM concentrations from the prior nd130 set-up.*

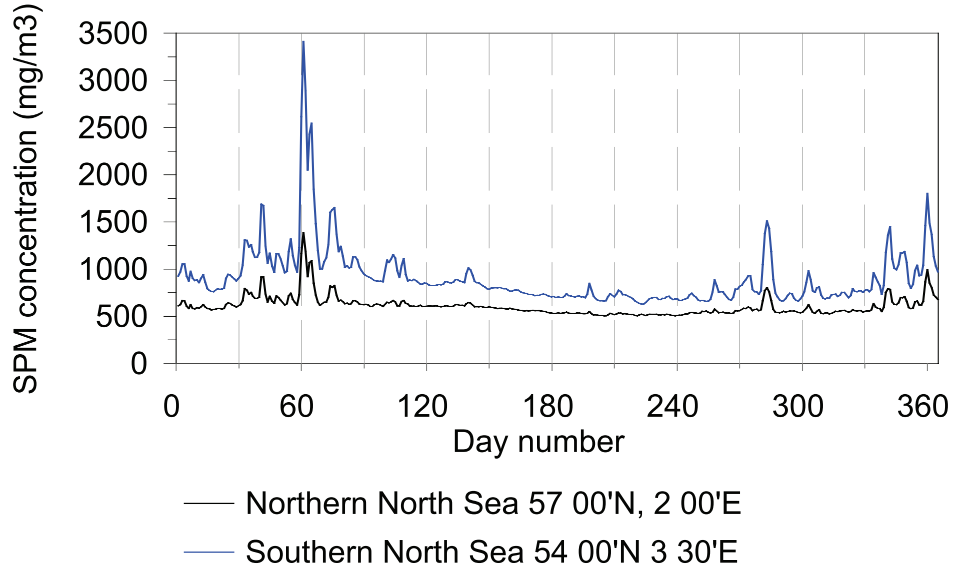


Figure 3.8 *Fitted values of SPM concentration in the upper layer at two locations in the North Sea from the multiple regression model. Northern North Sea site: depth 88m, mean tidal speed 0.19 cm s^{-1}, salinity 35.07. Southern North Sea site: depth 42m, mean tidal speed 0.27 cm s^{-1}, salinity 34.64.*

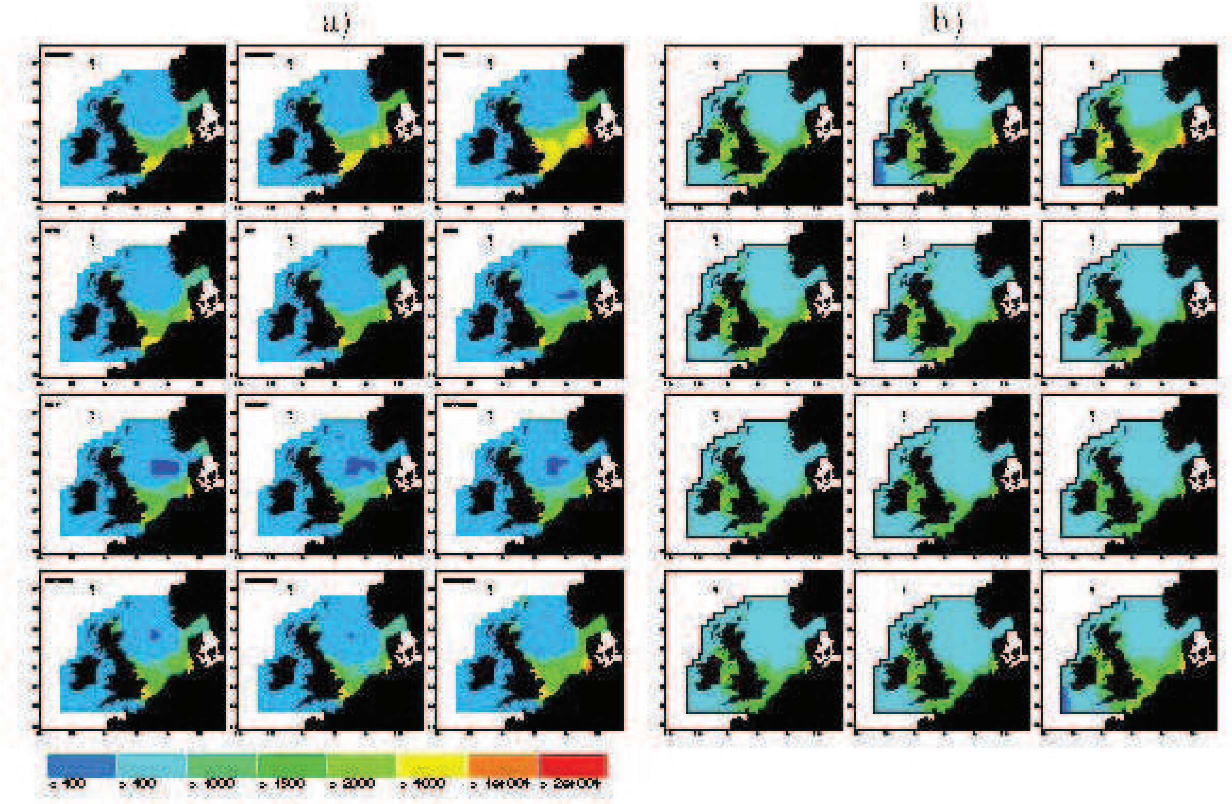


Figure 3.9 *a) Monthly averaged values of SPM concentration (mg* m^{-3}*) as used in the nd130 North Sea version of ERSEM and based on sediment transport model output calibrated from observations (Default values for areas west of the British Isles). b) Monthly averaged fitted values of SPM concentration (mg* m^{-3}*) from the daily multiple regression model.*

Temperature

Daily values of temperature [°C] were derived from the climatological data set used to force the LTT hydrodynamical model (Figure 3.10). For the North Sea these values coincide with those used in the “nd130“ set-up.

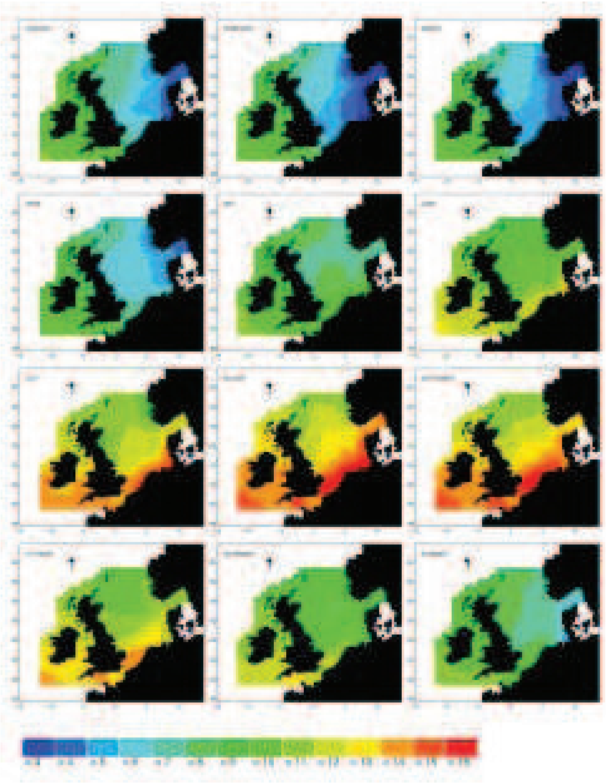


Figure 3.10 *Monthly mean temperature [°C].*

River input

Calculation of the land-based inputs of nutrients to each of the coastal boxes of the ERSEM model (daily for Scotland and continental Europe, monthly averaged for all other regions), has been fully described in Task 2.

Atmospheric nitrogen deposition

Atmospheric deposition of both nitrate and ammonia is a potentially significant spatially and temporally variable source of nutrients to the upper layers of the sea. There have been some assessments of these inputs for the North Sea, but nothing comparable for the waters in the western extension area of the sc278 ERSEM model. Given the limited resources available in this project, it was decided not to devote effort to this aspect and atmospheric inputs were set to zero over the whole model domain.

Boundary values

The model comprises 96 prognostic state variables which are dynamically simulated in the interior boxes of the model only. For each of these, values have to be prescribed at the open ocean and Baltic Sea lateral boundaries. For the "nd130" setup only nutrient and mesozooplankton values could be resolved temporally at the boundaries. For the rest of the variables the values were held constant on the boundaries. This procedure was also applied in this project.

Boundary nutrient data

Monthly average values of nutrient and chlorophyll concentrations in a matrix of 0.5° latitude x 1° longitude cells and 2 depth layers (0-30m and >30m) for the years 1965-1994, were obtained from the ICES Hydrographic Data Centre in Copenhagen. The nutrient variables available were ammonia, total nitrogen, total phosphorus, and silicate.

There were insufficient data for any of the individual climate years to be simulated with ERSEM to produce comprehensive year-specific boundary nutrient data. The data from 1965-1994 were therefore averaged by month to produce a climatological monthly-resolution annual cycle data set for each variable. These data were then recast onto the 278 inner boxes and 32 boundary boxes of the sc278 set-up by estimating the area proportion of each of the ERSEM boxes which coincided with each of the cells in the original data set, and applying this proportion as a weighting factor in a weighted average of the 0.5° latitude x 1° longitude data. Even after this degree of data aggregation, there remained voids in the monthly coverage of many of the boundary and inner boxes of the ERSEM set-up. These were finally filled by interpolation from neighbouring boxes. The 'raw' monthly coverage of the model domain by the recast data, and the final interpolated maps of inner and boundary box nutrient concentrations are shown in Appendix 5. The boundary data were necessary for running the model, while the interior winter values were used for initialisation. The interior data are also available for comparison with model results.

Boundary zooplankton data

Broekhuizen *et al*. (1995) described in detail the methodology for compiling monthly averaged biomass of omnivorous and carnivorous functional groups of zooplankton for each of the compartments of an earlier North Sea version of ERSEM, from Continuous Plankton Recorder (CPR) Survey data. We followed the same procedure to extend the spatial coverage to include waters west of the UK, and then regridded the data to conform with the spatial boxes of the sc278 ERSEM.

Data on the abundances (numbers per unit volume at a fixed depth of around 10m) of a range of zooplankton taxa, geometrically averaged by month over a matrix of rectangular spatial compartments for the years 1958-1999, were purchased from the Sir Alister Hardy Foundation for Ocean Sciences, who administer the CPR Surveys. Average abundance (m^{-3}) of each taxon was rescaled to account for undersampling, and then converted to carbon biomass (mgC m^{-3}) by applying either a month-specific or annual mean carbon weight per individual as described by Broekhuizen *et al.* (1995) (Table 3.1). The taxa were then categorised as either omnivores or carnivores depending on knowledge of their diet and behaviour, and the relevant biomass-by-species data summed to derive the biomass of the two functional groups.

Since the data were too sparse to compile year specific monthly estimates of zooplankton biomass for every compartment of the rectangular grid, the data were further averaged (geometrically) by month and compartment over all the sampling years. The outcome was a climatological monthly resolution data set for the matrix of rectangular compartments.

The next stage of the analysis was to recast the rectangular compartmentalised data onto the upper (0-30m depth) layer interior and boundary boxes of the sc278 ERSEM. This was carried out by estimating the area proportion of each of the ERSEM boxes which coincided with each of the rectangular compartments, and applying this proportion as a weighting factor in a weighted geometrical average of the compartmentalised data (Figures 3.11 and 3.12).

Finally, the zooplankton biomass in each of the lower ERSEM boxes (deeper than 30m) was estimated to be 30% of the monthly value in the overlying upper boxes, as according to Broekhuizen *et al*. (1995).

Table 3.1 *Zooplankton taxa, carbon weights, scaling factors and their allocations to functional groups.*

Taxon	**Carbon weight/individual (mg)**	**Rescaling factor**	**Functional grouping**
Evadne	0.00101	4	Omnivore
Limacina	.00409	4	Omnivore
Euchaeta	0.018	1.64	Carnivore
Tomopteris	0.2	1.64	Carnivore
Hyperiid amphipod	0.123	1.64	Carnivore
Euphausea	Month specific: J: 12.8, F: 12.8, M: 12.8, A: 15.7, M: 17.4, J: 17.4, J: 21.6, A: 20.8, S: 24.9, O: 9.5, N: 12.6, D: 9.6	1.64	Carnivore
Chaetognaths	0.024	1.64	Carnivore
Small copepods (see Appendix 6)	Month specific: J: 0.0552, F: 0.0544, M: 0.0608, A: 0.0608, M: 0.0612, J: 0.0584, J: 0.0608, A: 0.0612, S: 0.0576, O: 0.0508, N: 0.0576, D: 0.0576	4	Omnivore
Calanus stages 1-4	0.00778	4	Omnivore
Calanus finmarchicus stage 5 & 6	0.0672	4	Omnivore
Calanus helgolandicus stages 5 & 6	0.0672	4	Omnivore

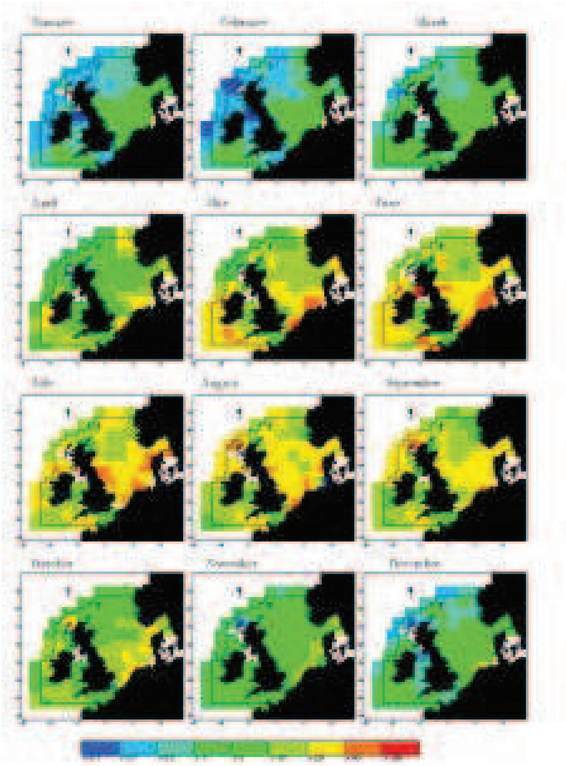


Figure 3.11 *Climatological monthly average omnivorous zooplankton biomass (mgC m^{-3}) in each of the upper layer ERSEM boxes. The boundary of the interior boxes is shown by a solid black line.*

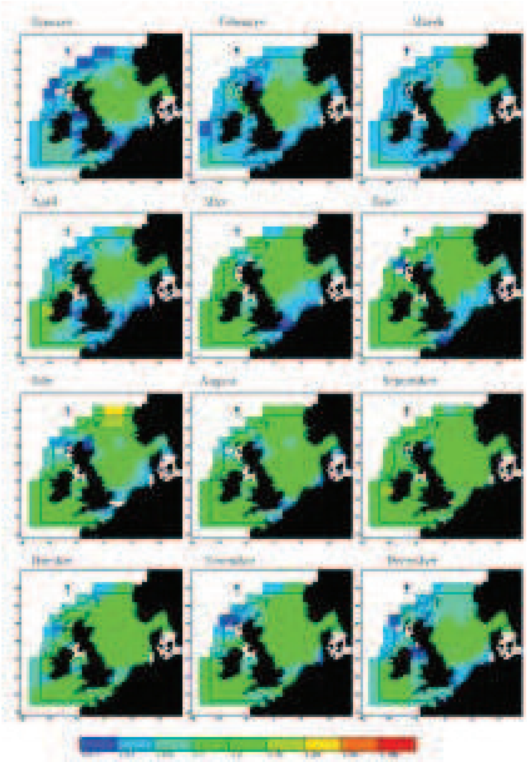


Figure 3.12 *Climatological monthly average carnivorous zooplankton biomass (mgC m^{-3}) in each of the upper layer ERSEM boxes. The boundary of the interior boxes is shown by a solid black line.*

Internal data

The model needs additional informations about the environment for the 278 internal boxes (sediment porosity, light extinction, mortality rates of zooplankton due to grazing by predators).

Sediment porosity

The water content and permeability of sediment are important for the chemical and biological processes which take place therein, and this dependency is incorporated into the ERSEM model. The water content is commonly reported as the weight per cent of the sediment. Water content as a percentage of sediment volume is referred to as the porosity which depends on the texture, shape, and sorting of particles. Sediment permeability is related to the porosity, and is a measure of the ability of water to circulate through the sediment. The ERSEM model requires the sediment porosity to be specified for each of the internal boxes which have contact with the seabed. In previous North Sea applications, values have been assembled from a combination of literature values and unpublished data (Ruardij and Raaphorst, 1995).

Ruardij and Raaphorst (1995) derived the following empirical relation between the proportion of silt in sediment (psilt) and porosity (poro):

$$\text{poro} = 0.38662 + 0.00415 * \text{psilt}$$

In order to implement the sc278 ERSEM it was necessary to assemble data on the characteristics of sediments in the regions west of the UK and Ireland. However, no data comparable to that used by Ruardij and Raaphorst (1995) to assemble the North Sea porosity distribution could be located for the western waters. As an alternative, data were digitised from maps produced by the British Geological Survey (Sea Bed Sediments around the United Kingdom; North and South Sheet), and the Atlas of the Seas around the British Isles. The Geological Survey maps provided higher resolution in terms of space and sediment type, but did not cover the entire domain required for the sc278 ERSEM. Data for the residual area not covered by the Geological Survey maps (south-west approaches and French Atlantic waters) were obtained from the Atlas.

The Geological Survey maps classified sediments according to 11 categories defined by the proportions of mud, sand and gravel. Hence a new empirical relationship was required to estimate the proportion of silt from the data on mud, sand and gravel, and hence the porosity from the Geological Survey maps. The silt relationship was obtained by reanalysis of existing raw data on sediment rain size from a range of different locations (P. Ruardij, Netherlands Institute of Sea Research):

$$\text{psilt} = (1.0 - \text{percentage gravel}) * \text{mud} / (\text{mud} + \text{sand})$$

This Atlas data provided a wider regional coverage than the Geological Survey maps but at a lower spatial resolution (1° x 1°), and for different sediment categories. A cross calibration was carried out between the Geological Survey maps and the Atlas, so that the Atlas categories (8) were redefined in terms of Survey map categories so that the estimation of porosity then proceeded accordingly.

In order to obtain a consistent data set for the whole of the sc278 model area, the analysis of Geological Survey maps and the Atlas was carried out for the entire sc278 model domain, including the North Sea for which data were available from the nd130 version of ERSEM. A comparison or the nd130 and sc278 porosity data is shown in Figure 3.13

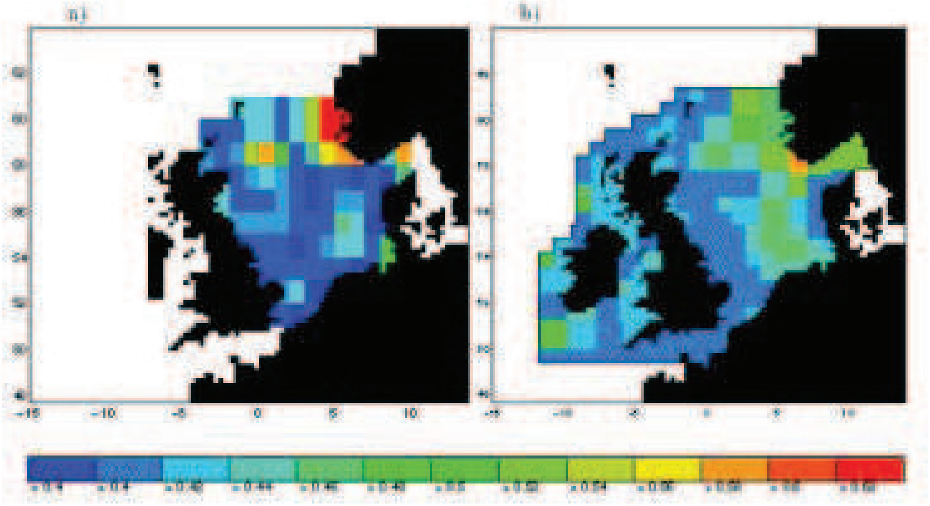


Figure 3.13 *Comparison between a) nd130 and b) sc278 porosity data.*

Light extinction coefficients

The mean light intensity in an ERSEM box is a function of the surface irradiance (forcing data), and the vertical attenuation of light in the water column. The latter is modelled as a function of the silt concentration (forcing data), the phytoplankton and detritus concentration (dynamically modelled), and the extinction coefficient of the water itself. Extinction coefficients (assumed constant over the year) must be applied as an internal data set for each box.

The extinction coefficient values from the nd130 ERSEM set-up were used for the North Sea region. For the extension area to the west of the UK and Ireland, uniformly low values were mainly assumed in the absence of direct measurements (Figure 3.14).

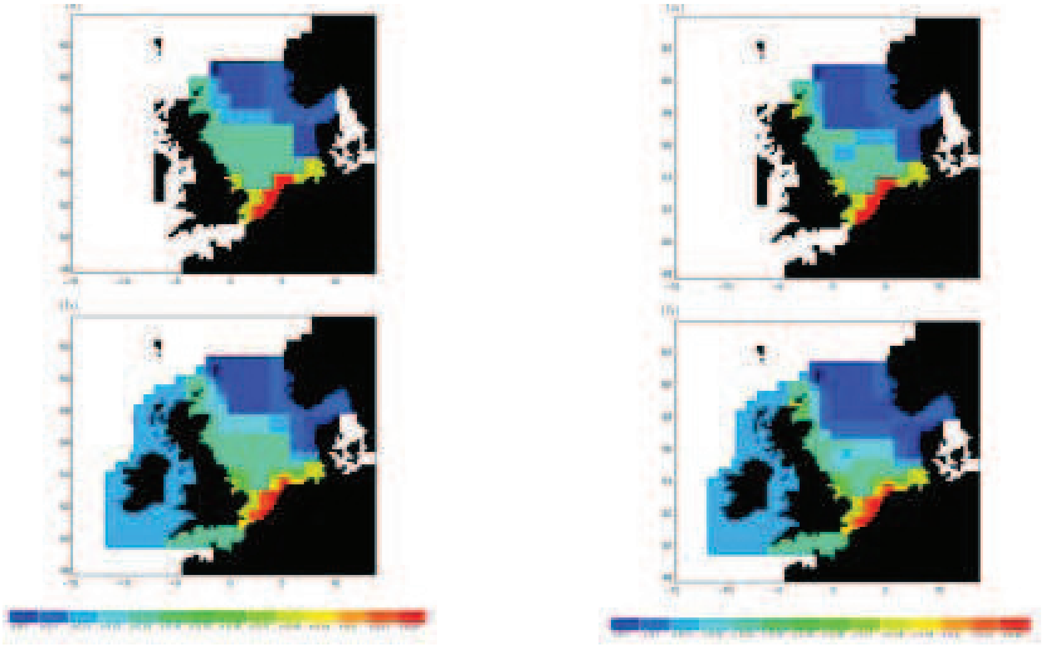


Figure 3.14 *Left hand pannels: Comparison between (upper) nd130 and (lower) sc278 surface box light extinction coefficients. Right hand pannels: as lefthand pannels but for deep or general boxes.*

Fish concentrations

Since the version of ERSEM used in this project included only trophic levels up to and including zooplankton, a closure term was required to represent non-density dependent mortality on the highest trophic level in the model. This was achieved by specifying a quarterly mortality rate for each box as an internal data set, nominally representing the consumption of zooplankton by fish. The relevant values for the North Sea boxes, derived as described by Bryant *et al*. (1995) were available from the nd130 version of ERSEM. Values for western waters were estimated by extrapolation from the nd130 data: English Channel values were extrapolated from the values of sc278 box 155, and other new values from boxes 10 or 171.

Model performance

The first runs of the sc278 model were carried out with the biological modules switched off, so that the system simply simulated the passive dispersal of a conservative tracer.

Full assessment of the performance of the entire model (with biological modules switched on) is a complex undertaking, involving a statistical comparison of model results with relevant measurements of key state variables for interior boxes. One of the major difficulties in this task is that whilst the hydrodynamic, irradiance, nutrient loading and other forcing datasets are specific to particular years, there are typically few measurements of state variables for individual years in the interior boxes. Usually it is necessary to assemble multi-year average data sets for interior boxes in order to resolve spatial and temporal details, which makes the comparison with model results difficult to interpret. In addition, the model is typically run for a number of sequential years with a repeating annual cycle of forcing data, until it attains a quasi-steady state condition. In this state, the model results are effectively independent of the initialisation values of the variables. In reality, the observed seasonal cycle in any given year is preconditioned by the climate in the previous year, whilst the steady state model is highly adapted to the forcing data. One solution might be to run the simulations for each of the years comprising the multi-annual testing dataset. In this case, the interior box data should all lie within the envelope of the simulations.

There were insufficient resources in this project to conduct the detailed comparison of simulated and measured data described above. Only a very cursory qualitative comparison was possible.

Passive tracer simulations

The purpose of testing the transport mechanism of the model alone was to address two questions: a) does the transport module of the new set-up provide reasonable results, and b) what effect do the inter-annual differences in hydrodynamic forcing alone have on the simulated distributions of matter? The test simulations were carried out in the following way:

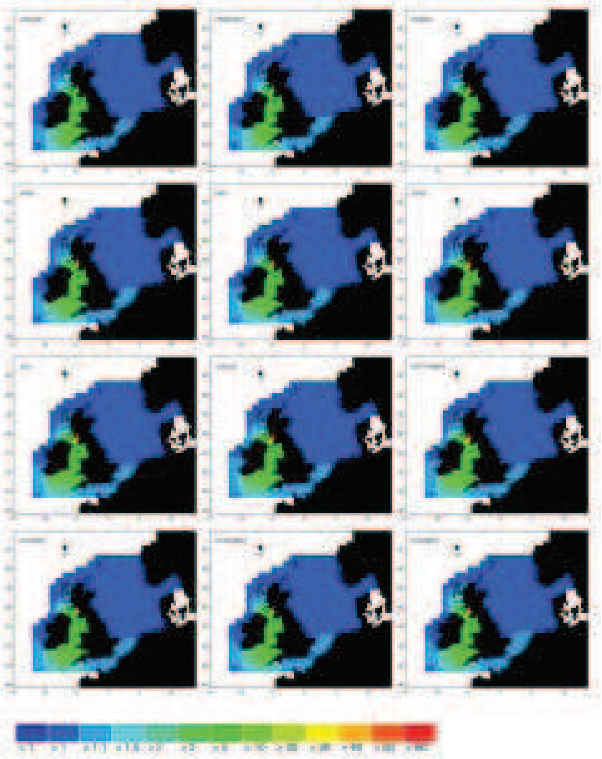
- The model was initialised with a passive tracer concentration (1 mmol m^{-3}) in each box.
- One box, representing a point source such as a river mouth, was set to receive 5000 kmol d^{-1} of the tracer throughout the simulation. If this tracer had been nitrogen, the source would have been equivalent to approximately one tenth of river Rhine total nitrogen load.
- Each of the years 1984, 1987 and 1990 was simulated three times one after the other.
- Data corresponding to the mid-point of each month were extracted from the third spin-up for examination.

The results of the passive tracer simulations represent the dispersal of some chemically and biologically inert material, and thus indicate the maximum possible dispersal from any point source. Biological or chemical reactivity would reduce the flux away from a point source as the material becomes bound up in the food web or chemically converted.

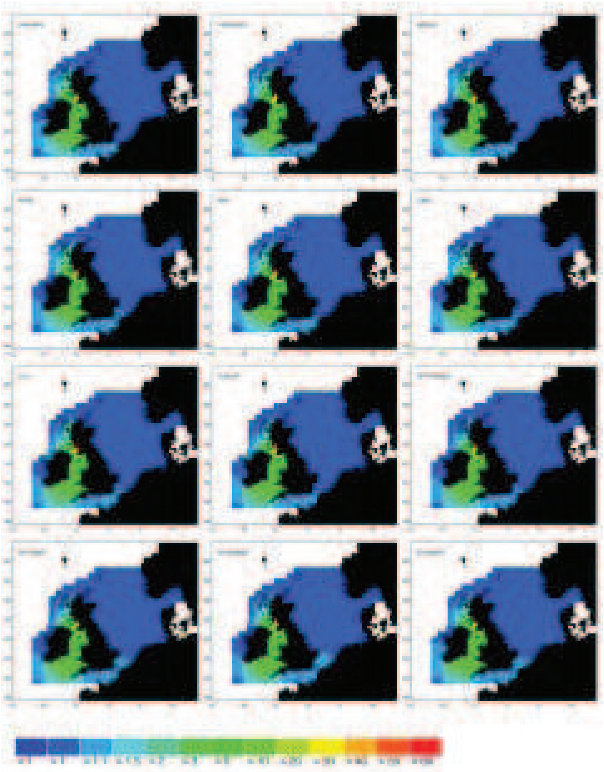
The Clyde scenario

Tracer was introduced into box 74 to represent discharge from the River Clyde. Figure 3.15 show the distribution of the passive tracer for the years of interest. For all years the main pattern was the same: The concentration within box 74 accumulated to more than 60 mmol m^{-3} due to the relatively slow flushing rate (flushing time: 24-32 days depending on climate scenario). Material advected and diffused out of box 74 was rapidly diluted and carried mainly into the Irish Sea and onwards towards the south. A small portion entered the area north west of Scotland. The small concentrations reaching the European Continent had made their way through the Channel but not via Scottish waters. The year with the largest tongue of increased concentrations at the Continental Coast was 1990. In this year the maximum concentration in box 74 was less than in the other years (63.7 mmol m^{-3} in 1990 vs. 96.6 mmol m^{-3} in 1984).

a) Dispersal from the Clyde in 1984



b) Dispersal from the Clyde in 1987



c) Dispersal from the Clyde in 1990

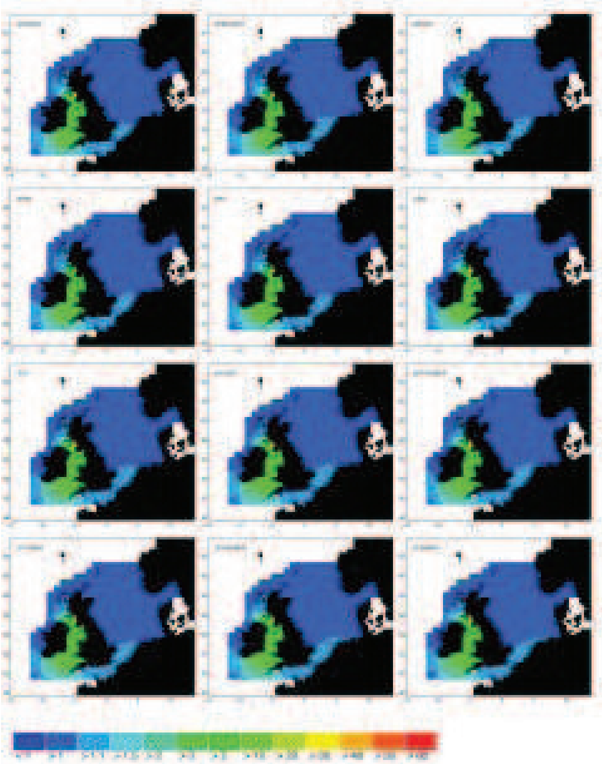


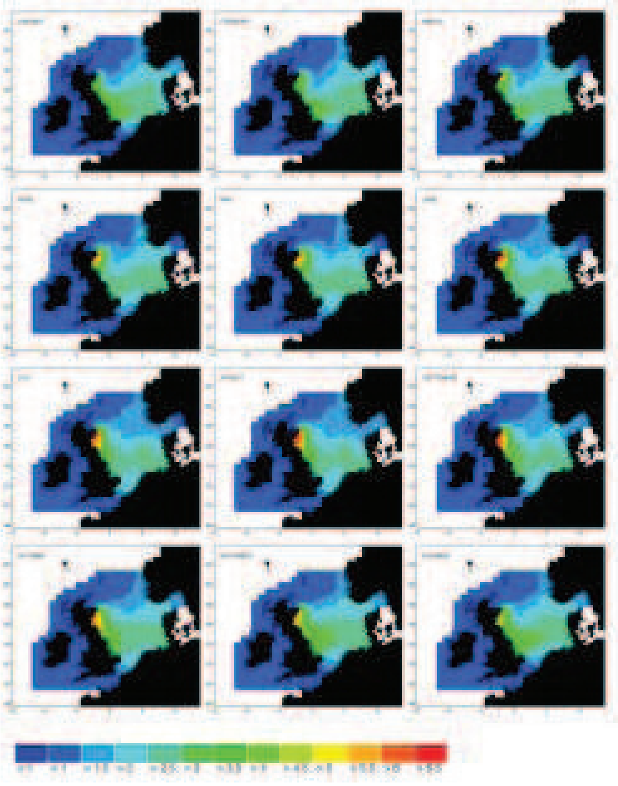
Figure 3.15 *Simulated concentrations [mmol m^{-3}] of the passive tracer with the point source at the mouth of river Clyde for the third annual cycle of the year, a) 1984, b) 1987 and c) 1990.*

The Ythan scenario

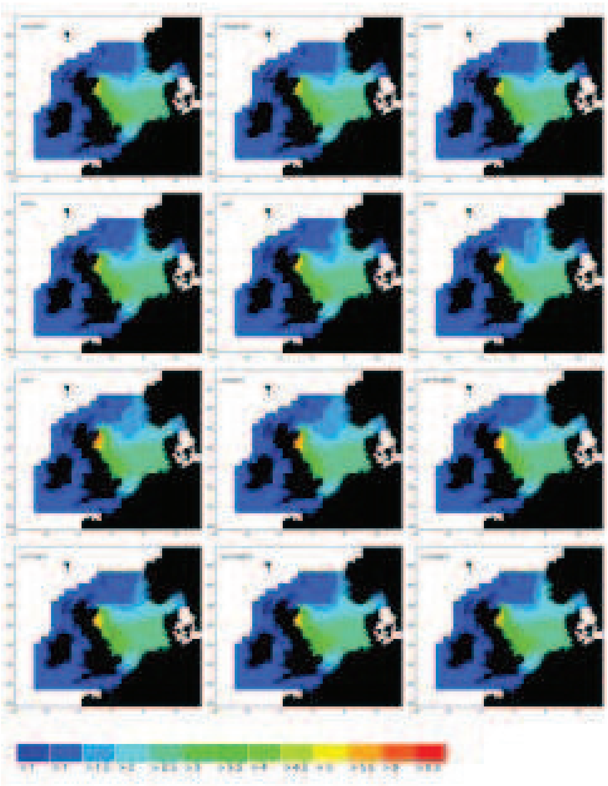
Tracer was introduced into box 49 to represent discharge from the River Ythan. Figure 3.16 shows the distribution of the passive tracer for the years of interest. Box 49 had a high flushing rate (flushing time: 4-6 days depending on climate scenario). Consequently, the tracer was more rapidly diluted than in the Clyde scenario and the maximum concentration within box 49 was only 9 mmol m^{-3}. The material was distributed at a low concentration over most of the central North Sea. Maximum concentrations at the eastern Netherlands's coast, in the German Bight, and at the Danish coast were around 1.5 mmol m^{-3} above the initial background. The Norwegian Trench exhibited smaller concentrations (around 0.5 mmol m^{-3} above background) and thus probably acted as an export region.

Comparing the distributions for the years of interest, 1990 showed the lowest concentrations on the continental coast. Nevertheless in this year the maximum concentration in box 49 was less than in the other years (6.9 mmol m^{-3} in 1990 vs. 8.3 mmol m^{-3} in 1984).

a) Dispersal from the Ythan in 1984



b) Dispersal from the Ythan in 1987



c) Dispersal from the Ythan in 1990

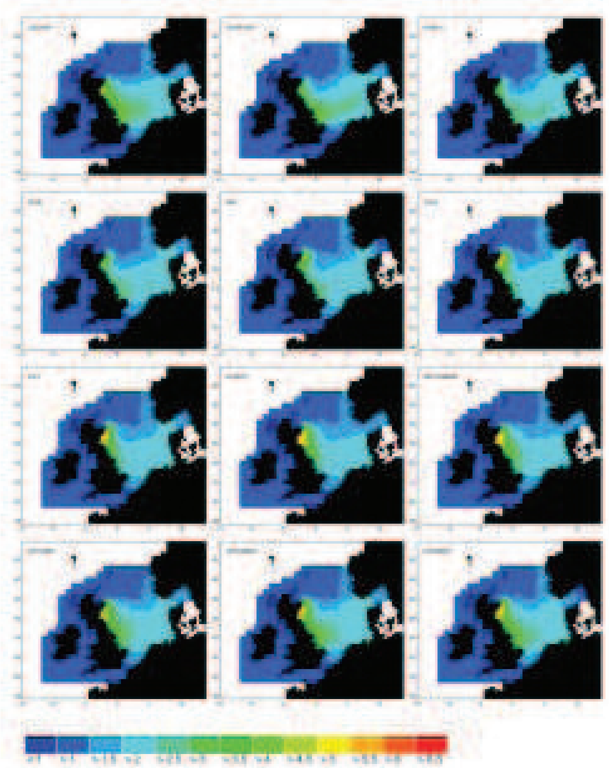


***Figure 3.16** Simulated concentrations [mmol m^{-3}] of the passive tracer with the point source at the mouth of river Ythan for the third annual cycle of the year, a) 1984, b) 1987 and c) 1990.*

Simulations including biological activity

Results from the North Sea nd130 version of ERSEM have been extensively compared with observations and the strengths and weaknesses of the system are well documented (Baretta-Bekker, 1995; Baretta-Bekker and Baretta, 1997). Since many of the nd130 configuration data were recycled in the sc278 version, we can expect the performance of the interior of the nd130 to be replicated in the sc278 version. The main priority is therefore to assess the performance of the western part of the sc278 version.

A brief assessment of the sc278 was carried out by by comparing monthly average simulated chlorophyll and phosphate concentrations from a run with 1990 hydrodynamic, irradiance and nutrient load forcing data, with the monthly average data for 1965-1994 derived from the ICES Hydrographic Data Centre records.

Chlorophyll results. In general terms, the annual cycle of monthly average chlorophyll is reasonably reproduced by the model, except that the spring increase in concentrations seems to occur slightly late compared to the observations (Figure 3.17). Peak spring bloom concentrations in April are simulated near the continental coast, off the Danish coast, at the south-east English coast and south of the Solway Firth. In general, both the model and the observations show that with the exception of the Irish Sea, the western waters support lower concentrations of chlorophyll than the North Sea.

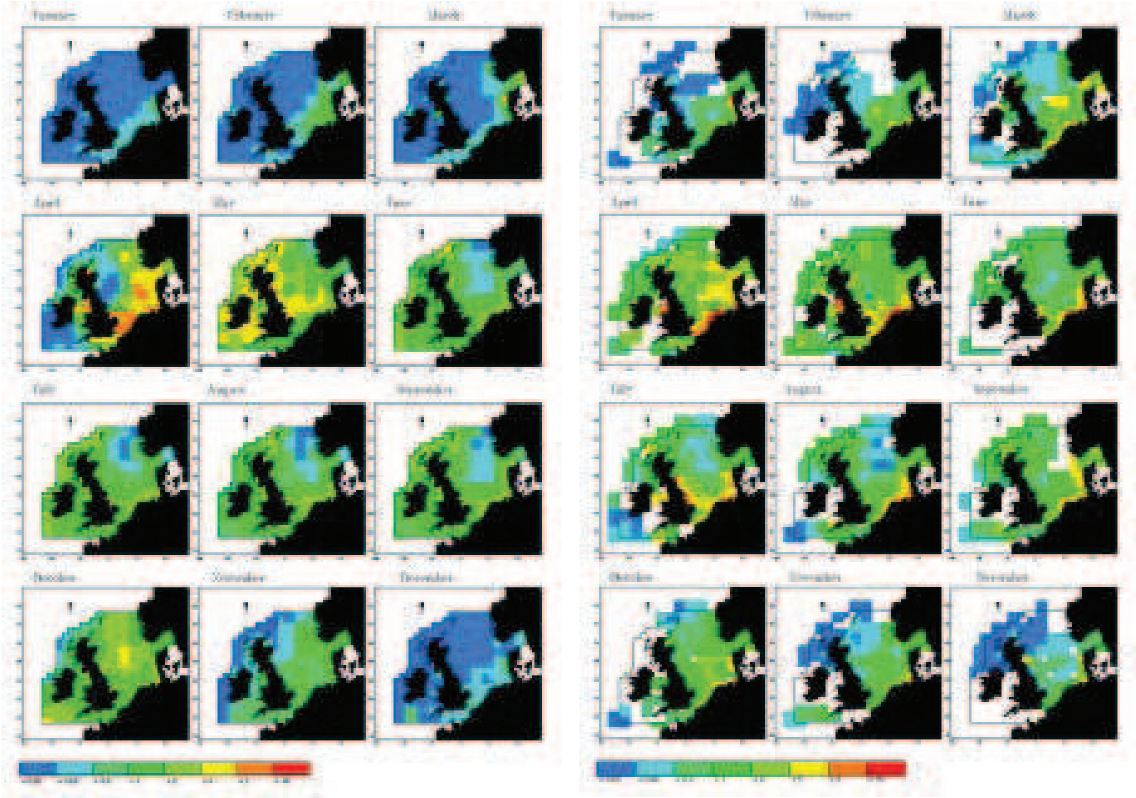


Figure 3.17 *Left-hand set of 12 pannel: monthly averages of chlorophyll concentrations (mg m^{-3}) simulated by the sc278 version of ERSEM forced by 1990 climate and nutrients loads. Right-hand set of 12 panels: Monthly average chlorophyll concentrations, averaged over 1965-1994, based on data from the ICES Hydrographic Data Centre.*

Nitrate results. The overall pattern of simulated nitrate concentrations corresponded reasonably well with the obervations (Figure 3.18). Elevated values occur over the whole model area in winter, especially along the continental coast. In April, the values decrease during the onset of plankton production so that by May the North Sea is depleted of nitrate whilst the west of the UK still exhibits elevated values. From early summer to September both the simulation and observations exhibit very low values in the North Sea, Irish Sea and Celtic Sea. In the vicinity of the major river mouths around the UK and on the contental coast the model generates values which are lower than the observations. These differences between model results and observations arise because the model does not simulated estuaries, the 10 m depth-line can be assumed to act as a border. The observations however include some estuarine locations. In the autumn, nitrate concentrations are generally well reproduced by the model, except in the region southwest of Ireland in October.

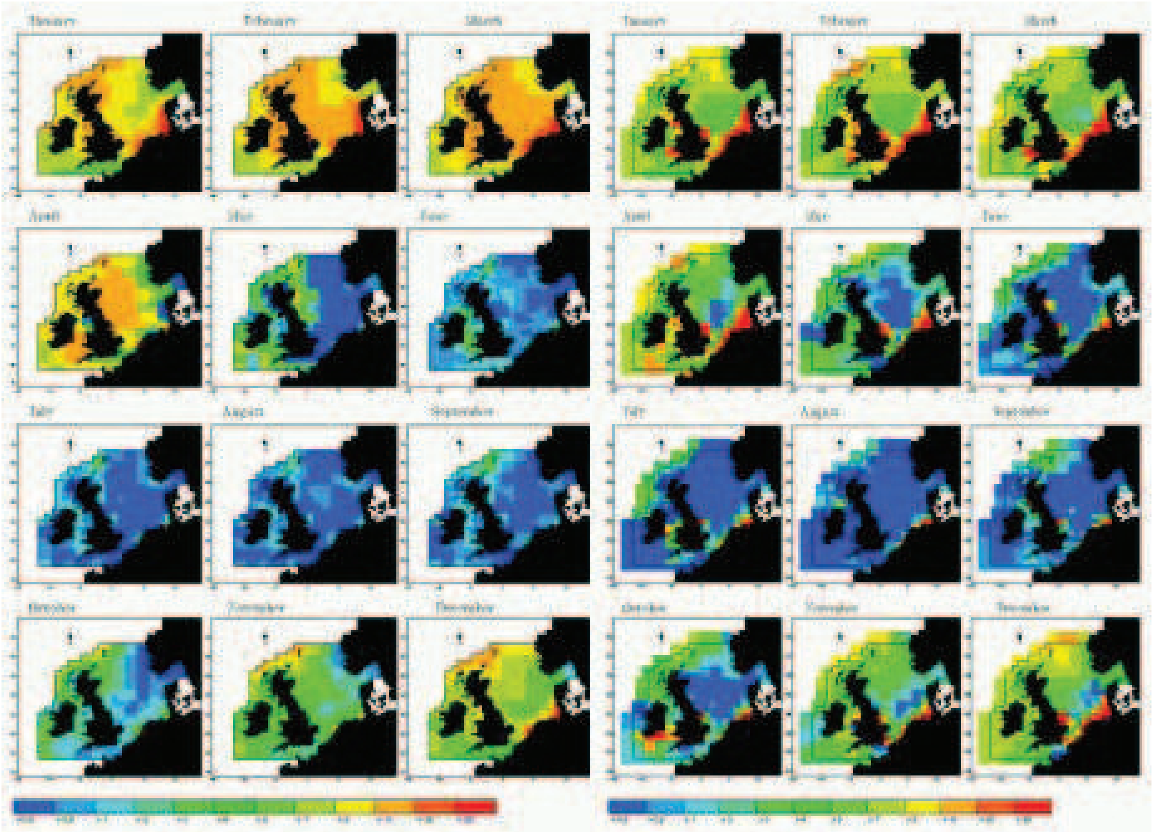


Figure 3.18 *Left-hand set of 12 pannel: monthly averages of nitrate concentrations (mM m^{-3}) simulated by the sc278 version of ERSEM forced by 1990 climate and nutrients loads. Right-hand set of 12 panels: Monthly average nitrate concentrations (mM m^{-3}), averaged over 1965-1994, based on data from the ICES Hydrographic Data Centre.*

Summary of the model set-up

- Boundary values for nutrients and mesozooplankton could only be prescribed climatologically. Even though nutrient data for the decades 1965-1974, 1975-1984 and 1985-1994 were available, it was necessary to use the total data set 1965-1994 in order to minimise the amount of interpolation.

- Boundary values for all other state variables were not available. They were prescribed by holding the values constant over time.

- Silt concentrations were implemented for a climatological annual cycle. Due to lack of observations, a statistical model was employed to extrapolate North Sea data to the west of the UK. Especially close to the coast, the light limiting effect of silt concentrations on phytoplankton growth under nutrient saturation plays an important role.

- No atmospheric nitrogen deposition was implemented. It is known that the whole North Sea receives atmospheric nitrogen deposition from a range of anthropogenic sources. The magnitude of this wide spread fertilisation is roughly equal to the amount of all riverine nitrogen loading. Due to the lack of information on spatial and temporal distribution of North Sea atmospheric inputs, or data from the waters west of the UK, this nitrogen source was omitted from the model-set-up.

- Temperature was implemented for a climatological annual cycle. The North Atlantic Oscillation clearly has an impact on inter-annual variations in temperature in the model area. Temperature influences the maximum growth rate of phytoplankton in the model.

- A brief qualitative assessment of the model performance indicates that the system captures most of the gross features of the annual cycles of at least nitrate and chlorophyll.

2.4 Task 4. Risk assessment of the areas affected by anthropogenic nutrients

Deliverables from Task 4:

Month 11: Draft designations of the sensitivity for compartments in the model around Scotland.
Month 14: Finalised designations of sensitivities for each compartment.

Results from Task 4

Introduction

The OSPAR procedure for identifying the eutrophication status of the maritime area under its jurisdiction (OSPAR 97/15/1, Annex 24) comprises two steps. The first step is a “broad brush” screening stage to identify areas which in practical terms are likely to be non-problem areas with regard to eutrophication. The second step is the Comprehensive (iterative) Procedure which should enable the classification of the maritime area in terms of problem areas, potential problem areas and non-problem areas with regard to eutrophication. The areas of European waters subject to the Comprehensive Procedure are shown in Figure 4.1. OSPAR 2000 agreed that all other parts of the OSPAR Maritime Area currently represent non-problem areas with regard to eutrophication.

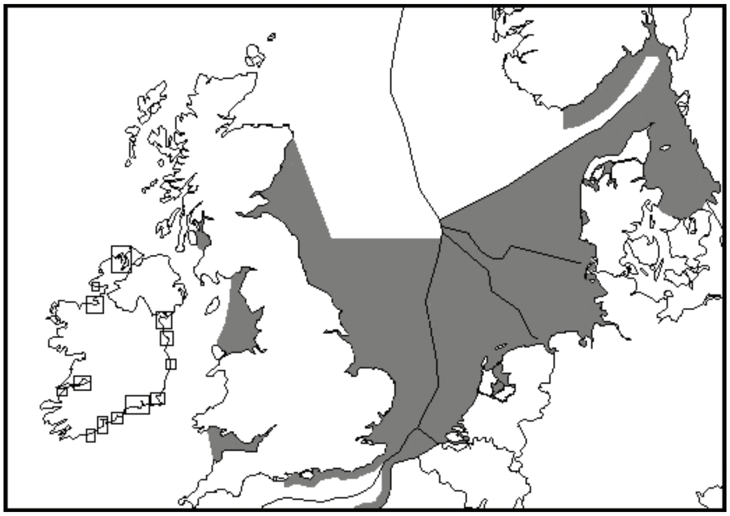


Figure 4.1 *Map showing the parts of OSPAR maritime waters subject to the Comprehensive Procedure for assessing eutrophication status. The unshaded areas are deemed to be “non problem areas” with regard to eutrophication, though it is recognised that there may be local areas of concern within the wider non problem zone. Shaded areas will be subject to the OSPAR Comprehensive Procedure to establish whether they are problem areas, potential problem areas, or non problem areas with regard to eutrophication. Solid lines within the North Sea represent sector boundaries.*

The purpose of Task 4 was to use the sc278 version of the ERSEM model to assess the consequences of various reduction scenarios applied to nutrient sources in Scotland, on the eutrophication status of the maritime waters and especially those subject to the OSPAR Comprehensive Procedure. Analysis of three different reduction scenarios was requested as follows:

UWWT Directive scenario

The Urban Waste Water Treatment Directive requires Member States to reduce the nitrogen and phosphorus loads from sewer discharges into waters defined as “sensitive” under the terms of the Directive by 75%. The ERSEM model should be used to simulate the impact of such reductions. Criteria for assessing eutrophication (Task 1) should be compared between model runs with existing loads (*i.e.* most recent year of available data), and with Scottish UWW loads reduced by 75% but loads from all other sources remaining unchanged. The assessment should focus on the North Sea at a variety of scales from local to regional.

OSPAR Scenario

The inputs affected by the OSPAR commitment to 50% reductions in nitrogen and phosphorus loadings are to cover all anthropogenic sources, including the diffuse component in inputs via rivers and the point source components arising from sewer/industrial discharges *i.e.* all categories of source for which HARP-NUT guidelines exist. Criteria for assessing eutrophication (Task 1) should be compared between model runs with existing loads (*i.e.* most recent year of available data), and with 50% reductions in the loads of all Scottish nutrient sources, focusing on the proposed Problem Areas identified by OSPAR.

Aquaculture scenario

Prompted by concerns over the possible impacts of salmon aquaculture on west of Scotland waters, the model should be used to assess the impact of reducing the nitrogen and phosphorus inputs from Scottish fish farms by 50%. The starting value should be based upon the most recently available production figures, using the HARP-NUT calculations to derive fish farm nutrient loads. Criteria for assessing eutrophication (Task 1) should be compared between model runs with these current loads, and with fish farm loads reduced by 50% but loads from all other sources remaining unchanged.

Detailed specification of the three assessment scenarios

The principle of the assessment procedure was to compare results from each reduction scenario run with equivalent results for a reference run or so called ″base case″. The reference run was intended to represent the present day nutrient loadings for a given climate situation. Different climate situations were represented by the three climate years 1984, 1987 and 1990.

The loading structure for each climate year reference run was constructed as follows, using 1984 as an example:

Loading structure for 1984 reference run

- 1999 UWW carbon, nitrogen and phosphorus loadings for Scotland, England and Wales
- 1999 industrial carbon, nitrogen and phosphorus loading for Scotland, England and Wales
- 2001 aquaculture carbon, nitrogen and phosphorus loading for Scotland
- **1984** geological and agriculture carbon, nitrogen, phosphorus and silicon for England, Wales and Scotland
- **1984** total carbon, nitrogen, phosphorus and silicon loadings for Ireland, Norway and Europe

UWW reduction scenarios

For each climate year 1984, 1987 and 1990, the Scottish UWW **carbon, nitrogen** and **phosphorus** loadings only were each reduced to 25% of their reference run values. All other Scottish loadings, and all loads for England, Wales, Ireland, Norway and Europe, remained as in the reference runs.

OSPAR 50% scenarios

For each climate year 1984, 1987 and 1990, the Scottish UWW, industrial and aquaculture **carbon, nitrogen** and **phosphorus** loads were reduced to 50% of their present day values. In addition, the Scottish river loads of **nitrogen** and **phosphorus** only were each reduced to 50% of their climate year values. Scottish river loads of **carbon** and **silicon** remained as in the reference runs. All loads for England, Wales, Ireland, Norway and Europe remained as in the reference runs.

The logic for not reducing carbon and silicon loads from Scottish rivers was that the intention of OSPAR is to test the effect of reducing anthropogenic loads. The 1988 OSPAR agreement states that there will be "*co-ordinated programmes and measures for the reduction of inputs of nutrients to the regions identified from municipal treatment plants, agriculture, fish farming, industry, combustion plants and vehicles*"

To meet this objective fully, one would need to further subdivide the estimated river loads into geological inputs of carbon, nitrogen, phosphorus and silicon, and agricultural inputs, and then reduce only the agricultural inputs by 50%. This may be possible using the MLURI land use modelling approach, but not in the time scale of this project. We therefore had to make an approximation, and assume that carbon and silicon inputs are primarily geological (and hence should not be subject to reduction scenarios), and that the nitrogen and phosphorus inputs are primarily anthropogenic and hence are to be reduced.

Aquaculture 50% scenarios

For each climate year 1984, 1987 and 1990, the Scottish aquaculture loads of **carbon, nitrogen** and **phosphorus** were reduced to 50% of their reference run values. All other Scottish loads, and all loads for England, Wales, Ireland, Norway and Europe, remained as in the reference runs.

Full details of the loading specification for each run are given in Appendix 7.

Summarising the model results

Assessment areas

It is important to condense the model output to a manageable level of detail in order to derive assessments. 21 groups of ERSEM boxes (identified by upper layer boxes, but including the connected lower layers as well for winter nutrient criteria) were averaged for assessing the impact of loading scenarios (Table 4.1).

Table 4.1 *Listing of the groups of ERSEM boxes forming larger assessment areas for the purposes of analysing model output.*

Area	**Name**	**Upper layer ERSEM boxes**
1	Belgian coast	147, 148, 155
2	Netherlands coast	122, 132, 133, 138, 145
3	German Bight	109, 110, 123, 124
4	Danish coast	82, 84, 96
5	Skagerrak	43, 44, 60
6	Norwegian coast	8, 23, 41, 42
7	English east coast	88, 101, 102, 115, 128, 129, 136, 143, 146
8a	Scottish east coast	49, 54, 65, 66, 67, 75, 76
8b	Moray Firth	35, 36, 37
8c	Orkney Isles/north coast	17, 18, 27, 28, 29
8d	Shetland Isles	2, 4, 5, 12, 13
9a	Minches	34, 47, 48, 53
9b	Western Isles	25, 26, 33, 46, 52
9c	Southern Hebrides	63, 64, 72, 73
10a	Clyde/North Channel	74, 86, 87
10b	Eastern Irish Sea	100, 114, 127
10c	Western Irish Sea	99, 113, 126, 134, 135
11	Bristol Channel	142, 151, 152
12	English Channel	153, 154, 159, 160, 161
13	Central southern North Sea	80, 81, 83, 89, 90, 91, 92, 93, 94, 95, 103, 104, 105, 106, 107, 108, 116, 117, 118, 119, 120, 121, 130, 131, 137, 144
14	Central northern North Sea	6, 7, 19, 20, 21, 22, 30, 31, 38, 39, 40, 50, 55, 56, 57, 58, 59, 68, 69, 77, 78, 79

The combination of areas 1, 2, 3, 4, 5, 7, 8a and 13 forms the OSPAR Comprehensive Procedure Regions in the North Sea

Box 74 alone represents the OSPAR region of the Clyde.

Area 10b forms the OSPAR region in the eastern Irish Sea.

The OSPAR regions in the Bristol Channel and English Channel are contained within areas 11 and 12 respectively, but the model is not designed to investigate impacts in these regions in any detail.

The outlines of the 21 assessment areas are shown in Figure 4.2

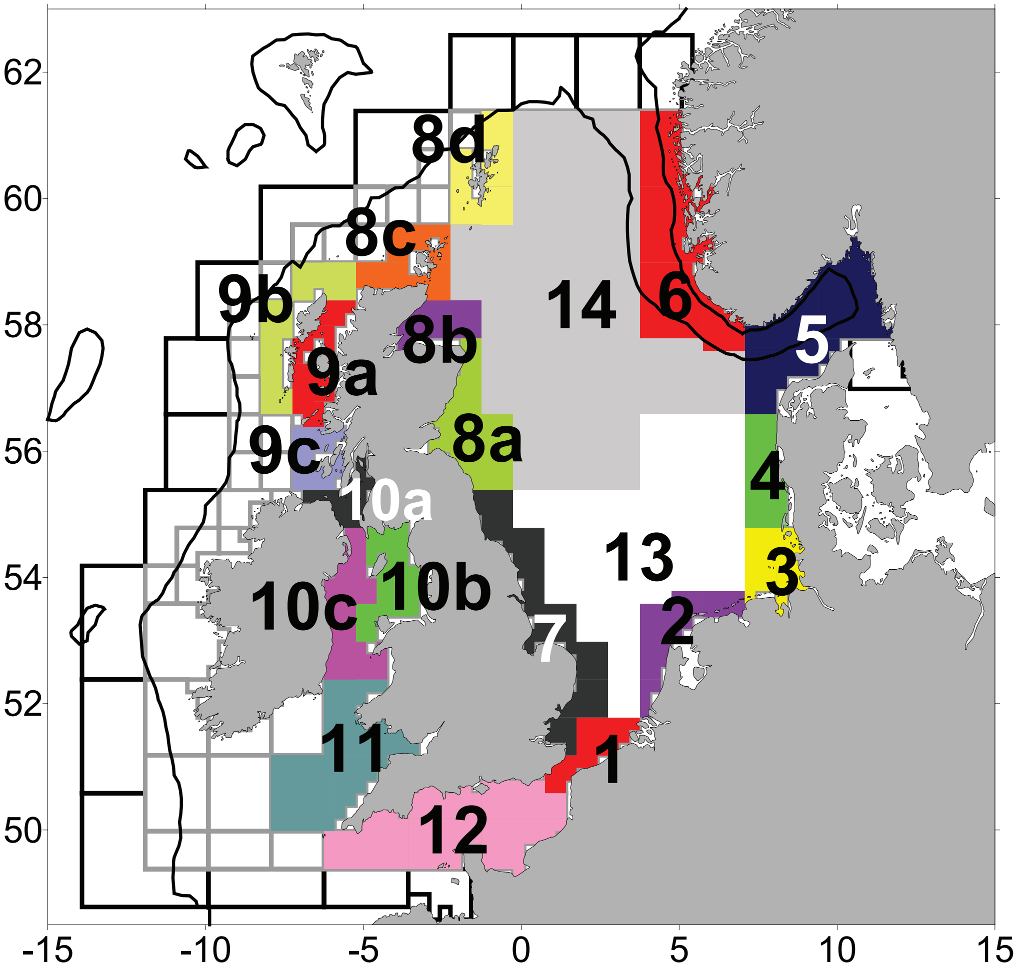


Figure 4.2 *Outlines of the 21 assessment areas used to summarise the spatial results from the ERSEM model runs. The thick black lines denote the boundaries of the regions which will be subject to the OSPAR Comprehensive Procedure to establish whether they are problem areas, potential problem areas, or non problem areas with regard to eutrophication.*

In addition, results were examined for six individual boxes (Table 4.2).

Table 4.2 *Individual ERSEM boxes for which model output data was include in the eutrophication assessment.*

Location	**Upper layer ERSEM box**
East coast	
Inverness Firth	35
Forth/Tay river plumes	65
Farne Islands	75
West coast	
Skye	47
Clyde Sea	74
Solway Firth	100

The locations of the 6 individual boxes are shown in Figure 4.3

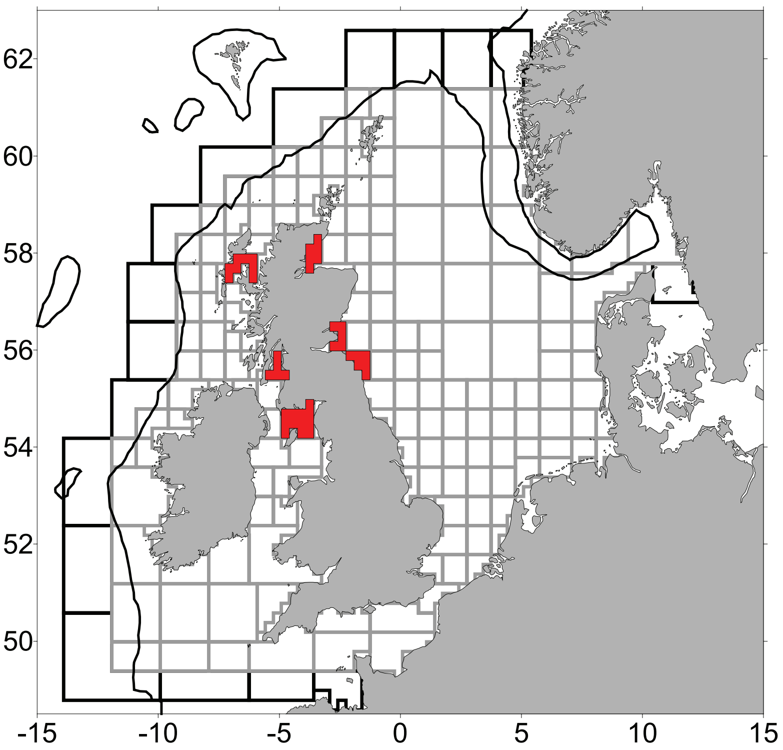


Figure 4.3 *Outlines of the 6 individual boxes for which ERSEM model results were extracted for each reduction scenario run*.

Assessment criteria

Results for a given reduction scenario run were expressed as the difference in value of each criterion between the reduction and reference runs, for each assessment area and climate year. The differences were expressed in both absolute units, and as percentages of the reference run values, and represent the eutrophication impact of the loading which has been removed in the reduction scenario.

In order to further summarise the model results for each reduction scenario, the percentage changes in the various criteria were combined into a single index of overall "change in water quality" by weighted averaging across criteria. The weighting applied to each criterion (Table 4.3) was chosen to reflect its considered importance as an indicator of eutrophication status. Thus, May-September average chlorophyll, and annual net primary production were assigned the highest weighting since these reflect the food web consequences of the reduction in nutrient loading reduction. The indices for each climate year were then averaged (without weighting) to produce the overall index.

Table 4.3 *Weighting values applied to each of the assessment criteria in producing an overall index of water quality.*

Assessment Criterion	Weighting
Winter dissolved inorganic phosphorus	0.75
Winter dissolved inorganic nitrogen	0.75
May-September average chlorophyll	1.00
Maximum weekly average chlorophyll	0.25
Annual net primary production	1.00
Maximum weekly net primary production	0.25
Diatom/flagellate ratio	-0.75

A key issue in the assessment process is the judgement as to whether changes in individual criterion, or in the overall water quality index, are significant in a general sense, *i.e.* large enough to merit classification of an area as a problem or potential problem zone with regard to eutrophication. This is potentially one of the most difficult aspects of assessment because there are no set guidelines as to acceptable or tolerable limits of change in either absolute or relative units. However, one quantitative approach to setting such limits is to compare the change in a criterion due to load reduction with the variability in values of the criterion due to climate variations alone (Figure 4.4). For a eutrophication effect to be of practical concern, the mean change in criterion value due to load reduction must be greater than the standard deviation of values due to climate variability under reference loading conditions. Certainly, if the change is less than that due to climate variability, then monitoring programmes will have great difficulty in detecting the impacts of loading reductions in the field.

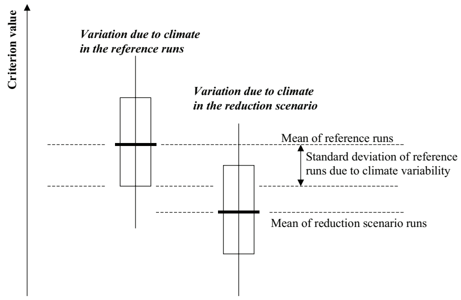


Figure 4.4 *Schematic diagram illustrating the principle behind relating the impact of load reductions on eutrophication criteria to the variability caused by climate fluctuations, as an objective means of judging the significance of the reduction in loading.*

Annual loadings to each assessment area

The annual loadings of nitrogen, phosphorus, carbon and silicon summarised by assessment areas are shown in Figure 4.5.

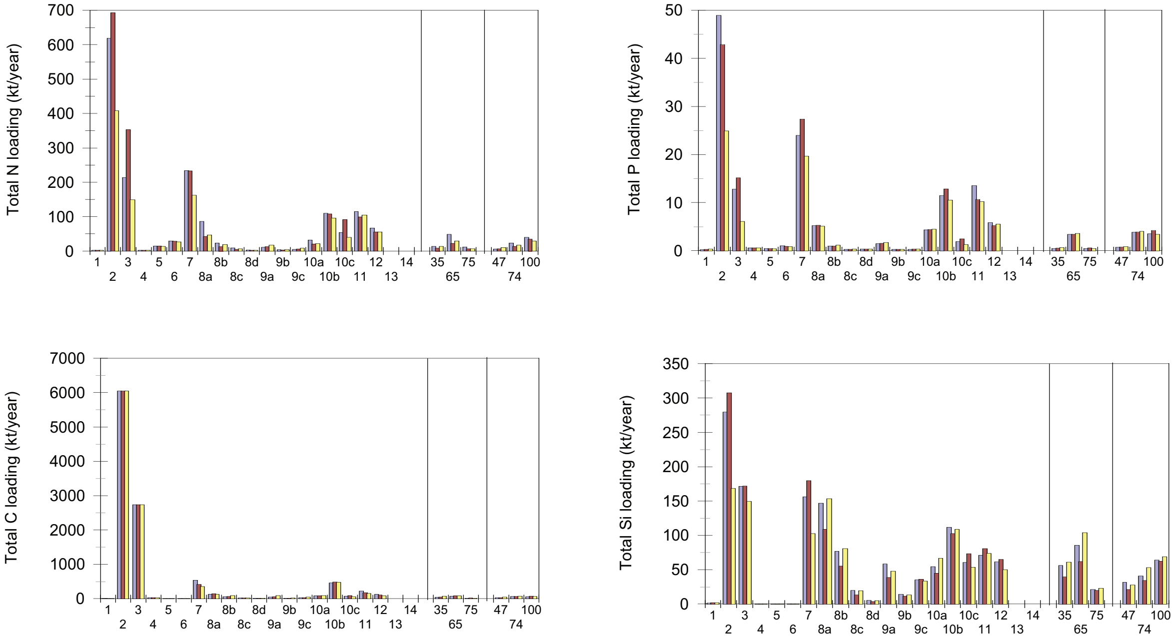


Figure 4.5 *Annual loadings for nitrogen, phosphorus, carbon and silicon to each of the 27 assessment areas. Blue bars refer to 1984 climatology, brown to 1987, and yellow to 1990. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). Carbon and silicon loading data were unavailable for areas 5 and 6, whilst carbon loadings for areas 2 and 3 were average values and not year specific.*

The most important areas in terms of nitrogen and phosphorus loading are 2, 3, 7, 10b and 11 (Netherlands coast, German Bight, English east coast, Eastern Irish Sea, and Bristol Channel). Of the Scottish assessment areas, only 8a (Scottish east coast) receives appreciable nitrogen and phosphorus load. Areas 2 and 3 receive almost an order of magnitude more carbon than any of the other areas. Silicon loads show a very different pattern, with the Scottish east coast area (8a) being amongst the highest loaded boxes due to the outflow and geology of the Forth/Tay catchment (box 65).

Year to year variability in loadings was examined by calculating the standard deviation of the 1984, 1987 and 1990 loadings for each assessment area, and expressing this as a percentage of the mean loading for each area (Figure 4.6). Climate variability in loadings was around 20% for nitrogen and carbon, and around 10% or less for phosphorus and silicon.

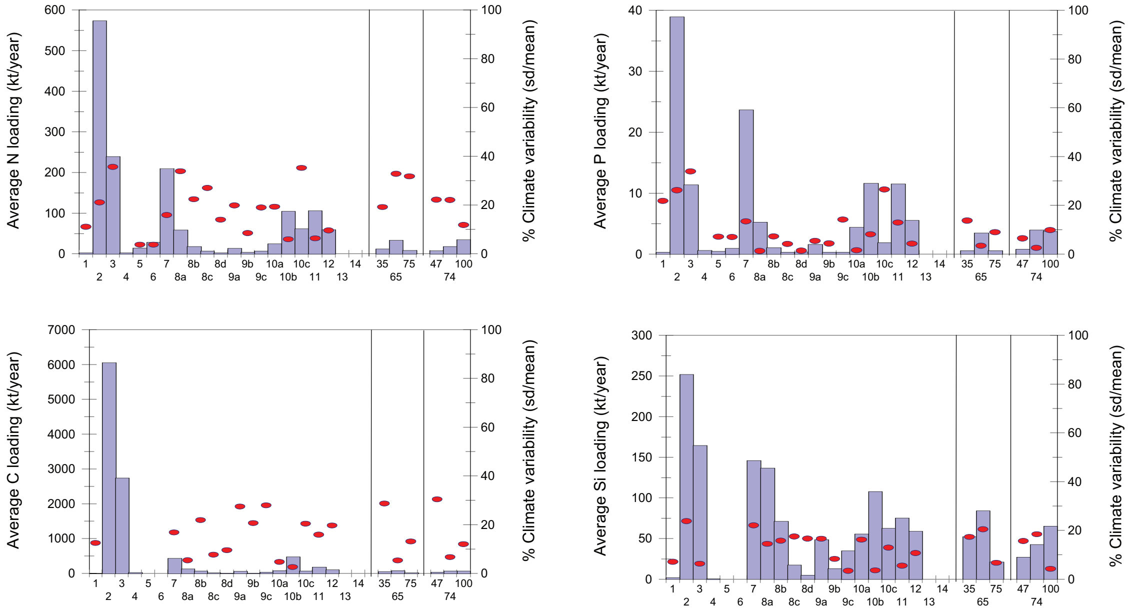


Figure 4.6 *Blue bars: average (1984, 1987 and 1990) annual loadings for nitrogen, phosphorus, carbon and silicon to each of the 27 assessment areas. Red symbols: Variability in annual loading to each assessment area given the standard deviation of year-specific values expressed as a percentage of the mean loading. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). Carbon and silicon loading data were unavailable for areas 5 and 6, and no estimate of standard deviation in carbon loading was available for areas 2 and 3.*

Variability between years in the ratios of nutrients in the loadings was qualitatively examined by plotting the loadings of phosphorus, carbon and silicon in turn against nitrogen loading. The results (Figure 4.7) show that in general nutrient ratios are similar for Scotland and other regions, and consistent from year-to-year. The exception is the silicon:nitrogen ratio where Scotland stands out as having a higher ratio than the rest of the UK and Europe.

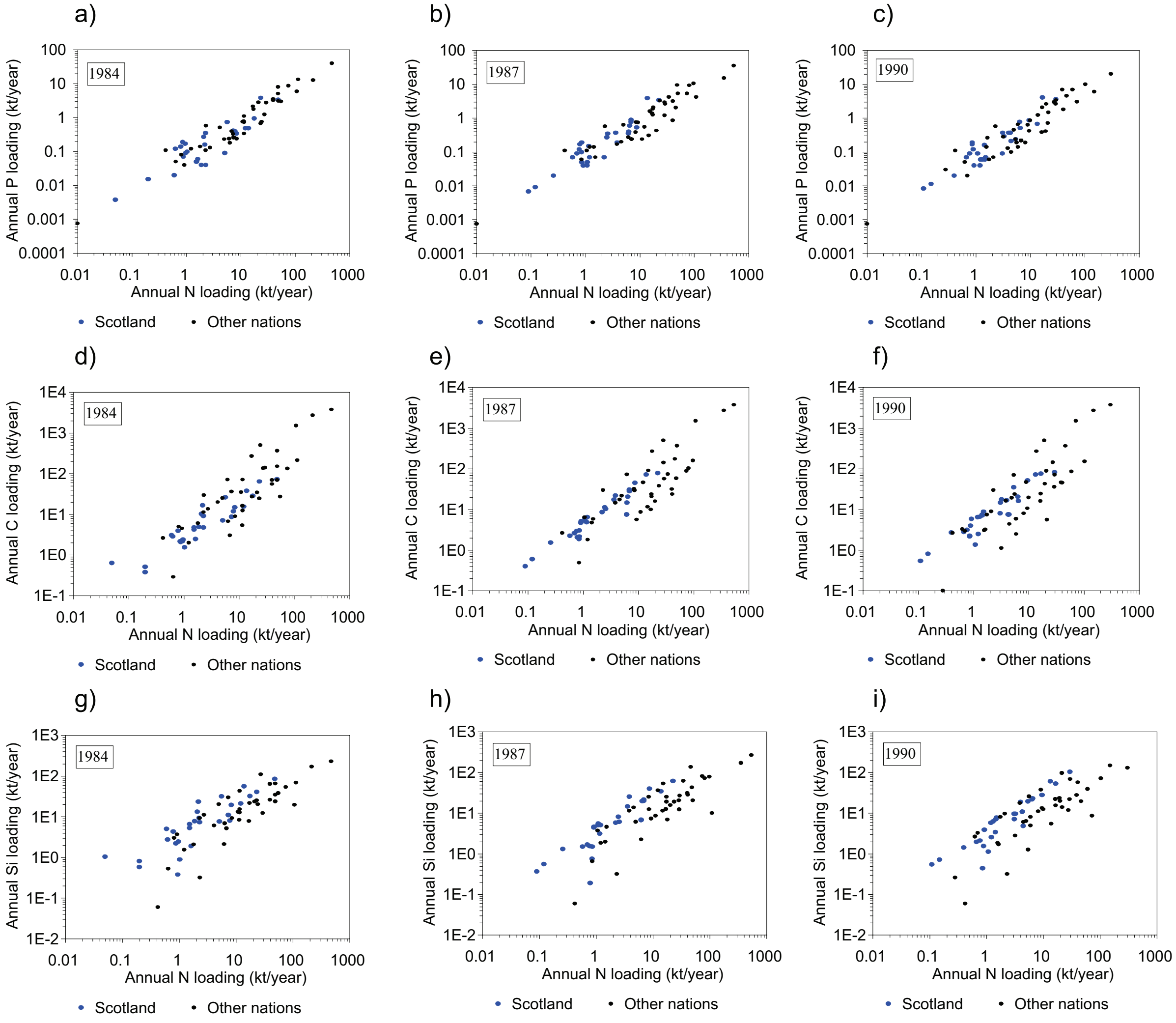


Figure 4.7 *Total annual phosphorus (a-c), carbon (d-f) and silicon (g-i) loads to each coastal ERSEM box for each of the climate years. Scottish coastal boxes indicated by blue symbols, coastal boxes of other nations by black symbols.*

Assessment area results for the Reference Run scenarios

Values of the 7 assessment criteria were calculated for the 21 composite assessment areas and 6 key individual boxes (Figure 4.8).

Winter nutrient concentrations varied very much less than loadings because a high proportion of the nutrient in a given area originates from transport across the open ocean boundaries of the model or from benthic-pelagic exchange, and not just from landward loadings. The importance of horizontal gradients in the interpretation of spatial data was illustrated by the fact that nutrient concentrations in the individual box 65 (Forth/Tay) were substantially higher than for the larger area 8a which includes box 65. Inter-annual variability in the winter nutrient concentrations was small except for the Continental European areas.

The chlorophyll criteria generally showed a similar pattern of spatial variability to the winter nutrient criteria. Inter-annual variability was greater for the chlorophyll criteria, and horizontal gradients seemed steeper especially for the maximum weekly chlorophyll criterion.

The net primary production criteria provided quite a different perspective on the system compared to the nutrient or chlorophyll criteria. Areas such as the Orkney and Shetland regions (8c and 8d) which were unexceptional in terms of winter nutrient or chlorophyll conditions, and had very low nutrient loading, returned amongst the highest rates of net primary production. Conversely, the Continental European areas which had high loading, high nutrient and high chlorophyll concentrations, showed relatively of rates of simulated net primary production. The reason is related to the substantially lower suspended sediment concentrations causing only weak light limitation in the northern North Sea regions compared to the southern North Sea, such that production per unit chlorophyll is higher in the north.

Spatial distribution of the diatom/flagellate ratio indicated that the simulated algal population in the southern North Sea and Continental European areas was in general flagellate dominated, whilst that in the northern and western areas was diatom dominated. Possibly this reflects the spatial pattern of silicate loading relative to nitrogen and phosphorus loading.

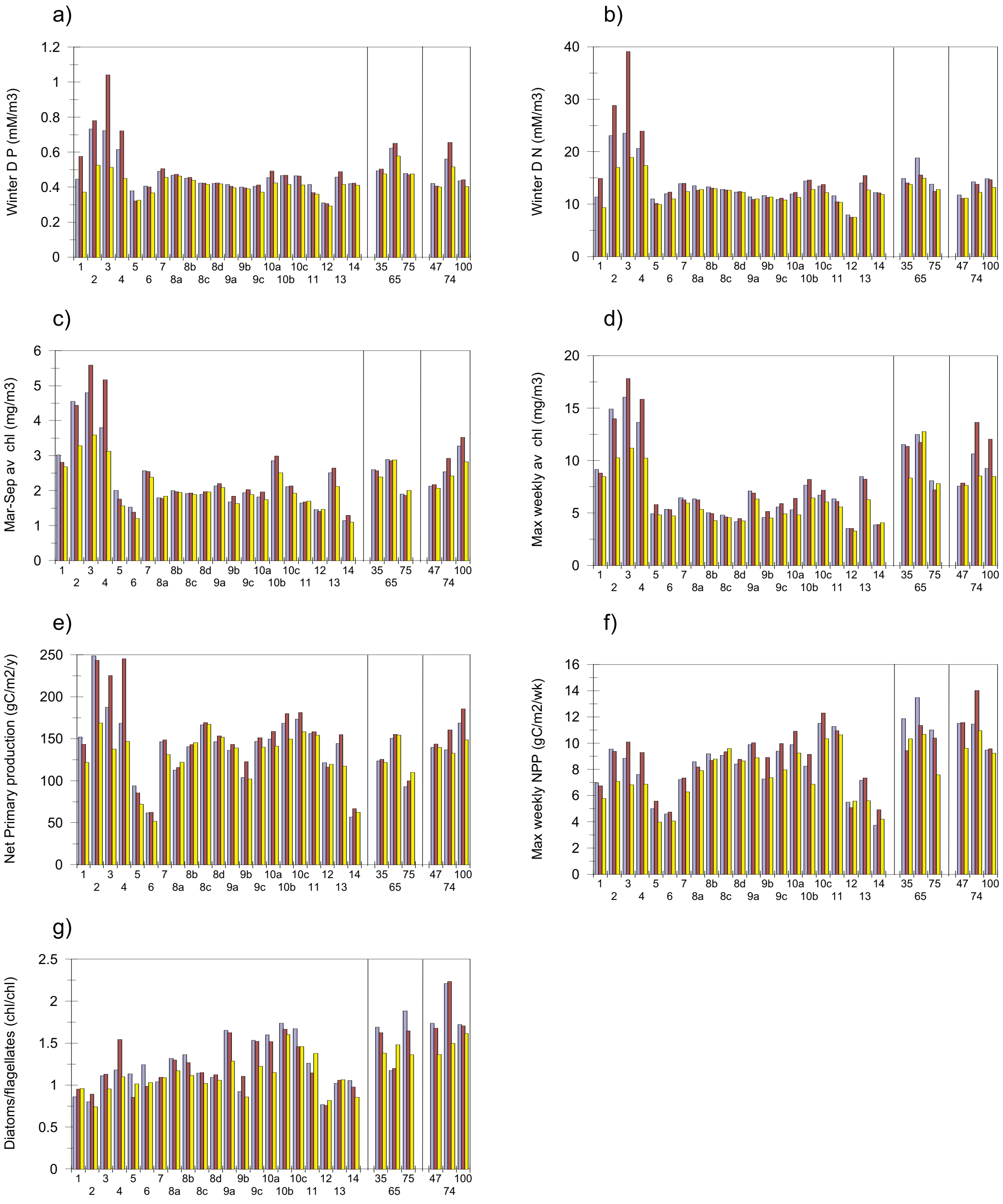


Figure 4.8 *ERSEM model* ***Reference Run*** *results for each of the assessment criteria by assessment areas. Blue bars refer to 1984 climatology, brown to 1987, and yellow to 1990. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). Panel a) average winter dissolved inorganic phosphate, b) average winter dissolved inorganic nitrogen, c) average chlorophyll during May-September, d) maximum weekly average chlorophyll, e) average annual net primary production, f) average weekly maximum net primary production, g) average ratio of diatom chlorophyll : flagellate chlorophyll during May-September.*

The variability in eutrophication criteria due to climate was assessed by calculating the standard deviation of criterion values for each assessment area from the results for 1984, 1987 and 1990, and expressing this as a percentage of the mean criterion value. These values were then combined to give an overall water quality variability index by weighted averaging, using the weighting values given in Table 4.3. Finally, the index was compared with the mean of the between year percentage standard deviation for nitrogen and phosphorus loadings shown in Figure 4.6. The results (Figure 4.9) indicate little overall relationship between variability in annual loadings, and variability in water quality *i.e.* some areas exhibited high variability in loading between the three years tested, but relatively little variability in water quality, whilst the reverse was the case in other areas. In general, the variability in water quality was smaller than that in the loadings.

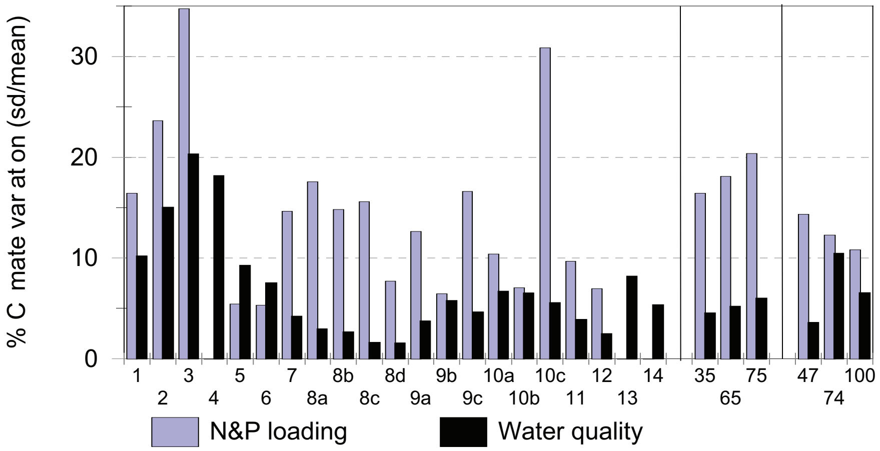


Figure 4.9 *Climate variability, expressed as the standard deviation as a percentage of the mean, for reference loadings and model run results using 1984, 1987 and 1990 environmental forcing. The water quality results were a weighted average of the percentage standard deviations for each of the seven assessment criteria.*

In contrast to the nd130 North Sea version of ERSEM, results from the sc278 version reported here have not been subject to the same critical evaluation in relation to measured observations. However, the set-up of the North Sea part of the sc278 version is largely identical to that in the nd130, so the results should be highly comparable. The major differences between the two versions of the model as far as the North Sea areas are concerned are that a) in sc278 the newly defined boundary conditions are further removed from the interior boxes representing the North Sea (which ought to make the results more dependent on the representation of internal processes), and b) the values of suspended sediment load are slightly different.

The report of the 1996 ASMO Eutrophication Modelling Workshop (OSPAR, 1998) tabulates nd130 results for the same assessment criteria, and for very similar North Sea assessment areas as have been used in this project. The ASMO results were simulated using 1985 environmental forcing, and 1985 nutrient loadings for Europe and the eastern UK, though the estimates of UK loadings not as comprehensive as we have produced in this project. A comparison of the ASMO nd130 results with the corresponding mean and climate variability from the current sc278 version is shown in Figure 4.10.

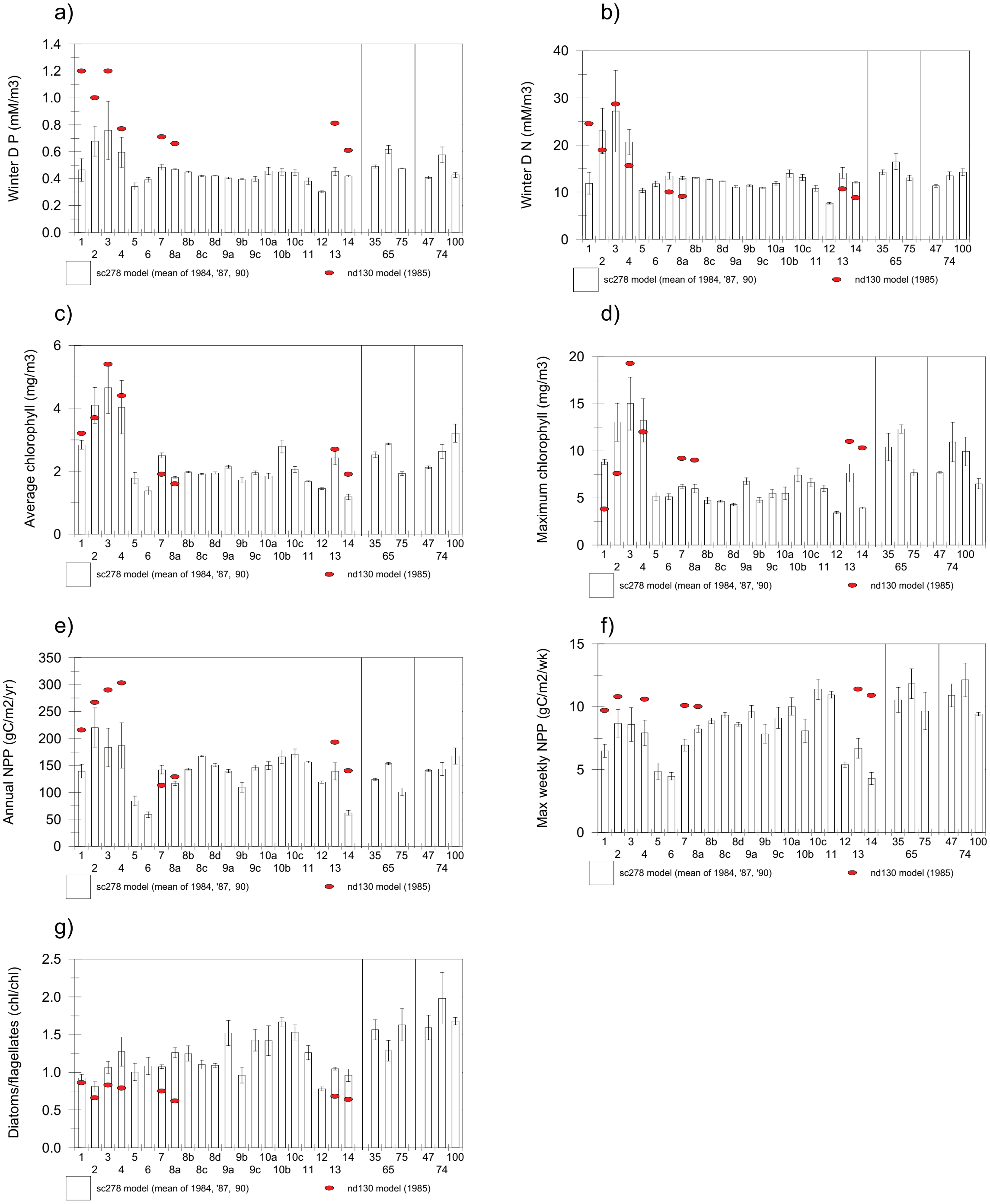


Figure 4.10 *Mean and variability of sc278 ERSEM model* ***Reference Run*** *results for each of the assessment criteria by assessment areas(histogram and range bars), compared with equivalent results from the nd130 version as reported in OSPAR 1998 (red symbols). Range bars on the sc278 results indicate 1sd either side of the mean value. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). Panel a) average winter dissolved inorganic phosphate, b) average winter dissolved inorganic nitrogen, c) average chlorophyll during May-September, d) maximum weekly average chlorophyll, e) average annual net primary production, f) average weekly maximum net primary production, g) average ratio of diatom chlorophyll : flagellate chlorophyll during May-September.*

Winter nitrate, May-September average chlorophyll and annual net primary production estimates from the sc278 version agree reasonably well with results obtained from the nd130 version, on the basis that many of the nd130 values lie close to or within the climate variability range of the sc278 version. However, winter phosphate concentrations are systematically lower in the sc278 version than in nd130, whilst the biomass of diatoms relative to other phytoplankton is systematically higher in sc278. These differences may be related to differences in the nutrient loading of the two versions as a consequence of the much more detailed analysis of UK inputs carried out here.

Reduction scenario results

The differences in simulated assessment criteria (absolute units and percentage values) between reference runs of the model and each of the reduction scenarios are shown in Figures 4.11 - 4.16.

UWW reduction scenario results

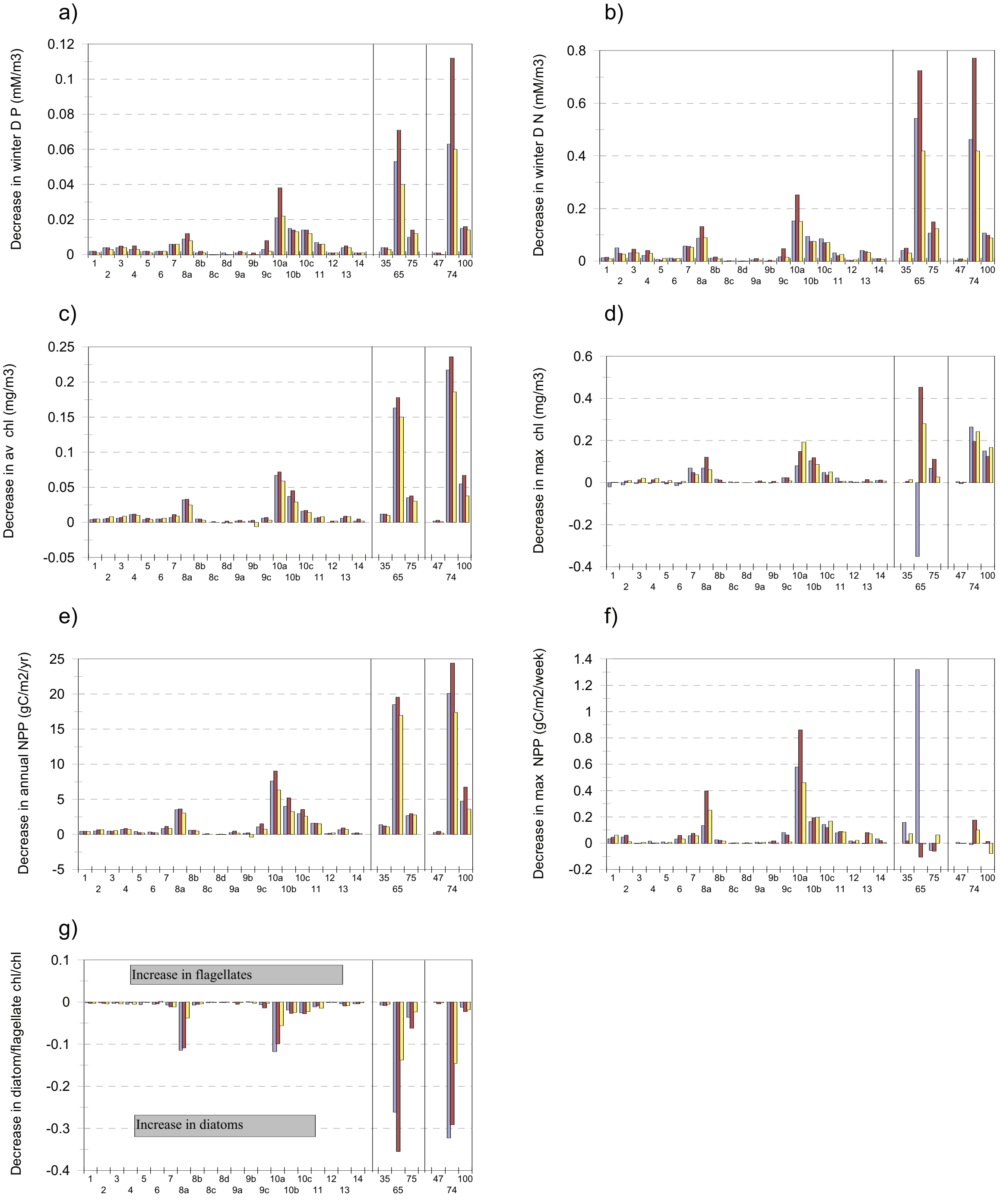


Figure 4.11 *Difference between reference and* ***Urban Waste Water 75% reduction*** *scenarios for each of the assessment criteria and areas, expressed* ***in absolute units****. Blue bars refer to 1984 climatology, brown to 1987, and yellow to 1990. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). Panel a) average winter dissolved inorganic phosphate, b) average winter dissolved inorganic nitrogen, c) average chlorophyll during May-September, d) maximum weekly average chlorophyll, e) average annual net primary production, f) average weekly maximum net primary production, g) average ratio of diatom chlorophyll : flagellate chlorophyll during May-September.*

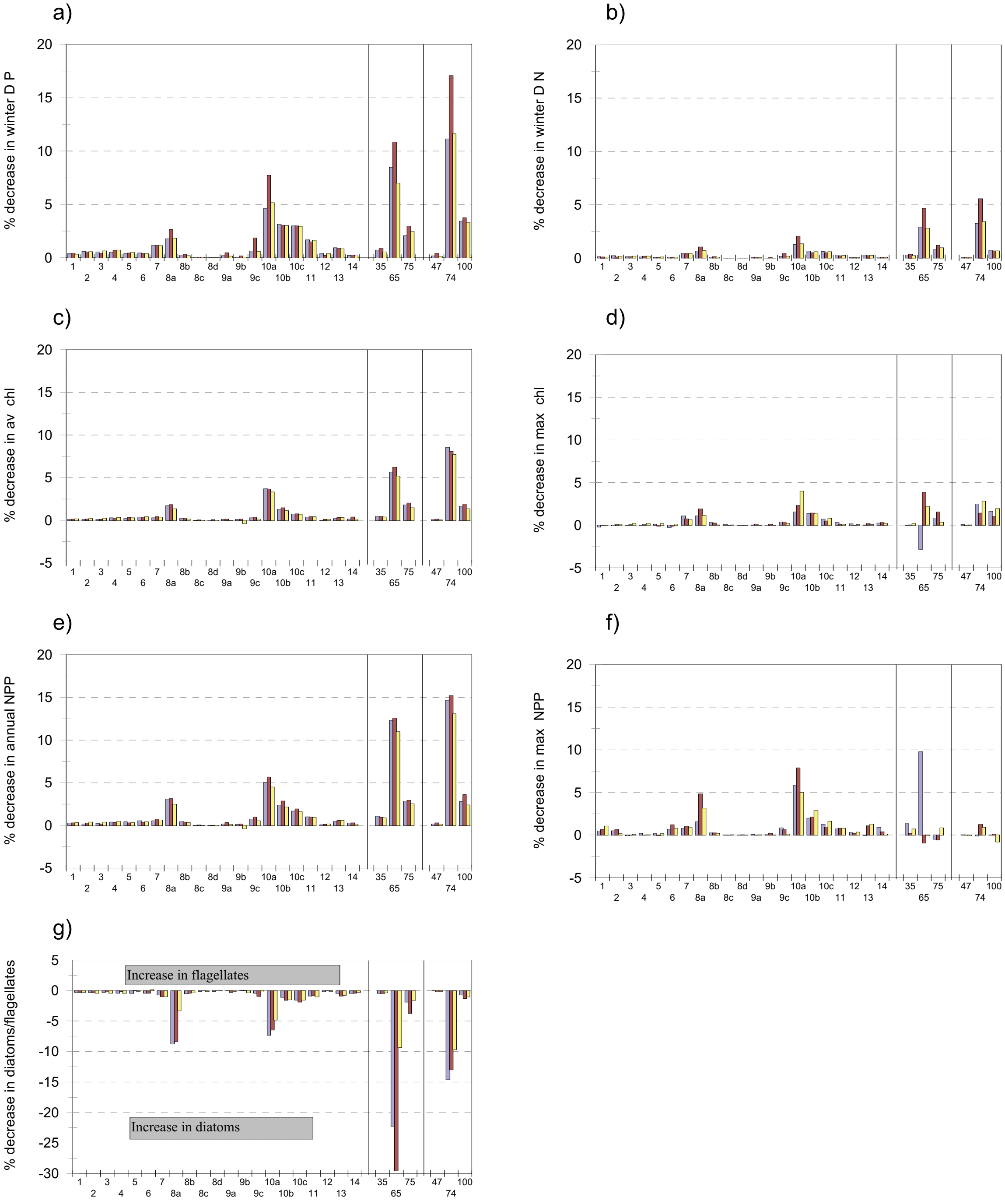


Figure 4.12 *Difference between reference and* ***Urban Waste Water 75% reduction*** *scenarios for each of the assessment criteria and areas, expressed* ***as percentages****. Blue bars refer to 1984 climatology, brown to 1987, and yellow to 1990. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). Panel a) average winter dissolved inorganic phosphate, b) average winter dissolved inorganic nitrogen, c) average chlorophyll during May-September, d) maximum weekly average chlorophyll, e) average annual net primary production, f) average weekly maximum net primary production, g) average ratio of diatom chlorophyll : flagellate chlorophyll during May-September.*

OSPAR reduction scenario results

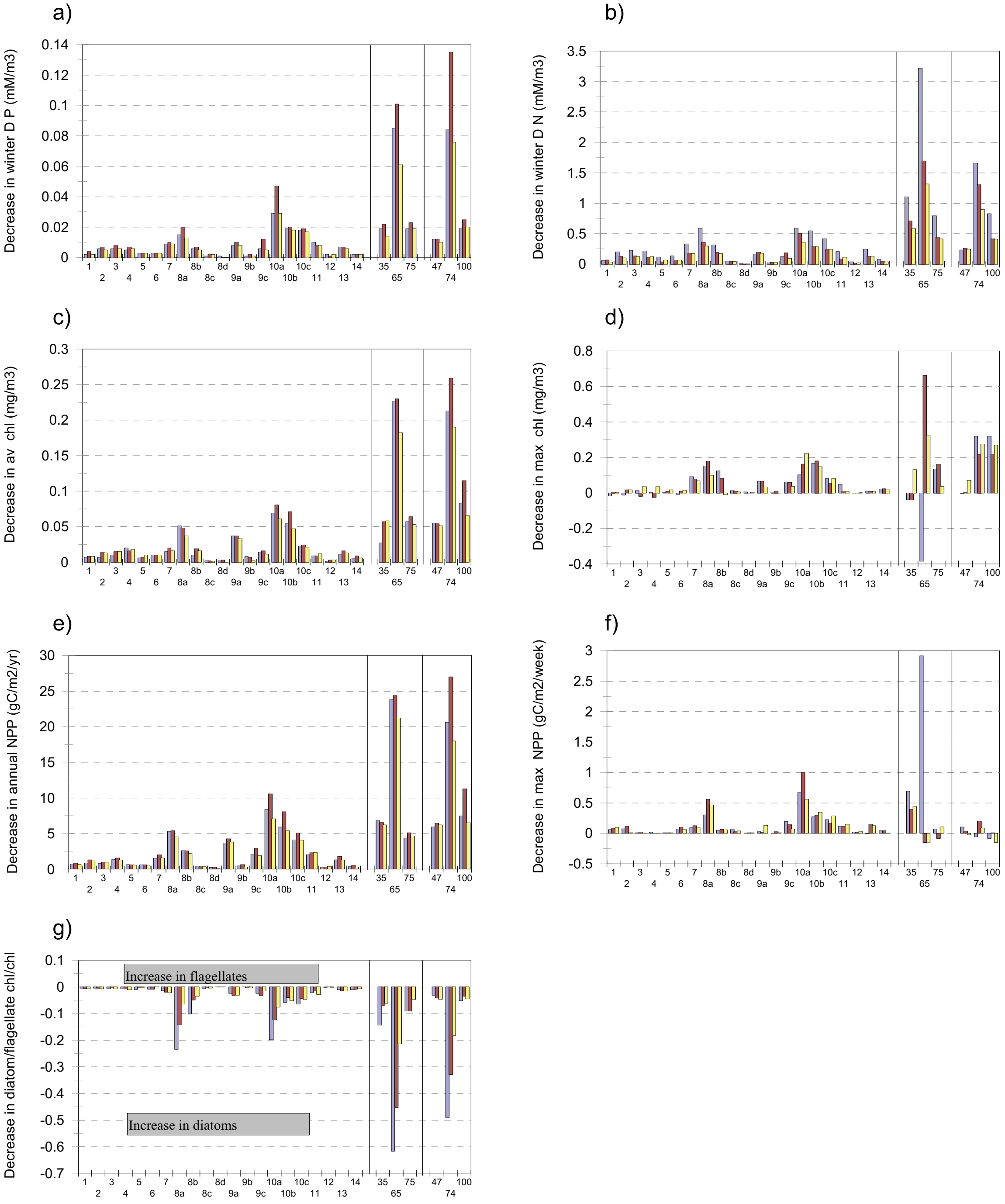


Figure 4.13 *Difference between reference and* ***OSPAR 50% reduction*** *scenarios for each of the assessment criteria and areas, expressed* ***in absolute units****. Blue bars refer to 1984 climatology, brown to 1987, and yellow to 1990. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). Panel a) average winter dissolved inorganic phosphate, b) average winter dissolved inorganic nitrogen, c) average chlorophyll during May-September, d) maximum weekly average chlorophyll, e) average annual net primary production, f) average weekly maximum net primary production, g) average ratio of diatom chlorophyll : flagellate chlorophyll during May-September.*

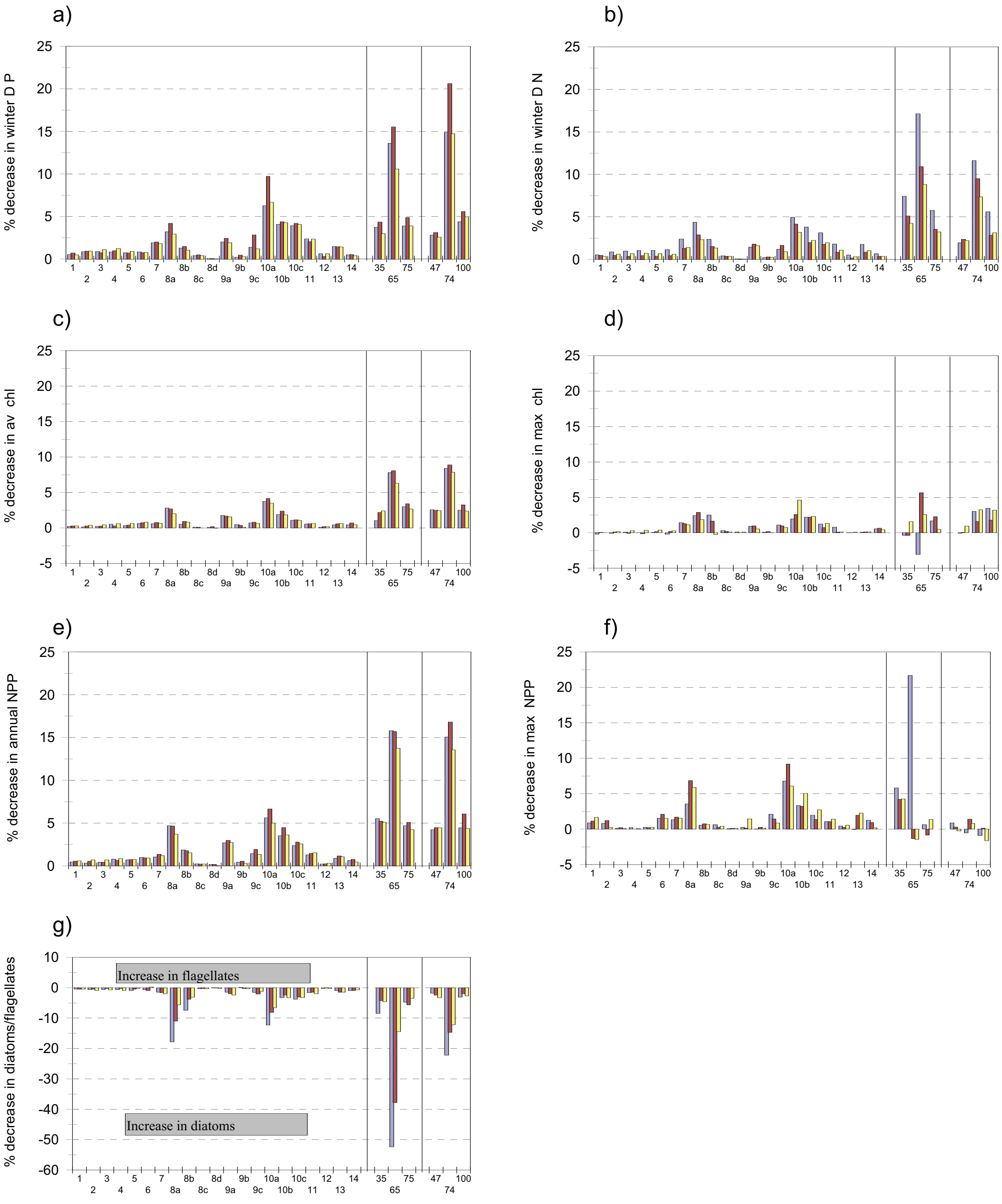


***Figure 4.14** Difference between reference and **OSPAR 50% reduction** scenarios for each of the assessment criteria and areas, expressed **as percentages**. Blue bars refer to 1984 climatology, brown to 1987, and yellow to 1990. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). Panel a) average winter dissolved inorganic phosphate, b) average winter dissolved inorganic nitrogen, c) average chlorophyll during May-September, d) maximum weekly average chlorophyll, e) average annual net primary production, f) average weekly maximum net primary production, g) average ratio of diatom chlorophyll : flagellate chlorophyll during May-September.*

Aquaculture reduction scenario results

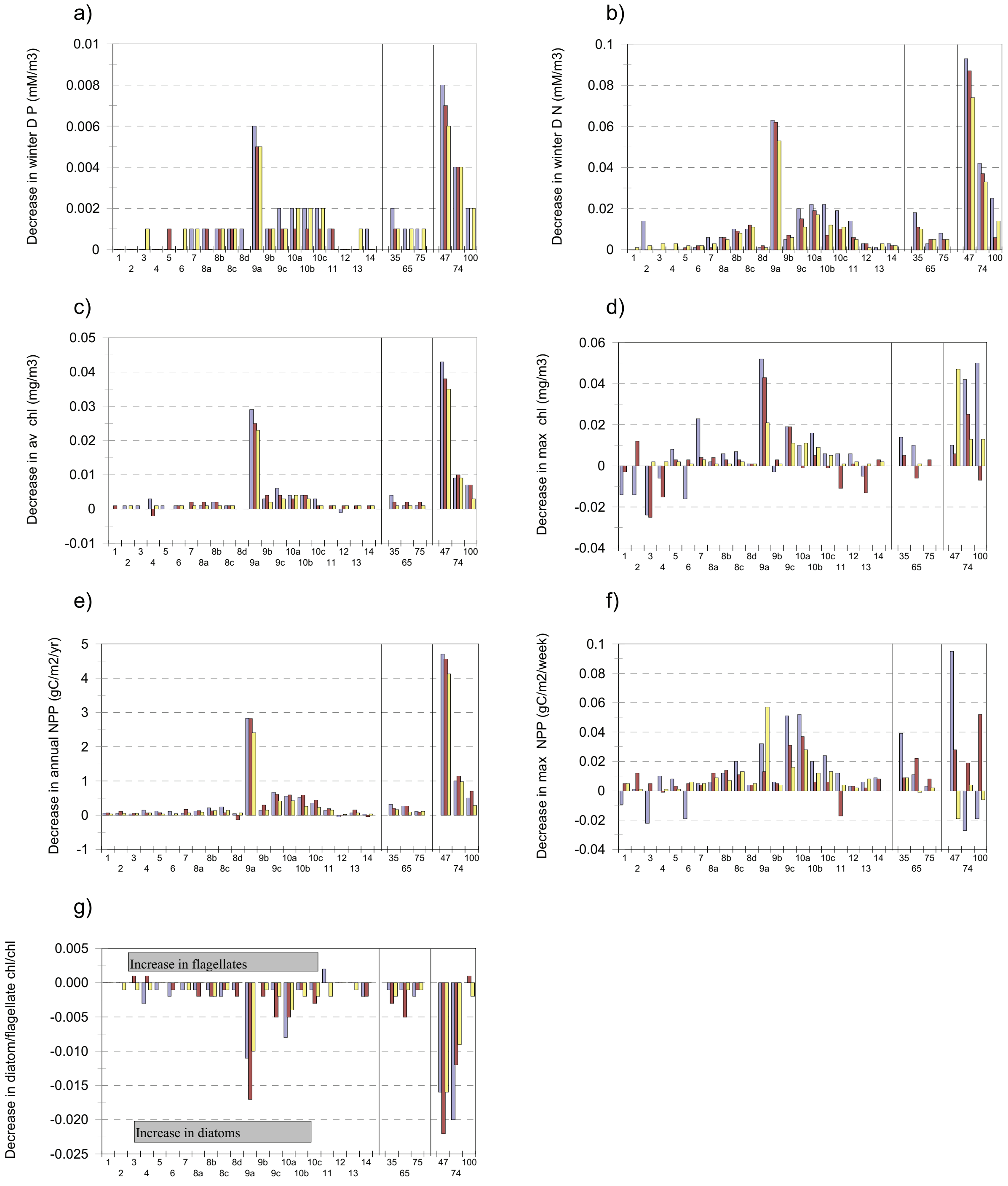


***Figure 4.15** Difference between reference and **AQUACULTURE 50% reduction** scenarios for each of the assessment criteria and areas, expressed **in absolute units**. Blue bars refer to 1984 climatology, brown to 1987, and yellow to 1990. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). Panel a) average winter dissolved inorganic phosphate, b) average winter dissolved inorganic nitrogen, c) average chlorophyll during May-September, d) maximum weekly average chlorophyll, e) average annual net primary production, f) average weekly maximum net primary production, g) average ratio of diatom chlorophyll : flagellate chlorophyll during May-September.*

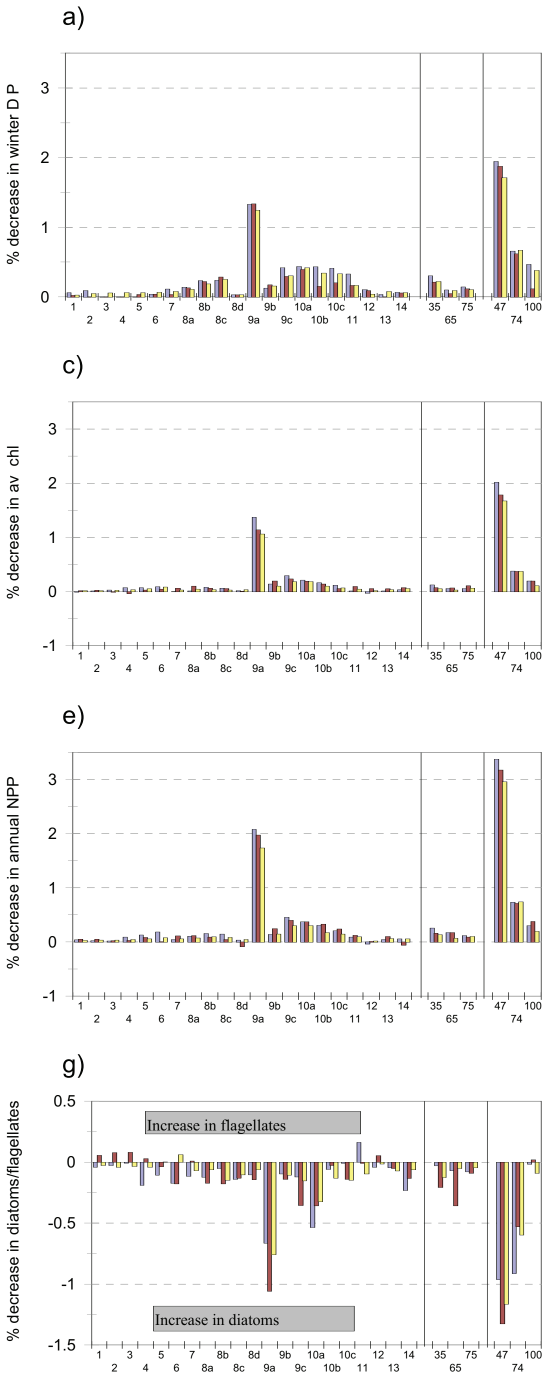


Figure 4.16 *Difference between reference and* ***AQUACULTURE 50% reduction*** *scenarios for each of the assessment criteria and areas, expressed* ***as percentages****. Blue bars refer to 1984 climatology, brown to 1987, and yellow to 1990. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). Panel a) average winter dissolved inorganic phosphate, b) average winter dissolved inorganic nitrogen, c) average chlorophyll during May-September, d) maximum weekly average chlorophyll, e) average annual net primary production, f) average weekly maximum net primary production, g) average ratio of diatom chlorophyll : flagellate chlorophyll during May-September.*

Overall results of the assessments

The first conclusion to draw from the comparison of reference and reduction scenario results is that the impact of load reductions is greatest in the individual boxes closest to the site of the loading. The impact is reduced to around half in the larger assessment area receiving the load, and diminishes rapidly with further distance from the loading site. Hence the biological consequences of nutrient loading are largely locally restricted. Presumably this is because, in the model, uptake and turn-over rates of nutrient elements (which tend to entrap material in the local area) are greater than passive dispersal rates. Lenhart and Radach (1995) investigated the interaction between transport and biological processes in a coarser box structure version of ERSEM. They concluded that for most areas of the North Sea the interaction was realistically reproduced by the model. However, numerical diffusion in the model leads to overestimates of transport in areas of strong concentration gradient. In such cases, the authors suggested the use of at least daily resolved forcing and a finer box structure. Both suggestions were adopted in the Scottish Seas application of ERSEM.

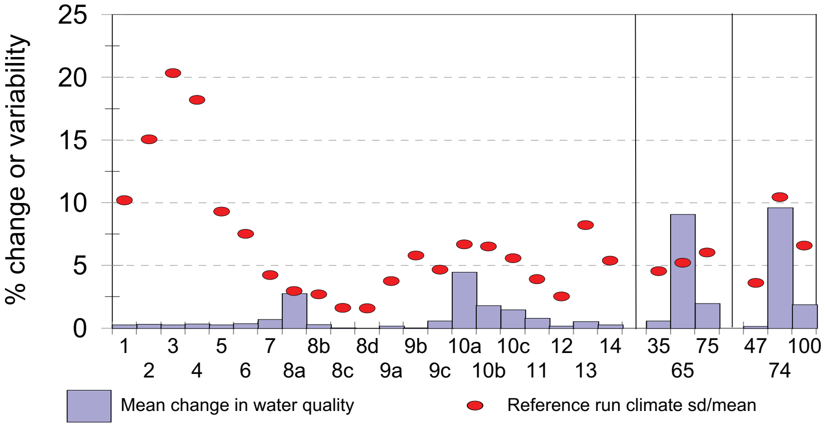
Comparison between the weighted average “change in water quality indices” for each reduction scenario and the standard deviation of reference run results (Figure 4.17) indicates that of the composite assessment areas, only area 8a (Scottish east coast) exhibited water quality changes which were out-with the variation due to climate fluctuations. The impact on water quality was clearly out-with the climate variation range for the OSPAR 50% reduction scenario, and close to the limit for the UWW 75% reduction scenario. Changes in the Clyde/North Channel area (10a) approached the climate variation limit only under the OSPAR 50% reduction scenario.

Considering the individual ERSEM box local area results, the impact of both the UWW 75% and OSPAR 50% reduction scenarios far exceeded the variability due to climate in the Forth/Tay river plume (box 65). Impacts in the Clyde (box 74) were also close to or exceeded the climate variability limit under both these scenarios. Impacts in the Inverness Firth (box 35) and around Skye (box 47) were close to but did not exceed the climate variation limit under the OSPAR 50% reduction scenario.

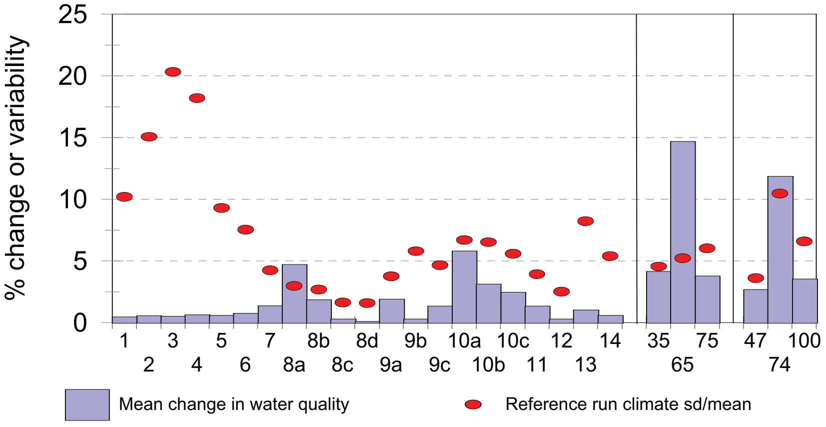
The impacts of nutrient reduction scenarios in the Solway Firth (box 100) were never close to the climate variation limit, which initially seems surprising since the total nutrient load to the Solway Firth is higher than either the Clyde or around Skye. However, the Solway receives nutrient inputs from both Scotland and England, and only the Scottish inputs were reduced in this study. Approximately 55% of nitrogen and 85% of phosphorus inputs to the Solway were estimated to originate from England.

None of the assessment areas exhibited impacts close to the climate variation limit under the AQUACULTURE 50% reduction scenario. The closest was the Skye local area (box 47) where the change in water quality was less than 2% which was around half of the variation due to climate, and represented around 4gC m-^{2} yr^{-1} decrease in annual net primary production, or less than 0.05mg chlorophyll m^{-3} averaged over May-September. However, this level of impact is similar to that produced in the OSPAR 50% reduction scenario, because around Skye (and some other areas of the west coast and Scottish islands), aquaculture represents a major part of the total nutrient loading.

a) Urban Waste Water 75% reduction scenario



b) OSPAR 50% reduction scenario



c) AQUACULTURE 50% reduction scenario

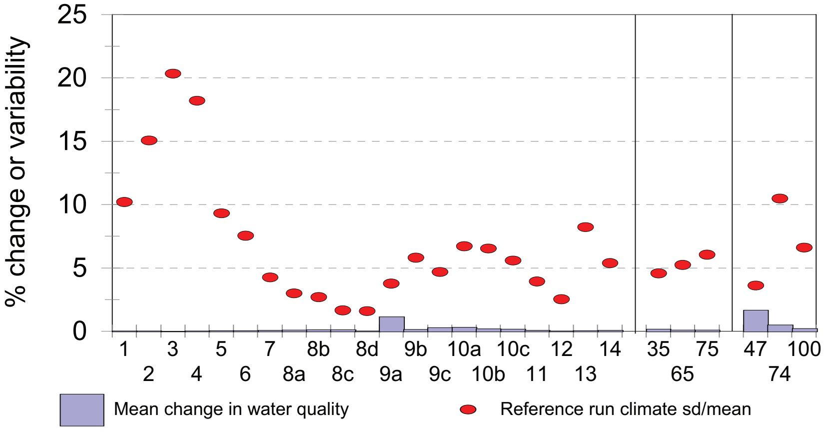


Figure 4.17 *Mean change in the water quality index due to each of the nutrient reduction scenarios (histogram bars), compared with climate induced variability in water quality (% sd/mean) in the reference runs (red symbols). Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively).*

Wider significance of the assessment results

It is important to bear in mind that the model based assessments presented in this report represent hypothetical scenarios in which only Scotland implemented nutrient discharge reductions whilst the rest of Europe remained at *status-quo* loading levels. Hence, the results do not give any indication of the scale of impact in any given area of nutrient loading from Scotland, relative to those from the rest of Europe or the UK.

In order to estimate the role of Scottish nutrients in the Europe-wide eutrophication impact, it would be necessary to repeat the various scenario runs with the appropriate percentage reductions in nutrient loadings from all contributing nations, not just Scotland. This has not yet been carried out using the sc278 version of ERSEM. However, the nd130 North Sea version of ERSEM was used by the 1996 ASMO Modelling Workshop (OSPAR, 1998) to assess the impact of a Europe-wide 50% reduction in nitrogen and phosphorus (approximately equivalent to the OSPAR 50% reduction scenario), as described earlier in relation to the evaluation of reference run results. For area 8a (Scottish east coast), which receives direct nutrient loading only from Scotland, the sc278 OSPAR 50% reduction scenario results described in this report, are similar to those calculated from the ASMO nd130 results (3-5% overall change in water quality; Figure 4.18). Differences between the two model version results could occur because of:

- structural differences in the model versions and their internal data sets (as described in relation to reference run results),
- different forcing climatology,
- referred impacts due to advection and diffusion of nutrients and plankton arising from loadings outside Scotland (*e.g.* England),
- the likelihood that all nutrient inputs were probably underestimated in the ASMO loading data set on account of the fact that they were based only on major river inputs and did not include the unmonitored diffuse inputs which this project has included for the UK.

Despite the lack of strict comparability between the sc278 and ASMO nd130 versions, it is clear that Scotland most probably has almost no impact on the eutrophication status of Continental European waters (areas 1, 2, 3 and 4) compared to the inputs from other nations. Furthermore, the impacts of nutrient loading in those areas which are likely to be mainly affected by inputs from Scotland (areas 8a, b, c, d, 9a, b and c and 10a) are small ($\leq$5% overall; 0.2-10gC/m^2/year net primary production) compared with those in areas which are mainly affected by inputs from some other nations (*e.g.* >15% overall; 39-77gC/m^2/year net primary production in areas 1, 2, 3 and 4). The reason is partly that in terms of total inputs of nitrogen and phosphorus, Scotland contributes less than 10% of the Europe-wide totals (see results from Task 2). Hence a 50% reduction in loading for Scotland represents a substantially smaller absolute reduction in nutrient load than it does for some other nations.

Despite the apparently large impact of a 50% reduction in Europe-wide nutrient loadings on the water quality of the European coastal areas (areas 1, 2, 3 and 4) simulated by the ASMO nd130 version, it is interesting to note that the climate-dependent variability in sc278 reference runs is also high in these areas (cf. Figures 4.8 and 4.9). Hence, the Europe-wide reduction impacts in European waters might be only marginally excess of the climate variability limit. Further examination of this must await further runs of the sc278 version.

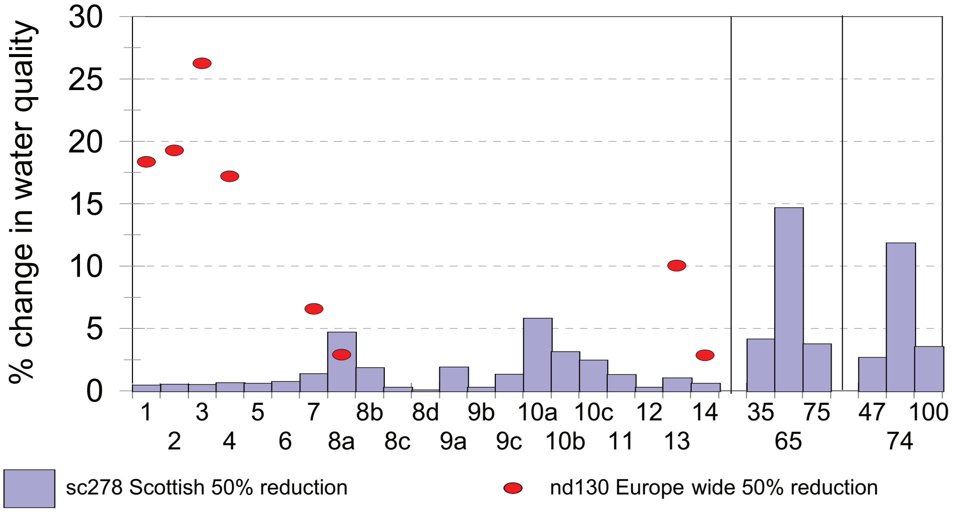


Figure 4.18 *Mean change in the water quality index due to the OSPAR 50% nutrient reduction scenario (histogram bars), compared with the equivalent changes in the index for North Sea regions only calculated from data reported by OSPAR (1998) (red symbols). The OSPAR data were results from the 1996 ASMO Workshop on eutrophication modelling, where Europe-wide 50% reductions in total nitrogen and phosphorus emissions were imposed on the nd130 version of ERSEM with 1985 climatology. Areas 1-14 are the composite areas made up of at least 3 individual ERSEM boxes. Areas 35, 65 and 75 are the individual ERSEM boxes on the Scottish east coast of the same numbers (Inverness Firth, Forth/Tay and Farne Islands respectively), and areas 47, 74 and 100 are the ERSEM boxes on the west coast of the same numbers (Skye, Clyde and Solway respectively). ASMO nd130 results were not available for the individual ERSEM boxes, or for the Skagerrak and Norwegian Coast (areas 5 and 6).*

Summary of assessments

Assuming the validity of the model, then an important conclusion of the assessments carried out here is that the impacts of nutrient loading are largely contained within the immediate locality of the inputs (at least on the scales resolved by this model). This is assumed to be because the biological processes act to entrap nutrients more quickly than they are transported by advection and diffusion. Thus, the impacts of Scottish nutrients on remote areas such as the continental coast or the central parts of the North Sea are far below the levels at which they could be detected by any measurement programme against the background of natural variability in ecological criteria.

At a local scale, the model identifies the Clyde Sea, and especially the Forth/Tay river plume as areas which should be examined in more detail and at a finer spatial scale. The impacts of both the Urban Waste Water 75% and OSPAR 50% reduction scenarios produced impacts in the Forth/Tay river plume which were far in excess of the natural variability in the system, and should therefore be detectable by monitoring programmes. The Scottish east coast (which includes the Forth/Tay river plume) was the only one of the larger regional areas examined which exhibited impacts in excess of natural variability in response to Scottish nutrient reductions.

The model indicates that, at the spatial scale of this model, the impact of a 50% reduction in nutrient discharges from Scottish salmon farming is likely to be small and far below the natural variability in the system. However, in the areas where marine aquaculture inputs are highest (around Skye), the impact of a 50% reduction is almost as large as that from a halving of all nutrient inputs. This is because for some areas of the west of Scotland, aquaculture inputs form a high proportion of the total estimated loading, though this is still small compared to almost all other areas of Europe.

3. Overall conclusions

3.1 Nutrient Loadings

In this project we have carried out the most detailed assessment to date of the nutrient loadings to coastal waters from Scotland and the rest of the UK. The critical issues which have been addressed are:

a) A substantial area of the UK catchment is not monitored by the river gauges maintained under the Harmonised Monitoring Scheme. For Scotland, approximately 50% of the catchment is gauged. We have extrapolated the HMS data to reflect 100% of the land area using a GIS model based on land use data.
b) For Scotland, we have produced estimates of the total urban waste water load which includes both the direct-to-sea components and the discharges to the freshwater catchments.
c) We have produced estimates of the nutrient loads due to aquaculture which include the nitrogen, phosphorus and carbon components.
d) We have resolved the loads spatially and chemically to a higher degree than has been achieved previously.

The results of the nutrient loading analysis show that although Scotland represents 25% of the land area of the British Isles (including the Republic of Ireland), it contributes 42% of the freshwater runoff. However, the nitrogen and phosphorus load from Scotland is only around 15% of the British Isles total (approximately 140,000 tonnes nitrogen and 14,000 tonnes phosphorus). Scotland contributes a disproportionate amount of silicon to the British Isles total loading, presumably due to the terrain and geology. On a Europe-wide basis, Scotland contributes less than 10% of the total nitrogen and phosphorus loading, but 26% of the silicon loading.

Urban waste water accounts for approximately 12% of Scotland’s nitrogen load, but 36% of the phosphorus load. Salmon farming contributes approximately 6% of nitrogen and 13% of phosphorus (based on 2001 production figures). Around 80% of the urban waste water load resulted from direct-to-sea discharges in 1999.

3.2 Eutrophication impacts of Scotland’s nutrient inputs

The European Regional Seas Ecosystem Model (ERSEM) represents a state of the art standard in eutrophication modelling. Nutrient loading scenario analyses derived from a North Sea-wide version of this model have previously been published in the scientific literature and OSPAR documents.

In this project we have more than doubled the spatial domain of the North Sea ERSEM, extending it to the west and south to cover the entire European shelf from 49° 30’N (Brittany coast) northwards to 61° 30’N, and 12°E to 12°W (Skagerrak to west of Ireland). This development work allows the system to be employed for assessing the eutrophication status of the whole of Scottish waters including those to the west of Scotland as well as in the North Sea.

The model criteria selected for assessing eutrophication status were those used by the 1996 ASMO Workshop on eutrophication modelling (winter concentrations of dissolved inorganic nitrogen and phosphorus, mean and maximum chlorophyll concentration and net primary production, and the ratio of diatom:non-diatom chlorophyll content). These criteria match the Category I and Category II Harmonised Assessment Criteria (direct and indirect effects of nutrient enrichment respectively) agreed with the OSPAR Secretariat in April 2002.

Reference runs of the model were carried out using 1984, 1987 and 1990 meteorological forcing of the ERSEM (non-anthropogenic nutrient loads, transport and irradiance), together with 1999 urban waste water and industrial loads and 2001 aquaculture loads. The meteorological years were selected to represent the extremes of climate in recent decades. The results were compared to the North Sea version of ERSEM operated by the 1996 ASMO Workshop, and used to derive indices of the natural climate-driven variability in the eutrophication criteria. The approach of "pre-running" the model using the repeated annual meteorological cycle of the year of interest may unrealistically increase the simulated differences between the results of the years 1984, 1987 and 1990 of the standard run. But this effect should be compensated by the use of climatological boundary conditions and climatological SPM concentrations.

The ERSEM was run for three load reduction scenarios and the results compared to those from the reference runs. The three scenarios were a) 75% reduction in Scottish urban waste water, b) 50% (OSPAR defined) reduction in all Scottish loads, and c) 50% reduction in Scottish aquaculture nutrient loads. The impacts of load reduction were considered to be significant if the mean change in a criterion was greater than or close to the standard deviation of the variability in reference run results due to the different meteorological forcing.

The impacts of nutrient load reductions were largely confined to the immediate locality of the inputs (at least on the scales resolved by the model). Thus, the impacts of Scottish nutrients on remote areas such as the continental coast or the central parts of the North Sea are far below the levels at which they could be detected by any measurement programme against the background of natural variability in ecological criteria.

At a local scale, the model identified the Clyde Sea, and especially the Forth/Tay river plume as areas which should be examined in more detail and at a finer spatial scale since the simulated impact of nutrient reductions was in excess of the natural variability. The wider Scottish east coast area was the only one of a number of regional areas examined which exhibited impacts in excess of natural variability in response to Scottish nutrient reductions.

The model indicated that the impact of a 50% reduction in nutrient discharges from Scottish salmon farming was likely to be small and far below the natural variability in the system (at the spatial scale of this model).

Comparing the 50% reduction scenario results from this study with those from the 1996 ASMO Workshop, the impact of Scotland's nutrients on coastal waters is considerably less than that of some other nations. A 50% reduction in Scottish nutrients produced a 5% or less mean change in overall water quality in Scottish east coast waters (equivalent to 0.2-10gC/m^2/year change in net primary production). The ASMO study simulated a similar change in Scottish waters, but around a 15% or greater change in Belgian, Dutch and German coastal waters (equivalent to 39-77gC/m^2/year net primary production).

4. Outstanding issues and needs for further investigation

- Need to undertake a thorough comparison of model results with available observations for validation of the model – especially the western waters. There has not been any time for this so far. (The North Sea parts of the model have already been thoroughly evaluated during the earlier projects in the mid-1990's).

- Various aspects of the model could be refined. In particular: 1) suspended sediment load data; 2) light extinction coefficients; 3) atmospheric inputs of nitrogen (currently ignored); 4) calculation of phosphorus loads (esp. organic fractions); 5) estimation of riverine loading data for 1999 to accompany UWW and aquaculture loads; 6) estimation of nitrite and organic silicon loads.

- The loading data needs more work to satisfactorily separate the UWW component from the total riverine inputs – especially in the Clyde catchment. Phosphorus inputs to the freshwater catchment from UWW are rapidly transformed in the watershed and their relationship to what emerges from the river mouth is uncertain. Also, UWW loads to the west of Scotland from Highlands and Islands settlements seem very low and may be underestimated (but maybe they are too small individually to be included in the Directive requirements).

- Need to improve loading data sets for Denmark and Norway, which are currently only rudimentary. Consideration could also be given to updating the continental European loadings to estimate the diffuse inputs and discharges not accounted for by the major river outflows.

- If the model is going to be used to investigate UWW reductions in England and Wales, then work needs to be done to separate out the components of the river-borne nutrient discharges from each catchment.

- For Scotland, and other areas of the UK, it would be valuable to attempt a separation of the loading due to agriculture from that due to geological processes in each catchment. This would allow a more meaningful interpretation of the OSPAR 50% reduction scenario set-up, since it is clearly unrealistic to include geological loadings in such an assessment.

Additional issues which could be investigated by the model:

- What would be the impact of a reduction in England and Wales inputs on Scottish water quality? It might be greater than an equivalent reduction in Scottish inputs.

- What are the magnitudes of the changes in the assessment criteria as a result of load reductions in other regions – *e.g.* the Continental European coast? How do the impacts of Scottish load reductions compare with those in other regions acknowledged to be eutrophic?

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6. Abbreviations

ASMO	Assessment and Monitoring Committee (of OSPAR)
DIN	Dissolved inorganic nitrogen
DIP	Dissolved inorganic phosphorus
DOC	Dissolved organic carbon
DON	Dissolved organic nitrogen
DOP	Dissolved organic phosphorus
EA	Environment Agency
ERSEM	European Regional Seas Ecosystem Model
FWC	Flow Weighted Concentration
HAMSOM	Hamburg Shelf Ocean Model
HARP-NUT	Harmonised Quantification and Reporting Procedures for Nutrients
HMS	Harmonised Monitoring Scheme
ICES	International Council for the Exploration of the Sea
LTT	refers to the output from a particular hydrodynamic model at Univ. Hamburg
NAO	North Atlantic Oscillation Index
NIOZ	Netherlands Institute for Sea Research
NRFA	National River Flow Archive
NSTF	North Sea Task Force
OS	Ordnance Survey
OSPAR	Oslo and Paris Commission
QSR	Quality Status Report
POC	Particulate organic carbon
PON	Particulate organic nitrogen
POP	Particulate organic phosphorus
POS	Particulate organic silicon
RID	Riverine Inputs and Direct Discharges
SEPA	Scottish Environment Protection Agency
SPM	Suspended Particulate Matter
UWW	Urban waste water
UWWT	Urban waste water treatment

Appendix 1

Depth [m], area [m^2] and volume [m^3] of the “sc278” ERSEM model boxes. Status: “t“= total water column, “u“= upper layer, “l“= lower layer.

box	depth	area	volume	status	box	depth	area	volume	status
1	30.00	0.358722E+10	0.107616E+12	u	**156**	30.00	0.959995E+10	0.287998E+12	u
2	30.00	0.358722E+10	0.107616E+12	u	**157**	30.00	0.959995E+10	0.287998E+12	u
3	30.00	0.365502E+10	0.109650E+12	u	**158**	30.00	0.799996E+10	0.239998E+12	u
4	30.00	0.243668E+10	0.731005E+11	u	**159**	30.00	0.170247E+11	0.510743E+12	u
5	30.00	0.325141E+10	0.975425E+11	u	**160**	30.00	0.127647E+11	0.382942E+12	u
6	30.00	0.144845E+11	0.434535E+12	u	**161**	36.05	0.127625E+11	0.460089E+12	t
7	30.00	0.144845E+11	0.434535E+12	u	**162**	259.83	0.358722E+10	0.932068E+12	l
8	30.00	0.104735E+11	0.314207E+12	u	**163**	118.28	0.358722E+10	0.424296E+12	l
9	30.00	0.372243E+10	0.111672E+12	u	**164**	233.27	0.365502E+10	0.852608E+12	l
10	30.00	0.372243E+10	0.111672E+12	u	**165**	57.54	0.243668E+10	0.140206E+12	l
11	30.00	0.372243E+10	0.111672E+12	u	**166**	53.61	0.325141E+10	0.174308E+12	l
12	30.00	0.331131E+10	0.993395E+11	u	**167**	115.14	0.144845E+11	0.166774E+13	l
13	30.00	0.372243E+10	0.111672E+12	u	**168**	167.65	0.144845E+11	0.242832E+13	l
14	30.00	0.378942E+10	0.113682E+12	u	**169**	209.48	0.104735E+11	0.219400E+13	l
15	30.00	0.378942E+10	0.113682E+12	u	**170**	349.75	0.372243E+10	0.130192E+13	l
16	30.00	0.378942E+10	0.113682E+12	u	**171**	170.12	0.372243E+10	0.633259E+12	l
17	30.00	0.336590E+10	0.100977E+12	u	**172**	61.38	0.372243E+10	0.228482E+12	l
18	36.59	0.294485E+10	0.107752E+12	t	**173**	55.03	0.331131E+10	0.182221E+12	l
19	30.00	0.378942E+10	0.113682E+12	u	**174**	84.04	0.372243E+10	0.312833E+12	l
20	30.00	0.378942E+10	0.113682E+12	u	**175**	398.02	0.378942E+10	0.150826E+13	l
21	30.00	0.150237E+11	0.450711E+12	u	**176**	97.14	0.378942E+10	0.368104E+12	l
22	30.00	0.150237E+11	0.450711E+12	u	**177**	64.01	0.378942E+10	0.242561E+12	l
23	30.00	0.146026E+11	0.438079E+12	u	**178**	42.07	0.336590E+10	0.141603E+12	l
24	30.00	0.385600E+10	0.115680E+12	u	**179**	65.44	0.378942E+10	0.247980E+12	l
25	30.00	0.342510E+10	0.102753E+12	u	**180**	100.92	0.378942E+10	0.382428E+12	l
26	30.00	0.385600E+10	0.115680E+12	u	**181**	86.91	0.150237E+11	0.130571E+13	l
27	30.00	0.256329E+10	0.768989E+11	u	**182**	121.28	0.150237E+11	0.182207E+13	l
28	30.00	0.213731E+10	0.641193E+11	u	**183**	191.68	0.146026E+11	0.279903E+13	l
29	30.00	0.343001E+10	0.102900E+12	u	**184**	474.83	0.385600E+10	0.183094E+13	l
30	30.00	0.385600E+10	0.115680E+12	u	**185**	81.80	0.342510E+10	0.280173E+12	l
31	30.00	0.385600E+10	0.115680E+12	u	**186**	62.16	0.385600E+10	0.239689E+12	l
32	30.00	0.392216E+10	0.117664E+12	u	**187**	34.99	0.256329E+10	0.896898E+11	l
33	30.00	0.392216E+10	0.117664E+12	u	**188**	30.00	0.213731E+10	0.641193E+11	l
34	30.00	0.260745E+10	0.782235E+11	u	**189**	33.25	0.343001E+10	0.114048E+12	l
35	33.66	0.262209E+10	0.882596E+11	t	**190**	65.78	0.385600E+10	0.253648E+12	l
36	30.00	0.392216E+10	0.117664E+12	u	**191**	95.41	0.385600E+10	0.367901E+12	l
37	30.00	0.392216E+10	0.117664E+12	u	**192**	397.03	0.392216E+10	0.155721E+13	l
38	30.00	0.392216E+10	0.117664E+12	u	**193**	70.35	0.392216E+10	0.275924E+12	l
39	30.00	0.155563E+11	0.466690E+12	u	**194**	28.33	0.260745E+10	0.738690E+11	l
40	30.00	0.155563E+11	0.466690E+12	u	**195**	31.14	0.392216E+10	0.122136E+12	l
41	30.00	0.151303E+11	0.453910E+12	u	**196**	54.55	0.392216E+10	0.213953E+12	l
42	30.00	0.655643E+10	0.196692E+12	u	**197**	76.43	0.392216E+10	0.299770E+12	l
43	30.00	0.100403E+11	0.301209E+12	u	**198**	99.12	0.155563E+11	0.154194E+13	l
44	30.00	0.172601E+11	0.517805E+12	u	**199**	71.56	0.155563E+11	0.111321E+13	l
45	30.00	0.398788E+10	0.119636E+12	u	**200**	183.98	0.151303E+11	0.278368E+13	l
46	30.00	0.265859E+10	0.797577E+11	u	**201**	227.57	0.655643E+10	0.149204E+13	l
47	30.00	0.352292E+10	0.105687E+12	u	**202**	290.54	0.100403E+11	0.291711E+13	l
48	30.00	0.358352E+10	0.107505E+12	u	**203**	149.46	0.172601E+11	0.257970E+13	l
49	30.00	0.265859E+10	0.797577E+11	u	**204**	242.98	0.398788E+10	0.968977E+12	l
50	30.00	0.398788E+10	0.119636E+12	u	**205**	54.18	0.265859E+10	0.144042E+12	l
51	30.00	0.405317E+10	0.121595E+12	u	**206**	17.46	0.352292E+10	0.615103E+11	l
52	30.00	0.360523E+10	0.108157E+12	u	**207**	17.44	0.358352E+10	0.624966E+11	l
53	30.00	0.316932E+10	0.950796E+11	u	**208**	38.67	0.265859E+10	0.102807E+12	l
54	30.00	0.450593E+10	0.135178E+12	u	**209**	60.26	0.398788E+10	0.240310E+12	l
55	30.00	0.405317E+10	0.121595E+12	u	**210**	244.89	0.405317E+10	0.992582E+12	l
56	30.00	0.160821E+11	0.482463E+12	u	**211**	71.67	0.360523E+10	0.258387E+12	l
57	30.00	0.160821E+11	0.482463E+12	u	**212**	31.35	0.316932E+10	0.993582E+11	l
58	30.00	0.160821E+11	0.482463E+12	u	**213**	35.14	0.450593E+10	0.158338E+12	l
59	30.00	0.895873E+10	0.268762E+12	u	**214**	42.66	0.405317E+10	0.172908E+12	l
60	30.00	0.129272E+11	0.387818E+12	u	**215**	60.06	0.160821E+11	0.965892E+12	l
61	30.00	0.411802E+10	0.123540E+12	u	**216**	42.61	0.160821E+11	0.685259E+12	l
62	30.00	0.411802E+10	0.123540E+12	u	**217**	36.26	0.160821E+11	0.583138E+12	l
63	30.00	0.183502E+10	0.550506E+11	u	**218**	39.73	0.895873E+10	0.355930E+12	l
64	35.81	0.229258E+10	0.820972E+11	t	**219**	18.63	0.129272E+11	0.240835E+12	l

65	39.64	0.228778E+10	0.906879E+11	t	**220**	229.52	0.411802E+10	0.945168E+12	l
66	30.00	0.411802E+10	0.123540E+12	u	**221**	80.99	0.411802E+10	0.333518E+12	l
67	30.00	0.411802E+10	0.123540E+12	u	**222**	40.00	0.183502E+10	0.734008E+11	l
68	30.00	0.411802E+10	0.123540E+12	u	**223**	21.56	0.411802E+10	0.887845E+11	l
69	30.00	0.411802E+10	0.123540E+12	u	**224**	49.85	0.411802E+10	0.205283E+12	l
70	30.00	0.418241E+10	0.125472E+12	u	**225**	61.00	0.411802E+10	0.251199E+12	l
71	30.00	0.418241E+10	0.125472E+12	u	**226**	59.77	0.411802E+10	0.246134E+12	l
72	30.00	0.372007E+10	0.111602E+12	u	**227**	133.78	0.418241E+10	0.559523E+12	l
73	38.79	0.185885E+10	0.721048E+11	t	**228**	54.02	0.418241E+10	0.225934E+12	l
74	30.00	0.232831E+10	0.698494E+11	u	**229**	24.51	0.372007E+10	0.911791E+11	l
75	30.00	0.278352E+10	0.835056E+11	u	**230**	19.03	0.232831E+10	0.443078E+11	l
76	30.00	0.418241E+10	0.125472E+12	u	**231**	39.51	0.278352E+10	0.109977E+12	l
77	30.00	0.418241E+10	0.125472E+12	u	**232**	45.69	0.418241E+10	0.191094E+12	l
78	30.00	0.418241E+10	0.125472E+12	u	**233**	51.21	0.418241E+10	0.214181E+12	l
79	30.00	0.166008E+11	0.498026E+12	u	**234**	47.86	0.418241E+10	0.200170E+12	l
80	30.00	0.166008E+11	0.498026E+12	u	**235**	38.20	0.166008E+11	0.634153E+12	l
81	37.08	0.549069E+10	0.203594E+12	t	**236**	19.88	0.166008E+11	0.330025E+12	l
82	25.44	0.411802E+10	0.104762E+12	t	**237**	66.19	0.518526E+10	0.343212E+12	l
83	41.49	0.557655E+10	0.231371E+12	t	**238**	36.75	0.188018E+10	0.690968E+11	l
84	18.99	0.464950E+10	0.882940E+11	t	**239**	47.88	0.424634E+10	0.203315E+12	l
85	30.00	0.518526E+10	0.155557E+12	u	**240**	45.35	0.518762E+10	0.235258E+12	l
86	30.00	0.188018E+10	0.564056E+11	u	**241**	46.11	0.424634E+10	0.195799E+12	l
87	30.00	0.424634E+10	0.127390E+12	u	**242**	14.85	0.424634E+10	0.630582E+11	l
88	30.00	0.518762E+10	0.155628E+12	u	**243**	13.45	0.424634E+10	0.571133E+11	l
89	30.00	0.424634E+10	0.127390E+12	u	**244**	12.32	0.424634E+10	0.523150E+11	l
90	30.00	0.424634E+10	0.127390E+12	u	**245**	628.96	0.478400E+10	0.300894E+13	l
91	28.87	0.424634E+10	0.122592E+12	t	**246**	26.54	0.238966E+10	0.634216E+11	l
92	29.79	0.424634E+10	0.126498E+12	t	**247**	42.09	0.335442E+10	0.141187E+12	l
93	30.00	0.424634E+10	0.127390E+12	u	**248**	24.76	0.190844E+10	0.472531E+11	l
94	30.00	0.424634E+10	0.127390E+12	u	**249**	30.41	0.430981E+10	0.131061E+12	l
95	38.83	0.566179E+10	0.219847E+12	t	**250**	12.58	0.430981E+10	0.542175E+11	l
96	19.58	0.566179E+10	0.110858E+12	t	**251**	11.45	0.430981E+10	0.493474E+11	l
97	30.00	0.478400E+10	0.143520E+12	u	**252**	17.34	0.430981E+10	0.747322E+11	l
98	30.00	0.238966E+10	0.716898E+11	u	**253**	12.66	0.430981E+10	0.545622E+11	l
99	30.00	0.335442E+10	0.100632E+12	u	**254**	693.20	0.437281E+10	0.303123E+13	l
100	27.08	0.573938E+10	0.155422E+12	t	**255**	162.47	0.437514E+10	0.710829E+12	l
101	30.00	0.190844E+10	0.572534E+11	u	**256**	37.13	0.632093E+10	0.234696E+12	l
102	30.00	0.430981E+10	0.129294E+12	u	257	12.54	0.437281E+10	0.548350E+11	l
103	30.00	0.430981E+10	0.129294E+12	u	**258**	15.50	0.437281E+10	0.677786E+11	l
104	28.02	0.430981E+10	0.120761E+12	t	**259**	12.00	0.437281E+10	0.524737E+11	l
105	30.00	0.430981E+10	0.129294E+12	u	**260**	13.43	0.437281E+10	0.587268E+11	l
106	30.00	0.430981E+10	0.129294E+12	u	**261**	118.69	0.198550E+11	0.235659E+13	l
107	30.00	0.430981E+10	0.129294E+12	u	**262**	30.00	0.443532E+10	0.133059E+12	l
108	39.75	0.574642E+10	0.228420E+12	t	**263**	14.95	0.491891E+10	0.735377E+11	l
109	25.35	0.430981E+10	0.109253E+12	t	**264**	32.57	0.449735E+10	0.146479E+12	l
110	8.44	0.335208E+10	0.282915E+11	t	**265**	243.88	0.163337E+11	0.398347E+13	l
111	30.00	0.437281E+10	0.131184E+12	u	**266**	49.42	0.719557E+10	0.355605E+12	l
112	30.00	0.437514E+10	0.131254E+12	u	**267**	44.57	0.122701E+11	0.546880E+12	l
113	30.00	0.632093E+10	0.189628E+12	u	**268**	27.13	0.183915E+11	0.498961E+12	l
114	28.92	0.583041E+10	0.168615E+12	t	**269**	475.45	0.188418E+11	0.895837E+13	l
115	31.84	0.437513E+10	0.139304E+12	t	**270**	83.42	0.188418E+11	0.157179E+13	l
116	30.00	0.437281E+10	0.131184E+12	u	**271**	67.16	0.188418E+11	0.126542E+13	l
117	30.00	0.437281E+10	0.131184E+12	u	**272**	23.31	0.781188E+10	0.182095E+12	l
118	30.00	0.437281E+10	0.131184E+12	u	**273**	14.45	0.892544E+10	0.128972E+12	l
119	30.00	0.437281E+10	0.131184E+12	u	**274**	374.29	0.959995E+10	0.359316E+13	l
120	37.66	0.290823E+10	0.109524E+12	t	**275**	92.91	0.959995E+10	0.891931E+12	l
121	32.87	0.387765E+10	0.127458E+12	t	**276**	80.90	0.799996E+10	0.647197E+12	l
122	15.98	0.391479E+10	0.625584E+11	t	**277**	49.03	0.170247E+11	0.834724E+12	l
123	28.40	0.339643E+10	0.964586E+11	t	**278**	35.55	0.127647E+11	0.453787E+12	l
124	9.36	0.388693E+10	0.363817E+11	t	**279**	30.00	0.108312E+11	0.324937E+12	u
125	30.00	0.198550E+11	0.595651E+12	u	**280**	30.00	0.139389E+11	0.418168E+12	u
126	30.00	0.443532E+10	0.133059E+12	u	**281**	30.00	0.139389E+11	0.418168E+12	u
127	30.00	0.491891E+10	0.147567E+12	u	**282**	30.00	0.139389E+11	0.418168E+12	u
128	21.47	0.296148E+10	0.635831E+11	t	**283**	30.00	0.180717E+11	0.542151E+12	u
129	23.22	0.443532E+10	0.102988E+12	t	**284**	30.00	0.149567E+11	0.448701E+12	u
130	29.89	0.443532E+10	0.132572E+12	t	**285**	30.00	0.116341E+11	0.349025E+12	u
131	30.33	0.443532E+10	0.134523E+12	t	**286**	30.00	0.160821E+11	0.482463E+12	u
132	28.32	0.443532E+10	0.125608E+12	t	**287**	30.00	0.166008E+11	0.498026E+12	u
133	21.08	0.441684E+10	0.931071E+11	t	**288**	30.00	0.142179E+11	0.426538E+12	u
134	30.00	0.449735E+10	0.134920E+12	u	**289**	30.00	0.266110E+11	0.798330E+12	u

135	34.02	0.399994E+10	0.136078E+12	t	**290**	30.00	0.277185E+11	0.831557E+12	u
136	32.31	0.499477E+10	0.161381E+12	t	**291**	30.00	0.385167E+11	0.115550E+13	u
137	28.22	0.449735E+10	0.126915E+12	t	**292**	30.00	0.178161E+11	0.534484E+12	u
138	18.74	0.399536E+10	0.748731E+11	t	**293**	30.00	0.129571E+11	0.388715E+12	u
139	30.00	0.163337E+11	0.490012E+12	u	**294**	37.22	0.102664E+11	0.382117E+12	t
140	30.00	0.719557E+10	0.215867E+12	u	**295**	27.61	0.933413E+10	0.257715E+12	t
141	30.00	0.122701E+11	0.368104E+12	u	**296**	176.89	0.108312E+11	0.191593E+13	l
142	30.00	0.183915E+11	0.551745E+12	u	**297**	398.36	0.139389E+11	0.555271E+13	l
143	34.31	0.608306E+10	0.208710E+12	t	**298**	511.91	0.139389E+11	0.713548E+13	l
144	27.88	0.455889E+10	0.127102E+12	t	**299**	850.83	0.139389E+11	0.118596E+14	l
145	16.24	0.202390E+10	0.328682E+11	t	**300**	803.38	0.180717E+11	0.145184E+14	l
146	21.74	0.358878E+10	0.780201E+11	t	**301**	828.19	0.149567E+11	0.123870E+14	l
147	33.54	0.461993E+10	0.154952E+12	t	**302**	1282.18	0.116341E+11	0.149171E+14	l
148	13.32	0.307545E+10	0.409650E+11	t	**303**	1672.52	0.160821E+11	0.268976E+14	l
149	30.00	0.188418E+11	0.565256E+12	u	**304**	1723.48	0.166008E+11	0.286112E+14	l
150	30.00	0.188418E+11	0.565256E+12	u	**305**	1633.57	0.142179E+11	0.232260E+14	l
151	30.00	0.188418E+11	0.565256E+12	u	**306**	794.77	0.266110E+11	0.211496E+14	l
152	30.00	0.781188E+10	0.234356E+12	u	**307**	1076.24	0.277185E+11	0.298318E+14	l
153	30.00	0.892544E+10	0.267763E+12	u	**308**	1707.76	0.385167E+11	0.657773E+14	l
154	40.38	0.115435E+11	0.466127E+12	t	**309**	105.46	0.178161E+11	0.187889E+13	l
155	30.03	0.519381E+10	0.155970E+12	t	**310**	68.28	0.129571E+11	0.884717E+12	l

Appendix 2

Set-up file for the ERSEM sc278 version indicating the switch settings for the various forcing, boundary and internal data settings.

File name: sc_set.dat

```
iy1            :   1990  :start year
im1            :     1   :start month
id1            :     1   :start day
iy2            :   1990  :ending year
im2            :    12   :ending month
id2            :    31   :ending day
istep_output   :     1   :delta t for output (d)
deltat_min     :   720.0 :timestep in minutes
relrate        :    0.15 :maximal relativ change per timestep
isw_bud        :     0   : switch for budget output
               :         :
               :         :SESAME.DAT
               :         :switches to set processing of biological
               :         :state variables on (=1) or off (=0).
iswp1$         :     1   :diatoms
iswp2$         :     1   :flagellates
iswp3$         :     1   :pico
iswp4$         :     1   :unedables
iswz3$         :     0   :carn. zoo
iswz4$         :     1   :omn. zoo
iswz5$         :     1   :
iswz6$         :     1   :
iswb1$         :     1   :
iswh1$         :     1   :
iswh2$         :     1   :
iswy1$         :     1   :
iswy2$         :     1   :
iswy3$         :     1   :
iswy4$         :     1   :
iswy5$         :     1   :
               :         :switches to select between alternative
               :         :submodules or to switch various
               :         :parts of the model on or off.
iswben$        :     1   :switch to select which benthic submodel is used
               :         :  = 1 for uo/pml benthic model (!)
               :         :  = 2 for simple benthic returns model
iswki$         :     2   :switch to select which benthic nutrient submodel
               :         :is used:
               :         : = 1 for nioz model (!)
               :         : = 2 for oldenburg model
iswzs$         :     0   :switch to select structured zooplankton module
               :         : = 0 no structured zooplankton (standard approach)
               :         : = 1 structured calanus model with weight classes
               :         :     (not available in this nd130 standard)
iswfish$       :     1   :switch to select which fish models are to be used
               :         : = 2     to call the dynamic fish
               :         : = 1 to call the static fish
               :         : = 0 no fish models are called
```

```
iswecol$      :    1    :switch to turn the ecological routines on
              :         :  = 1 to turn the ecology on
              :         :  = 0 only the transport is calculated
iswtrsp$      :    1    :switch to select net or gros transport
              :         : = 1 net transport
              :         : > 10 : only dispersive transport
              :         : > 20 : no transports
iswbudg$      :    0    :switch to select budget computations or not
              :         : = 0 no budget
              :         : = 1 buget is calculated
iswhold$      :    1    :switch to select reflecting or initial
              :         :conditions for sea boundaries for those
              :         :variables without time series
              :         : = 1 initial conditions are used
              :         : = 0 reflecting conditions are set
iswcls$       :    0    :switch to avoid advective and dispersive
              :         :transport over boundaries
              :         : = 0 transport over boundaries, etc
              :         : = 1 no transport over boundaries, via rivers,
              :         :     via atmosphere, only senseful
              :         :     for mass balance check of the full system,
              :         :     see budget routine.
iend          :    0    :end of switch list
p1c(1-278)
p2c(1-278)
p3c(1-278)
p4c(1-278)
n1p(1-278)
n3n(1-278)
n4n(1-278)
n5s(1-278)
p1s(1-278)
p1p(1-278)
p1n(1-278)
p2p(1-278)
p2n(1-278)
p3p(1-278)
p3n(1-278)
p4p(1-278)
p4n(1-278)
z4p(1-278)
z4n(1-278)
z5p(1-278)
z5n(1-278)
z6p(1-278)
z6n(1-278)
b1p(1-278)
b1n(1-278)
r6s(1-278)
r6p(1-278)
r6n(1-278)
```

Appendix 3

Which years to simulate with the ERSEM model?

Hydrodynamic data for driving ERSEM were taken from the Hamburg LTT model. This provides simulated daily data on the three-dimensional advection and vertical diffusion regime for the years 1955-1993.

Which years should chosen for the ERSEM simulations, and how should these be matched with hydrological data?

Is it necessary to perform runs with hydrodynamic and hydrological data from the same year, or can we mix-and-match years to create strategic scenarios covering the extremes of transport and runoff?

It was proposed to run simulations with combinations of hydrodynamic and hydrological years from the period 1955-1993 to represent strategic scenarios. The combinations were defined by the following matrix:

Hydrodynamics ⇒ Hydrology ⇓	**Year of minimum annual shelf transport**	**Year of median annual shelf transport**	**Year of maximum annual shelf transport**
Year of minimum annual precipitation	X	X	X
Year of median annual precipitation	X	X	X
Year of maximum annual precipitation	X	X	X

These combinations of hydrodynamics and hydrology should encompass the full range of climatic conditions that can be expected, based on the data from 1955-1993. Taking the simulated annual cycles of a given parameter (*e.g.* marine nitrate concentration) in an ERSEM box, the test of the models performance would be that all of the available observations should fall within the envelope of the 9 simulations.

However, if there is some common underlying structure to the patterns of runoff and transport, then some combinations in the above table may not be representative of any realisable scenario. Hence, we may be able to reduce the number of scenarios to be simulated.

Five data sets were analysed in order to determine which years to select for driving ERSEM. The data were:

- Annual volume inflow to the North Sea through the a transect at 59°N, 3°W-1°W in the LTT model. We take this as an index of the shelf transport in the model.
- Annual rainfall anomalies at 7 locations in Scotland (3 on the western side – Dumfries, Paisley and Auchincruvie; and 4 on the east – Dunbar, Haddington, Dyce and Wick). The anomalies were averaged for the east and west of Scotland locations. The balance of rainfall between western and eastern Scotland was given by difference between the western anomaly and the eastern anomaly.
- Frequency of winds from the southwesterly quadrant in each year.
- 0-30m annual average sea temperature anomalies in the northern North Sea (57° 30'N–62°N, 1°W-6°E).
- The winter anomalies of the North Atlantic Oscillation index (NAO).

The correlation matrix for the 7 time series variables, is shown below. Time series plots for pairs of variables are shown at the end of this document.

	Inflow	SW winds	Western rain	Eastern rain	W-E rain	Temperature	NAO
Inflow	1						
SW winds	0.356	1					
Western rain	0.591	-0.009	1				
Eastern rain	-0.099	-0.312	0.511	1			
W-E rain	0.747	0.246	0.709	-0.243	1		
Temperature	0.228	0.650	-0.116	-0.660	0.411	1	
NAO	0.549	0.803	0.274	-0.196	0.469	0.530	1

The patterns which emerges are:

- Sea temperature, SW winds and the NAO are all strongly inter-related,
- Inflow to the North Sea is positively related to the NAO, but only weakly to the SW wind frequency,
- West of Scotland rainfall is positively related to the North Sea inflow,
- East and west of Scotland rainfall are positively related,
- East of Scotland rainfall is inversely related to sea temperature and SW winds, but shows no or possibly a very weak inverse relationship with North Sea inflow (see time series plots).
- North Sea inflow is strongly correlated to the balance of rainfall between western and eastern Scotland.
- The balance of rainfall between western and eastern Scotland is correlated with western rainfall since this has double the variance of eastern rainfall. (Mean rainfall on western Scotland is also higher then to the east).

In summary, the climate conditions which promote strong transport of water into the North Sea also cause high rainfall, and a higher proportion of annual rainfall to fall on the western side of Scotland compared to the east.

The outcome of this is that conditions of high transport and low rainfall, or low transport and high rainfall, are not encountered (at least they have not occurred in the period 1955-1990), and hence are irrelevant simulation scenarios.

The years 1990 represents the high extreme of both transport and predominance of western rainfall. 1969 (and to a lesser extent 1984) represent the opposite extremes of low transport and low predominance of western rainfall. The years 1957, 1959, 1963, 1965, 1973, 1974, 1975, 1977, 1979 or 1987 are clustered around the average in terms of both transport and rainfall. Of these, 1957, 1977 and 1987 are closest to the average of the temperature series.

On the basis of the above analysis, the ideal suite of years to simulate would appear to be 1969 and 1990 as the extremes and 1977 as the average as is approximately mid-way between the extreme years. However, other considerations are:

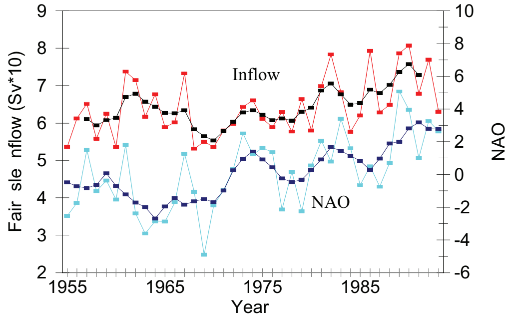
- The availability of freshwater nutrient data for the selected years,
- The relevance of the “average” year to the present-day situation.

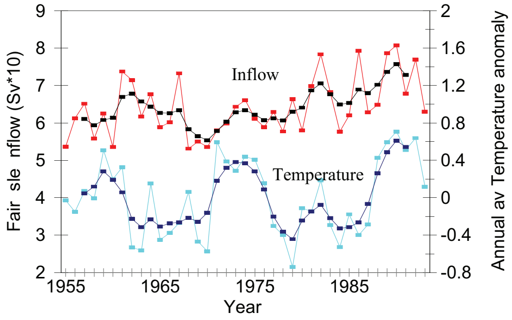
When these factors are taken into account, 1969 is problematic since comprehensive freshwater nutrient data are scarce prior to 1970. Regarding the average year, 1987 is, from other considerations, more similar to the present-day than 1977.

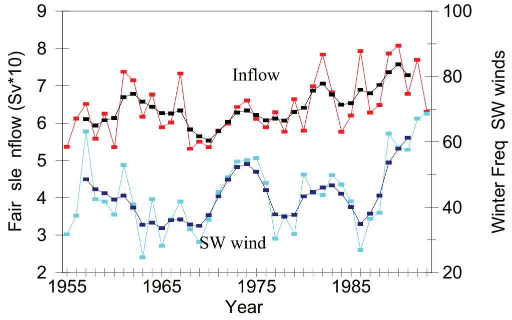
Taking all factors into consideration, our final choice of simulation years is:

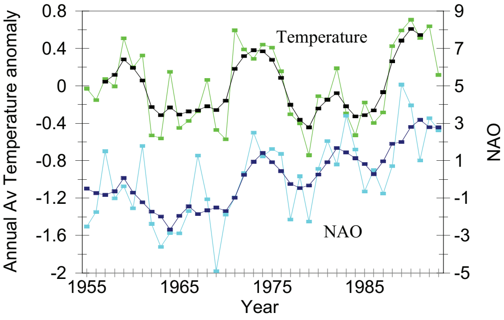
- *1984 as representative of weak transport and predominance of eastern rainfall,*
- *1990 as representative of strong transport and predominance of western rainfall,*
- *1987 as representative of an average year.*

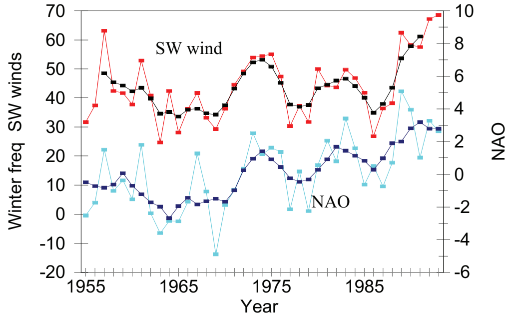
Relationships between transport and climate indices:

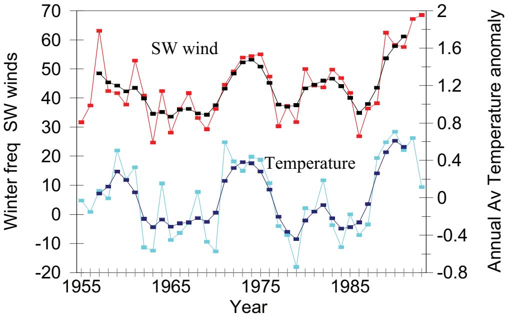




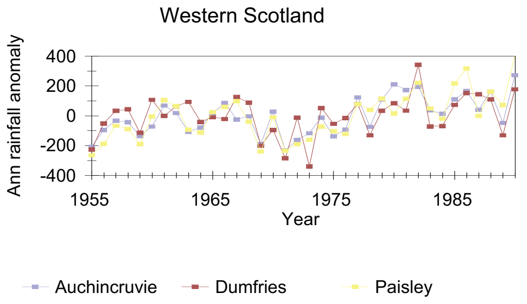


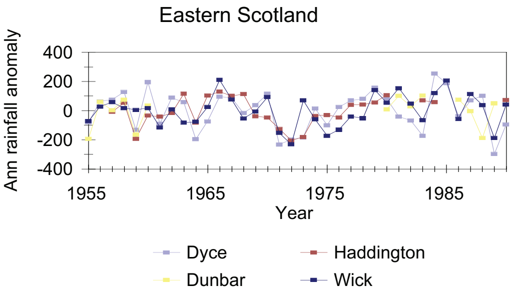


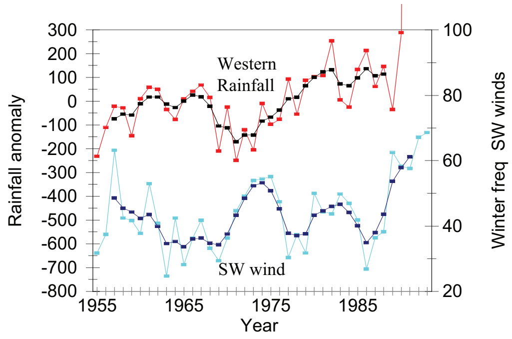


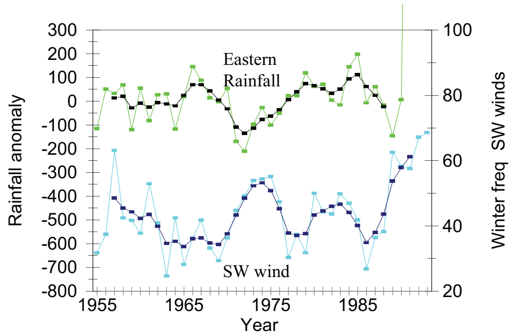


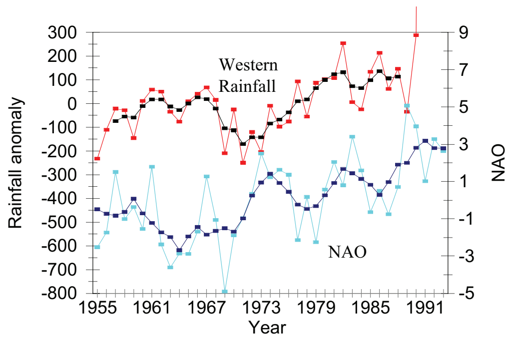
Relationships between rainfall and climate indices

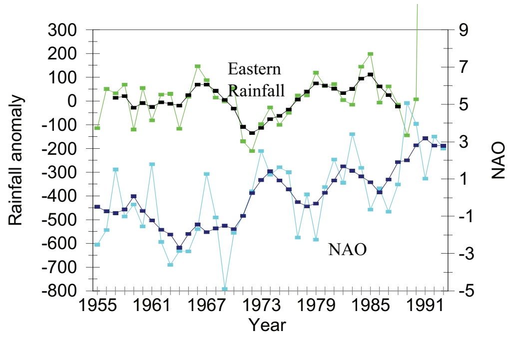


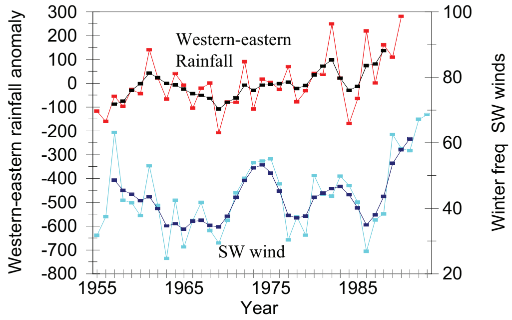


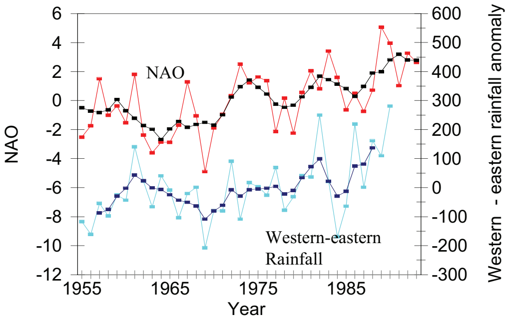




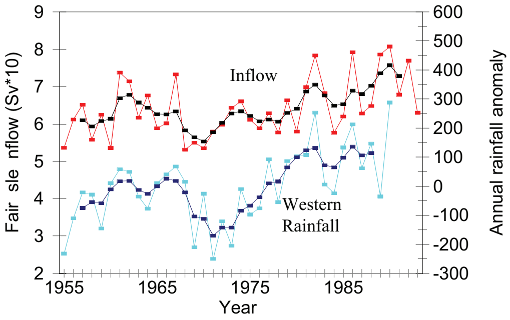


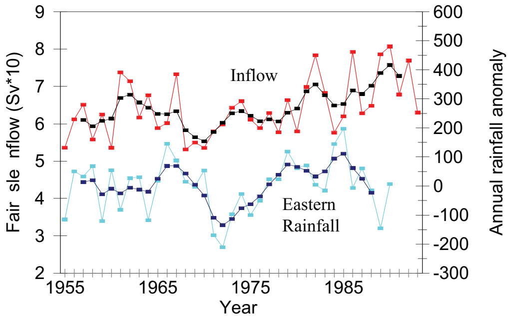


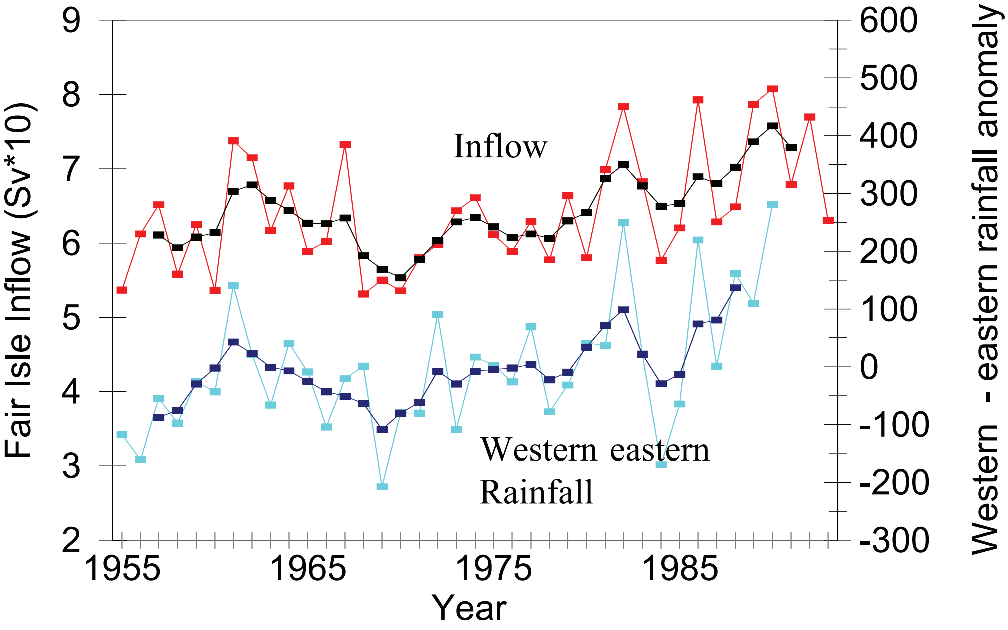


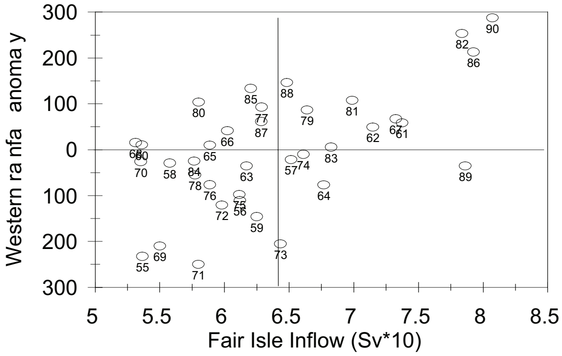


Relationships between inflow and rainfall

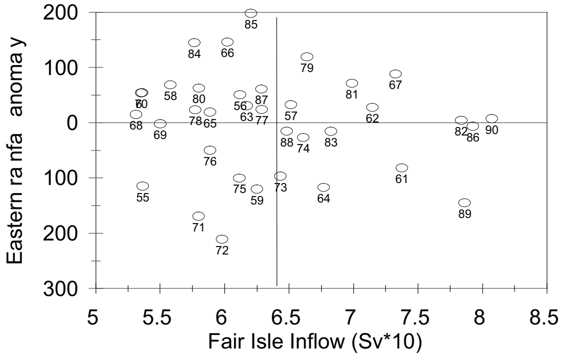




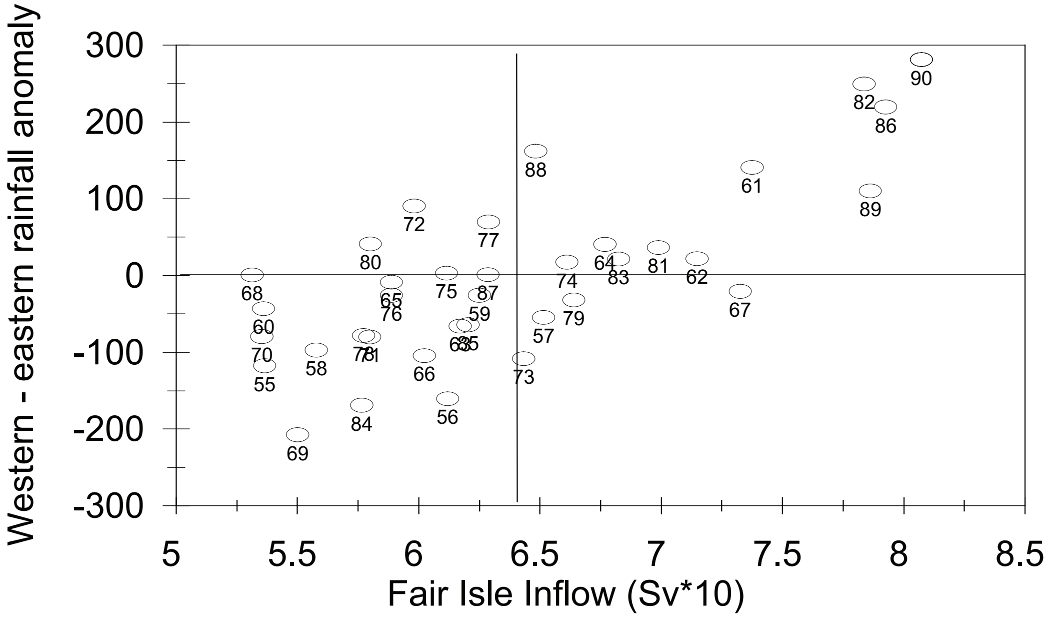




Western ra nfa anoma y
300
200
100
0
100
200
300
5
5.5
6
6.5
7
7.5
8
8.5
Fair Isle Inflow (Sv*10)



Eastern ra nfa anoma y
200
100
0
100
200
300
5
5.5
6
6.5
7
7.5
8
8.5
Fair Isle Inflow (Sv*10)



Western - eastern rainfall anomaly
300
200
100
0
-100
-200
-300
5
5.5
6
6.5
7
7.5
8
8.5
Fair Isle Inflow (Sv*10)

Appendix 4

Mean flushing times [d] of the ERSEM model boxes for the years of interest.

box	1984	1987	1990
1	5.372	6.055	4.996
2	5.926	6.614	5.325
3	5.409	5.807	5.210
4	5.565	6.016	5.117
5	9.657	10.088	8.818
6	15.029	16.989	13.845
7	15.018	15.960	13.815
8	14.216	14.615	13.337
9	4.512	4.766	4.319
10	3.937	4.054	3.659
11	4.300	4.414	3.739
12	4.425	4.374	3.712
13	7.769	8.141	7.038
14	4.737	4.852	4.655
15	4.977	5.125	4.535
16	5.378	5.521	4.645
17	5.871	5.940	4.921
18	6.775	6.739	5.689
19	4.354	4.262	3.567
20	7.275	7.972	6.267
21	15.931	17.025	14.461
22	14.755	15.331	12.837
23	15.525	15.704	15.000
24	4.109	4.082	3.827
25	5.419	5.423	4.640
26	7.954	8.106	6.881
27	8.863	9.196	7.048
28	7.251	7.440	5.710
29	7.769	7.823	6.272
30	5.412	5.427	4.303
31	6.125	6.514	4.928
32	5.721	5.683	5.359
33	6.417	6.290	5.596
34	12.500	13.090	11.048
35	35.494	38.235	30.047
36	10.387	10.847	8.213
37	5.834	6.160	4.617
38	5.945	6.314	4.755
39	14.718	15.357	13.090
40	14.287	14.645	12.759
41	12.156	12.621	11.714
42	6.232	6.446	6.027
43	5.321	5.632	5.127
44	16.694	17.681	16.749
45	7.504	7.482	6.929
46	6.341	6.338	5.513
47	18.227	18.724	16.536
48	11.263	11.856	10.510
49	5.974	6.070	4.864
50	6.895	7.246	5.511
51	7.969	8.045	7.230
52	8.188	8.270	7.206
53	8.936	9.540	8.126
54	11.716	12.572	9.797
55	7.301	7.745	5.938
56	16.741	17.839	14.082
57	16.877	18.339	14.978
58	12.317	13.754	10.728
59	5.611	5.974	4.928
60	4.822	5.243	4.360
61	9.057	9.236	7.829
62	10.294	10.534	9.139
63	5.417	5.772	5.111
64	17.357	18.769	15.287
65	21.366	22.517	17.863
66	8.986	9.772	7.779

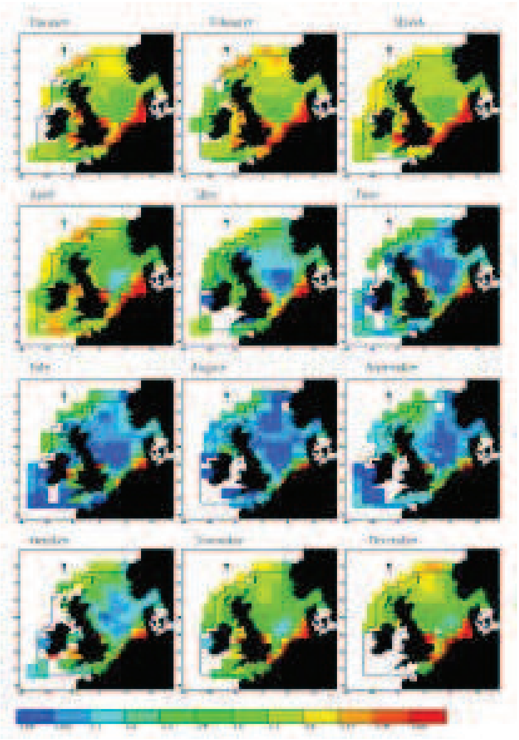
67	8.022	8.915	6.547
68	8.993	9.984	7.179
69	9.118	10.072	7.482
70	8.391	8.524	7.045
71	9.356	9.652	7.341
72	5.989	6.590	5.352
73	9.190	10.503	8.192
74	28.784	32.005	24.075
75	7.846	8.606	6.892
76	8.723	9.843	7.341
77	8.668	10.067	7.311
78	8.099	9.682	6.859
79	15.246	16.655	13.637
80	15.920	17.363	14.914
81	8.127	8.113	7.169
82	7.704	8.480	7.225
83	10.825	11.023	9.549
84	7.022	7.790	6.359
85	10.591	10.868	9.394
86	3.213	3.503	3.070
87	8.350	8.984	7.854
88	11.011	12.263	9.509
89	8.961	9.765	7.814
90	8.287	9.338	7.214
91	7.827	8.880	6.790
92	8.276	9.157	7.303
93	9.363	9.869	8.681
94	10.373	10.451	9.725
95	10.820	11.015	9.323
96	10.506	11.879	9.301
97	4.933	5.169	4.749
98	6.896	7.230	6.640
99	7.373	8.121	6.674
100	33.814	35.180	30.053
101	8.046	8.758	6.891
102	8.721	8.934	7.811
103	8.839	9.244	7.856
104	8.553	9.277	7.372
105	9.877	10.813	8.653
106	10.732	11.018	9.697
107	10.128	10.380	9.117
108	12.065	12.687	10.456
109	11.329	12.729	10.031
110	17.579	19.029	16.253
111	2.581	2.704	2.612
112	3.731	3.983	3.871
113	10.273	10.678	9.752
114	36.607	37.333	34.874
115	13.692	13.250	12.638
116	10.855	10.486	9.866
117	10.206	10.219	8.954
118	9.704	9.943	8.464
119	7.567	7.564	6.586
120	7.388	7.570	6.308
121	9.307	10.084	7.875
122	11.521	12.584	9.370
123	13.892	15.508	11.751
124	27.021	28.577	23.830
125	18.898	18.032	17.153
126	8.660	9.086	7.959
127	10.951	11.020	10.691
128	16.373	16.395	14.142
129	13.721	13.252	11.953
130	11.027	10.887	9.543
131	9.168	9.191	7.982
132	7.803	7.867	6.707
133	8.011	8.344	6.597
134	9.261	9.686	8.297
135	17.464	17.739	15.769
136	16.086	16.123	14.252
137	14.251	14.576	12.610

138	12.524	12.715	10.853
139	15.204	14.996	14.231
140	12.512	12.836	10.778
141	19.284	20.007	17.148
142	22.476	23.038	20.682
143	19.159	19.585	16.743
144	17.372	18.026	15.037
145	16.182	16.655	14.071
146	7.522	7.674	6.748
147	12.526	12.875	11.301
148	10.356	10.690	9.127
149	16.458	15.804	14.826
150	23.576	23.841	21.448
151	21.299	21.517	18.360
152	20.010	19.838	17.429
153	26.542	26.847	24.937
154	30.040	30.844	27.273
155	11.600	11.874	10.453
156	9.248	8.974	8.700
157	15.589	15.713	14.202
158	13.192	13.471	12.228
159	21.875	21.945	18.995
160	16.771	17.222	16.075
161	40.237	41.421	37.541
162	12.520	12.935	11.978
163	9.586	10.065	9.184
164	10.036	10.083	9.562
165	6.639	6.933	6.305
166	15.787	16.026	14.350
167	31.371	33.580	29.612
168	30.591	32.567	27.695
169	22.809	23.445	19.387
170	9.872	9.859	9.645
171	5.608	5.568	5.272
172	5.009	4.994	4.514
173	7.070	6.953	5.985
174	13.311	14.128	11.330
175	8.903	8.867	8.760
176	5.961	5.880	5.534
177	7.387	7.239	6.530
178	6.402	6.287	5.286
179	7.722	7.489	6.424
180	15.202	15.898	13.077
181	27.446	28.435	24.265
182	31.739	32.484	28.891
183	29.448	29.542	24.733
184	8.949	8.852	8.637
185	6.903	6.734	6.065
186	14.361	13.894	11.443
187	18.546	18.884	14.329
188	13.662	14.119	10.778
189	14.055	13.892	11.529
190	8.619	8.198	6.887
191	12.744	12.205	10.100
192	9.752	9.645	9.474
193	6.812	6.488	5.921
194	18.160	17.727	13.901
195	18.664	18.761	15.216
196	12.320	12.453	9.705
197	11.884	11.528	9.171
198	29.129	29.696	27.177
199	17.939	18.008	17.285
200	26.965	27.002	23.030
201	17.249	17.686	14.937
202	23.828	25.223	21.885
203	41.189	42.236	39.493
204	11.776	11.541	11.091
205	10.333	9.754	8.547
206	19.393	19.256	15.960
207	15.571	16.167	12.948
208	10.335	10.055	8.337

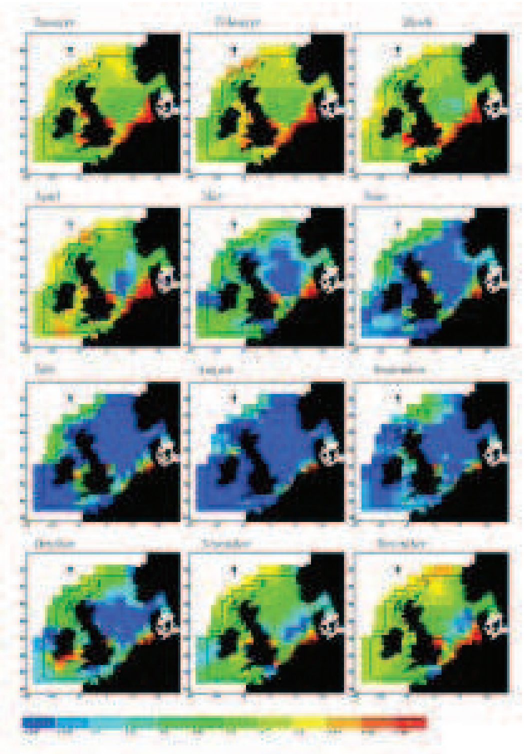
209	14.818	14.591	11.982
210	15.125	14.891	14.287
211	14.539	13.753	12.118
212	16.870	17.414	14.365
213	30.121	33.268	26.341
214	14.778	16.124	13.229
215	28.552	30.856	27.219
216	25.799	28.500	24.476
217	13.853	15.305	12.632
218	8.019	8.693	7.265
219	5.019	5.969	4.472
220	18.932	18.821	18.157
221	17.388	16.744	14.265
222	8.682	8.770	7.717
223	14.376	14.659	13.325
224	17.810	19.183	16.479
225	17.367	18.774	16.001
226	15.621	16.568	14.277
227	17.372	17.250	16.306
228	16.915	17.156	13.808
229	8.807	9.185	8.532
230	27.820	32.433	22.538
231	14.328	14.951	13.181
232	14.505	15.851	14.388
233	13.468	15.610	13.481
234	13.758	16.088	13.176
235	28.303	30.531	24.584
236	18.138	19.845	15.822
237	10.647	10.561	10.000
238	6.079	6.715	5.731
239	18.943	20.884	17.642
240	26.432	28.197	26.272
241	21.796	23.783	20.795
242	16.844	18.403	15.244
243	14.264	14.427	12.829
244	11.197	10.996	9.981
245	5.549	5.614	5.597
246	6.272	6.688	6.305
247	16.616	18.002	15.435
248	14.888	15.569	14.323
249	25.629	26.336	24.082
250	21.505	20.876	18.840
251	18.396	18.832	17.209
252	14.295	14.212	12.484
253	13.166	13.135	11.319
254	2.464	2.502	2.478
255	2.940	3.067	2.978
256	21.408	23.053	20.360
257	15.691	15.511	13.283
258	20.534	19.938	17.521
259	17.209	16.984	14.694
260	10.621	10.557	9.025
261	17.791	18.049	17.472
262	12.411	13.614	11.339
263	14.035	14.623	13.373
264	13.672	14.968	12.008
265	28.664	27.633	28.040
266	22.114	22.038	19.588
267	40.909	40.399	36.781
268	43.000	44.310	38.763
269	32.021	31.675	31.676
270	59.145	59.570	51.850
271	65.420	65.816	53.260
272	31.492	33.580	26.089
273	22.577	22.483	20.903
274	17.808	17.760	17.796
275	54.111	57.439	51.272
276	43.311	44.367	39.063
277	47.450	48.403	43.132
278	42.817	44.361	39.736

Appendix 5

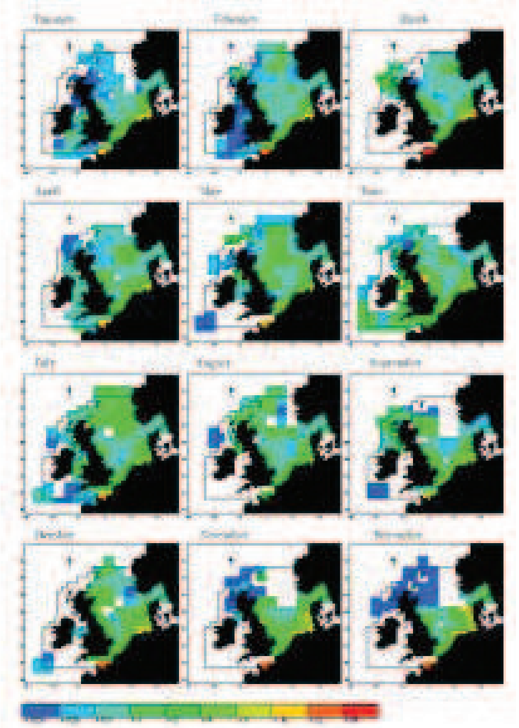
Climatological average monthly distributions of nutrient concentrations over the ERSEM model area (upper boxes), based on data from ICES for the years 1965-1994. Left column: "raw" data with void areas due to missing data. Right column: interpolated data in which data voids have been filled.



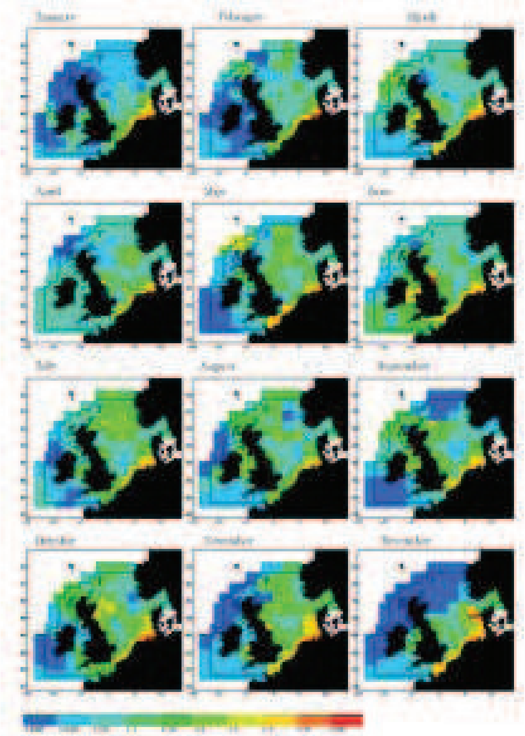
Raw data on total dissolved nitrogen (TN) concentration mM m^{-3}



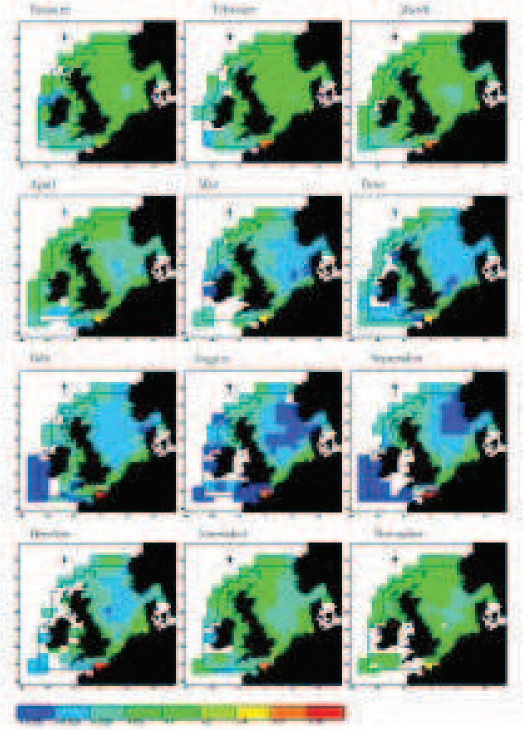
Interpolated nitrate concentration mM m^{-3} (Nitrate TN-ammonia)



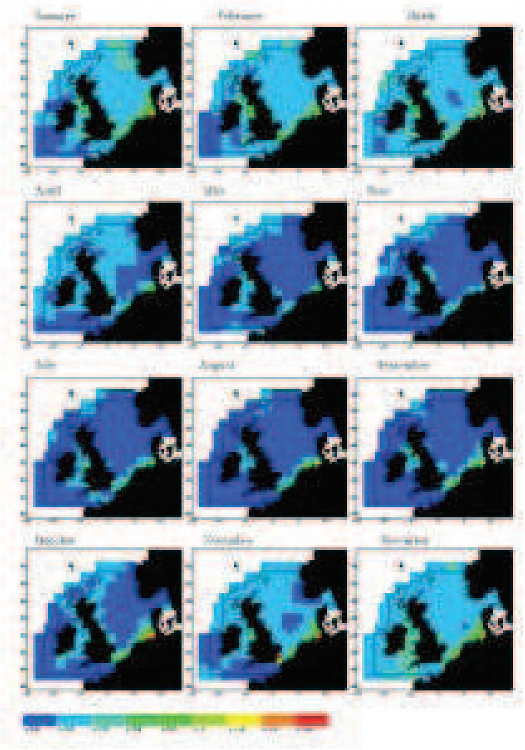
Raw data on ammonia concentration mM m^{-3}



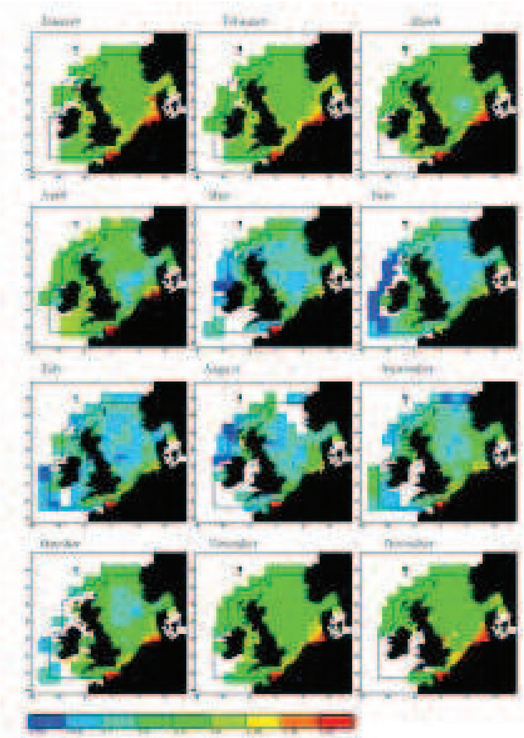
Interpolated ammonia concentration mM m^{-3}



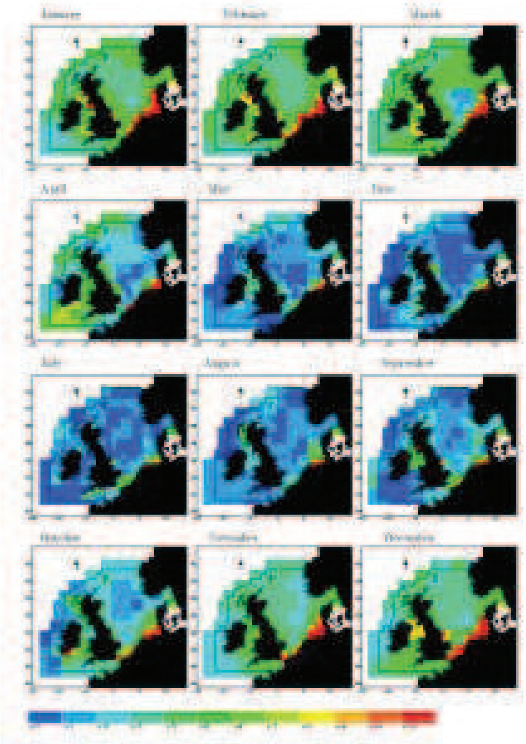
Raw data on total dissolved phosphorus (TP) concentration mM m^{-3}



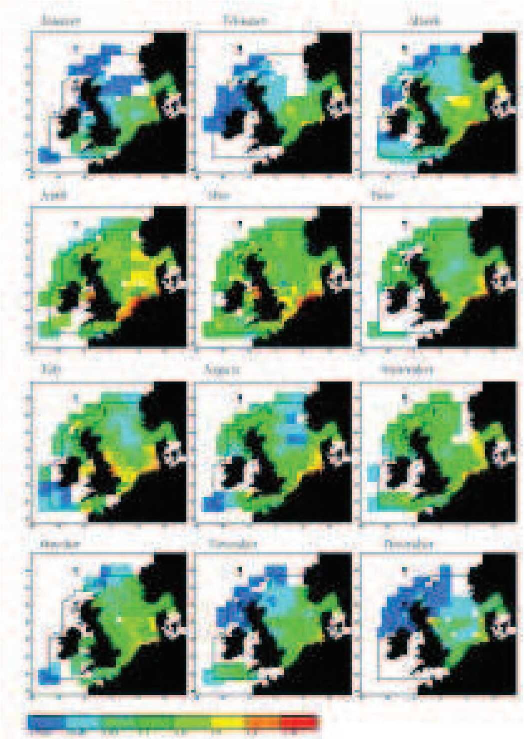
Interpolated phosphate concentration mM m^{-3} (Phosphate TP/2)



Raw data on silicate concentration mM m^{-3}



Interpolated silicate concentration mM m^{-3}



Raw data on chlorophyll concentration mg m^{-3}

Appendix 6

List of copepod species included in the "Small copepods" category of the Continuous Plankton Recorder data.

- *Acartia amboinensis*
- *Acartia danae*
- *Acartia longiremis*
- *Acartia negligens*
- *Acartia tonsa*
- *Acartia tumida*
- *Acartia spp.*
- *Acrocalanus spp.*
- *Aetidius armatus*
- *Alteutha spp.*
- *Amallothrix spp.*
- *Anomalocera patersoni*
- *Augaptilus spp.*
- *Calanoides carinatus*
- *Calanopia americanus*
- *Calanopia elliptica*
- *Calanopia minor*
- *Caligoida*
- *Calocalanus spp.*
- *Candacia armata*
- *Candacia bipinnata*
- *Candacia colombiae*
- *Candacia curta*
- *Candacia ethiopica*
- *Candacia giesbrechti*
- *Candacia I-IV*
- *Candacia longimana*
- *Candacia norvegica*
- *Candacia pachydactyla*
- *Candacia tenuimana*
- *Candacia varicans*
- *Canthocalanus pauper*
- *Centropages abdominalis*
- *Centropages bradyi*
- *Centropages calaninus*
- *Centropages chierchiae eyecount*
- *Centropages chierchiae traverse*
- *Centropages furcatus*
- *Centropages gracilis*
- *Centropages hamatus*
- *Centropages typicus*
- *Centropages violaceus*
- *Chiridius armatus*
- *Clausocalanus spp.*
- *Clytemnestra spp.*
- Copepod eggs
- *Copepod nauplii*
- *Copilia spp.*
- *Corycaeus speciosus*
- *Corycaeus spp.*
- *Ctenocalanus vanus*
- *Diaixis hibernica*
- *Diaixis pygmoea*
- *Epilabidocera amphrites*
- *Euaetideus giesbrechti*
- *Eucalanus attenuatus*
- *Eucalanus bungii*
- *Eucalanus crassus*
- *Eucalanus elongatus*
- *Eucalanus monachus*
- *Eucalanus mucronatus*
- *Eucalanus pileatus*
- *Euchirella amoena*
- *Euchirella bella*
- *Euchirella brevis*
- *Euchirella curticauda*
- *Euchirella maxima*
- *Euchirella messinensis*
- *Euchirella pulchra*
- *Euchirella rostrata*
- *Euterpina acutifrons*
- *Farranula gracilis*
- *Gaetanus minor*
- *Gaidius spp.*
- *Gaidius tenuispinus*
- *Halithalestris croni*
- *Haloptilus acutifrons*
- *Haloptilus longicornis*
- *Haloptilus spiniceps*
- *Harpacticoida Total*
- *Heterorhabdus abyssalis*
- *Heterorhabdus clausi*
- *Heterorhabdus norvegicus*
- *Heterorhabdus papilliger*
- *Heterorhabdus spinifer*
- *Heterorhabdus tanneri*
- *Heterostylites longicornis*
- *Isias clavipes*
- *Labidocera acuta*
- *Labidocera acutifrons*
- *Labidocera aestiva*
- *Labidocera wollastoni*
- *Lophothrix spp.*
- *Lubbockia spp.*
- *Lucicutia spp.*
- *Macrosetella gracilis*
- *Mecynocera clausi*
- *Metridia I-IV*
- *Metridia longa*
- *Metridia lucens*
- *Metridia okhotensis*
- *Metridia pacifica*
- *Metridia Total traverse*
- *Microcalanus spp.*
- *Miracia efferata*
- *Monstrilla longiremis*
- *Nannocalanus minor*
- *Neocalanus cristatus I-iv*
- *Neocalanus cristatus v-vi*
- *Neocalanus flemingeri v-vi*
- *Neocalanus gracilis*
- *Neocalanus plumchrus ii*
- *Neocalanus plumchrus i-iv*
- *Neocalanus plumchrus total traverse*
- *Neocalanus plumchrus iii*
- *Neocalanus plumchrus iv*
- *Neocalanus plumchrus v*
- *Neocalanus plumchrus vi (f)*
- *Neocalanus plumchrus vi (m)*
- *Neocalanus spp.*
- *Neocalanus robustior*
- *Oculosetella gracilis*
- *Oithona spp.*
- *Oncaea spp.*
- *Paracandacia bispinosa*
- *Paracandacia simplex*
- *Paraeuchaeta elongata*
- *Paraeuchaeta sp.*
- *Parapontella brevicornis*
- *Para-pseudocalanus spp.*
- *Phaenna spinifera*
- *Pleuromamma abdominalis*
- *Pleuromamma borealis*
- *Pleuromamma gracilis*
- *Pleuromamma indica*
- *Pleuromamma piseki*
- *Pleuromamma robusta*
- *Pleuromamma xiphias*
- *Pontellina plumata*
- *Pontellina securifer*
- *Pontellopsis perspicax*
- *Pontellopsis regalis*
- *Pseudocalanus elongatus* Adult
- *Pseudochirella spp.*
- *Rhincalanus cornutus*
- *Rhincalanus nasutus*
- *Saphirella tropica*
- *Sapphirina spp.*
- *Scaphocalanus echinatus*
- *Scolecithricella spp.*
- *Scolecithrix bradyi*
- *Scolecithrix danae*
- *Scottocalanus persecans*
- *Scottocalanus securifrons*
- Spiny egg *(Candacia egg)*
- *Temora longicornis*
- *Temora stylifera*
- *Temora turbinata*
- *Tortanus discaudatus*
- Total Eyecount Copepoda
- *Undeuchaeta major*
- *Undeuchaeta plumosa*
- *Undinopsis bradyi*
- *Undinopsis spp.*
- *Undinula darwini*
- *Undinula vulgaris*
- Unidentified *Calanopia spp.*
- Unidentified *Candacia spp.*
- Unidentified *Centropages spp.*
- Unidentified *Eucalanus spp.*
- Unidentified *Euchaeta spp.*
- Unidentified *Euchirella spp.*
- Unidentified *Farranula spp.*
- Unidentified *Heterorhabdus spp.*
- Unidentified *Labidocera spp.*
- Unidentified *Paracandacia spp.*
- Unidentified *Pleuromamma spp.*
- Unidentified *Scaphocalanus spp.*
- Unidentified *Undeuchaeta spp.*
- *Urocorycaeus spp.*
- *Xanthocalanus spp.*

Appendix 7

Configuration of loading data sets for each of the ERSEM model runs. Columns detail the different scenarios (combinations of nutrient reduction and climate year), whilst rows detail different categories of nutrient input.

			Reference run	**Reference run**	**Reference run**	**UWW scenario**	**UWW scenario**	**UWW scenario**	**OSPAR scenario**	**OSPAR scenario**	**OSPAR scenario**	**Aquaculture scenario**	**Aquaculture scenario**	**Aquaculture scenario**
			1984	**1987**	**1990**	**1984**	**1987**	**1990**	**1984**	**1987**	**1990**	**1984**	**1987**	**1990**
Scotland	UWW	N	100% of 1999	100% of 1999	100% of 1999	**25% of 1999**	**25% of 1999**	**25% of 1999**	**50% of 1999**	**50% of 1999**	**50% of 1999**	100% of 1999	100% of 1999	100% of 1999
		P	100% of 1999	100% of 1999	100% of 1999	**25% of 1999**	**25% of 1999**	**25% of 1999**	**50% of 1999**	**50% of 1999**	**50% of 1999**	100% of 1999	100% of 1999	100% of 1999
		C	100% of 1999	100% of 1999	100% of 1999	**25% of 1999**	**25% of 1999**	**25% of 1999**	**50% of 1999**	**50% of 1999**	**50% of 1999**	100% of 1999	100% of 1999	100% of 1999
	ndustrial	N	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	**50% of 1999**	**50% of 1999**	**50% of 1999**	100% of 1999	100% of 1999	100% of 1999
		P	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	**50% of 1999**	**50% of 1999**	**50% of 1999**	100% of 1999	100% of 1999	100% of 1999
		C	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	**50% of 1999**	**50% of 1999**	**50% of 1999**	100% of 1999	100% of 1999	100% of 1999
	Aquaculture	N	100% of 2001	100% of 2001	100% of 2001	100% of 2001	100% of 2001	100% of 2001	**50% of 2001**	**50% of 2001**	**50% of 2001**	**50% of 2001**	**50% of 2001**	**50% of 2001**
		P	100% of 2001	100% of 2001	100% of 2001	100% of 2001	100% of 2001	100% of 2001	**50% of 2001**	**50% of 2001**	**50% of 2001**	**50% of 2001**	**50% of 2001**	**50% of 2001**
		C	100% of 2001	100% of 2001	100% of 2001	100% of 2001	100% of 2001	100% of 2001	**50% of 2001**	**50% of 2001**	**50% of 2001**	**50% of 2001**	**50% of 2001**	**50% of 2001**
	Rivers and agriculture	N	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	**50% of 1984**	**50% of 1987**	**50% of 1990**	100% 1984	100% 1987	100% 1990
		P	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	**50% of 1984**	**50% of 1987**	**50% of 1990**	100% 1984	100% 1987	100% 1990
		C	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		Si	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
England and Wales	UWW	N	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999
		P	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999
		C	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999
	ndustrial	N	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999
		P	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999
		C	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999	100% of 1999
	Rivers and agriculture	N	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		P	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		C	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		Si	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
Ireland	Total load	N	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		P	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		C	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		Si	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990

Norway	Total load	N	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		P	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		C	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		Si	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
Continental Europe	Total load	N	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		P	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		C	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990
		Si	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990	100% 1984	100% 1987	100% 1990