Application of the European Regional Seas Ecosystem Model (ERSEM) to assessing the eutrophication status in the OSPAR Maritime Area, with particular reference to nutrient discharges from Scottish salmonid aquaculture.

Presented by the UK

Background

1. Aquaculture production of salmonids in Scotland has grown over the last 15 years, exceeded 150,000 tonnes in 2001. There have been conflicting views as to the likely ecological impact of nutrient discharges from this activity.

2. Whilst quantitative assessments of aquaculture nutrient discharges have been carried out, the debate regarding possible eutrophication impacts of these discharges has so far been largely speculative. In order to provide a quantitative basis for this discussion, a marine ecosystem model was used to simulate the consequences of a 50% reduction in aquaculture nutrient discharges, and the results are presented here.

Activity

3. 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 order to carry out the study described here, the spatial domain of the North Sea ERSEM was extended to cover north-west European waters out to the shelf edge in the west, and from the Brittany coast in the south to north of the Shetland Islands in the north. Around Scotland, the spatial resolution of the model was 50 x 50 km.

4. Natural runoff of nutrients to each of the Scottish coastal compartments of the ERSEM was calculated for 3 contrasting climate scenario years (1984, 1987 and 1990). Urban waste and industrial discharges were derived from data for 1999, and aquaculture discharges from production figures for 2001, using HARPNUT guidelines.

Approach

5. The model output variables 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 for use in the initial application of the OSPAR Comprehensive Procedure. Model criteria were analysed for a number of designated assessment regions around Scotland. The criteria were combined into an integrated water quality index for summarising the simulated eutrophication status.

6. Reference runs of the model were carried out using meteorological forcing for each of the three climate scenario years. The results were used to derive indices of the natural climate-driven variability in the eutrophication criteria.

7. The model was then used to simulate eutrophication criteria for each climate year with the aquaculture nutrient load reduced by 50%, and the results compared to those from the reference runs.

Results

8. The simulated reduction in nutrient load due to a 50% decrease in Scottish aquaculture discharges produced less than 0.3% change in water quality in all but one of the assessment regions. Even in the worst case region (Minches) the change was only 1.1%. At the local scale, the worst case change in water quality (around the Isle of Skye) was 1.7%, equivalent to around 4 gC m^{-2} yr^{-1} decrease in annual net primary production, or less than 0.05mg chlorophyll m^{-3} averaged over May-September. These changes were clearly smaller than the 50% threshold defined in the Comprehensive Procedures for designation of elevated levels of assessment criteria, and were less than half the natural variation due to climate (3.6%).

9. On the basis of these results it is concluded that, at the spatial scale of these simulations (50 x 50 km), there is no case for suggesting that nutrients from Scottish aquaculture have a discernible eutrophication impact on the coastal and offshore waters west and north of Scotland.

Action

10. ASMO is invited to consider the report.

Application of the European Regional Seas Ecosystem Model (ERSEM) to assessing the eutrophication status in the OSPAR Maritime Area, with particular reference to nutrient discharges from Scottish salmonid aquaculture.

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1. Background

1.1 The overall goal of the study described in this report was to provide a strategic ecosystem simulation tool for identifying maritime regions 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 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.

1.2 The European Regional Seas Ecosystem Model (ERSEM) was chosen as the basis for the project. ERSEM had previously been implemented at 50 x 50 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.

1.3 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 a number of nutrient reduction scenarios. This report focuses on a scenario in which the aquaculture nutrient load was reduced by 50% and the simulation results compared to those from the reference runs.

1.4 Full details of the data synthesis supporting the model runs described here, together with the results of other reduction scenarios, are available from Heath *et al*. (2002) (http://www.scotland.gov.uk/library5/fisheries/ersem_report_final.pdf).

2. Overview of the ERSEM model

2.1 The starting point for this project was the “nd130” North Sea version of the ERSEM model (Baretta-Bekker, 1995; Baretta-Bekker and Baretta, 1997), as previously reviewed by the ASMO Modelling Workshop on Eutrophication Issues (OSPAR, 1998). To address the issues relevant to the impact of Scottish nutrients, the model needed to be extended to cover the waters west of the UK.

2.2 The ERSEM nd130 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

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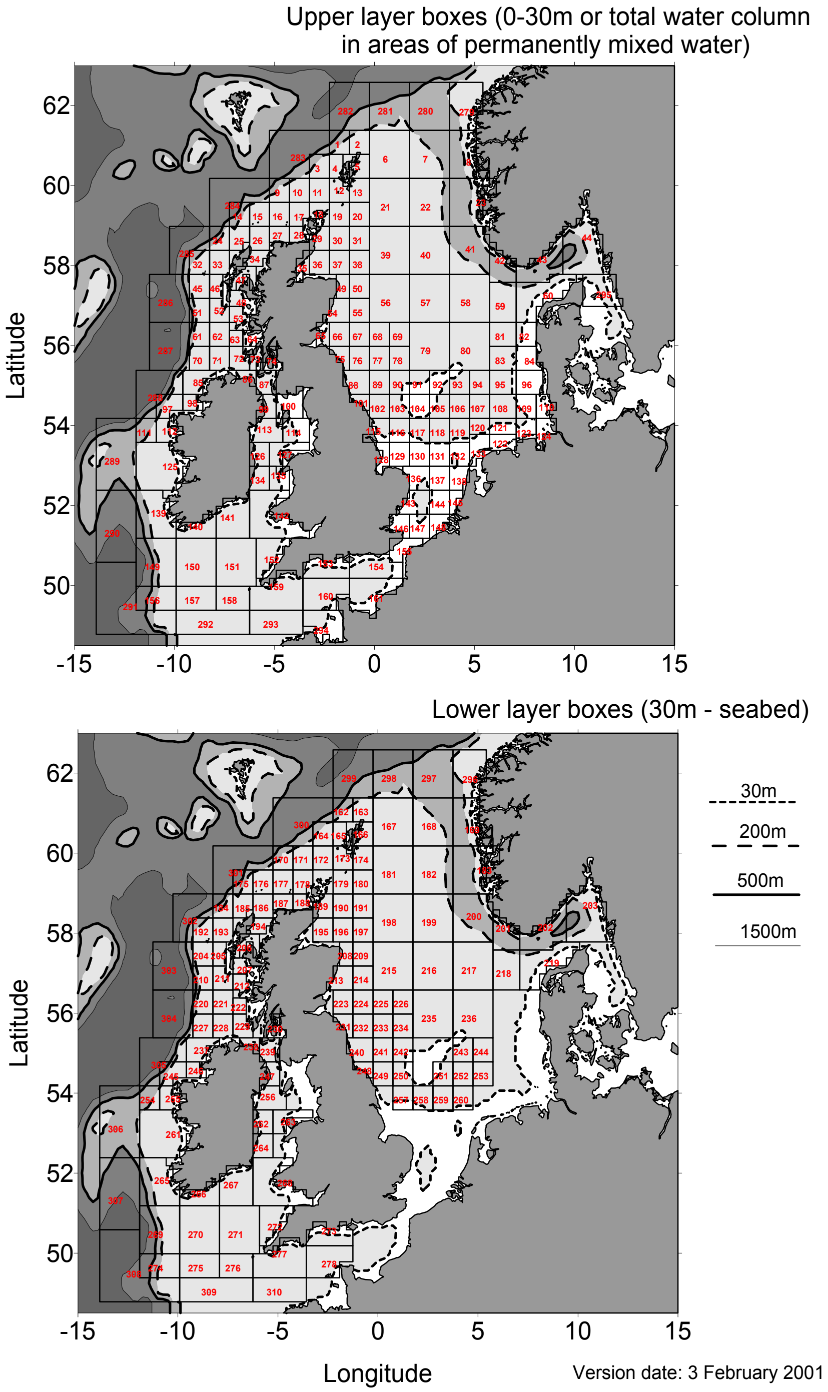
boxes, each representing a volume of water which is considered to be homogeneous. The choice of box configuration is therefore important for describing the topographic structure of the ecosystem. The box structure established for this project (Figure 1) consisted of 310 boxes in two layers, comprising 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.



Version date: 3 February 2001

Figure 1. *Configuration of upper and lower layer boxes in the “sc278” ERSEM model*

2.3 The model needs several driving data time series for each of the internal boxes of the model domain :

- Daily horizontal and vertical transport between each adjoining pair of boxes in 1984, 1987 and 1990 – derived from the LTT (long-term trend) 1955-1993 application of the HAMSOM (Hamburg Shelf-Ocean Model; Backhaus, 1985; Pätsch and Radach, 1997).
- Daily irradiance at the sea surface of each internal box for the years 1984, 1987 and 1990.
- Daily silt concentration in each internal box - derived from a statistical model relating silt to julian day, seabed depth, maximum tidal current speed, and salinity.
- Climatological daily seawater temperature in each internal box – taken from the LTT hydrodynamic model.
- Daily terrestrial inputs of nutrients – derived as described later.
- Daily atmospheric nitrogen inputs to each of the upper layer internal boxes – not yet implemented.

2.4 The model needs monthly average time series of various data for each of the boundary boxes of the model domain :

- Monthly average nutrient and chlorophyll concentrations - compiled from 1965-1994 archived data obtained from the ICES Hydrographic Data Centre.
- Monthly average omnivorous zooplankton biomass - compiled from Continuous Plankton recorder data supplied by the Sir Alister Hardy Foundation for Ocean Science.

3. Strategy for use of the model

3.1 The strategy for using of the model was to compare results from a reference run or so called ÒbasecaseÓ with equivalent results from a run with reduced nutrient inputs from a particular source, in this case from Scottish aquaculture. 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.

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

- 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

3.3 The runs representing reduced aquaculture inputs were constructed as follows. 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.

4. Synthesis of model outputs

4.1 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 1).

Table 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

4.2 The combination of areas 1, 2, 3, 4, 5, 7, 8a and 13 forms the OSPAR Comprehensive Procedure Region 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 2.

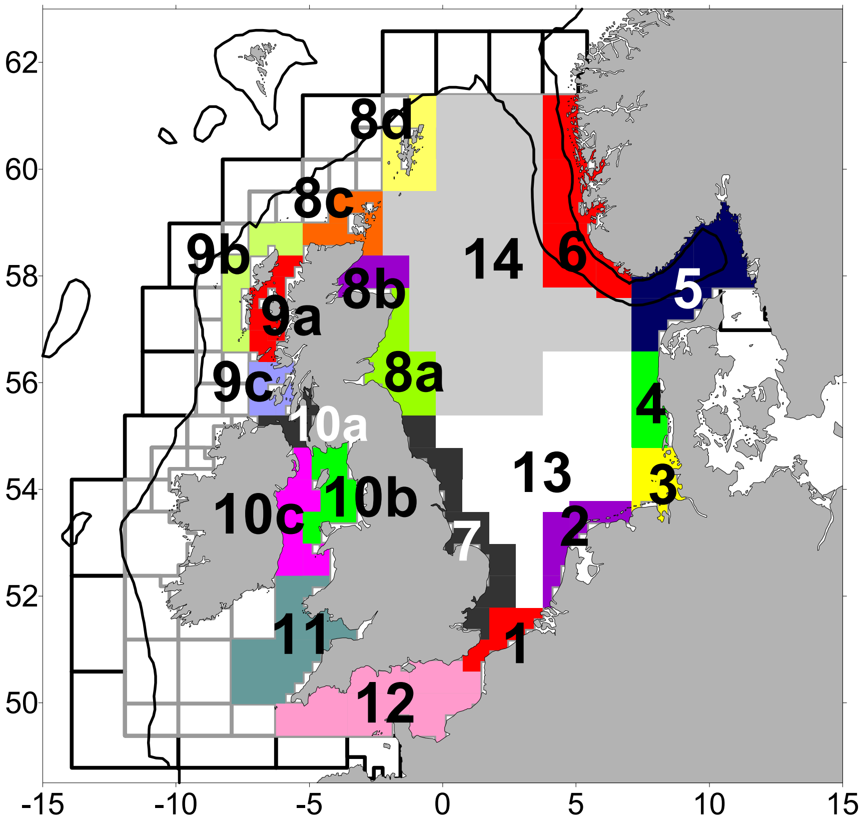


Figure 2. *Outlines of the 21 assessment areas used to summarise the spatial results from the ERSEM model runs.*

4.3 In addition, results were examined for six individual boxes (Table 2).

Table 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

4.4 Seven output variables from the model were selected as criteria for assessing eutrophication status (Table 3).). The criteria matched the Category I and Category II Harmonised Assessment Criteria (direct and indirect effects of nutrient enrichment respectively) agreed for use in the initial application of the OSPAR Comprehensive Procedure (ASMO 2002). 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 represented the eutrophication impact of the loading which had been removed in the reduction scenario.

4.5 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 3) was chosen to reflect its considered importance as an indicator of eutrophication status. Thus, March-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 3. *Weighting values applied to each of the assessment criteria in producing an overall index of water quality.*

Assessment Criterion	**Weighting**
Mean winter dissolved inorganic phosphorus	0.75
Mean winter dissolved inorganic nitrogen	0.75
March-September average chlorophyll	1.00
Maximum weekly average chlorophyll	0.25
Annual net primary production	1.00
Maximum weekly net primary production	0.25
March-September diatom chlorophyll / non-diatom chlorophyll	-0.75

4.6 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. According to the OSPAR Comprehensive Procedure, criteria are considered to be ‘elevated’ if contemporary values are more than 50% greater than region specific background values established from historical data. In the context of the simulations described here, this means that if a simulated nutrient reduction scenario leads to greater than 50% change in criterion values compared to the status-quo reference run results, then we should consider this to indicate a potential problem.

4.7 An additional approach to assessing the impact of a nutrient reduction is to compare the simulated change in criterion values due to load reduction, with the variability in values due to climate variations alone (Figure 3). For a eutrophication effect to be of any practical concern, the mean change in criterion value due to load reduction must be at least 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 would have great difficulty in detecting the impacts of loading reductions in the field.

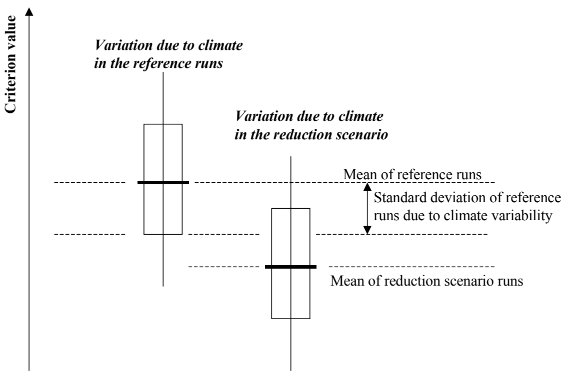


Figure 3. *Schematic diagram illustrating the principle behind relating the impact of load reductions on eutrophication criteria to the variability caused by climate fluctuations, as an objective means of judging the significance of the reduction in loading.*

5. Assembly of nutrient input data

5.1 Riverine nutrient concentration and flow data from 1984, 1987 and 1990, together with anthropogenic nutrient discharge data for 1999 and 2001, were used to synthesise three annual time series of spatially resolved daily inputs of natural and anthropogenic nitrogen, phosphorus, carbon and silicon from Scottish sources. The methodology followed HARPNUT guidelines. The time series represented three years of contrasting climate (extreme low annual rainfall in western Scotland and weak shelf transport (1984); extreme high annual rainfall in western Scotland and strong shelf transport (1990); and a 'typical' climate year for the 1980's period (1987)).

5.2 The major scientific problem arose from the fact that whilst the gauged river flows in Scotland monitor 50% of the total catchment area of the country, the requirement was to assess the nutrient runoff from 100% of the catchment. Further scientific problems arose from the need to disaggregate the Scottish riverine inputs into urban waste-water and other components.

5.3 The spatial resolution applied to the nutrient inputs was dictated by the set-up of the ERSEM which had a resolution of approximately 50km x 50km. Terrain modelling was used to delineate the terrestrial catchment associated with each 50km x 50km compartment of the marine model.

5.4 The discrepancy between gauged catchment and total catchment area associated with each model compartment was resolved by applying a GIS-based land-use model to raise the 1984, 1987 and 1990 daily flow-weighted concentration estimates from the gauging data to the total catchment.

5.5 The urban-waste water component of daily riverine nutrient discharge was estimated by summing the 1999 inputs from sewage treatment works to each of the terrestrial catchments. Direct-to-sea discharges of treated urban-waste water were considered separately. Nutrient inputs due to natural erosion and agriculture were estimated as the difference between the total riverine inputs and that due to sewage treatment works within each catchment.

5.6 Aquaculture inputs of nitrogen, phosphorus and carbon to each 50km x 50km compartment were estimated from the sea-loch specific consented production figures for 2001 and 1999 (to coincide with the urban-waste data). HARPNUT Guideline 2 (OSPAR, 2000) was applied, based on a feed conversion ratio of 1.2, feed composition data from the latest manufacturers data sheets, and accepted compositions of harvested salmonids. These figures implied a release rate of 53.4kg nitrogen and 12.1kg phosphorus per tonne of annual production. For comparison, MacGarvine (2000) quotes 60kg nitrogen and 9.9kg phosphorus per tonne. The annual release rate was converted to month-specific daily rates by scaling to reflect the seasonal changes in stock composition over a 2-yearly production cycle, and ambient temperatures.

5.7 Summing over all sources, the total annual elemental inputs from Scotland are shown in Table 4. 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), 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 4. *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

5.8 All of the silicon in the annual load was estimated to derive from the agricultural and geological (natural erosion) runoff in rivers (Table 5). 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.

Table 5. *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. Urban waste inputs are the sum of discharges to catchments and direct to sea. 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

5.9 The spatial distribution of the annual Scottish nutrient load, illustrated by the annual nitrogen load for the typical climate year, is shown in Figure 4. 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.

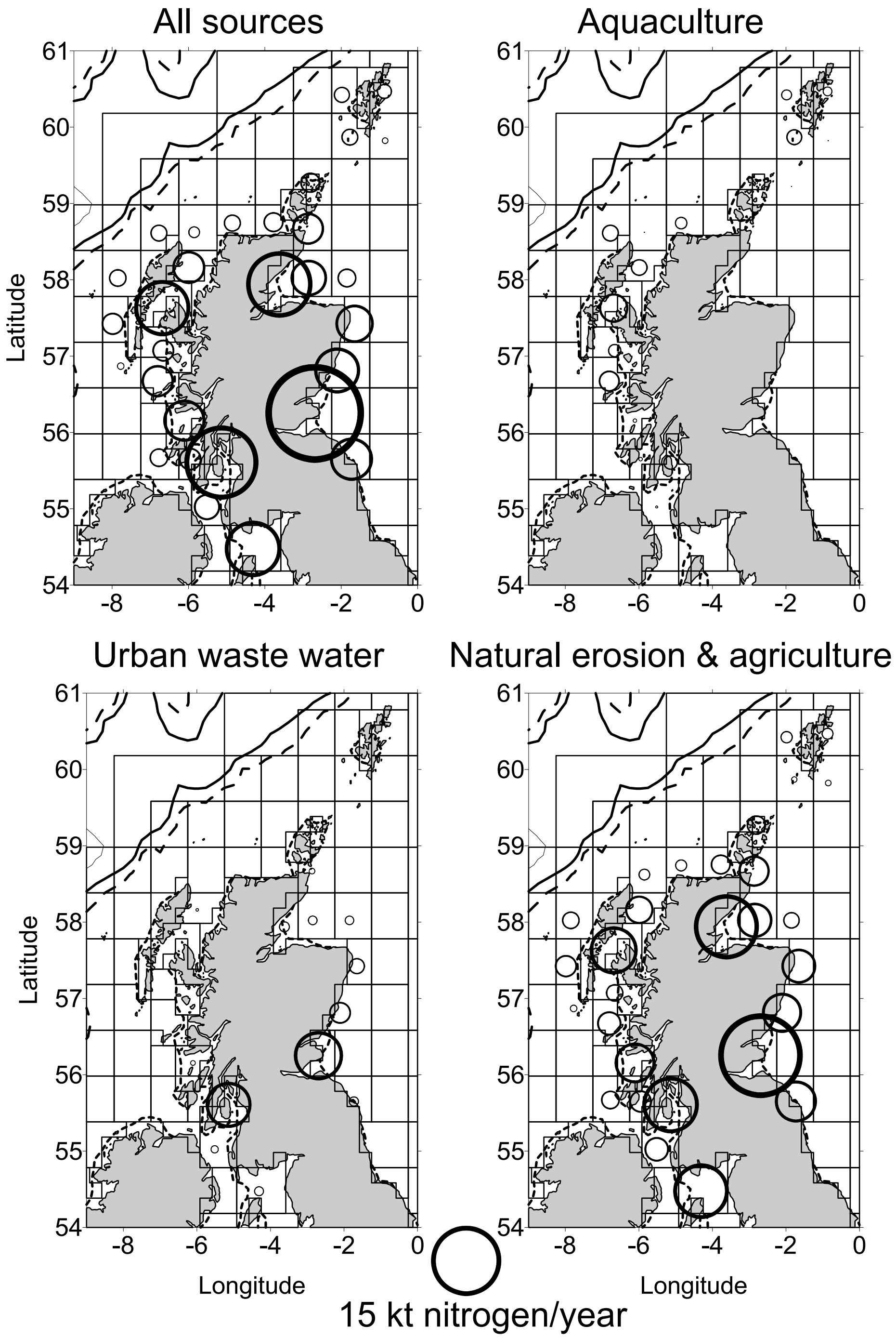


Figure 4. *Spatial variation in 1990 annual nitrogen load as expressed by the input to each coastal box of the ERSEM model adjoining the Scottish coastline. Data broken down by source (excluding industrial which was too small to display) and represented by circles of area scaled to the magnitude of the input.*

5.10 Focusing on the areas with inputs from aquaculture (Shetland, Orkney and the western seaboard of Scotland), the composition of nutrient loads to each of the ERSEM assessment regions is shown in Figure 5.

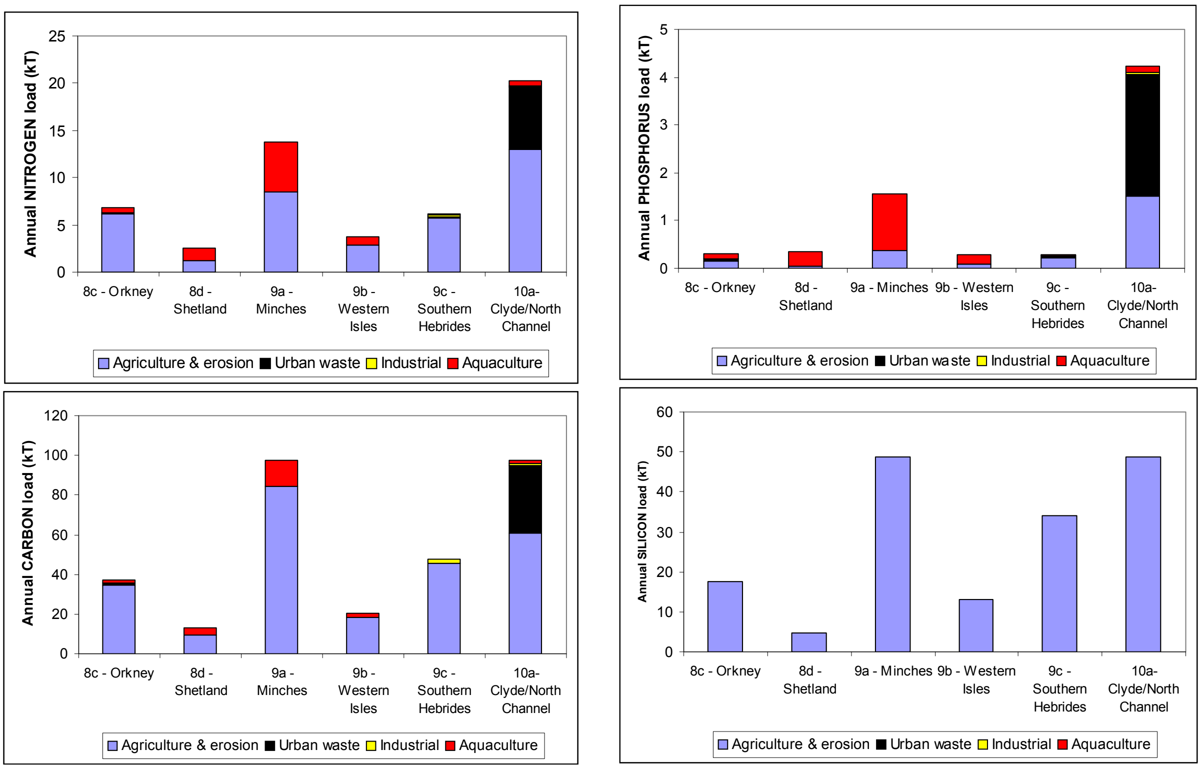


Figure 5. *Source composition of nutrient loads to each of the assessment regions with inputs from aquaculture. Upper left panel: annual nitrogen loads; upper right: annual phosphorus loads; lower left: annual carbon loads; lower right: annual silicon loads.*

5.11 An equivalent process of data assembly was followed to compile monthly resolution time series of nutrient inputs from Norway, Ireland, England and Wales to each adjoining compartment of the marine model. Daily inputs from Continental European river sources were available from ‘ ftp.ifm.uni-hamburg.de‘ under the directory ‘pub/data/riverload‘.

6. Reference run results

6.1 The overall pattern of simulated nutrient concentrations in the reference runs corresponded reasonably well with the obervations (Figure 6). 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.

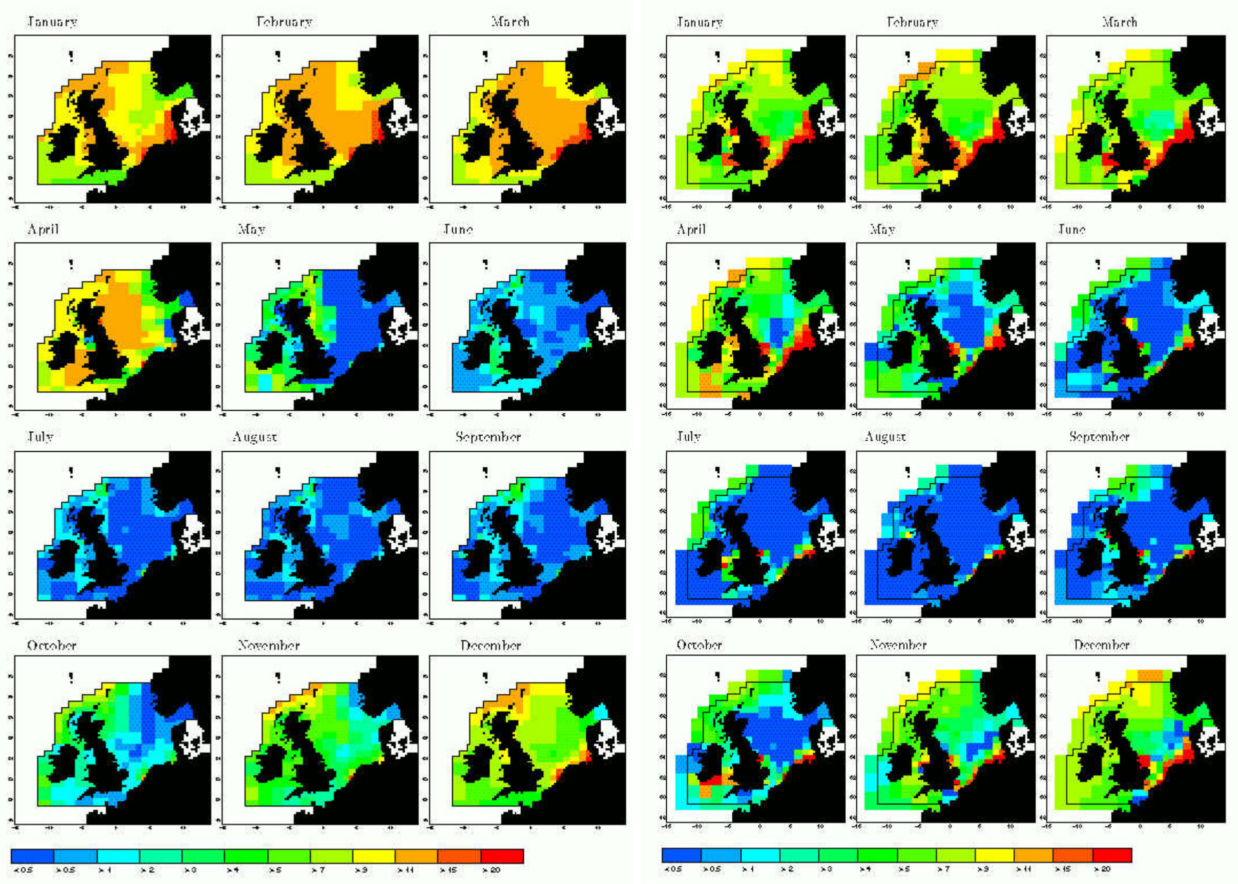


Figure 6. *Left-hand set of 12 pannel: monthly averages of nitrate concentrations (mM m^{-3}) simulated by the sc278 version of ERSEM forced by 1990 climate and nutrients loads. Right-hand set of 12 panels: Monthly average nitrate concentrations (mM m^{-3}), averaged over 1965-1994, based on data from the ICES Hydrographic Data Centre.*

6.2 In general terms, the annual cycle of monthly average chlorophyll was reasonably reproduced by the model reference runs, except that the spring increase in concentrations seems to occur slightly late compared to the observations (Figure 7). Peak spring bloom concentrations in April were 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.

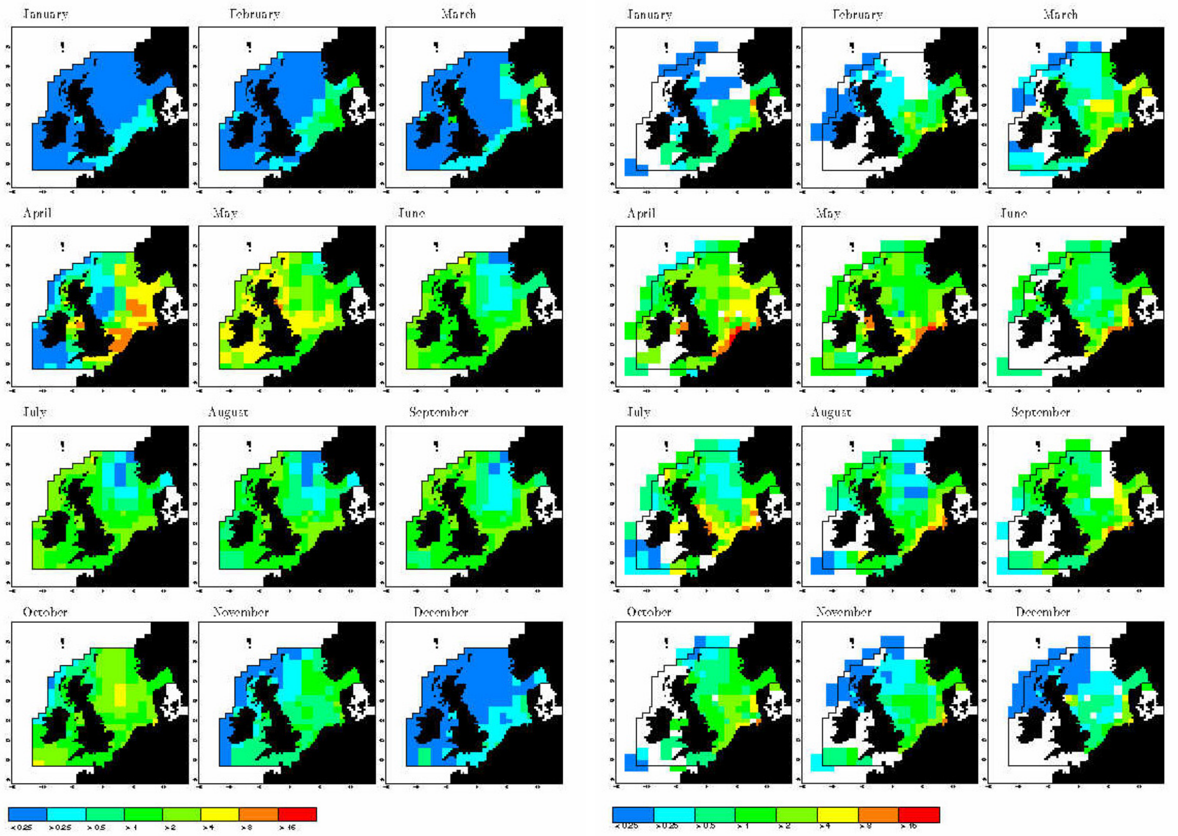


Figure 7 . *Left-hand set of 12 panel: monthly averages of chlorophyll concentrations (mg m^{-3}) simulated by the sc278 version of ERSEM forced by 1990 climate and nutrients loads. Right-hand set of 12 panels: Monthly average chlorophyll concentrations, averaged over 1965-1994, based on data from the ICES Hydrographic Data Centre.*

6.3 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 low 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.

6.4 The variability in eutrophication criteria due to climate was assessed by calculating the standard deviation of each of the 7 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 index of water quality**.** Finally, the index was compared with the mean of the between year percentage standard deviation for nitrogen and phosphorus loadings. The results (Figure 8) indicate little overall relationship between climatic 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.

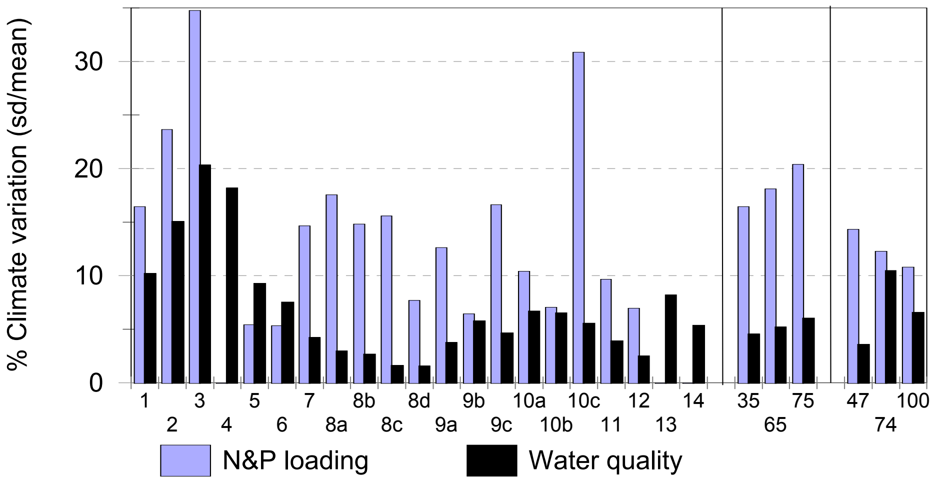


Figure 8 . *Climate variability in each assessment area, expressed as the standard deviation as a percentage of the mean, for reference loadings and model run results using 1984, 1987 and 1990 environmental forcing. The water quality results were a weighted average of the percentage standard deviations for each of the seven assessment criteria.*

7. Aquaculture reduction scenario analysis

7.1 The changes in regional and local assessment criteria due to a simulated 50% reduction in aquaculture nutrient load were well below the 50% threshold defined by the OSPAR Comprehensive Procedures as indicating a problematic impact. In addition, none of the assessment areas exhibited impacts close to the climate variation limit. 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.

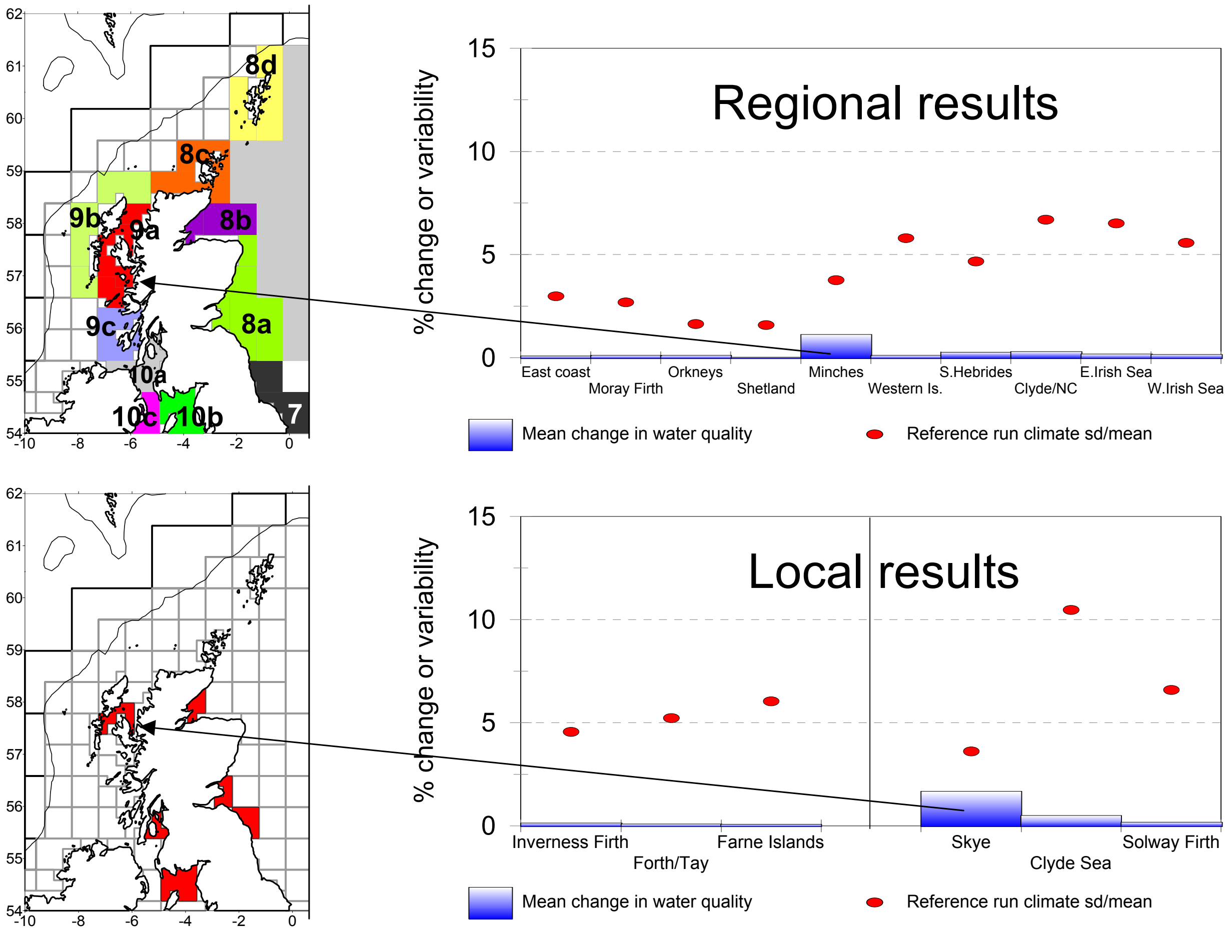


Figure 9. *Mean change in the water quality index due to a 50% reduction in aquaculture nutrient inputs (histogram bars), compared with climate induced variability in water quality (% sd/mean) in the reference runs (red symbols). Regions 7-10c (see Table 3) are composites of at least 3 individual ERSEM boxes. Local areas are individual ERSEM boxes - on the Scottish east coast: Inverness Firth, Forth/Tay and Farne Islands (boxes 35, 65 and 75 respectively), and on the west coast: Skye, Clyde and Solway (boxes 47, 74 and 100 respectively).*

8. Summary of analysis of nutrient Loadings

8.1 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) We have extrapolated the Harmonised Monitoring Scheme data using land-use information and a GIS model in order to estimate the nutrient runoff from the entire Scottish land catchment.
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.

8.2 Salmon farming contributes approximately 6% of Scotland's nitrogen and 13% of phosphorus input to the sea (based on 2001 production figures). In comparison, urban waste water accounts for approximately 12% of Scotland's nitrogen load, and 36% of the phosphorus load.

9. Summary of ERSEM results on eutrophication impacts.

9.1 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.

9.2 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.

9.3 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 for use in the initial application of the OSPAR Comprehensive Procedure.

9.4 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 used to derive indices of the natural climate-driven variability in the eutrophication criteria.

9.5 The ERSEM was used to simulate eutrophication criteria under a scenario in which the aquaculture nutrient load was reduced by 50%, and the results compared to those from the reference runs. The simulated reduction in nutrient load produced less than 0.3% change in water quality in all but one of the assessment regions. Even in the worst case region (Minches) the change was only 1.1%. At the local scale, the worst case change in water quality (box 47, Skye) was 1.7%, equivalent to around 4gC m^{-2} yr^{-1} decrease in annual net primary production, or less than 0.05mg chlorophyll m^{-3} averaged over May-September. These changes were clearly smaller than the 50% threshold defined in the Comprehensive Procedures for designation of elevated levels of assessment criteria, and were less than half the natural variation due to climate (3.6%).

9.6 On the basis of these results we conclude that, at the spatial scale of these simulations (50 x 50 km), there is no case for suggesting that nutrients from Scottish aquaculture have a discernible eutrophication impact on the coastal and offshore waters west and north of Scotland.

10. References

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