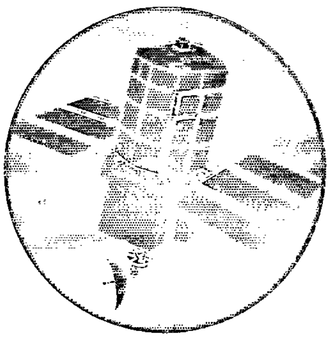
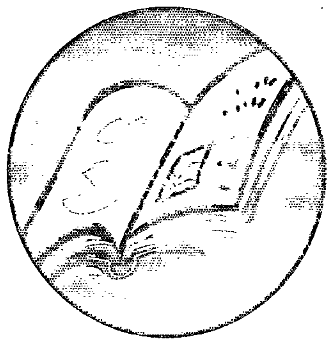
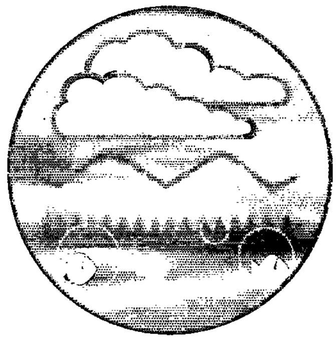
The Distribution of Phytoplankton and Nutrients in the North East Irish Sea during 1997

Research and Development

Technical Report

E55

THE UNIVERSITY of LIVERPOOL

ENVIRONMENT AGENCY

The Distribution of Phytoplankton and Nutrients in the North East Irish Sea During 1997

Technical Report E55

K Kennington, J R Allen, T M Shammon, R G Hartnoll, A Wither and P Jones

Research Contractor:
University of Liverpool, Port Erin Marine Laboratory

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This report summaries the findings of collaborative research between the Environment Ageny and Port Erin Marine Laboratory on nutrient and phytoplankton distributions in the north east Irish Sea during 1997. The information within this document is for use by EA stafff and others involved in the research and management of coastal waters with respect to hyper-nutrification and eutrophication.

Research contractor
This document was produced under R&D Project E1-049 by:

University of Liverpool
School of Biological Sciences
Port Erin Marine Laboratory
Port Erin, Isle of Man
IM9 6JA

Tel:01624 831000 Fax: 01624 831001

Environment Agency Project Leader
The Environment Agency's Project Leader for R&D Project E1-049 was:
Mr A Wither, Environment Agency, North-West Region

Amendments
Any corrections or proposed amendments to this manual should be made through the regional Agency representative on the Water Resources National Abstraction Licensing Group.

Contents

EXECUTIVE SUMMARY
Phytoplankton And Nutrient Distributions In The North-East Irish Sea During 1997.

The results presented summarise the findings of collaborative research between the Environment Agency (North-West Region) and Port Erin Marine Laboratory (University of Liverpool). The objectives of this research have been to monitor the spatial and temporal distributions of nutrient salt concentrations and phytoplankton abundances in the north-eastern Irish Sea. Specific objectives have been to identify areas within these waters that are potentially at risk from the adverse effects of nutrient discharges from sewage, industrial and riverine sources within the region. This is the third year of collaboration between the two organisations and prevvious findings are to be found in Allen *et al.* (1996) & Kennington *et al.* (1997).

Industrial discharges into the region are readily apparent from the data presented and support the findings of previous years. Two point sources of inorganic nutrients in particular are located at Albright & Wilson, Whitehaven and at BNFL Sellafield, where elevated concentrations of phosphorus and nitrogenous compounds are found respectively. Waters along the Cumbrian coast exceeded the guidelines of the Comprehensive Studies Task Team (CSTT) with regard to winter levels of DAIN & DAIP during 1997. The summer concentrations of surface chlorophyll along the Cumbrian Coast during 1997 were generally lower than those reported for 1996 and did not exceed the 10µg/litre threshold outlined by the CSTT.

Industrial discharges from Albright & Wilson are expected to decrease over the next few years, however discharges of nitrogenous and phosphorus compounds from BNFL Sellafield are likely to increase in the next few years owing to increased throughput and new operations.

The results presented show winter concentrations of nitrogenous compounds in particular to have increased across the region when compared to the findings of previous years [Jones & Folkard 1971, Allen *et al.* 1996, Kennington *et al.* 1997]. This has subsequently raised the N:Si ratio across the entire region which now exceeds the guidelines of the CSTT and this level is suggested under these guidelines to be prone to future eutrophication. Such an alteration, it is argued, may present itself by altering the phytoplankton community structure favouring non-siliceous organisms and possibly increasing the occurrences of nuisance algae.

Discharges of nutrient salts into Liverpool Bay stem mainly from the rivers Mersey, Ribble and Dee and also from sewage sludge disposal. Nutrient concentrations were highest towards the south-east of the study area on all sampling dates. The waters in this region failed the recommendations of the CSTT with regard to winter levels of DAIN & DAIP and to summer concentrations of surface chlorophyll. These findings reinforce those presented for 1996 and support the recommendation that the Wirral HNDA should not be classified as less sensitive. Winter levels of N:Si (along the coast from the Mersey westwards) exceed the recommendations of the CSTT, suggesting that these waters may be prone to future eutrophication.

KEY WORDS: Irish Sea, Cumbria coast, Liverpool Bay, Nitrate, Phosphate, Silicate, Nutrients, Phytoplankton, *Phaeocystis*, Stratification.

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THE DISTRIBUTION OF PHYTOPLANKTON AND NUTRIENTS IN THE NORTH EAST IRISH SEA DURING 1997.

1.0 INTRODUCTION

This report summarises collaborative work between the Environment Agency (E.A., North West Region) and the University of Liverpool's Port Erin Marine Laboratory during 1997. This has been the third year of collaboration between the two organisations investigating the spatial and temporal dynamics of nutrient concentrations in the eastern Irish Sea and associated changes in the phytoplankton community structure. Reports on the previous two year's research have been produced and the current report continues on from those produced for 1995 (Allen *et. al.* 1996) and 1996 (Kennington *et al.* 1997).

Scientific investigations into nutrient salt concentrations have been undertaken at Port Erin since the mid 1950s (Slinn 1990). This has enabled the development of a time series for all the major nutrient groups which has indicated increased dissolved inorganic forms of both phosphorus and nitrogen (see Allen *et al* 1998). It can be seen from figures 1 a-d that phosphate and nitrogenous compounds have approximately doubled over this time interval. Silicate concentrations over this time have shown only a slight increase in concentration whilst vernal phytoplankton productivity (as µg/litre chlorophyll) has increased significantly.

The eastern Irish Sea currently has three designated 'Less Sensitive Areas' under the European Union's Urban Waste Water Treatment Directive (UWWTD), these being Workington North, Workington South and Braystones. A fourth candidate region at North Wirral, formerly classed as a High Natural Dispersal Area (HNDA), is expected to have its HNDA classification status withdrawn. Under the UWWTD the remaining three designated LSA's must receive primary treatment to specified standards and prove by comprehensive studies that any sewage discharges will not adversely effect the environment (article 6.2). The designated areas must also be reviewed at intervals of no more than four years (article 6.4) and results of the comprehensive studies must be subject to scrutiny by the European commission who may make further proposals to the relevant council (articles 6.2 & 6.3).

Criteria for confirming that primary treatment into LSA's will satisfy the requirements of the UWWTD are considered in detail in the Comprehensive Studies Task Team (CSTT) report published in 1997. Under provisions outlined in this report waters are said to be adversely affected by nutrient inputs if;

a) Winter concentrations of Dissolved Available Inorganic Nitrogen (DAIN) exceed 12 mmol/m^{-3} (170µg/litre) in the presence of at least 0.2 mmol/m^{-3} (6.2 µg/litre) Dissolved Available Inorganic Phosphate (DAIP) or;
b) Summer concentrations of Chlorophyll *a* exceed 10 µg/litre.

Should the above criteria be exceeded then a water body is termed hypernutrified. Suggestions by the CSTT also state that a water body with an N:Si ratio of greater than 2 (when expressed in $mmol/m^{-3}$, µg-at/litre etc.) is indicative of waters that are liable to future eutrophication problems. A distinction between hypernutrification and eutrophication should be made as hypernutrified waters may not necessarily be eutrophic.

Eutrophication is the enrichment of a water mass with organic and inorganic plant nutrients. In freshwater bodies eutrophication can be a completely natural process. In such environments eutrophication is a slow process of enrichment and is generally associated with an ageing process of the water body in response to factors operating within its catchment. Such a definition is inadequate when discussing the cultural eutrophication of coastal waters. However, the semi-enclosed nature of the Irish Sea has many similarities with freshwater bodies. Factors operating within the Irish Sea 'catchment' will have dramatic effects upon its water quality and biota. For the purpose of this report eutrophication may be defined as nutrient enrichment from anthropogenic sources, leading to increased phytoplankton production and possible changes in the phytoplankton community structure. The cultural eutrophication of coastal waters has been associated with environmental problems in other European coastal areas (e.g. Hallegraeff 1995, Smayda 1990, Paerl 1988). These problems include excessive growth of algae, deoxygenation of bottom waters resulting in mortality of benthic organisms, increased abundances of nuisance algal blooms and the loss of benthic fisheries.

The effect that nutrient changes have upon phytoplankton population structure is very difficult to predict as the causal relationship between phytoplankton stocks and eutrophication is not wholly understood. Increasing loadings of N and P into coastal waters can have several potential effects upon the phytoplankton community. A general increase in productivity, especially of populations that may normally be limited by N and P, can be observed (Smayda 1990), which can subsequently lead to the classic problems associated with eutrophication described above. Increases in the N:Si ratio can lead to a silica limitation of diatom dominated communities, which in turn can produce a shift from diatom dominated to smaller flagellated dominated algal groups (Officer & Ryther 1980, Billen *et al.* 1991). Associated with such changes in the relative ratios of one nutrient species to another is the increase in novel or nuisance algal blooms (Hallegraeff 1995). This shift from diatom dominated to the smaller flagellate dominated algal groups has potential effects upon the nutrient cycling and trophic energy flow in coastal marine systems. Diatoms being the larger planktonic autotrophs of the coastal environment are the major contributors to direct energy transfer to the higher trophic levels. The smaller flagellated algal groups are generally more involved in the 'microbial loop' (Doering *et al.* 1989) than the planktonic food chain. Any such changes in the phytoplankton community structure have potentially severe consequences, not only for the modification of nutrient salt concentrations and ratios, but also for the transfer of energy from one trophic level to the next.

A generalised response of the phytoplankton community structure to changing nutrient salt concentrations cannot be given. Different water bodies around Europe have been shown to respond in different ways to enhanced nutrient loadings. A common bloom-forming alga of European coastal waters is *Phaeocystis globosa*. This prymnesiophyte alga has not been conclusively linked with increased nutrient enrichment of coastal waters but it seems likely that this is the case (Lancelot *et al.* 1987). Riegman *et al* (1992) suggested that high abundances of this species may be a result of elevated concentrations of phosphorus. Blooms of *Phaeocystis* species have occurred almost annually in Dutch coastal waters since 1978 (Bäetje & Michaelis 1986) and reports of blooms are also common in regions of the Irish Sea (Irish Sea Study Group 1991, Jones & Haq 1963, Jones & Folkard 1971, Kennington *et al.* 1998).

Increased reports of toxic algal species such as the dinoflagellates *Dinophysis acuta*, *Dinophysis acuminata* and *D. norvegica* have also been linked to changing nutrient ratios of coastal waters, having severe implications for both public health and shell fisheries. The unarmoured dinoflagellate *Gyrodinium aureolum* has occurred in massive numbers in Norwegian coastal waters and has been responsible for the death of thousands of farmed fish since it was first reported in 1966 (Tangen 1977). Long term decreases in the Si:P ratio within the Black Sea have been associated with an increase in blooms of the dinoflagellate *Prorocentrum cordatum* (Bodeanu & Usurelu 1979). Machetti's (1992) study of the semi-enclosed Adriatic Sea highlighted a connection between dense blooms of diatoms and dinoflagellates and eutrophication of the Po Delta, which led to deoxygenation of bottom waters and the production of surface scums.

2.0 DESCRIPTION OF THE STUDY AREA

Comprehensive reviews of the biological, chemical, geological and physical characteristics of the Irish Sea are contained in several reports (Irish Sea Study Group 1990, Dickson & Boelens 1988). The Irish Sea encompasses the semi-enclosed sea area bounded by latitudes 52° and 54°N. Deepest waters are found to the west of the Isle of Man in the Beauforts Dyke (~275m). These deeper waters are found in a long open ended trench connected to the Celtic Sea via the S[t] George's Channel in the south and the Malin Shelf via the North Channel in the north. Atlantic waters enter the Irish Sea via both entrances. To the east of the Isle of Man waters are generally much shallower (<50m). The total volume of the Irish Sea has been calculated as 2430 km^3 (Dickson & Boelens 1988), equivalent to only 6% of the total volume of the North Sea, 80% of this volume lying to the west of the Isle of Man. The north-eastern Irish Sea is defined as including the marine and coastal waters extending from the Solway Firth to the North Wales coast and from the English coast to the Isle of Man

In the eastern Irish Sea currents typically show a southward drift off S[t] Bees Head and a two layer circulation is found in Liverpool Bay. Differences in surface and bottom currents have also been identified to the north east of the Isle of Man with surface currents running westwards out of the Solway Firth and bottom currents running eastwards. Figure 2 shows the summer hydrographic conditions in the Irish Sea (after Pingree & Griffiths 1978). The majority of the Irish Sea is shallow and well mixed. The main area of summer stratification can be found to the west of the Isle of Man due to increased water depth and reduced currents. Summer (thermal) stratification can also be found in Liverpool Bay. It can be seen from Figure 2 that large areas of the eastern Irish Sea are composed of transitional waters. These areas, particularly off the Lancashire and Cumbrian coasts, can become stratified during winter and spring owing to haline effects. It has also been shown that summer thermal stratification can occur in these areas particularly when climate and current regimes are favourable (Allen *et al.* 1996). Several frontal regions have been identified to the north and south of the stratified regions in the western Irish Sea and also an east-west frontal region running just north of the 54°N parallel. A fourth frontal region is located between the Isle of Man and the southern part of the Solway Firth which has received relatively less study than those mentioned previously. A further frontal region is located within Liverpool Bay.

The eastern Irish Sea receives land based nutrient inputs from major river, sewage and industrial sources (See Table 1).The most important individual inputs of nitrogen in the eastern Irish Sea are from the River Mersey (35%), the River Ribble (22%), the River Eden (10%), BNFL Sellafield (3%) and from sewage sludge disposal (12%). Individual sewage outfalls in the area are of minor importance by comparison with a total of all major outfalls in the area, accounting only for approximately 3.5% of all inputs. Nitrogen inputs from Sellafield are set to increase in the near future as the THORP nuclear fuel reprocessing plant increases production. Phosphorus inputs into the eastern Irish Sea are dominated by the industrial outfall of Albright & Wilson at Whitehaven. This contribution currently represents approximately 29% of total inputs of phosphorus (EA 1997 data). The sum of all sewage outfalls is responsible for around 6% and all rivers for 49% (dominated by the Rivers Mersey and Ribble) of total phosphorus inputs from land.

Phytoplankton studies in the Irish and Celtic Seas have generally concentrated around frontal systems (Pingree *et al.* 1976, Savidge 1976, Fogg *et al.* 1985). Recent studies include those of Gowen *et al.* (1995) and Gowen & Bloomfield (1996) on the regional differences in stratification and its effect on phytoplankton production in the north-west Irish Sea. Studies on phytoplankton from the north-east Irish Sea are particularly scarce however, and the effect increasing nutrient concentrations in the Irish Sea have on phytoplankton communities is unclear. A comprehensive study of the eastern Irish Sea was conducted by Jones & Folkard (1971) who played particular attention to the distribution of nutrient salts in the region. Allen *et al.*(1996) provided some evidence for elevated summer phytoplankton biomass in the area that was associated with regions of high winter nutrient concentrations. Previous research into the possible associations of winter nutrient salt concentrations and the spring phytoplankton community structure in the eastern Irish Sea suggested that concentrations of winter Total Oxidised Nitrogen (TON) and silicate may best explain the spring phytoplankton community structure, suggesting a possible nitrate-N limiting environment (Kennington *et al.* 1998).

Table 1

Estimated nutrient loads from the English coast directly to coastal waters of the north-east Irish Sea (Liverpool Bay to Workington and east of the Isle of Man). Estimated loads are in tonnes/annum. All figures are derived from EA data. Industrial contributions are estimates supplied by the Environment Agency (figures for 1997), N as DIN, P as P_2O_5-P. Loads from major rivers are a catchment total for 1994, as DIN and ortho-P and include major tributary and sewage input. Sewage figures are based on flows and the composition of 'standard sewage' based on total nitrogen (as N) or phosphorus (as P). No estimates for atmospheric deposition of N and P are given.

	N	P
Industrial		
Albright & Wilson (Whitehaven)	----	1800
BNFL Sellafield	900	65
BNFL Springfield	815	-----
Rivers		
Eden	3211	157
Derwent	838	11
Leven	403	9
Kent	601	6
Lune	983	10
Wyre	337	216
Ribble	7065	996
Mersey	11346	1838
Total eastern Irish Sea Rivers	24794	3050
Sewage Direct to Coastal Waters		
Workington/Whitehaven area	280	94
Millom	60	20
Barrow in Furness	165	55
Morecambe	116	39
Blackpool	471	157
North Wirral	420	59
Total Coastal Sewage	1092	365
Sewage sludge from NWW	3749	1095
Total of all major inputs to the eastern Irish Sea	**31770**	**6177**

3. CUMBRIAN COAST SURVEYS

3.1 Sampling Protocol and Methodology

3.1.1 Dates of Cruises and Location of Sampling Sites

The initial aim was to take samples off the Cumbrian coast on three sampling occasions throughout the seasonal productivity cycle. Sampling trips were planned for mid-February (winter nutrient maximum), mid-May (spring phytoplankton maximum) and mid July (post peak summer sample). PEML sampled on an offshore grid and the EA sampled on an inshore grid (see figures 3 & 4). It was planned that the two vessels, the R V Roagan (PEML) and R V Coastal Guardian (EA), would carry out sampling concurrently on the separate grids. The actual dates of sampling were as follows;

C.C.Inshore Grid	C.C Offshore Grid
19/5/97	03/3/97
17/6/97	19/5/97
18/7/97	16/7/97

The cruise pattern for the offshore grid consisted of 14 legs in a zigzag pattern to boundaries nominally defined by 16 to <1 nautical miles from Maryport, S[t] Bees Head and Hipsford Point. Further samples were collected during transit to and from the offshore grid. The inshore grid ranged from the closest practical point inshore to 6 nautical miles offshore, and within the same latitude boundaries as the offshore grid giving 16 legs.

A total of 72 sampling sites were distributed over the 14 legs (& transit legs) of the offshore grid (figure 4) nominal positions and site identifiers are given in appendix A. Surface phytoplankton, nutrients, salinity, temperature and fluorescence were recorded at stations along the offshore grid. A CTD cast and bottom water nutrient samples were taken at the ends and middle of each grid leg (a total of 29 sites). Surface water samples were taken for chlorophyll *a* analysis at transit sites and at the ends and middle of each leg.

3.1.2 Sampling and Analytical Methods

Sampling and analytical methods remained the same as for the 1995 sampling program as outlined in Allen *et al.* (1996), & Kennington *et al.* (1997). The analytical methods outlined below are for the PEML samples only. EA analysed samples were determined using methods normally used on coastal surveys. 'Surface water' supply on board the R.V. Roagan is supplied by a direct intake pipe situated approximately 2m below water surface level. Surface temperature was recorded using a Meteorological Office mercury thermometer placed in the running water. Water samples for salinity were stored in stoppered glass bottles and analysed using a Plessey 9230N bench salinometer.

Water for nutrient analysis was filtered through Watmans GF/C filter papers and placed directly into a freezer. Two samples were taken at each site and only one set of samples thawed for analysis. Nutrients were analysed by using an ALPKEM RF/A2 autoanalyser using standard colorimetric techniques as advised by the manufacturer. Artificial seawater was used for blanks and background wash to overcome salinity effects (Grasshoff 1976). De-ionised UHQ water was used in artificial seawater for ammonia determination and washwater.

Surface fluorescence was determined using a Turner Designs fluorometer with continuous water supply, calibrated using results from simultaneously collected chlorophyll *a* samples. Chlorophyll *a* was determined via slow acetone extraction using the formulae given by HMSO (1980), 3 litres of water being filtered for each sample. It should be noted that the assessment of chlorophyll in the present study is labelled "chlorophyll *a*" although in reality this should be qualified as "chlorophyll *a* and related pigments" (CSTT 1997).

Bottom water samples for nutrient and salinity analysis were collected using an IOS type sampling bottle deployed in conjunction with the CTD. Profiles for salinity, temperature, density and fluorescence were obtained using a SEACAT SBE 19 (Seabird electronics LTD) CTD profiler. 'SEASOFT' software was used to align data and to produce results averaged over 1m depth intervals. Standing stocks for the water column (mg Chlor. *a* m^{-2}) were calculated by summing each 1m depth value for the whole cast. Simpson's stratification parameter was calculated from CTD data to give an indication of the degree of mixing in the water column (Simpson *et al.* 1978). In previous years the degree of stratification was calculated by a template written by P.Edwards. In order to be in keeping with other studies in the Irish Sea using the Simpson formulae, the stratification parameters presented follow those of Dickey-Collas *et al.* (1996) where a value of greater than 20 is indicative of stratification and values in the range of 10-20 are indicative of intermediate waters.

Data collected on the inshore grid included nutrients (which were analysed using an onboard Skalar Auto-analyser), physical parameters (temperature and salinity) and chlorophyll were measured using a 'towed body' (Chelsea Instruments Ltd AQUASHUTTLE). Surface water supply on board the RV Coastal Guardian is pumped from approximately 1.5m depth.

Phytoplankton samples were preserved immediately in acidified Lugols iodide for February only. May and July samples were preserved in non-acidified Lugols iodine. All samples were analysed by PEML. Subsamples were settled in Utermöhl chambers and samples counted using a Leitz DM 1L inverting microscope at magnifications of X200 and X400. Phytoplankton samples were identified according to the 26 categories outlined in appendix B. The use of restricted taxonomic groups allows for more rapid enumeration and helps avoid problems associated with the identification of preserved samples to species level. Images of the most common species were captured for future reference using an image analyser.

3.1.3 Quality Control

PEML currently subscribes to the Water Research Centre AQUACHECK analytical check sample scheme, providing a continuing audit on the accuracy of the analytical results obtained by the laboratory for nutrients in saline waters. During 1996 QUASIMEME (Quality Assurance of Information for Marine Environmental Monitoring in Europe) launched a laboratory testing scheme for chemical measurement in marine sciences. PEML also participates in this scheme.

A stringent laboratory protocol for sample treatment and analysis is in place at the laboratory and essentially complies with recommendations given by Gillooly *et al.* (1992). Some modification to these disciplines are made as improvements become apparent. Blank determinations and repeatability checks are performed throughout the analyses. Procedures include a laboratory reference standard. Accurate determinations of ammonia in seawater present notorious difficulties (Kirkwood & Aminot 1995). The laboratory remains aware of these problems, especially at low concentrations.

3.2 PRESENTATION OF RESULTS

All contour diagrams are produced by Surfer® for Windows version 5.03 (Golden Software). Position of contours is determined using the kriging method and grids are blanked using a detailed land boundary. This process extrapolates data for areas where no samples were taken, so close attention to the location of sampling sites (figures 3, 4, 67, 68, 69, 70 & 71) should be made when making detailed study of any trends. In particular no samples were taken from the north west of the mapped area, due north of the Isle of Man. Separate diagrams are drawn for EA and PEML data. These maps are not corrected for the curvature of the earth and there is some distortion from north to south when compared to Admiralty charts. An average scaling factor for the area of 1 degree longitude to 1.7153 degrees latitude was used in plotting the maps. All SURFER plots are located at the end of the report where data are available for both inshore and offshore grids for the Cumbrian coast surveys, PEML (offshore grid) data are plotted first.

Multivariate statistical analysis and associated plots were carried out using PRIMER version 4.0 (Plymouth Marine Laboratory).All other statistical analysis was undertaken using SPSS for windows version 6.0 (Microsoft).

3.3 MULTIVARIATE ANALYSIS TECHNIQUES

Multivariate statistical analysis was undertaken on the data to try and further describe the complexities of phytoplankton community data and to identify any trends or discrete groups for each sampling occasion. Additionally an attempt was made to relate these phytoplankton groupings to environmental variables. All statistical analysis were carried out using PRIMER.

3.3.1 Cluster Analysis

Cluster analysis (or classification) aims to identify similarities or "natural groupings" in the species composition between samples (sites). Such an exercise was undertaken using the CLUSTER procedure in PRIMER. A similarity matrix was calculated from Bray-Curtis similarity coefficients and hierarchical agglomorative clustering performed using the group average linking method to produce a dendrogram. Clustering is designed to delineate groups of samples that have a distinct community structure. Such an exercise may be misleading however if there are gradations in species assemblages. To overcome such potential problems clustering was used in conjunction with ordination techniques (non-metric multi-dimensional scaling).

3.3.2 Non-metric multi-dimensional scaling (MDS)

Ordination techniques may be defined as any method that arranges site points in the best possible way in a continuum such that points that are close together correspond to sites that are similar in species composition, and points which are far apart correspond to sites that are dissimilar. A particular ordination technique is obtained by further specifying what 'similar' means and what 'best' is. A measure of similarity (or dissimilarity) between sites is chosen and replaces the original species composition data with a matrix of dissimilarity values between sites which can then be expressed via an ordination diagram. This final step is termed multi-dimensional scaling. MDS has many advantages over other ordination techniques (PCA, CCA, DCA etc.) as it is based on ranks and makes few model assumptions about the form of the data. MDS uses these ranks of similarities to construct a two dimensional 'map' of the samples. Most data sets produce some distortion or 'stress' between the similarity ranking and the corresponding distance rankings on the plot. The stress level produced by the MDS procedure gives an indication of the adequacy of the MDS representation. Stress levels less than 0.1 indicate good representation of the data, stresses over 0.3 indicate that the points are close to being arbitrarily placed. Stress values of less than 0.2 can give a potentially useful 2-dimensional picture and it was therefore decided that further consideration of patterns highlighted by MDS would only be carried out for plots with stresses less than 0.2. MDS was performed using PRIMER on species-sample data based on fourth root transformations and Bray-Curtis (dis)similarity coefficients.

3.3.3 Linking Community Analyses to Environmental Variables

Patterns in community structure identified by the above techniques can be linked to environmental variables using the BIOENV procedure of PRIMER in which ranks of similarities are compared using rank correlation coefficients (weighted Spearman coefficient). Such an exercise was performed on groups of samples that proved to have low stress values in the species-samples MDS plots. Correlations were performed between species-sample similarity (from MDS) and environmental dis-similarity matrices (based on untransformed data and Euclidean distance). A coefficient close to zero implies no match between patterns of species-samples and environmental variables while values close to -1 or 1 imply complete opposition or agreement in the two sets of similarities. No assessment of the significance of the match in pattern can be made since the ranks are based on a large number of strongly interdependent similarity comparisons. BIOENV identifies the individual or combination of environmental variables that 'best match' the pattern in community structure. However, no conclusions can be made regarding the causality of any relationships, only suggested relationships may be assumed which may highlight any variable (or combination of variables) for further investigation. BIOENV requires a full data set, so it was necessary to reduce species and environmental data to only those sites with no missing determinands.

3.3.4 The Determination of Discriminating Species

Distinct community structures or trends in floral assemblages identified by MDS were further worked to identify any characteristic species categories. This was achieved by carrying out MDS on the species similarities to determine which species varied in association with each other. The species list was ordered according to the position on the sample similarities MDS plots and cluster diagrams carried out previously. Discriminating species were also identified by dissimilarity breakdown using the SIMPER procedure of PRIMER.

3.3.5 Standard Procedure

Phytoplankton species abundance and environmental data for each sample date were converted to a standard format used in PRIMER. Information from offshore grids alone were analysed. Similarity matrices and cluster dendrograms were produced for phytoplankton abundances. MDS plots were constructed from ranked matrices and the stress value noted. For sample sets having an MDS stress of less than 0.2 some distinct patterns in phytoplankton communities were assumed and further analysis was carried out to determine discriminating species (SIMPER) and to link patterns to environmental data (BIOENV).

4.0 RESULTS

4.1 PHYSICAL PATTERNS

Sea surface temperatures (SST) showed a general east-west trend on all sampling occasions. During March (figure 5) coldest temperatures (~6.5°C) were found along the Cumbrian Coast and warmest temperatures were found to the west of the study area (~8.5°C). Coldest temperatures during May were found to the west of the study area (~10.5°C) and warmest waters were found to the south-east of the region where waters reached a maximum of 13°C (figures 6). Temperatures during June were recorded from the inshore grid only (figure 7) and reached a maximum of 16°C adjacent to S[t] Bees Head. Cooler waters (<15°C) were located to the south-east of the sector. During July the east-west trend continued with coolest waters still located to the west of the study area (~14°C). Warmest temperatures were found to the north-west of the region between the Ravenglass estuary and the Solway Firth where temperatures reached a maximum of 16.5°C (figure 8)

Surface water salinities showed an increasing trend from the north-east to the south-west on all sampling occasions (figures 9-12). Lowest salinities were recorded around the Solway Firth and extended along the English Coast. Higher surface water salinities (>34) were found to the south-west of the Isle of Man. Penetration of low surface water salinities was greatest during March and May and lowest during July.

The degree of mixing between surface and bottom waters can be restricted at certain times of the year by stratification of the water column. Stratification may be caused when the density of surface waters is altered by freshwater run-off or by insolation. CTD casts taken at the ends and middle of the 'zigzag' transects showed there to be some stratification in the north eastern Irish Sea on all sampling occasions. An assessment of the degree and nature of stratification is given by the Simpson's stratification parameter (after Simpson *et al.* 1978)..

Results presented for the 1995 and 1996 surveys (Allen *et al* 1996, Kennington *et al.* 1997) estimated the degree of stratification according to Simpson *et al.* (1978) using a template written by P.Edwards. Edwards's template showed waters having a stratification parameter value of less than -9 to be indicative of stratified conditions. In order to be in keeping with other studies in the Irish Sea using the Simson formulae, the stratification parameters presented followed those of Dickey-Collas et al. (1996) where a value of greater than 20 is suggested to indicate stratified conditions (Gowen *et al.* 1985) and values of between 10-20 are indicative of intermediate or transitional waters.

During March the influence of the Solway is very marked on the physical stability of the water column (figure 13). High stratification values (>20) were recorded around the Solway at this time. A plume of stratified waters runs offshore from the Cumbrian Coast whilst waters closer to the coastline are more indicative of transitional/non-stratified conditions. The stratification during March was caused by the discharge of

lower salinity waters via the Solway. The apparent decrease in density stratification along the inshore waters may be a product of increased mixing caused by strong south south-westerly winds in the week prior to sampling which averaged approximately 20 knots and had gusts of up to 50 knots (see Appendix A).
During May stratification was much less evident. The study area at this time can be divided into two broad regions, a well mixed, non-stratified region to the north and an intermediate/transitional region to the south (figure 14). The southern region is considered to have some vertical structure with regard to haline stratification although this is considered to be marginal. According to the numerical model of Pingree & Griffiths (1978) a frontal region occurs during some summer months between the Isle of Man and Morecambe Bay. The boundary between the southern intermediate region and the northern non-stratified region identified during May fits well into Pingree & Griffiths model and could indicate the early development of this frontal system.
During July a region of strongly stratified waters was located to the south of S^t Bees Head extending to the South of the Ravenglass estuary (see figure 15). This region of stratified waters has a very marked thermocline with a 4° C temperature change occurring over a few meters vertical distance. Surrounding this region of thermally stratified waters are transitional waters extending into the Solway Firth and south to a region approximating to the Duddon estuary. The southern extent of these transitional waters are again coincidental with the approximate position of the summer frontal region noted by Pingree & Griffiths (1978). It should be noted however that owing to poor weather conditions during the July sampling period, stations 36W, 44W and 52W were not sampled.

4.2 PATTERNS OF NUTRIENT DISTRIBUTION

During the winter and spring surveys (March & May) the majority of dissolved available inorganic nitrogen was present as nitrate. The distribution of Total Oxidised Nitrogen (TON) during March showed a northeast-southwest trend with maximum concentrations (400-650µg/litre) being found along the Cumbrian Coast between the Solway Firth and Ravenglass estuary (figure 16). Waters to the south-west of the study area had average TON concentrations of 200µg/litre. Nitrite concentrations during March had maximum concentrations (~20µg/litre) to the south-east of the study area (figure 17). The maximum March concentrations of ammoniacal nitrogen were found along the Cumbrian Coast and to the south-east of the region with maximum concentrations (>50µg/litre) being found adjacent to Sellafield and offshore from the Duddon estuary (figure 18).

Concentrations of all nitrogenous compounds had decreased dramatically by May. Data collected by PEML during May show concentrations of TON to be greatest in waters adjacent to the Isle of Man where concentrations reached 70µg/litre. Concentrations of TON along the Cumbrian coast were generally less than 15µg/litre (figure 19) except for a region adjacent to Sellafield where concentrations reached approximately 40µg/litre (PEML data). Nitrite concentrations during May were very low, often being below detectable limits with average concentrations being approximately 3µg/litre (figures 20). The concentrations of ammoniacal nitrogen during May had also decreased considerably since March. Highest concentrations were found towards the Solway Firth (~70µg/litre) and in a small patch located midway between S^t Bees Head and the north of the Isle of Man. (~80µg/litre).The concentrations of ammoniacal nitrogen along most of the Cumbrian coast (south of S^t Bees Head) were much reduced during this time with concentrations not exceeding 15µg/litre (figure 21). The apparent decrease in all nitrogenous compounds between March and May suggests that the May samples were collected after the onset of increased phytoplankton growth.

Data on the nutrient salt concentrations during June are available from the inshore grid only. It can be seen from figures 22-24 that the majority of dissolved available inorganic nitrogen was available as ammoniacal nitrogen. Concentrations of both nitrate and ammoniacal nitrogen were highest in waters extending from the Ravenglass estuary to Sellafield (~15 & 20µg/litre respectively). Elevated levels of nitrate were also located in waters adjacent to Workington (figure 22). Nitrite concentrations during June were extremely low often being below detection limits (figure 24).

Nutrient salt data for July is only available for the offshore grid. The concentrations of all nitrogenous compounds with the exception of ammoniacal nitrogen had decreased since the June survey (figures 25, 26 & 27). Maximum concentrations of TON (~27µg/litre) were recorded at one site to the south of the study area (figure 25).

March concentrations of soluble reactive phosphate (SRP) were highest in waters between the southern end of the Solway Firth and an area south of the Ravenglass estuary (figure 28). Maximum concentrations of SRP were found in waters adjacent to S^t Bees Head (~53µg/litre) and Sellafield (43µg/litre). Concentrations of SRP had decreased across the region by May but highest concentrations were still found adjacent to S^t Bees Head (~13µg/litre) (figure 29). The apparent decrease in SRP concentrations between March and May reinforce the notion that the May samples were taken after the onset of the spring bloom.

Concentrations of SRP during June remained highest in waters to the north of S^t Bees Head (maximum 28µg/litre). The remainder of the coastal waters recorded much lower concentrations and were generally less than 10µg/litre (figure 30). Elevated levels of SRP continued to be located in waters around S^t Bees Head during July (figure 31), highest levels at this time were however centred around Sellafield (>40µg/litre).

Silicate concentrations during March were highest along the Cumbrian coast particularly within the Solway Firth where maximum concentrations of >750µg/litre were recorded. Lowest concentrations were found to the south-west of the study area where concentrations were generally lower than 300µg/litre (figure 32). Silicate concentrations had decreased considerably across the study site by May. Highest concentrations of silicate were now found offshore in waters to the north and east of the Isle of Man where concentrations reached a maximum of <400µg/litre. Coastal waters had concentrations generally less than 75µg/litre (figure 33). Silicate concentrations for June are available from the inshore grid only (EA data). It can be seen from figure 36 that silicate concentrations had decreased since May, highest concentrations being located toward the Solway Firth (>150µg/litre) and in waters between Sellafield and the Ravenglass Estuary (<120μg/litre).

Silicate continued to decrease in concentrations through to July . At this time the distribution becomes more patchy with isolated increases in concentration to the east of the study area, around Sellafield and to the south of the region in waters adjacent to the Duddon estuary (maximum concentration ~220μg/litre, figure 35).

4.3 THE DISTRIBUTION OF PHYTOPLANKTON, CHLOROPHYLL AND STANDING CROP

4.3.1 March 1997

Chlorophyll distributions across the region during March did not suggest the same trends in productivity as indicated by the phytoplankton counts (figure 39). It can be seen from figure 36 that surface chlorophyll concentrations are relatively low during this time with concentrations being below 1.5μg/litre across the whole study area. Highest surface chlorophyll concentrations are found to the north-west of the study area and also along the Cumbrian coast between Sellafield and the Duddon estuary.

An indication of total water column productivity is represented by the calculation of standing stocks. These represent the phytoplankton biomass summed over the whole water column. In areas where water depth is shallower than the critical depth for photosynthesis, the standing crop may be lower due to water depth rather than to factors limiting phytoplankton growth. The distribution of the standing crop (as mg/m^2) during March showed a region of elevated phytoplankton biomass to the centre of the study area and also in waters between Sellafield and the Duddon Estuary (figure 37). Since the majority of the eastern Irish Sea is relatively shallow (<50m depth) the standing crop has also been expressed as a function of depth, here the data has been averaged over one meter depth intervals. Such an exercise gives an average indication of phytoplankton biomass throughout the water column. It can be seen from figure 38 that when the standing crop is expressed in such a manner that the distribution is very different to either surface water chlorophyll or total water column standing crop.

The abundances of all the major taxonomic phytoplankton groups are plotted for the region and are presented in figures 39-42. It can be seen that total phytoplankton abundances (expressed as cells/litre) are low throughout the north-eastern Irish Sea during March. Highest abundances of phytoplankton were located along the Cumbrian coast and decreased westwards. The plankton flora during this time was dominated by diatoms and to a lesser extent by small flagellated algae (figures 40 & 41). Dinoflagellates were much less abundant but still found in highest concentrations along the Cumbrian coast (figure 42). Pearson correlation coefficients indicate significant positive (P=<0.05) correlations between the distribution and abundance of total phytoplankton groups and ammoniacal nitrogen, TON and silicate (P =0.007, 0.0001 & 0.001 respectively). Strong positive correlations also existed between total diatom counts and these variables (P = 0.01, 0.001 and 0.037 respectively).

4.3.2 May 1997

Surface chlorophyll concentrations during May are available from both the offshore (PEML) and inshore (EA) grids. Data from the offshore grid (figure 43) suggest highest surface water productivity to be found to the north-west of the study area where concentrations reached 9µg/litre. A second higher productivity region was also found north of S^t^ Bees Head towards the Solway Firth..

Standing crop concentrations during May show that total water column productivity is highest to the west of the study area where the standing crop concentrations reached 189mg/m^2 (figure 44). When standing crop is expressed as a function of depth (figure 45) it can be seen that highest water column productivity is now found in coastal waters around the Solway Firth and between the Ravenglass & Duddon estuaries (maximum concentrations = 9mg/m^3).

The species abundance data for May are plotted in figures 46-50. It can be seen from these figures that the most abundant planktonic organisms during May were the diatoms and the prymnesiophyte alga *Phaeocystis globosa*. This prymnesiophyte was most abundant in waters to the north of the region (figure 46). Pearson correlation coefficients between surface chlorophyll and *Phaeocystis globosa* showed a strong positive correlation (P = 0.0001). A strong positive correlation was also recorded between surface chlorophyll and the abundances of total diatom numbers (P = 0.001). Monads and small flagellated algae were also abundant during May especially along the Cumbrian coast to the south of Whitehaven (figure 49). Dinoflagellates were recorded in highest concentrations (~30000 cells/litre) to the south-east of the study area and were well correlated with the distribution of the small flagellated algae and microzooplankton (P = 0.000 & 0.005 respectively). Significant positive correlations also existed for these three taxonomic groups (monads/small flagellates, dinoflagellates & microzooplankton) and the Simpson stratification parameter for May suggesting a possible association between these planktonic organisms and water stratification during this time (P = 0.035, 0.024 & 0.026 respectively).

4.3.3 June 1997

The only assessment of surface water productivity during June 1997 comes from surface chlorophyll measurements undertaken by the Environment Agency along the inshore grid. It can be seen from figure 50b that surface water productivity had decreased significantly since May and highest concentrations were found along the Cumbrian coast south of S^t^ Bees Head but most noticeably to the extreme south east of the study area where concentrations reached approximately 2µg/litre.

4.3.4 July 1997

The concentration of surface chlorophyll (figure 51) remained relatively low during July with maximum concentrations not exceeding 3µg/litre. Highest concentrations were recorded in waters associated with the Duddon estuary. Standing crop concentrations (figure 52) suggest a significant reduction in water column productivity between May and July. Highest coastal values were found between Workington and the Ravenglass estuary (~20mg/m^2). When expressed as a function of depth it can be seen that highest standing crop values are found offshore between Sellafield and the Ravenglass estuary with a maximum concentration of approximately 7mg/m^3 (figure 53).

The total abundance of phytoplankton for July is plotted in figure 58. No significant correlation coefficients were found between surface chlorophyll and any planktonic group during July. Monads and small flagellated algae were the most abundant organisms during the summer of 1997. Highest abundances of these plankton were found offshore from the Isle of Man (figure 54) and also in waters around Workington. Diatoms were relatively less abundant at this time with highest concentrations (~80 000 cells/litre) being found in waters adjacent to Sellafield (also a region of elevated silicate concentrations) and in waters to the south-east of the Isle of Man (figure 55). The abundances of dinoflagellates had increased significantly since May and abundances of over 100 000 cells/litre were found to the south-east of the study area (figure 56). The potentially toxic dinoflagellate species *Dinophysis acuta* and *D.acuminata* were also found in concentration exceeding those recommended under Environment Agency monitoring procedures. It can be seen from figure 57 that abundances of these species exceeded 2000 cells/litre in waters offshore from Workington.

4.4 Analysis of Phytoplankton Community Structure and Environmental Variables - Results of Statistical Analysis

4.4.1 March 1997

Cluster and MDS analysis undertaken on the March phytoplankton data showed no clear grouping, all sites having a similar floral assemblage and abundance of species. An MDS stress of 0.215 was recorded for the sample set so no further analysis was undertaken.

4.4.2 May 1997

Variation in phytoplankton community structure was most noticeable during May. For the purpose of the MDS exercise all transit sites were removed from the data set to decrease the MDS stress and provide clear groupings of coastal planktonic communities. An MDS stress of 0.13 was applied to the plot. Two groups were identified according to the similarity of species abundances, the two groups reflect sites from the north (group 1) and south (group 2) of the sampling area (figure 59). A closer examination of the community structure within the two groups suggests that it is the presence of higher abundances of *Phaeocystis globosa* in the northern group that was most important in discerning groups of samples from each end of the spectrum. *P. globosa* accounted for 30% of the dissimilarity. Next in order of importance in differentiating the two groups are the diatom grouping of *Rhizosolenia* short (mainly *Guinardia deliculata*) and *Chaetoceros* sp. (accounting for 24 and 13% respectively). The dinoflagellate group Gymnodiniales and small flagellates/monads were also important in discerning the two groups accounting for 8 and 7% of the variation respectively (figure 64).

The patterns in phytoplankton community structure identified from the ordination exercise were used in the BIOENV procedure to identify which physical or chemical variables best explain the distribution of spring phytoplankton communities. Winter (March) nutrient and spring (May) salinity and temperature variables were run against the spring phytoplankton data. The BIOENV procedure conducted suggested some relationship between the spring phytoplankton and winter nutrient concentrations. The highest correlation of any single determinand explaining the distribution of spring phytoplankton communities was SST (sea surface temperatures) ($r = 0.127$), followed by nitrite ($r = 0.061$), TON ($r = 0.023$) and silicate ($r = 0.012$). The best match between combined environmental variables was achieved with a combination of nitrite, ammoniacal nitrogen, TON and SST ($r = 0.108$).

MDS ordinations between spring phytoplankton and winter nutrient salt concentrations (with the exception of nitrite) showed no discernible differences between groups 1 and 2 in figure 59. Figure 60 represents the proportion or concentration of nitrite at these sites. The size of the hexagons in figure 60 are proportional to winter nitrite concentrations (larger hexagonals represent higher nitrite concentrations.

4.4.3 July 1997

Cluster and MDS analysis performed on the July phytoplankton data showed no clear groupings and produced an MDS stress of 0.214, as such no further analysis was carried out.

4.5 Cumbria Coast Surveys

4.5.1 Summary

4.5.2 Major Spatial and Temporal Trends

Sea surface temperatures, salinity and nutrient salts generally showed an east-west trend on all sampling occasions. SSTs during March were positively correlated with salinity whilst May and July SST's were negatively correlated. The penetration of low salinity surface waters was greatest during the March sampling period. The influence of freshwater discharges from the Solway Firth on Salinity, TON and silicate was most noticeable during March and June whilst its influence on the productivity of the region was most noticeable during May. Soluble Reactive Phosphorus (SRP) concentrations were highest in waters between the Ravenglass estuary and the Solway Firth on all sampling occasions but especially in waters adjacent to S^{t} Bees Head/Whitehaven. Ammoniacal nitrogen, TON, SRP and silicate were all positively correlated (P = <0.05) across the region during March (see figure 61). These relationships had broken down considerably by May after modification of the nutrient salts by the phytoplankton. During May the only significant correlation was between TON and silicate (see figure 62). The post bloom sampling period (July) showed significant positive correlations to exist between nitrite and SRP and between ammoniacal nitrogen and TON. However, it should be reiterated that nitrite was recorded in very low concentrations during July often being below detectable limits (figure 63).

Levels of all nutrient salts had decreased significantly between March and May and between May and July. An exception to this was SRP which had concentration of between 30-55μg/litre during May in waters extending from Workington to the Ravenglass estuary, with maximum concentrations centred around Whitehaven and Sellafield. Elevated concentrations of SRP continued to be recorded in waters adjacent to Whitehaven during May and June although the concentrations had decreased in comparison to the March survey. By July concentrations of SRP had increased once more with maximum values being recorded in waters adjacent to Sellafield, concentrations of which were of the same order of magnitude as those recorded during March.

The spring increase in chlorophyll was greatest in waters to the north-east of the Isle of Man and toward the Solway Firth. These higher chlorophyll concentrations were reflected in the total phytoplankton counts where increased abundance of phytoplankton was also recorded to the north-east of the Isle of Man and towards the Solway Firth. A breakdown of the phytoplankton counts suggest that these waters were dominated by *Phaeocystis globosa* and the diatoms *Guinardia deliculata* and *Chaetoceros* sp. Waters to the south of the study area and along the Cumbrian coast south of S*t* Bees Head recorded increased abundances of small flagellated algae and dinoflagellates during May (figure 64). Information on the standing crop showed that the elevated surface productivity recorded to the north-east of the Isle of Man extended throughout the water column, however, the elevated concentrations of surface chlorophyll around the Solway Firth was not reflected in the standing crop measurements during May. When the standing crop is expressed as a function of depth the influence of freshwater discharges on productivity of the region is noticeable with increased standing crop/depth values around the Ravenglass and Duddon estuaries and also in waters associated with the Solway Firth.

Results from previous years suggested that the spring phytoplankton communities were often dominated by small cells (*Phaeocystis globosa,* monads etc.) and dinoflagellates (Allen *et al.* 1996, Kennington *et al.* 1997). A consistent pattern with regard to the dinoflagellate population during the spring suggests that waters to the south of the region tend to have increased abundances of dinoflagellates especially of the Gymnodiniales group. This pattern of spring dinoflagellate distribution has occurred over the past three years (Allen *et al.* 1996, Kennington *et al.* 1997).

Phytoplankton abundances during July were greatest in waters to the north of the region and generally reflected increased abundances of small flagellated forms. Diatoms were most abundant in waters adjacent to Sellafield and towards the south-east of the Isle of Man. The increased abundances of diatoms around Sellafield are also in agreement with observations by Allen *et al.* (1996) and Kennington *et al.* (1997) for the previous two years. Interestingly elevated levels of silicate were recorded in these waters during July by these studies and in the present study. If the silicate is a product derived from discharges in the local region around Sellafield this may account for the increased diatom production during the summer months as elevated levels of both TON and SRP were also associated with these waters during July of 1997, 1996 & 1995. The relative decline in diatom numbers away from the coastal waters around Sellafield suggest that the diatoms may be silicate limited during July and are therefore in increased abundances where 'pools' of silica enriched waters are to be found.

MDS results of the spring phytoplankton data suggest two distinct clusters distinguishing phytoplankton communities from the north and south of the regions (figure 59). The two clusters do have some overlap with regard to the abundances of the various phytoplanktonic forms. The northern group is however distinguished by the fact that it was heavily populated with *Phaeocystis globosa, Guinardia deliculata* and *Chaetoceros* sp.. whilst the southern group was more heavily populated with dinoflagellates and small flagellated forms. These two groups identified in the present study are in good general agreement with previous years findings (Allen *et al.* 1996, Kennington *et al.* 1997).

A comparison of winter nutrient and spring phytoplankton using BIOENV suggests that spring sea surface temperatures and winter nitrite concentrations best explain the differences in spring phytoplankton populations (figure 60). These results do not support the findings of previous years where winter TON, silicate and salinity differences were reported to explain the two phytoplankton groups. However, nitrite concentration during March were relatively low when compared to TON and as such these results should be viewed with caution. A combination of ammoniacal nitrogen, TON and nitrite did provide a strong association in the BIOENV test and it is most likely that winter concentration of nitrogenous compounds and physical conditions of the water column during spring may be responsible for the differences in the spring plankton community structure.

4.5.3 Evidence of Impact of Nutrient Inputs

The input of nutrients via riverine sources into the eastern Irish sea was most evident during March. Elevated concentrations of silicate, ammoniacal nitrogen and TON were associated with waters around the Solway Firth and the Ravenglass estuary. The influence of industrial sources of nutrient enrichment was apparent on all sampling occasions. High SRP loadings into the region from Albright and Wilson is apparent on all sampling occasions. Elevated concentrations of SRP during July between Workington South and the Ravenglass estuary were however centred on Sellafield and not Whitehaven, this phenomenon being also reported during July 1996 (Kennington *et al.* 1997). Discharges of nitrogenous compounds from BNFL Sellafield were also apparent throughout the year. Silicate concentrations around Sellafield appeared higher than most other coastal sites during March and July.

Long term changes in the nutrient salt concentrations and altering nutrient ratios have been shown to cause associated changes in the community structure and abundance of the phytoplankton (Lancelot *et al.* 1987, Hallegraeff 1995, Paerl 1988). Evidence from the present study does not suggest any major alteration in the phytoplankton community. The spring (May, 1997) survey did however record very high abundances of the nuisance algae *Phaeocystis globosa.* This species occurs reasonably frequently around the British Isles and north Atlantic coasts and it has been suggested that it could be linked to high amounts of inorganic nutrients (Veldhuis *et al.* 1986), and more specifically to decreasing ratios of N:P (Riegman *et al.* 1992).

Under guidelines of the Comprehensive Studies Task Team (CSTT 1997) of the Marine Pollution Monitoring Group, an area is suggested to be adversely affected by nutrient inputs if winter concentrations of dissolved available inorganic nitrogen (DAIN) are greater than 12 mmol/m^3 (=170µg/litre) in the presence of at least 0.2 mmol/m^3 (=6.2µg/litre) DAIP, or, if summer concentrations of surface chlorophyll are greater than 10µg/litre. Data collected during March 1997 showed DAIN levels were above the limits outlined by the CSTT across most of the sampling area. DAIN levels during this time varied from 111-677 µg/litre (10.5-48.4 µg-at/litre) and averaged 369 µg/litre (26.4 µg-at/litre). DAIP concentrations varied from 16-53 µg/litre (0.5-1.7µg-at/litre) and had an average of 28.8µg/litre (0.93µg-at/litre).

Chlorophyll concentrations did not exceed the 10µg/litre limit on any sampling period, however some cause for concern must be registered regarding the winter concentrations of DAIN and DAIP across the region.

It has been suggested that a molar ratio of winter N:Si greater than 2 (µg-at/litre) is indicative of 'hypernutrified' waters or waters 'likely to become eutrophic' (NRA 1996). It can be seen from figure 65 that waters across the entire north-eastern Irish sea during March 1997 exceeded this threshold. These high N:Si are reflected in the disproportionate increase in winter concentrations of N between 1996 and 1997 (see Kennington *et al.* 1997, figures 15, 21 & 47). Winter maximum concentrations for

1997 are approximately 300μg/litre higher than those recorded for February 1996. Long term studies at PEML show that nutrient salt concentrations tend to peak during February for SRP and during March for TON (figure 66). The winter 1997 survey was undertaken a week later than that for 1996, which may account for some of the increased levels of N for 1997 as concentrations may still be increasing at this time. It is however unlikely that this factor alone accounts for such a marked increase. Winter silicate concentrations between the two years indicate only a slight increase in silicate during 1997. Results from the AQUACHECK quality control procedures do not suggest any significant differences between results obtained from PEML and other laboratories involved.

4.5.4 Occurrence of Nuisance Algae

Evidence of severe phytoplankton blooms has been reported in the north-eastern Irish Sea in recent years. (MBCC 1995,1996,1997.). Results from the present study show that the nuisance alga *Phaeocystis globosa* was present in high abundances in waters to the north of the region during May 1997. Although thought not to be toxic this alga has been responsible for the production of surface scums which can be unpleasant to bathers and beach users as well as clogging the nets of fishermen. This species has also been associated with the production of Di-Methyl Sulphide (DMS) an abundant volatile sulphur compound in sea water which contributes to the production of acid rain (Malin, Turner & Liss 1992). High concentrations of this alga could potentially pose a threat to benthic fauna and flora after bloom die-back owing to decreased light penetration and reduced bottom water oxygen concentrations.

Large blooms of the dinoflagellate *Noctiluca scintillans* were reported along the Cumbrian, Lancashire and Manx coastlines during mid-July (MBCC 1998, Shammon *et al* 1997). Concentrations along the Manx coastline reached levels of 4 x 10^5 cells/litre (Shammon *et al.* 1997).

The potentially toxic dinoflagellates *Dinophysis acuta* and *D.acuminata* were found at several locations along the Cumbria coast during May and July in concentrations exceeding guideline levels of 100 cells/litre. Concentrations of up to 2700 cells/litre were also reported during late August from the Cypris station located approximately 5km to the west of Port Erin, Isle of Man (Shammon *et al.* 1997).

5.0 FUTURE CONSIDERATIONS

Workington North, Workington South and Braystones HNDA's were designated LSA's (Less Sensitive Areas) in March 1997 under the European Union Urban Waste Water Treatment Directive. Articles 6 & 15 of this directive stipulate certain requirements with regard to the continued monitoring of LSA water and for the status of the water quality to be reviewed at periods of not more than four years. Results obtained from the 1997 surveys continue to suggest that the three LSA's are hypernutrified in winter according to the CSTT (1997) guidelines. After the spring bloom surface concentrations of nutrient salts and chlorophyll decrease to acceptable concentrations. However, there is some evidence to suggest increasing winter nutrient concentrations of N and P within these coastal waters (compare values in Allen *et al.* 1996, Kennington *et al.* 1997, and herein) and other regions of the Irish Sea (Allen *et al.* 1998).

The influence of industrial sources of inorganic nutrients on the eastern Irish sea is very evident. BNFL Sellafield is a major point source of oxidised nitrogen, current consent limits allowing discharges of 4080 te/N per annum. The actual discharge for 1997 was approximately 900 te/N, but the input of nitrogenous compounds from Sellafield is set to increase in the future as reprocessing activity increases.

Phosphate discharges from Albright & Wilson near Whitehaven are readily apparent in the nutrient data. The discharge has been estimated to be responsible for approximately 45% of the total phosphorus input to the region (Kennington *et al.* 1997). The phosphorus discharge from Albright & Wilson currently runs at approximately 1800 te/P/annum: the company is set to undertake further treatment in the future. Although this is primarily for heavy metal recovery, phosphate discharges are also expected to benefit from this treatment.

Elevated concentrations of SRP were reported in waters adjacent to Sellafield during May and July of 1996, this phenomenon being found again during the July 1997 survey. SRP discharges from Sellafield have decreased slightly in recent years from approximately 72 te/P/annum in 1994 to approximately 65 te/P/annum in 1996.

The effect that increased anthropogenic sources of nutrients will have on the coastal environment in the north-east Irish Sea can only be tentatively considered. Data recorded over the last three years suggest increasing ratios of winter N:Si and N:P. At present the system, although hypernutrified, shows few signs of eutrophic conditions although such enrichment of other enclosed or semi-enclosed water bodies has proven to have had deleterious consequences.

The collaboration between the EA (North-West Region) and PEML over the last three years has highlighted spatial and temporal trends in the surface nutrient and phytoplankton dynamics of the north-eastern Irish Sea. Work on these interrelationships will continue during 1998, more emphasis, however, will be spent on the monitoring and recording of nutrient salt concentrations and phytoplankton abundances at varying depths within the water column.

6.0 CUMBRIA COAST SURVEY: CONCLUSIONS

- Winter concentration of dissolved available inorganic nitrogen (DAIN) varied between 111-677µg/litre (10.5-48.4 µg-at/litre) and winter levels of dissolved available inorganic phosphorus (DAIP) varied between 16-53 µg/litre (0.5-1.7µg-at/litre). Under the guidelines of the Comprehensive Studies Task Team (CSTT 1997) waters within the study area are classed as hypernutrified.

- Concentrations of Soluble Reactive Phosphate were highest around Whitehaven/S[t] Bees Head or Sellafield on all sampling occasions. These results are in agreement with those of Allen *et al.* (1996) and Kennington *et al.* (1997) who also reported elevated concentration of SRP around these locations.

- Winter concentrations of TON were highest between the Solway Firth and Ravenglass estuary. Concentrations of TON decreased rapidly after the onset of spring phytoplankton production.

- Winter ratios of N:Si of greater than 2 were recorded across the region, such high ratios it has been suggested (NRA 1996) being indicative of waters subject to future eutrophication.

- Water column stratification was especially apparent in regions of the north-east Irish Sea during March and July. During March waters around the Solway Firth showed a marked haline stratification whilst during July waters to the south of S[t] Bees Head were thermally stratified.

- Concentrations of surface chlorophyll across the north-eastern Irish Sea did not exceed the 10µg/litre threshold outlined by the CSTT on any of the sampling occasions.

- All winter nutrient salt concentrations and distributions are strongly positively correlated ($P= <0.05$) reflecting the strong east-west gradient in concentrations during March. This relationship breaks down during May as a consequence of selective modification of the nutrient salts by the plankton flora.

- Diatoms and small flagellated algae were the dominant representatives of the phytoplankton during March. During May the nuisance alga *Phaeocystis globosa* was the dominant member of the plankton and occurred in very high abundances towards the north of the region. Phytoplankton community structure analysis undertaken on the May phytoplankton data showed two distinct groups, one to the north of the region dominated by *Phaeocystis globosa*, *Guinardia deliculata*, *Nitzschia* spp. and *Chaetoceros* spp. (in order of importance), whilst the group to the south of the region was dominated by *Phaeocystis globosa*, monads/small flagellates, Gymnodiniales and microzooplankton (in order of importance). July phytoplankton abundances show that diatoms are much less abundant during the summer and monads/small flagellates, *Ceratium* spp. and the Gymnodiniales account for the greatest percentage of the plankton. Microzooplankton was also present in high concentrations during July. Concentrations of the potentially toxic dinoflagellates *Dinophysis acuta* and *D. acuminata* were found at concentrations substantially exceeding 100 cells/litre at some sites (i.e. above EA action levels) during May and July.

7.0 LIVERPOOL BAY SURVEYS

7.1 INTRODUCTION

A series of five sampling trips weas undertaken in Liverpool Bay and the results are presented below. All data were collected by the R.V. Coastal Guardian and sampling protocols and techniques remain the same as for the Cumbrian coast surveys. As with all SURFER plots the reader should pay close attention to the location of the sampling sites as SURFER extrapolates data for areas where no samples are taken (figures 67-71). The actual sampling dates were as follows;

Liverpool Bay

28/01/97
16/04/97
09/06/97
11/11/97
01/12/97

7.2 RESULTS

7.2.1 Physical Patterns

Sea surface temperatures (SST) showed a northwest-southeast trend within Liverpool Bay on all sampling occasions. During January, warmest SST's (~6°C) were found offshore and to the northwest of the bay (see figure 72) whilst coldest waters were found inshore (~4°C). During April the trend had reversed (figure 73) and warmest temperatures (~12°C) were found to the southeast of the study area particularly around the Dee and Mersey estuaries. Coldest SST's (~8°C) during April were located offshore. This trend continued during June where inshore waters reached ~16°C and offshore waters approximately 11°C (figure 74). November and December SST's (see Figures 75 & 76) saw a reversal of the spring/summer SST distribution with offshore waters once again being warmer than offshore waters (warmest SST's during these months being ~12 & 11°C respectively).

Surface water salinities showed a very similar trend on all sampling occasions. Lowest surface salinities were found in coastal waters especially around the Dee and Mersey estuaries. Penetration of low salinity surface waters was greatest during January, April, November & December and lowest during June (figures 77-81).

7.2.2 Patterns of Nutrient Distribution

During January, April, November and December 1997 the majority of total inorganic nitrogen (DIN) was present as nitrate, whilst highest concentrations of DIN during June were available as ammoniacal nitrogen. Concentrations of TON (Total Oxidised

Nitrogen) during January were highest along the coastline of Liverpool Bay where levels of up to 450μg/litre were recorded (figure 82). Highest concentrations of nitrate were found between the Ribble and Mersey estuaries (figure 83). These high values of nitrate decrease westwards, where concentrations of less than 200μg/litre are recorded. Concentrations of ammoniacal nitrogen during January were also highest along the coastlines of England and Wales with maximum concentrations being located between Formby Point and Llandudno (figure 84). Nitrite concentrations during this time were highest between Llandudno and Prestatyn (figure 85).

Concentrations of TON remained relatively high around the Mersey and Ribble estuaries during April (figure 86). Highest concentrations were noted in waters adjacent to the Mersey where TON concentrations reached 350μg/litre. Concentrations of TON along the north Wales coast had decreased considerably since January and were generally less than 60μg/litre at this time. TON concentrations continued to decrease between April and June. By June 1997 concentrations across the majority of the area averaged <50 μg/litre. Waters adjacent to the Ribble and Mersey estuaries had the highest concentrations of TON with maximum values approximating 300μg/litre (figure 87). Concentrations of TON had increased by November 1997 and elevated levels were found along the majority of the English and Welsh coasts (figure 88). Maximum concentrations during this time reached approximately 430μg/litre. The highest recording of TON was found during December 1997. Concentrations during this time reached a maximum of 800μg/litre and were centred around the Mersey estuary (figure 89).

Concentrations of ammoniacal nitrogen generally followed the distribution of TON on each sampling date. Concentrations during January were highest along the coast between Liverpool and Southport with maximum values of 120μg/litre (figure 90). Elevated concentrations remained to be found around the Mersey during April with maximum concentrations reaching approximately 100μg/litre (figure 91). Concentrations of ammoniacal nitrogen had increased between April and June. Maximum concentrations (~ 200μg/litre) were found along the coastline between Rhyl and Southport (figure 92). Concentrations decreased once more by November with values now not exceeding 130μg/litre. Highest values were recorded in coastal waters between Morecambe Bay and the Ribble estuary (figure 93). Concentrations of ammoniacal nitrogen during December had highest values (~130μg/litre) recorded from the Mersey and Dee estuaries (figure 94).

Concentrations of Soluble Reactive Phosphate (SRP) within Liverpool Bay appeared to remain relatively high throughout the year. During January and April highest concentrations (68 & 61 μg/litre respectively) were located towards the south-east of the study area (figures 95 & 96). Concentrations across most of the region during June had decreased (figure 97), however, waters associated with the Mersey estuary showed levels higher than those recorded for January and April (maximum concentrations ~ 75μg/litre). Concentrations had increased across the region by November (figure 98), highest concentrations being located to the south-east of the bay and to the north of the Ribble Estuary (maximum concentration ~117μg/litre). The maximum value recorded of any sampling period was for December 1997. At this time concentrations were generally higher to the east of the study area with maximum concentration (~ 160µg/litre) found in waters associated with the Mersey Estuary (figure 99).

Concentrations of silicate during January showed a south-east /north-west trend with highest concentrations (>1000µg/litre) located to the south-east (figure 100). Concentrations had decreased considerably between January and April with highest concentrations (500µg/litre) now being recorded in waters to the north-east of the region (figure 101). Coastal waters between the Wirral peninsula and Llandudno had greatly decreased in concentration and average concentrations in these waters were less than 100µg/litre. Silicate concentrations fell further between April and June with higher concentrations (~ 400µg/litre) being found along the north Wales and Cheshire coasts (figure 102). High silicate concentrations had returned by November with maximum concentrations (~ 650µg/litre) being associated with waters adjacent to the Mersey Estuary and along the coast north of the River Ribble (figure 103). Concentrations continued to increase through December and highest concentrations (~1000µg/litre) were found in waters to the south-east of the study area, particularly around the Dee estuary (figure 104).

7.2.3 The Distribution of Surface Chlorophyll

Data on the speciation and distribution of phytoplankton within Liverpool Bay are only available for the June survey. Surface chlorophyll values are given for each of the sampling dates. During January the majority of Liverpool Bay had surface chlorophyll concentrations of less than 2µg/litre. Coastal water to the north of the study area recorded chlorophyll concentrations of up to 7µg/litre whilst those around the Mersey and Dee estuaries had concentrations of between 2-4µg/litre (figure 105). Chlorophyll concentrations had significantly increased across the region by April, reflecting the increased phytoplankton production during this time. Waters to the north of 53.5N generally had concentrations of less than 8µg/litre. Waters to the south of 53.5N had much higher concentrations, coastal waters between Llandudno and the Wirral Peninsula recording concentrations as high as 38µg/litre (figure 106). This period of increased phytoplankton activity had decreased by June and concentrations across the region were less than 8µg/litre (figure 107). Coastal waters around the Ribble estuary had the highest concentrations of chlorophyll during June. The abundances of phytoplankton during June are shown in figure 110. It can be seen that abundances of total phytoplankton are generally highest to the south-east of the study area. Maximum phytoplankton abundances occurred in waters offshore from Southport where they reached approximately 28000 cells/litre. Surface chlorophyll concentrations had decreased by November and waters in the Bay at this time had concentrations of less than 3.5µg/litre (figure 108). Concentrations during December were below 1.5µg/litre across the entire region (figure 109).

8.0 LIVERPOOL BAY SURVEYS: SUMMARY

8.1 MAJOR SPATIAL AND TEMPORAL TRENDS

Physical parameters (SST and surface salinities) showed a general southeast-northwest trend within Liverpool Bay on all sampling occasions. Warmest SST's were found offshore during January, November and December and inshore during April and June. Surface water salinities were greatest offshore on all sampling occasions. The penetration of low salinity surface waters was evident throughout the year. The influence of freshwater runoff from estuaries within the Liverpool Bay catchment on silicate, salinity and nutrients was apparent on all sampling occasions.

Levels of nitrate and silicate generally reflect a combination of coastal inputs and patterns of phytoplankton growth, being more depleted in areas of increased phytoplankton production, particularly during April. The increased productivity during April was very high in waters associated with the Mersey and Dee estuaries where concentrations reached 38µg/litre. Concentrations of inorganic nitrogen were especially low during June when compared to the winter/spring concentrations. Levels of nitrogenous compounds recorded during April were higher than those recorded for June suggesting that the April samples were collected prior to the onset of major phytoplankton production.

Nutrient concentrations within the Bay were highest during January before any major modification by the phytoplankton. Silicate and nitrogenous compounds rapidly decreased in concentration over the bay between January and April, whilst SRP concentrations remained relatively high over most of the region. However, concentrations of SRP along the north Wales coastline decreased considerably between these two sampling dates. The distribution of winter nutrients within the Bay appear to be controlled to a great extent by physical parameters operating within the area. The high winter nutrient loadings are associated with less saline waters discharging from the Dee, Mersey and Ribble estuaries.

Previous studies within Liverpool Bay have shown that the spring productivity peak generally occurs during May and early June (Foster *et al.* 1982). It is therefore possible that the spring chlorophyll maximum may have been missed in the present study. The relatively low chlorophyll levels recorded during the June survey may represent levels after peak production. The high chlorophyll levels recorded during April suggest the spring phytoplankton bloom may have occurred earlier during 1997 than in previous years. Studies on the chlorophyll concentration during 1996 showed that summer productivity remained relatively high with concentrations reaching 25µg/litre during August (Kennington *et al.* 1997), but this phenomenon was not recorded during 1997 as no late summer survey was conducted.

8.2 EVIDENCE OF IMPACT OF NUTRIENT INPUTS

The input of nutrient salts into Liverpool Bay arises from several sources. Agricultural run-off of fertiliser applications in excess of those that can readily be taken up by crops are washed into the water courses within the Liverpool Bay catchment and subsequently find their way to the marine environment. Discharges of silicate from at least one point source within the Mersey catchment are known. The discharge of domestic sewage into Liverpool Bay is a major contributor of nutrient salts which can be especially high in nitrogenous compounds (Taylor & Parker 1993). The dumping of sewage sludge into Liverpool Bay during 1996 has been estimated to contribute approximately 3749 tonnes/N and 1095 tonnes/P respectively. The majority of sewage sludge dumping in the region occurs at a region nominally defined as approximately 10 nautical miles north of the Rhyl Flats in north Wales.

The influence of riverine inputs of nutrient salts into the Bay was most evident during winter and early spring especially around the Dee and Mersey estuaries. These observations support those found in previous years (Irish Sea Study Group 1990, Gillooly *et al.* 1992). These observations suggest that the Mersey, Dee and Ribble estuaries continue to enrich the nutrient pool of Liverpool Bay throughout the year.

Guidelines set out by the CSTT (1997) suggest an area to be adversely affected by nutrient inputs if;

1) Observations of winter dissolved available inorganic nitrogen (DAIN) are greater than 12mmol/m^{-3} (~170μg/litre) in the presence of at least 0.2mmol/m^{-3} (~6.2μg/litre) dissolved available inorganic phosphate or,

2) Summer chlorophyll concentrations are greater than 10μg/litre.

Winter nutrient concentrations exceeded the above criteria at most of the sampling sites regarding concentrations of DAIN which had a range of 63-669μg/litre. Winter concentrations of DAIP ranged from 23-98μg/litre at every sampling site, far exceeding the concentration recommended by the CSTT. Chlorophyll concentrations during April exceeded the recommended 10μg/litre threshold but had declined by June when no sites in the study area reached this threshold.

The winter ratios of N:Si within the bay show an extensive area of coastline between the Mersey and the western extent of the sampling area to have ratios greater than 2. Under suggestions of the CSTT such high ratios are indicative of waters liable to future eutrophication (figure 111).

8.3 LIVERPOOL BAY SURVEYS: CONCLUSIONS

- Under guidelines of the Comprehensive Studies Task Team (CSTT 1997) of the Marine Pollution Monitoring Management Group (MPMMG) waters along the north Wales coast and adjacent to the Mersey and Dee estuaries are adversely affected by nutrient inputs. The relatively high concentration of winter DAIN and DAIP support the recommendation made in 1997, to withdraw the HNDA (LSA) status of the North Wirral outflow waters.

- On all sampling occasions nutrient concentrations were highest towards the south-east of the study area, particularly around the Dee, Mersey and Ribble estuaries.

- Surface chlorophyll concentrations were highest during the April survey with maximum levels being found along the north Wales coast. Concentrations declined during the summer months and did not exceed the 10µg/litre threshold outlined by the CSTT.

- Ratios of N:Si exceeded 2 along the North Wales coastline. According to suggestions made by the CSTT such high ratios are indicative of waters subject to future eutrophication.

9.0 THE DISTRIBUTION OF NUTRIENTS AND PHYTOPLANKTON IN THE EASTERN IRISH SEA DURING 1997.

9.1 SUMMARY OF MAJOR CONCLUSIONS

- Winter levels of DAIN and DAIP along the Cumbrian coastline exceeded those reported during the 1996 sampling period. Under guidelines set out by the CSTT these waters are classed as hypernutrified (CSTT 1997) and possibly subject to future eutrophication according to current winter N:Si ratios which show that all waters in the study area have ratios of greater than 2. Winter levels of DAIN and DAIP within Liverpool Bay also exceeded these guidelines and waters along the north Wales coastline also showed winter N:Si ratios of greater than 2.

- Results from the Cumbria coast survey show concentrations of SRP to be highest around S^t^ Bees Head on all sampling occasions. Elevated levels of SRP were also reported around Sellafield during July. The influence of BNFL Sellafield on ~~concentrations of nitrogenous compounds within the region is also readily apparent~~ from the survey data especially during March and June. These results are in good general agreement with the finding of previous years (Jones & Folkard 1971, Allen *et al.* 1996, Kennington *et al.* 1997). Highest concentrations of nutrient salts within Liverpool Bay were found around the south-east of the study area, particularly around waters associated with the north Wales coastline and the Dee and Mersey estuaries.

- Concentrations of surface chlorophyll recorded during the summer months did not exceed the 10μg/litre threshold outlined by the CSTT (1997) for either the Cumbria coast or Liverpool Bay. Concentrations within Liverpool Bay did however exceed these guidelines during the April survey.

- Results from the Cumbria coast survey show that water column stratification was apparent on most sampling dates. Winter (haline) stratification was recorded towards the Solway Firth and in a region towards the west of the study area. Summer (thermal) stratification was also noted in waters extending offshore from Sellafield.

- Comparisons between winter nutrient concentrations and spring phytoplankton data for the Cumbria coast surveys were not as conclusive as in previous years (see Allen *et al.* 1996, Kennington *et al.* 1997). Two distinct phytoplankton populations were identified for the region, one to the north dominated by *Phaeocystis globosa, Guinardia deliculata* and *Chaetoceros* spp and one to the south dominated by *Phaeocystis globosa,* monads/small flagellates, gymnodiniales and *Nitzschia* spp.

MDS ordinations undertaken between winter nutrient variables and spring physical/phytoplankton variables indicated sea surface temperature to be important in discerning the two groups, followed by nitrite, TON and silicate in order of importance. Evidence from previous years has indicated winter concentrations of TON and Silicate (Allen *et al.* 1996, Kennington *et al.* 1997) as being potentially responsible for discriminating discrete phytoplankton populations during the spring.

- Evidence of severe nuisance algae blooms was reported during 1997. The prymnesiophyte *Phaeocystis globosa* was recorded in very dense concentrations in waters to the north of the Cumbrian coast survey during May. Notifiable concentrations of the potentially toxic dinoflagellates *Dinophysis acuta* and *D. acuminata* were also reported along the Cumbrian coast during May and July. Large blooms of the bioluminescent dinoflagellate *Noctiluca scintillans* were also reported along the Cumbrian, Lancashire and Manx coastlines during July (Shammon *et al.* 1997).

Appendix A. Daily Weather Recordings at Ronaldsway for the Week Prior to Sampling Trips Along the Cumbrian Coast.

	Max Temp Degrees Celsius	Min Temp Degrees Celsius	Rain total (mm)	Sunshine Total (HOURS)	Wind Dir (Deg. True)	Average Wind (Knots)	Max Gust direction (Knots)
24-Feb-97	9.1	5.5	1.3	5.5	230	24	49 sw
25-Feb-97	9.5	5.6	0.7	3.9	250	20	55 wsw
26-Feb-97	7.5	5.3	4	1.2	280	15	46 wnw
27-Feb-97	9.6	4.1	6.6	0	200	20	45 ssw
28-Feb-97	10.3	6.6	0	8.3	200	18	46 ssw
01-Mar-97	10	6.9	1.8	0	200	25	49 ssw
02-Mar-97	9	5.9	0	8.1	210	21	48 ssw
03-Mar-97	8.2	4.8	0.1	1.9	250	8	19 wsw
04-Mar-97	8.9	-0.2	0	2.7	80	10	27 ene
12-May-97	12.5	7.9	0.1	5.7	210	17	32 ssw
13-May-97	12.6	8.7	0.1	8	210	13	28 ssw
14-May-97	12.5	7.1	0	3.5	190	5	15 s
15-May-97	16.8	5.2	0	12.1	80	7	19 e
16-May-97	16.4	8.5	3.8	9.3	60	12	22 ene
17-May-97	15.6	11	6	1.4	70	8	22 ene
18-May-97	13.7	11.5	0.2	3.1	180	6	18 s
19-May-97	17.4	6.9	0.6	5.2	70	7	19 ene
10-Jul-97	20.9	10.2	0	11	90	8	22 e
11-Jul-97	18.6	13.4	0	6.3	70	4	15 ene
12-Jul-97	18.1	13.9	8.8	3.3	170	4	13 s
13-Jul-97	17.3	13.3	0.3	1.2	290	6	24 wnw
14-Jul-97	16.6	9.3	3.3	7.9	180	7	24 s
15-Jul-97	16.3	13.4	0.1	0.6	210	7	21 ssw
16-Jul-97	18.5	13.9	2.7	1	270	9	25 w
17-Jul-97	17.2	12	0	15.1	320	15	33 nnw

Appendix B

Categories for Plankton Enumeration

Thalassiosira
Skeletonema
Chaetoceros
Rhizosolenia (long)
Rhizosolenia (short)
Leptocylindrus
Thalassionema
Asterionella
Chain centric diatoms
Small solitary centrics (<50µm diameter)
Large solitary centrics (>50µm diameter)
Nitzschia
Naviculoid/ other pennales
Sigmoidal
Bacillaria
Prorocentrales
Dinophysiales
Gymnodiniales
Noctilucales
Peridinales
Ceratium
Silicoflagellates
Small flagellates/monads 5-15µm in length
Other phytoplankton
Microzooplankton

Phaeocystis cells were also counted.

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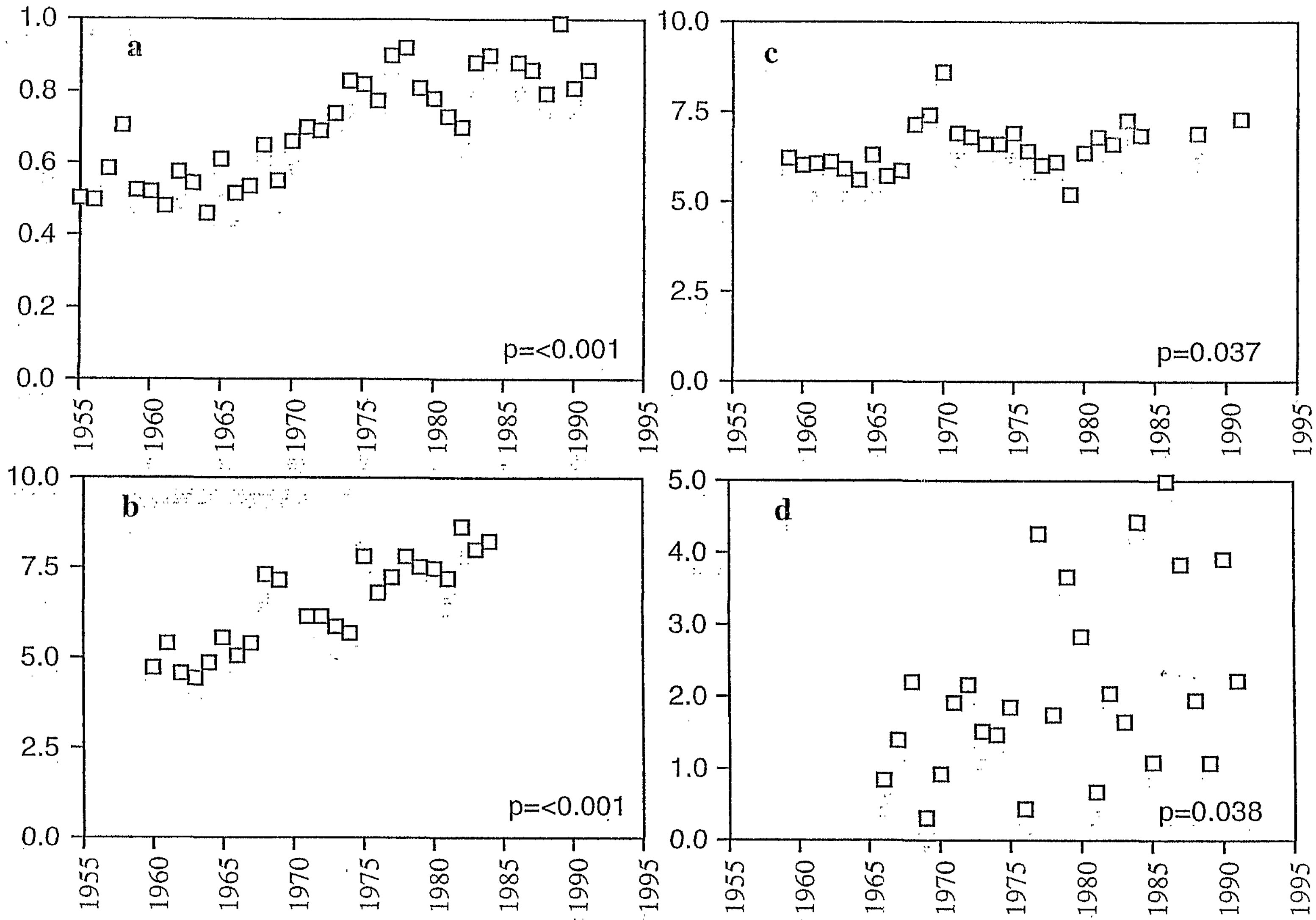

Fig. 1 **a** to **c** Time series of median nutrient concentrations for January-February, a) soluble reactive phosphate, b) total oxidised nitrogen, c) dissolved silicate, µmol/l as P, N and Si respectively. **Fig 1d** Time series of median chlorophyll concentrations for May-June, µg/l. P values are derived from non-parametric trend analysis according to Hirsh & Slack (1984), all parameters show significant increasing trends with time ($p<0.05$).

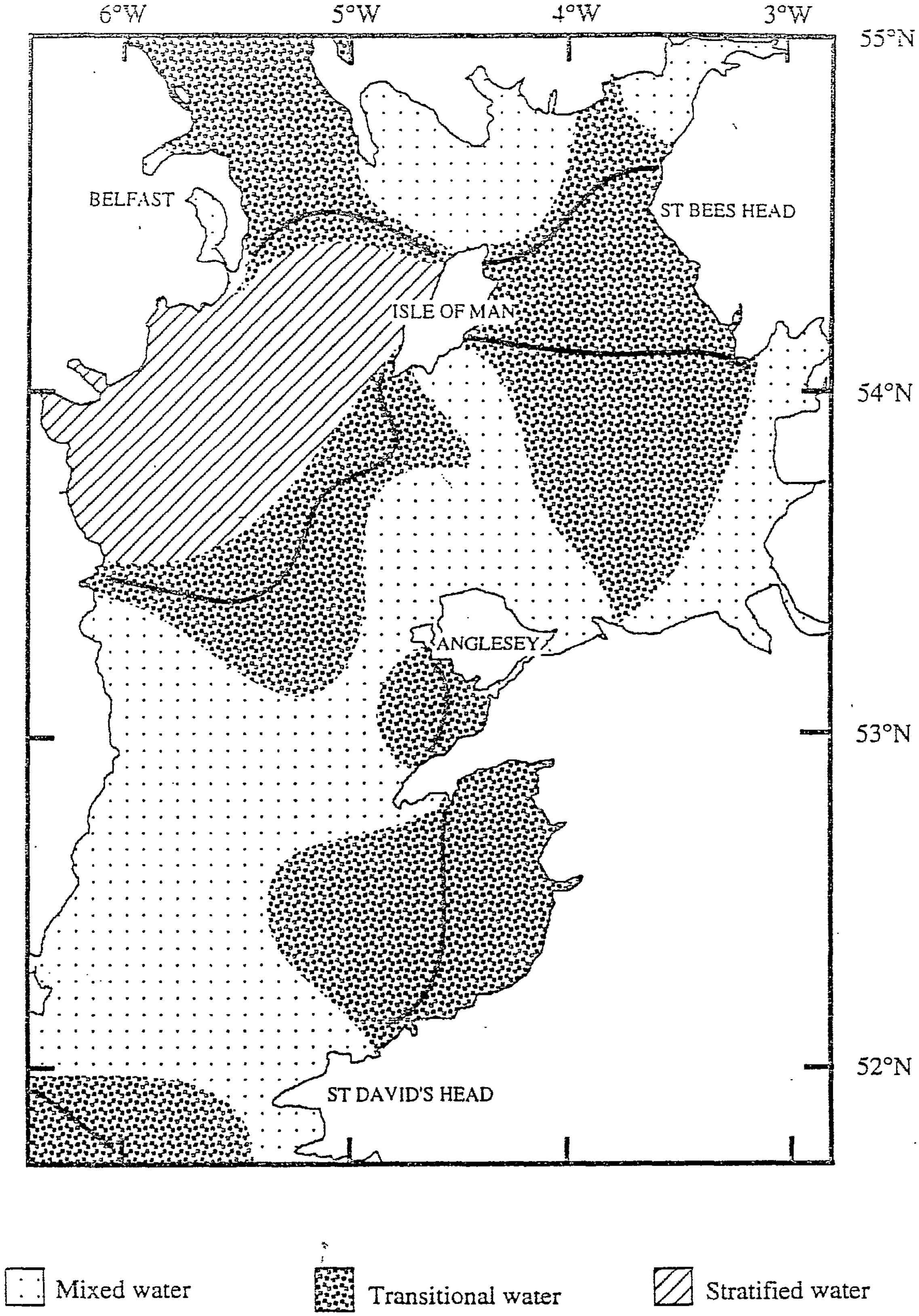

Figure 2. Summer hydrographic conditions in the Irish Sea as predicted from the numerical model of Pingree & Griffiths (1978), showing areas of mixed, transitional and stratified water and frontal regions. The approximate position of the fronts is indicated by bold lines (From Brand & Wilson 1996).

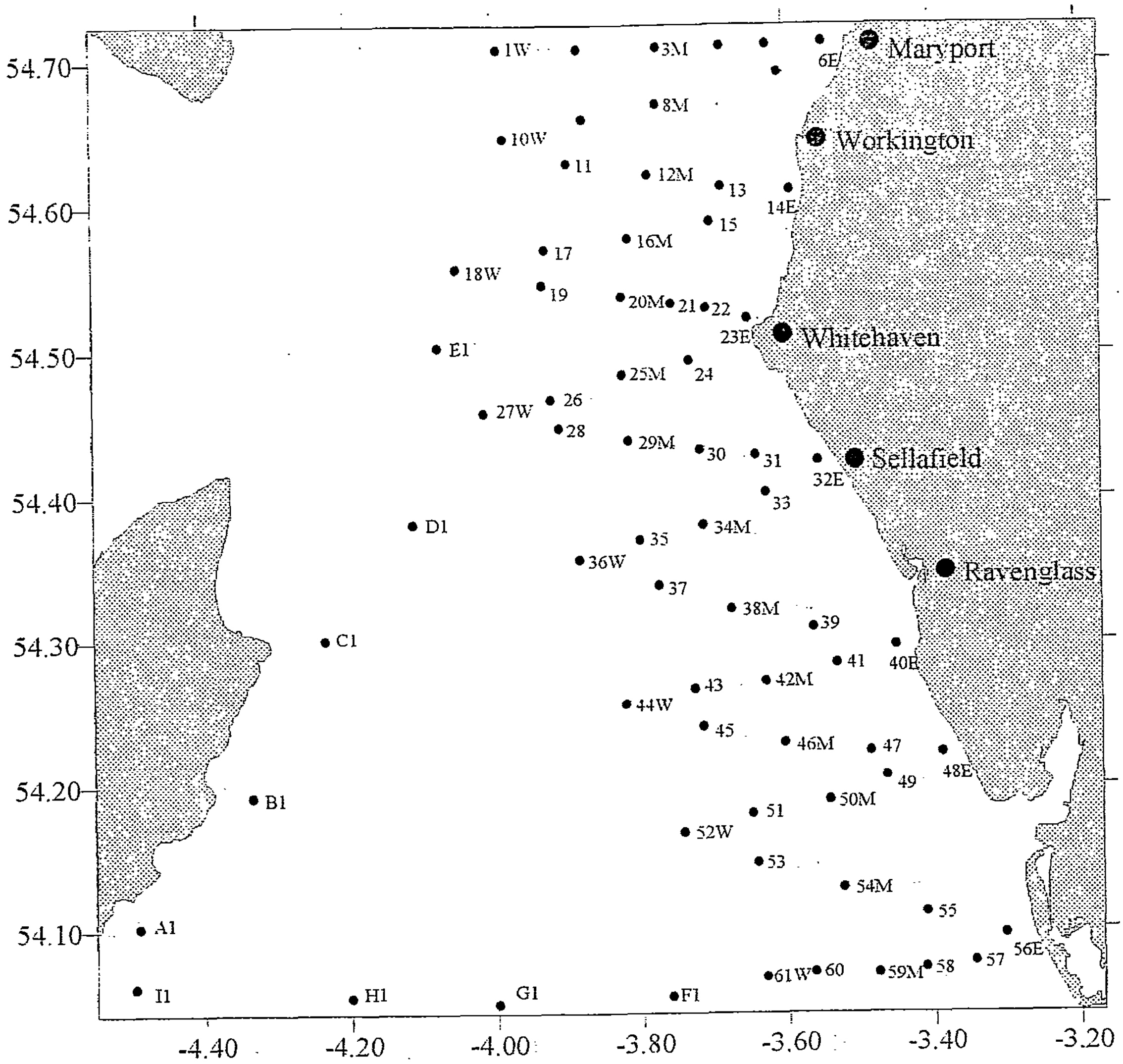

Figure 3. Cumbria coast surveys. Nominal sampling positions and site identifiers.
PEML Samples-Offshore grid

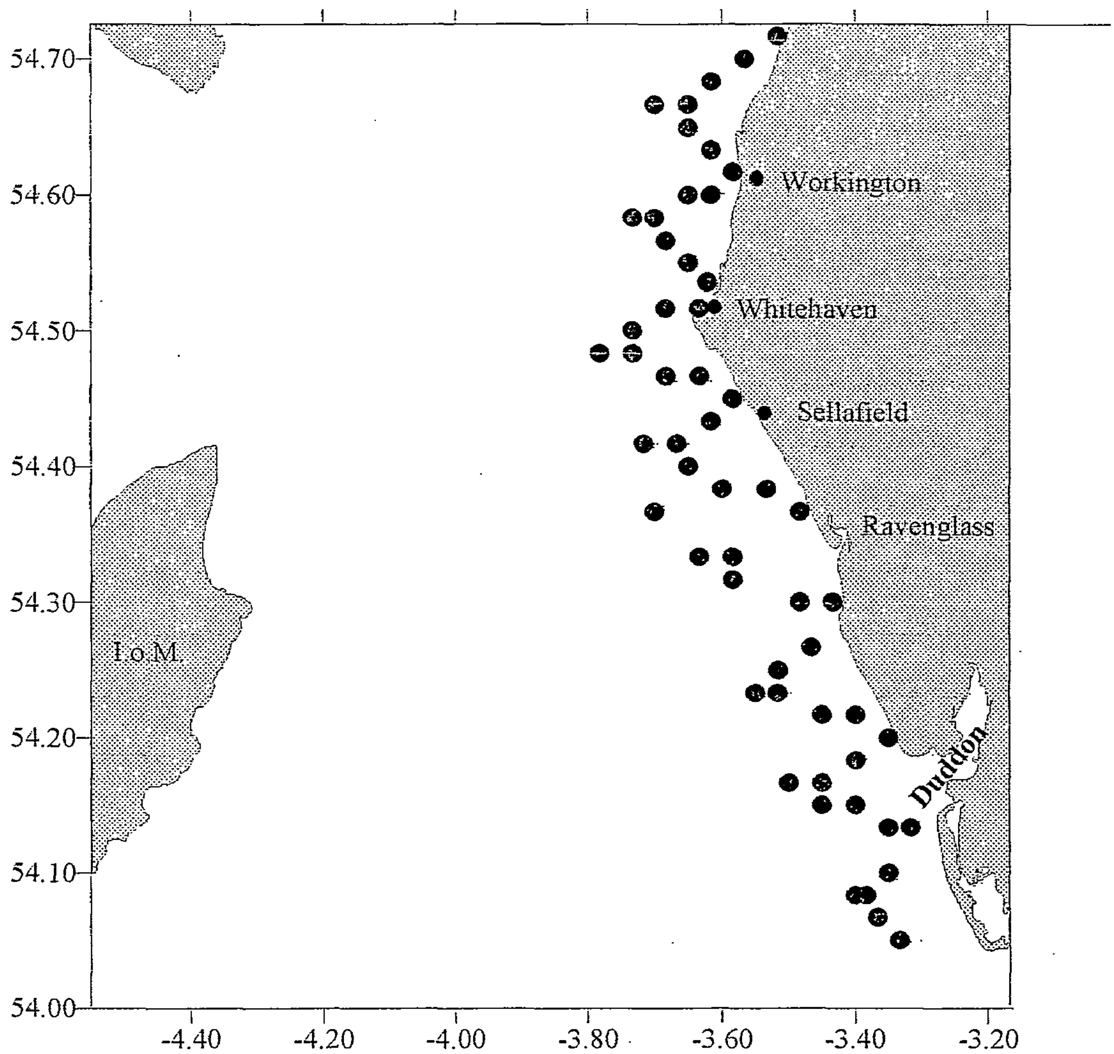

Figure 4. Discrete sampling sites for (EA) inshore-grid locations. Skalar samples were taken every 20 seconds between discrete sampling sites.

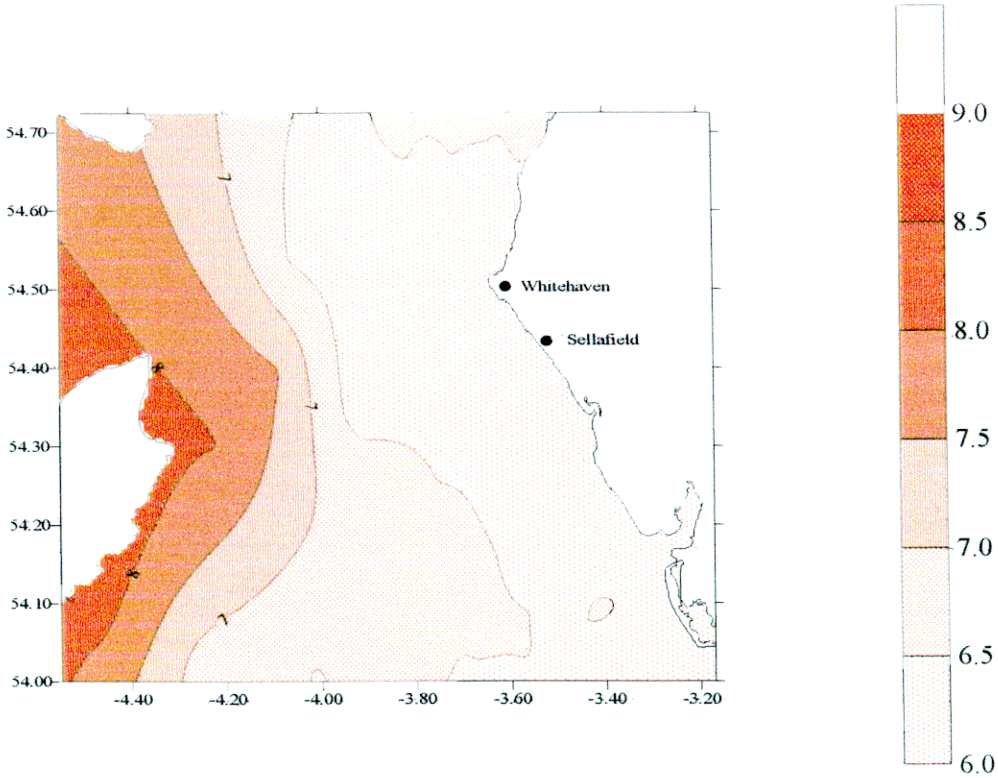

Figure 5. Cumbria Coast Survey March 1997. Temperature Degrees Celsius

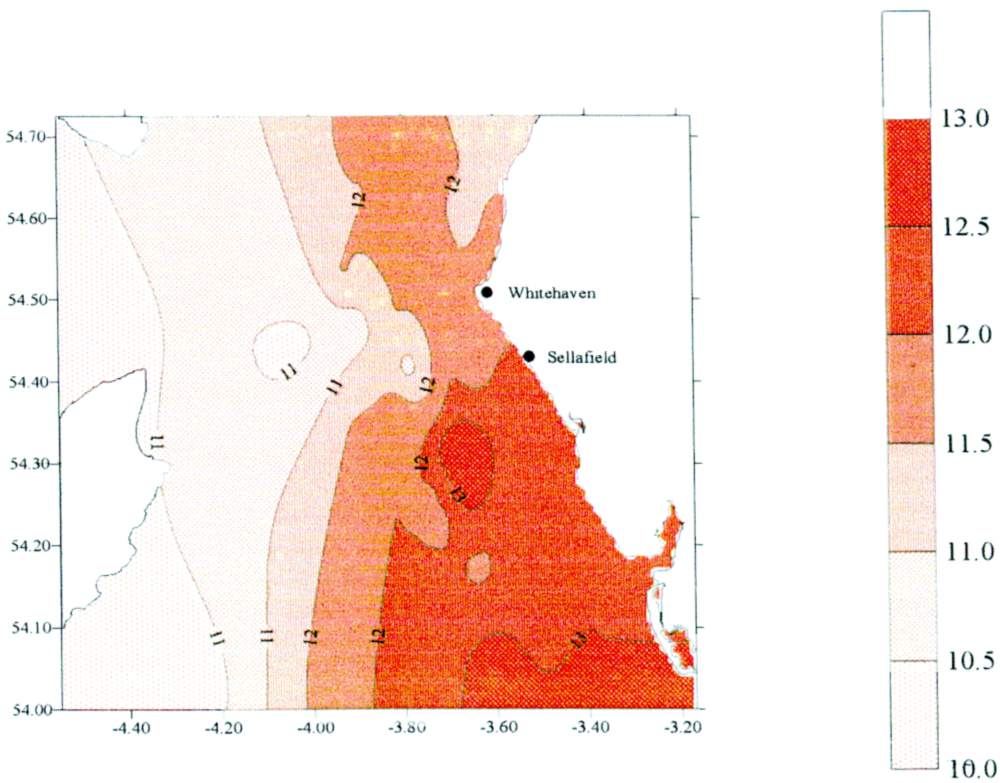

Figure 6. Cumbria Coast Survey May 1997. Temperature Degrees Celsius

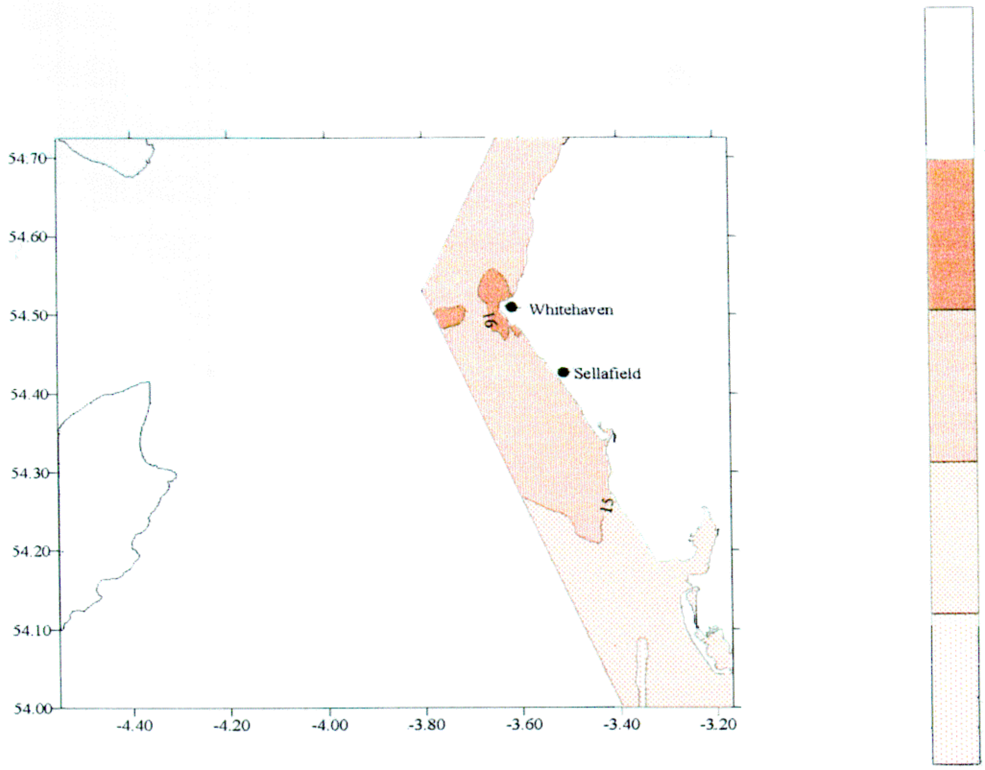

Figure 7.Cumbria coast survey June 1997. Temperature Degrees Celsius.

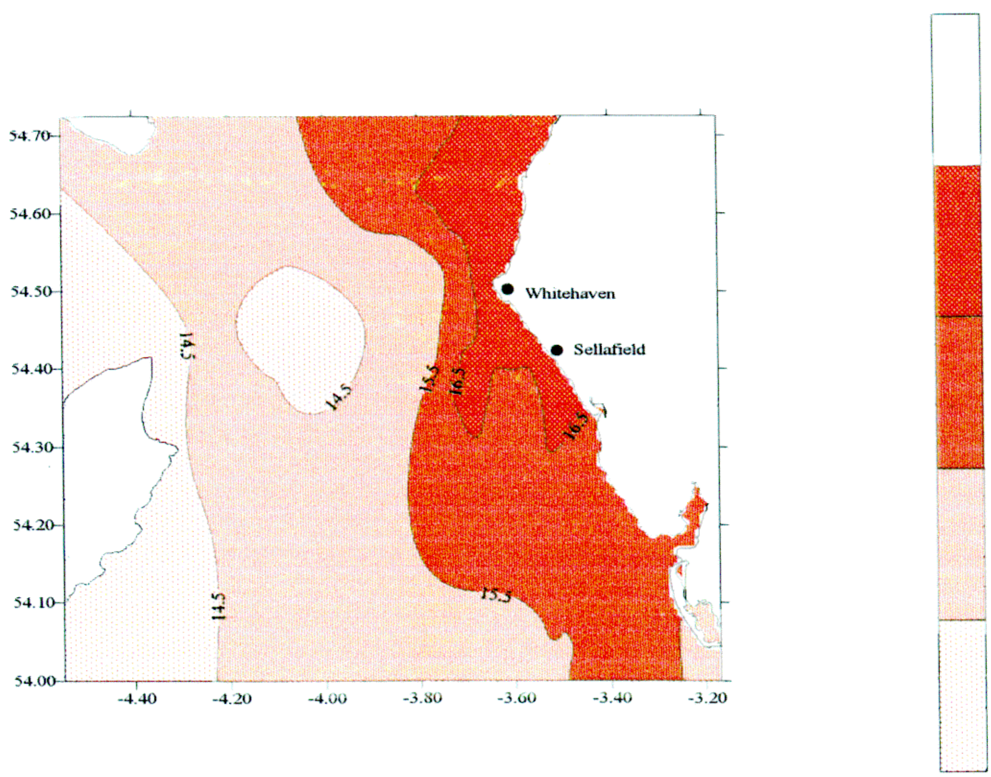

Figure 8. Cumbria Coast Survey July 1997. Temperature Degrees Celsius

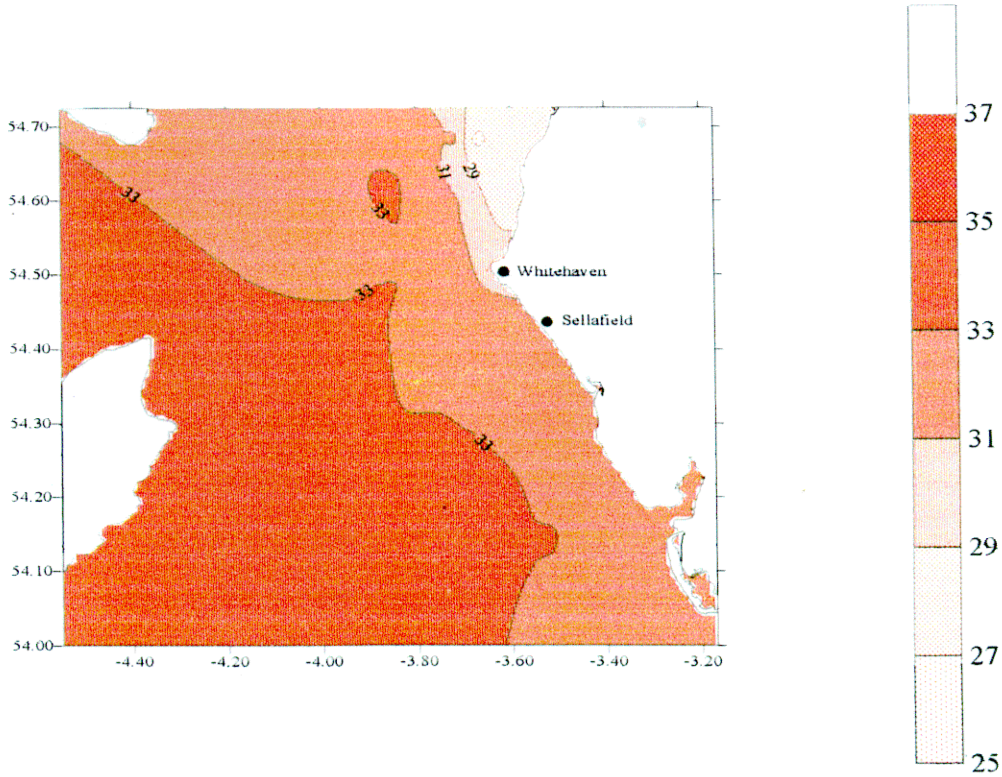

Figure 9. Cumbria Coast Survey March 1997. Salinity

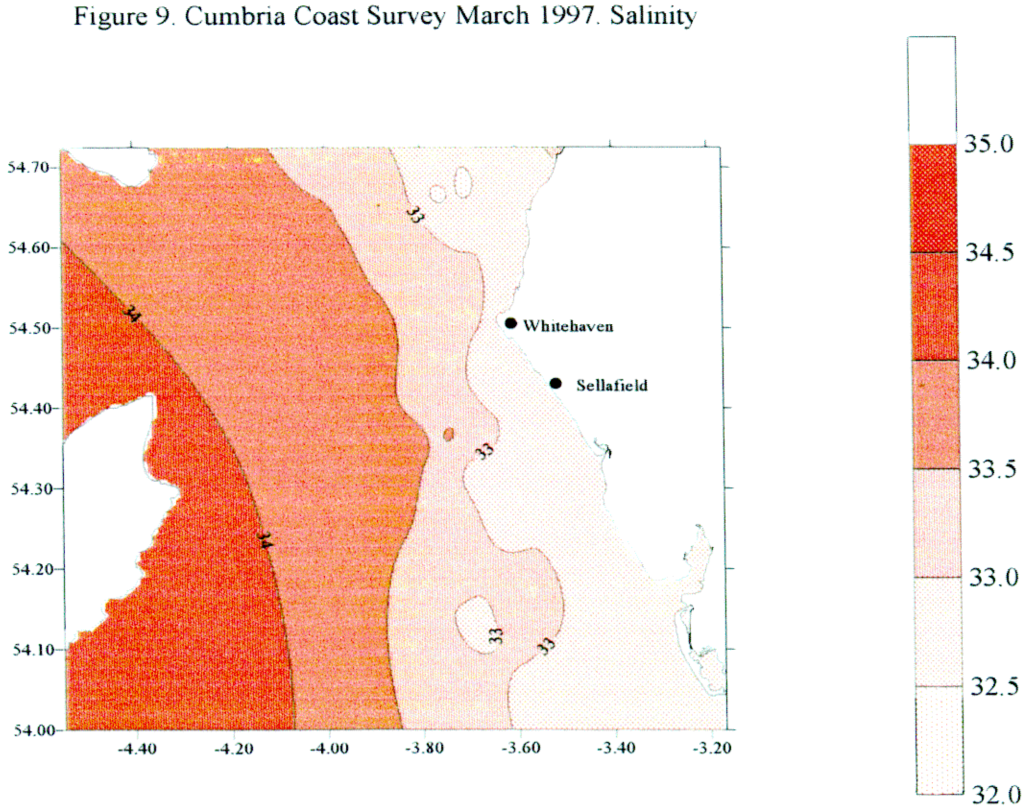

Figure 10. Cumbria Coast Survey May 1997 Salinity

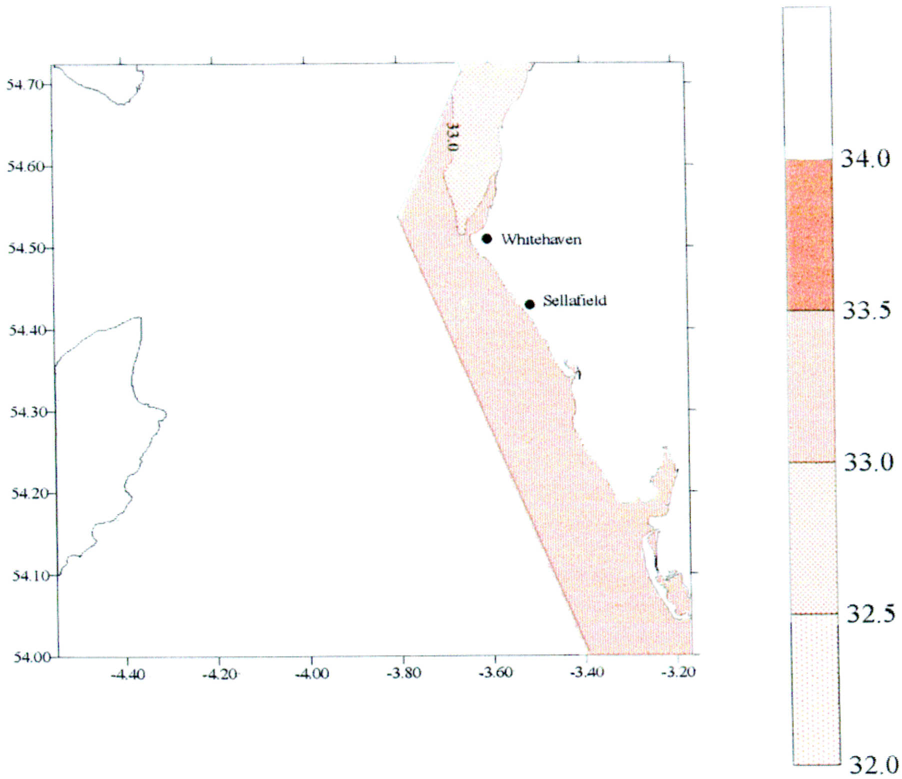

Figure 11. Cumbria coast survey June 1997. Salinity.

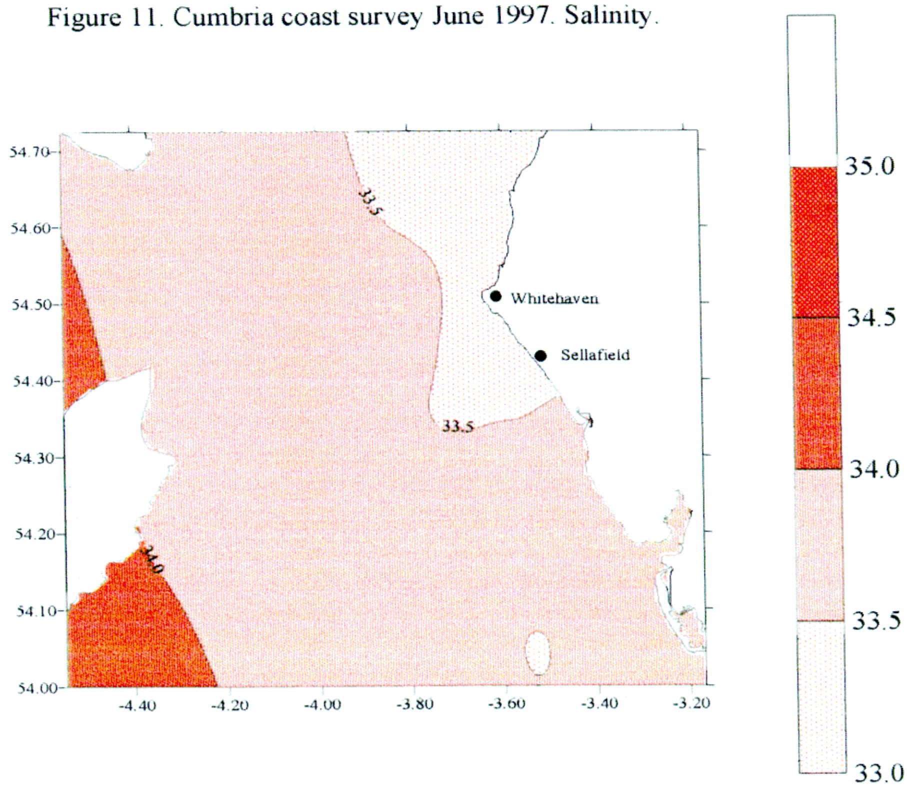

Figure 12. Cumbria Coast survey July 1997. Salinity

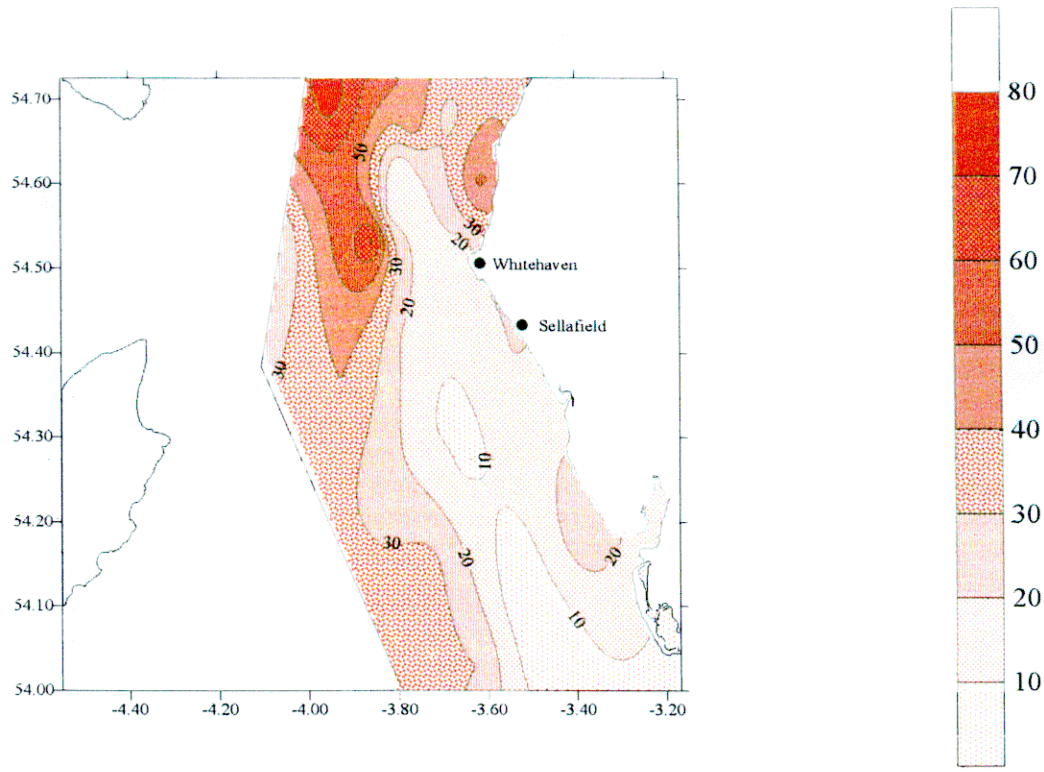

Figure 13. Cumbria Coast survey March 1997. Simpson stratification parameter. Values >20 are indicative of stratified waters. Values between 10-20 are indicative of intermediate waters.

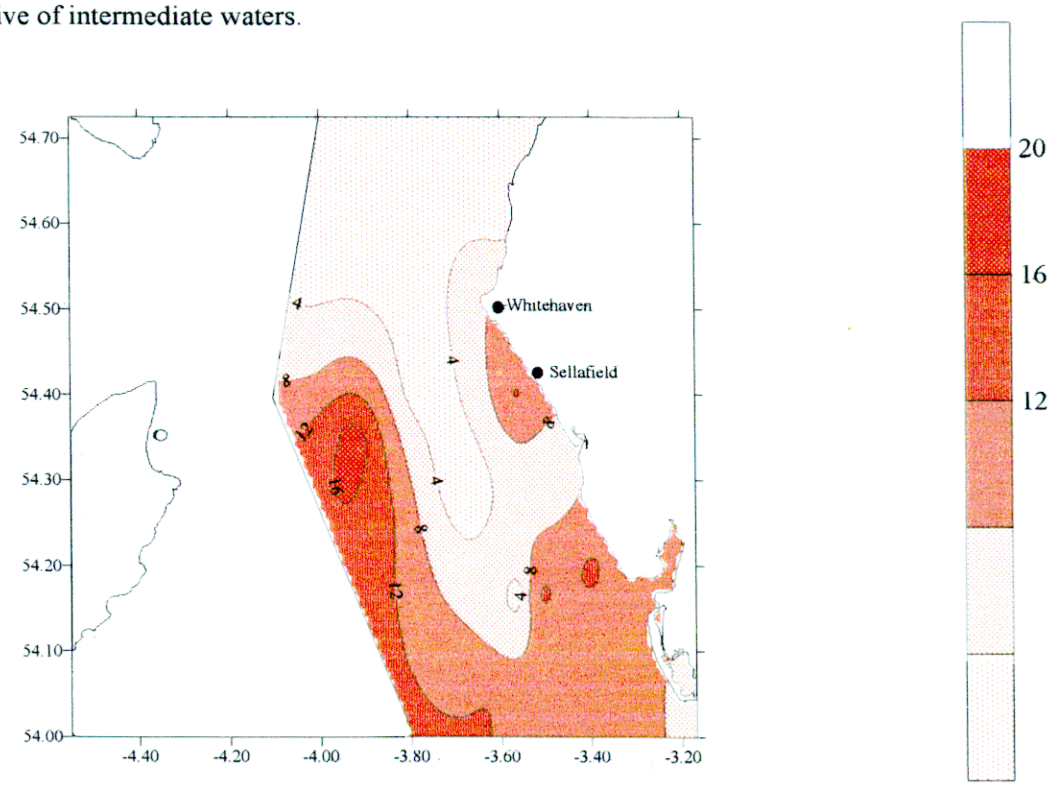

Figure 14. Cumbria Coast survey May 1997. Simpson stratification parameter. Values >20 indicative of stratified waters. Values between 10-20 indicative of intermediate waters.

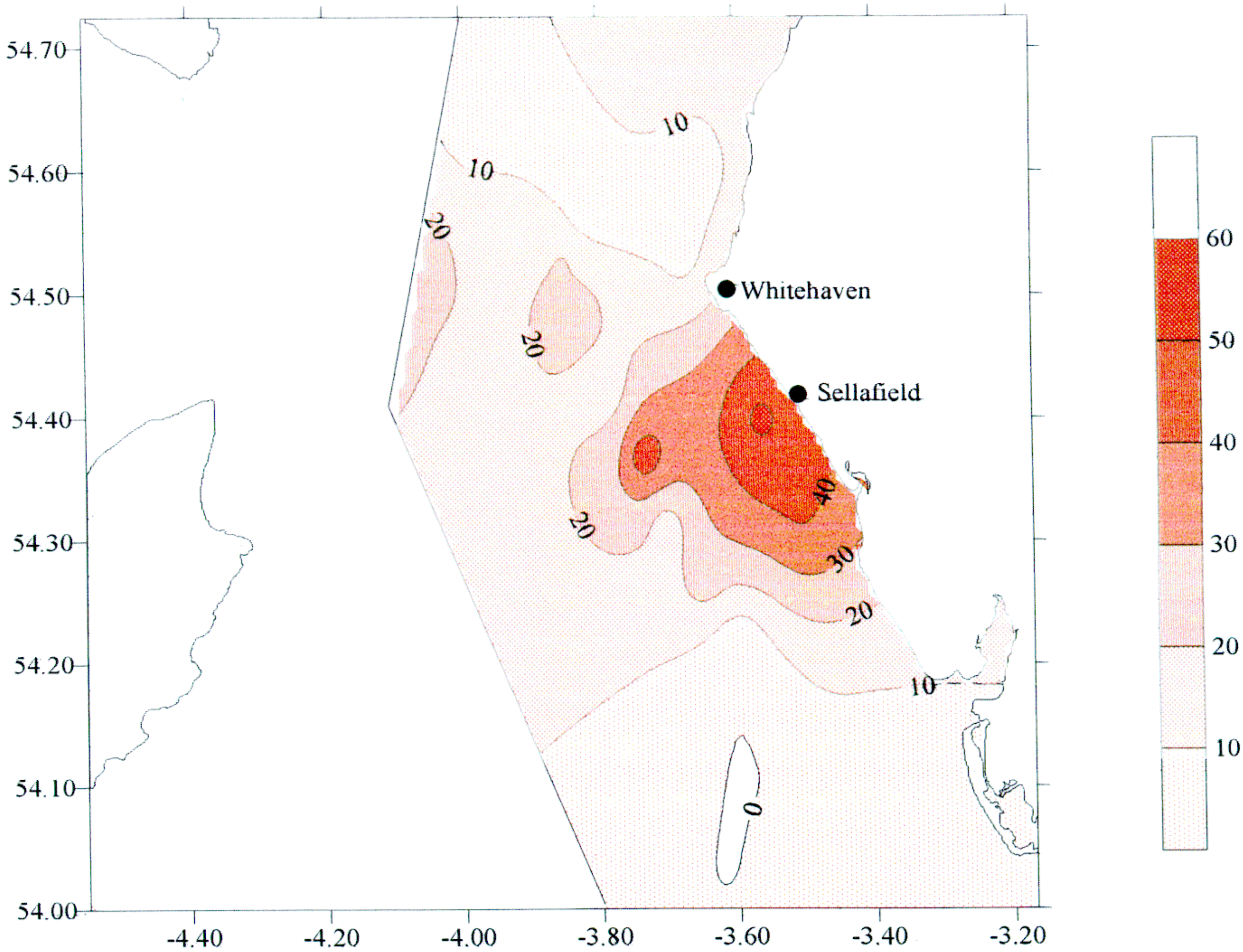

Figure 15. Cumbria Coast Survey July 1997. Simpsons Stratification Parameter. Values >20 are indicative of stratified waters. Values between 10-20 are indicative of intermediate waters.

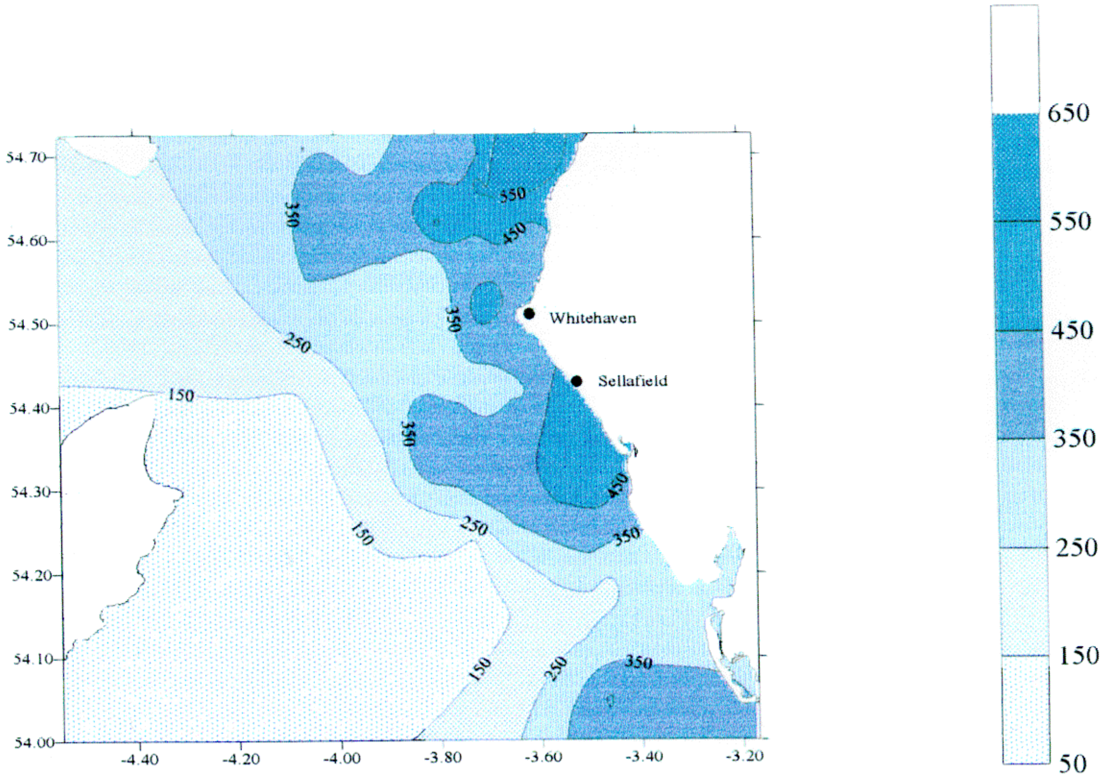

Figure 16. Cumbria Coast Survey March 1997. TON µg/litre.

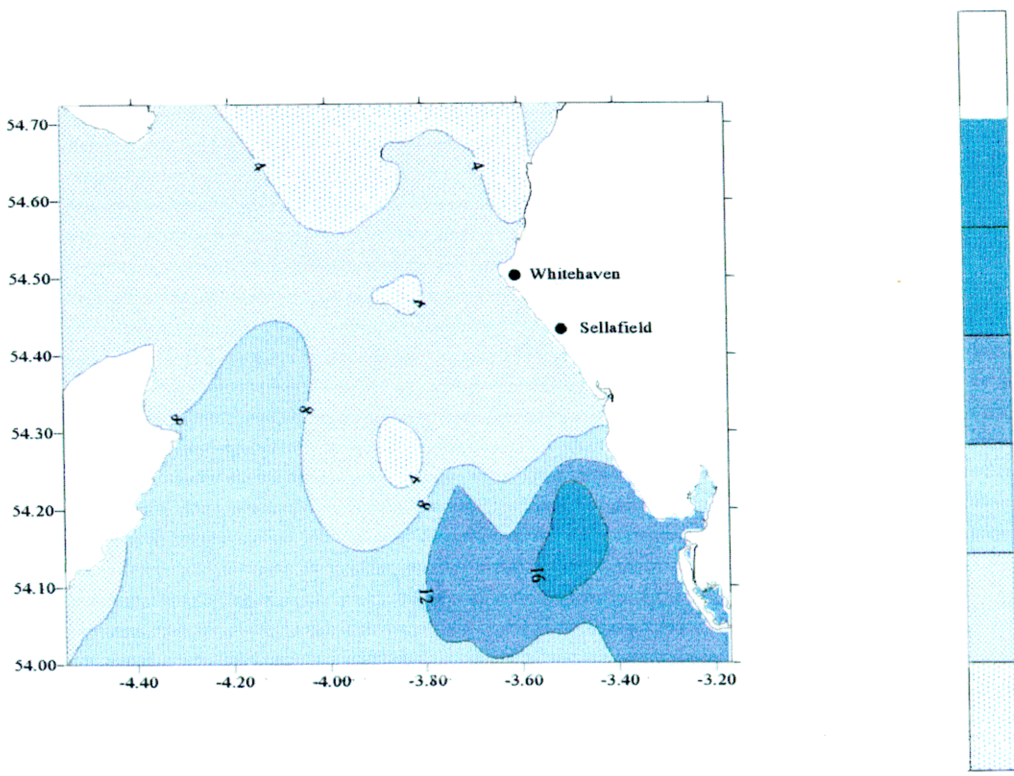

Figure 17. Cumbria Coast Survey March 1997. Nitrite µg/litre

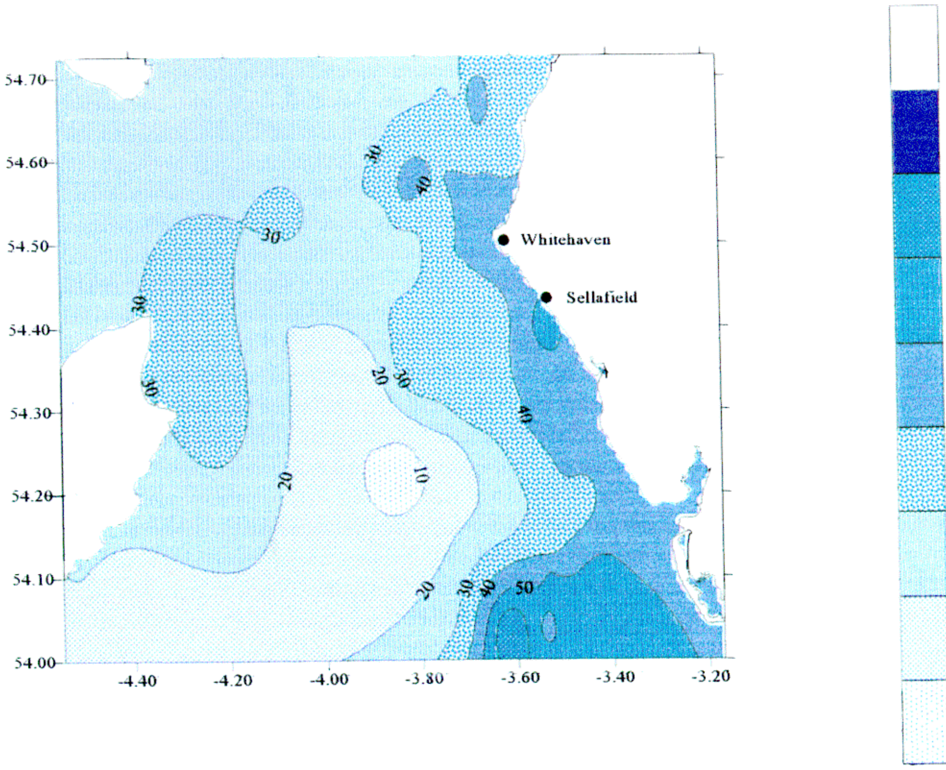

Figure 18. Cumbria Coast Survey March 1997 Ammoniacal nitrogen µg/litre

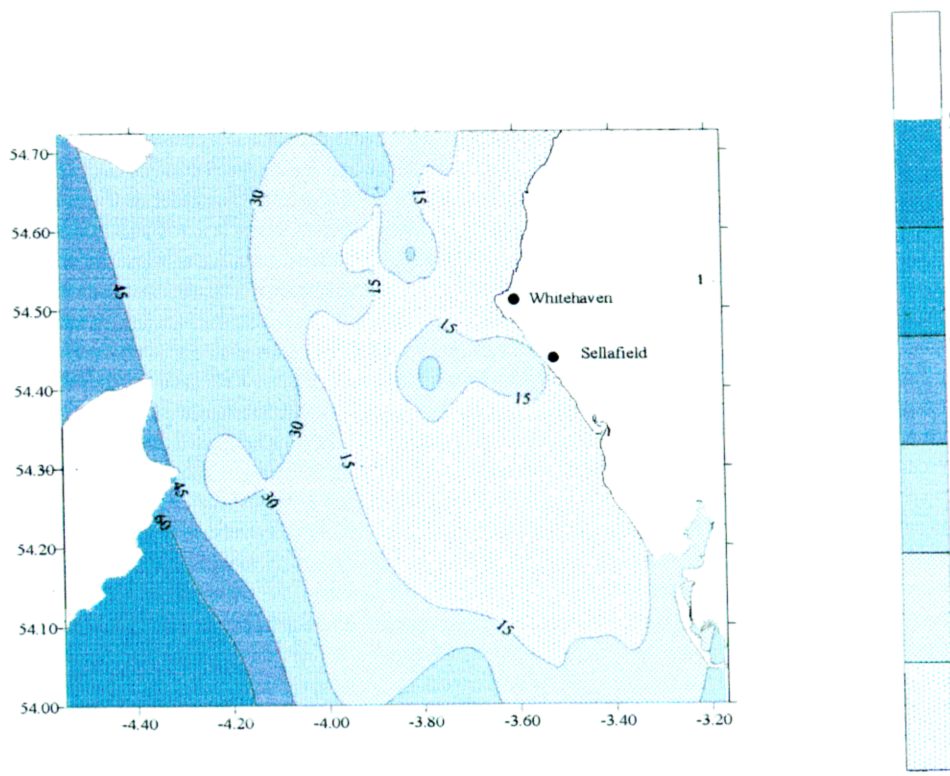

Figure 19. Cumbrian coast survey May 1997 TON µg/litre

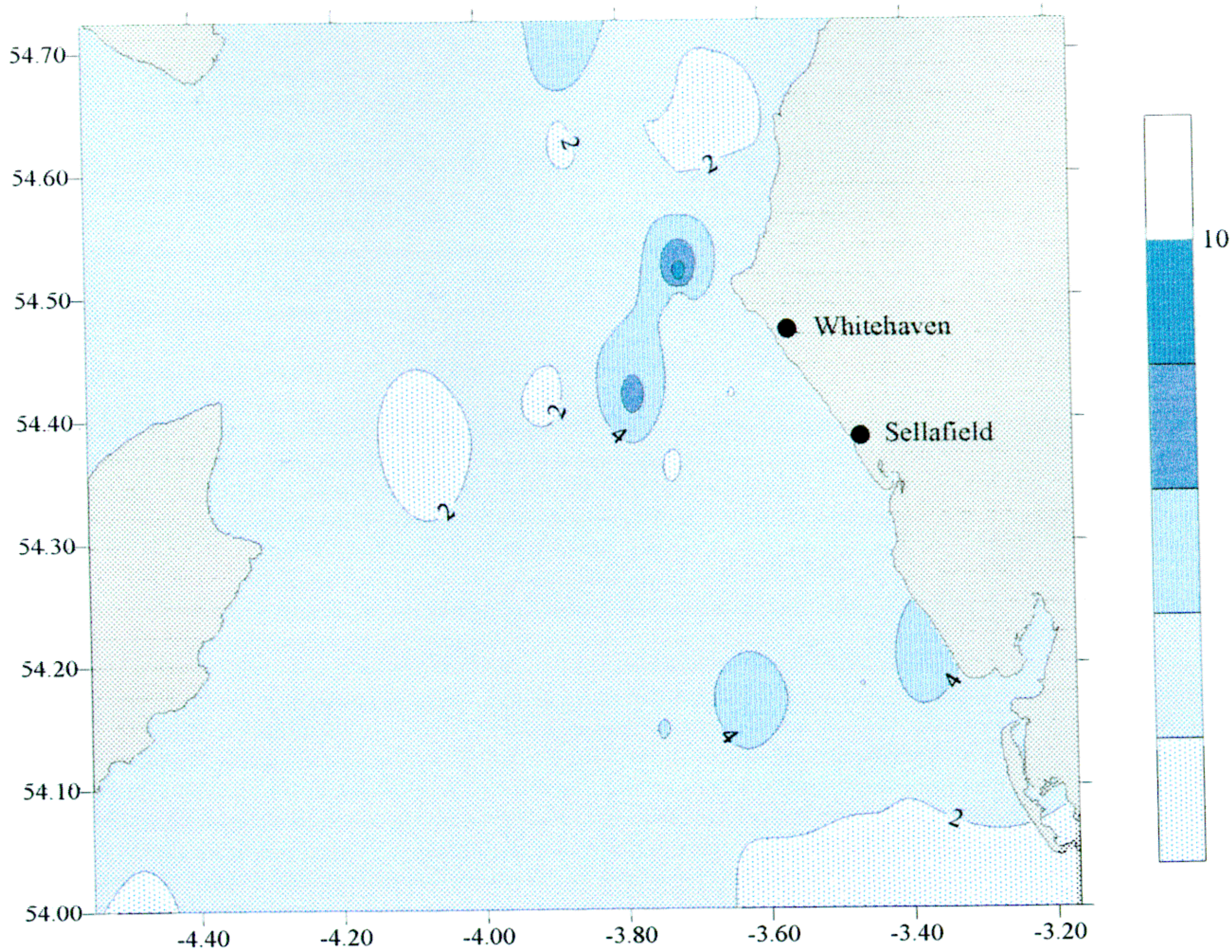

Figure 20. Cumbria coast survey May 1997. Nitrite µg/litre

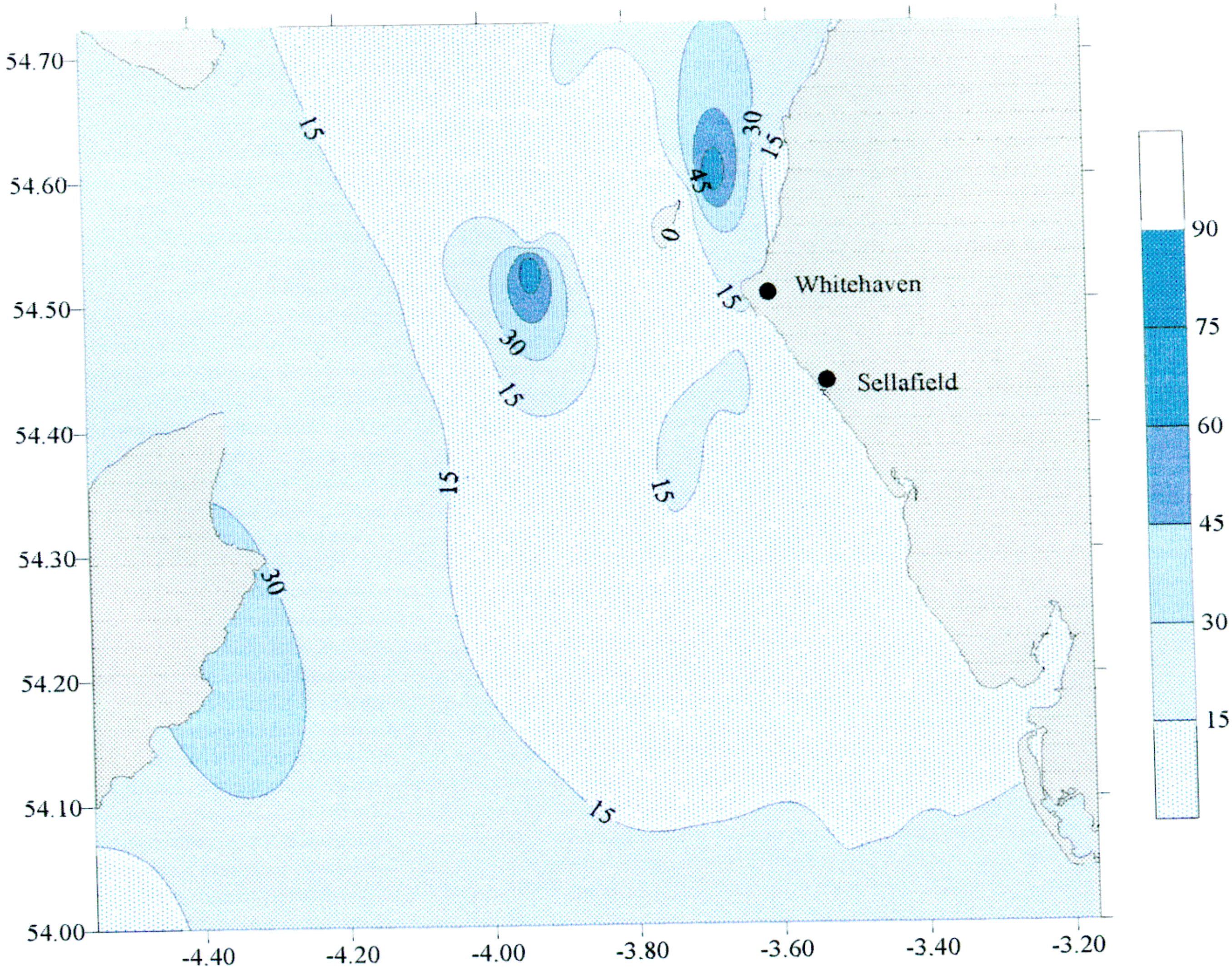

Figure 21. Cumbria coast survey May 1997. Ammoniacal nitrogen µg/litre.

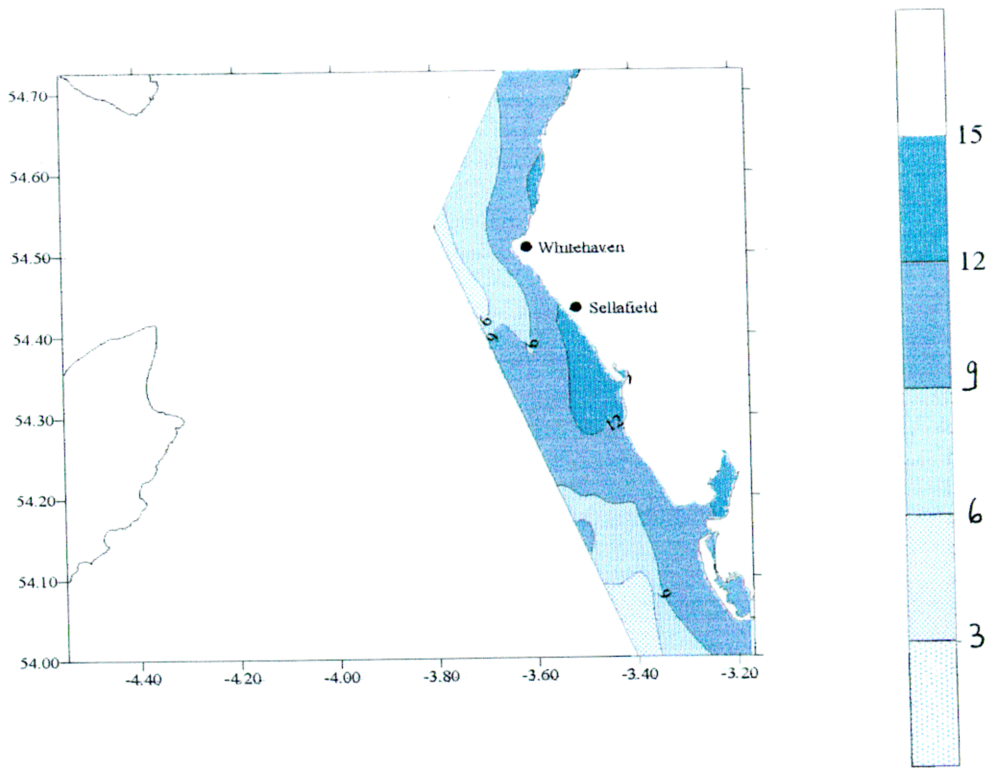

Figure 22. Cumbria coast survey June 1997. Nitrate µg/litre.

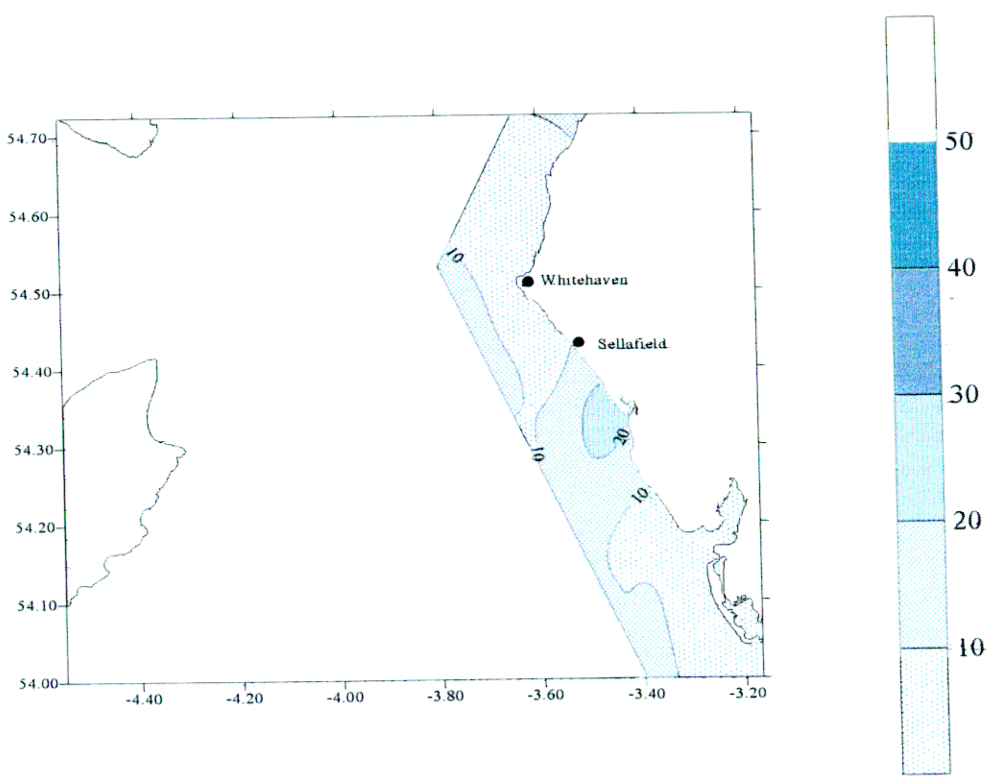

Figure 23. Cumbria coast survey June 1997. Ammoniacal nitrogen µg/litre

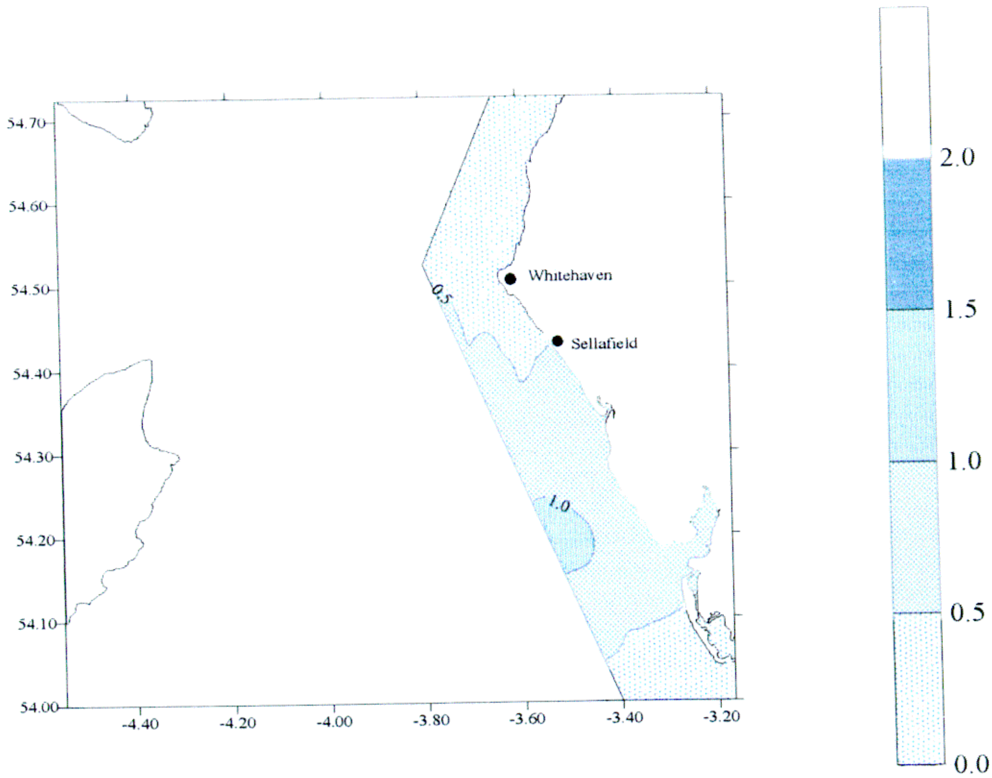

Figure 24. Cumbria coast survey June 1997. Nitrite µg/litre.

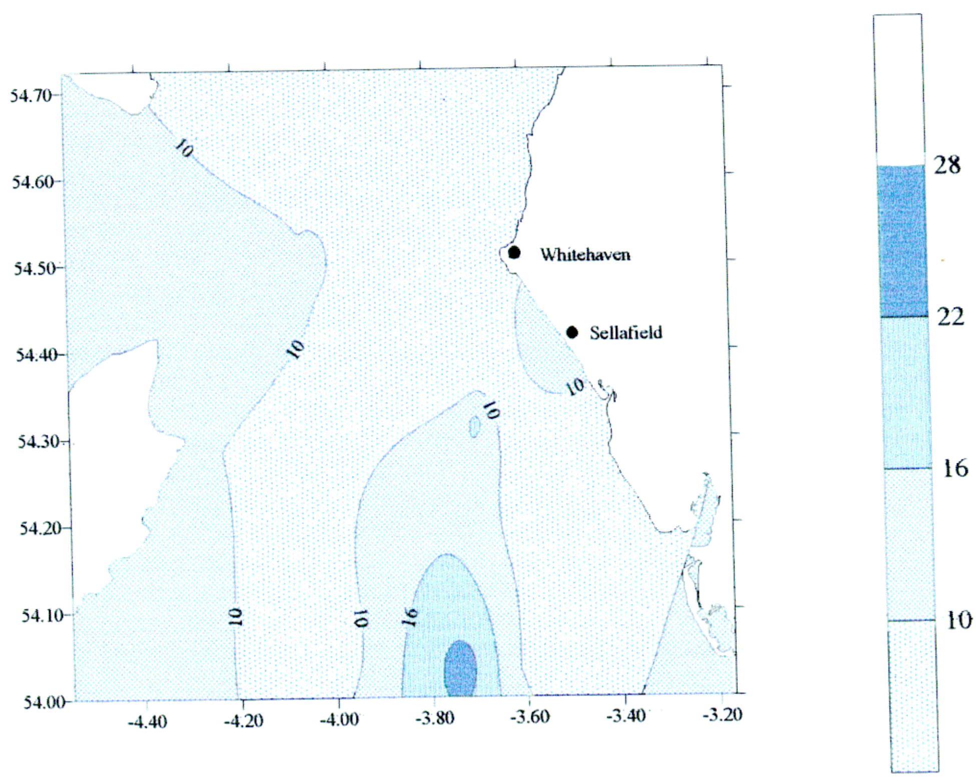

Figure 25. Cumbria Coast Survey July 1997. TON µg/litre.

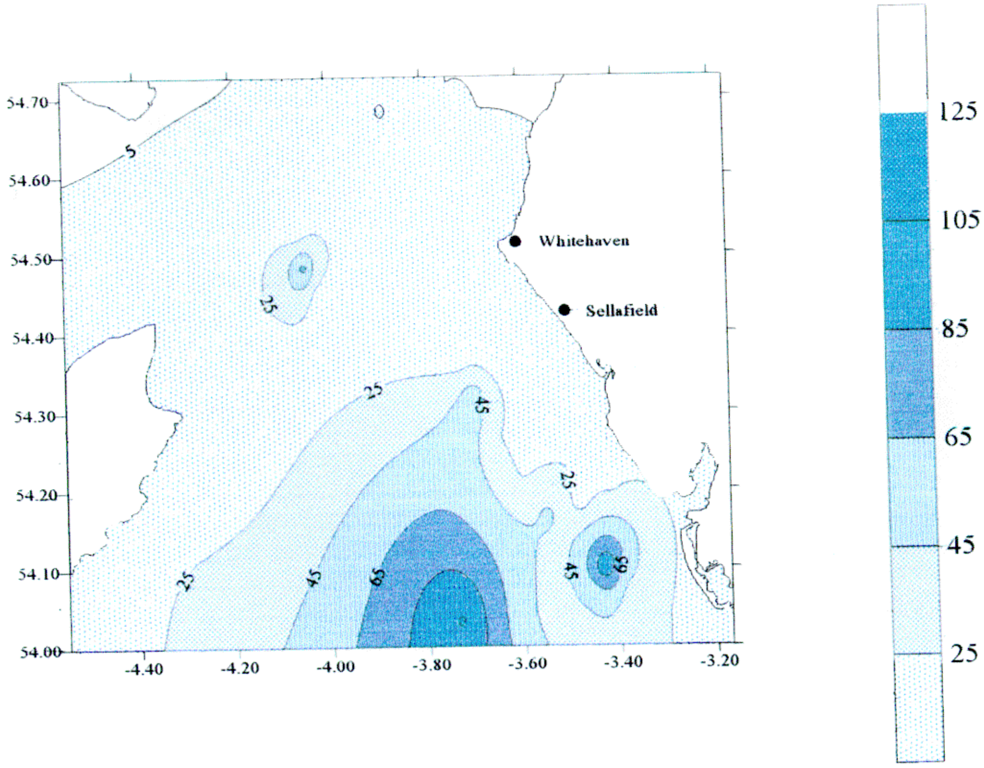

Figure 26. Cumbria Coast Survey July 1997. Ammoniacal nitrogen µg/litre.

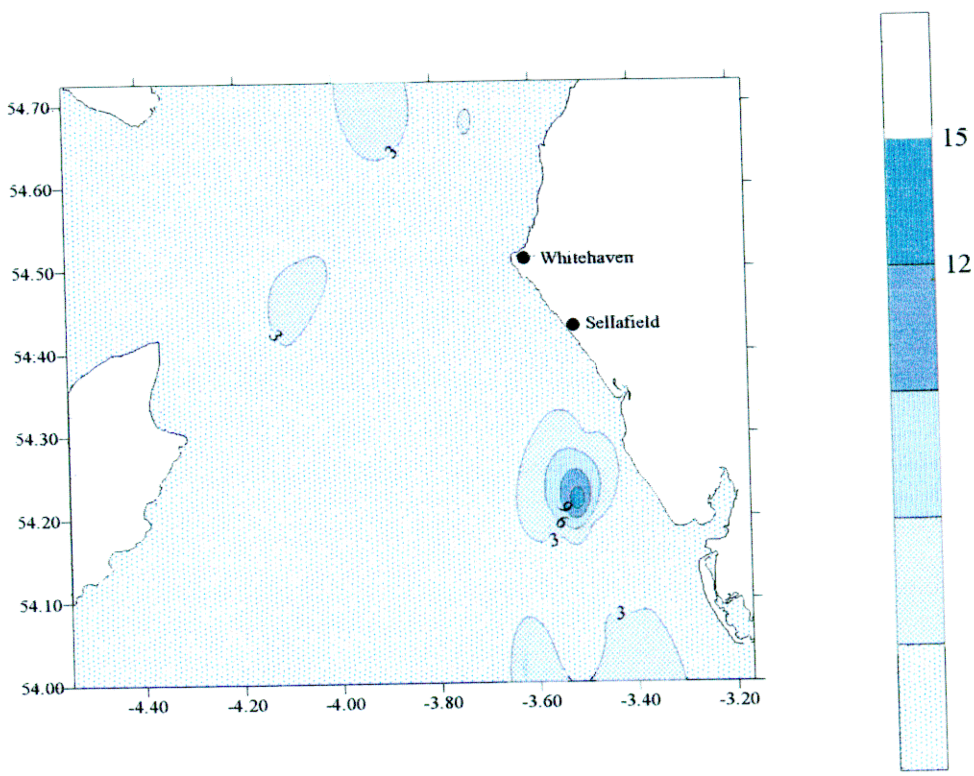

Figure 27. Cumbria Coast Survey July 1997. Nitrite µg/litre.

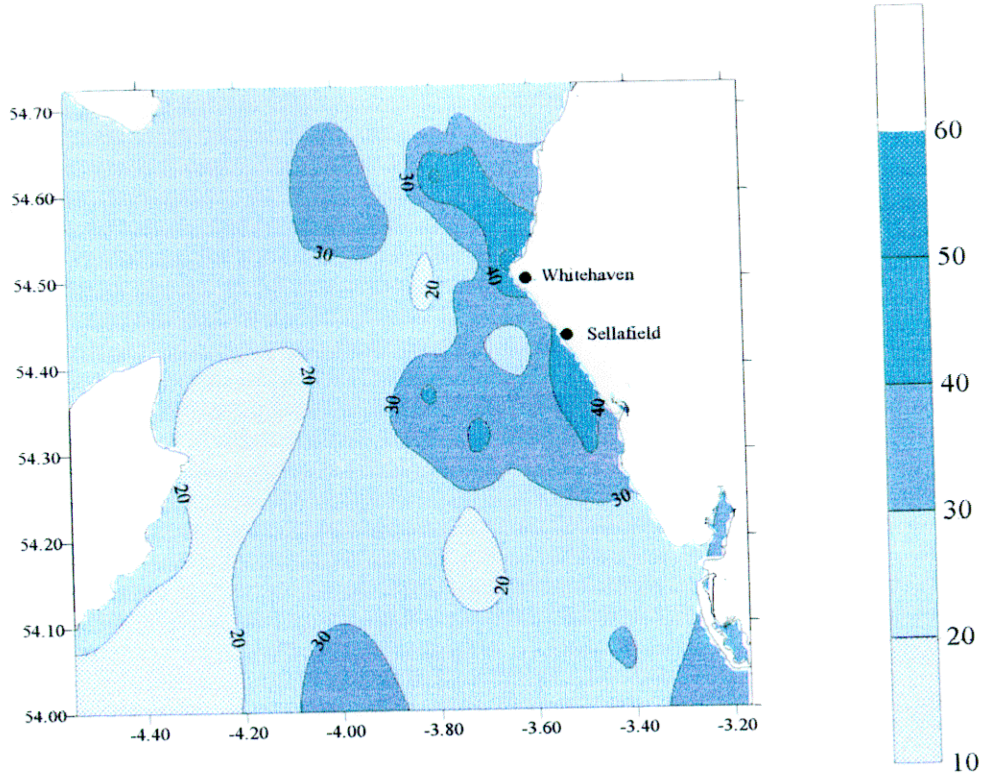

Figure 28. Cumbria Coast Survey March 1997. SRP µg/litre

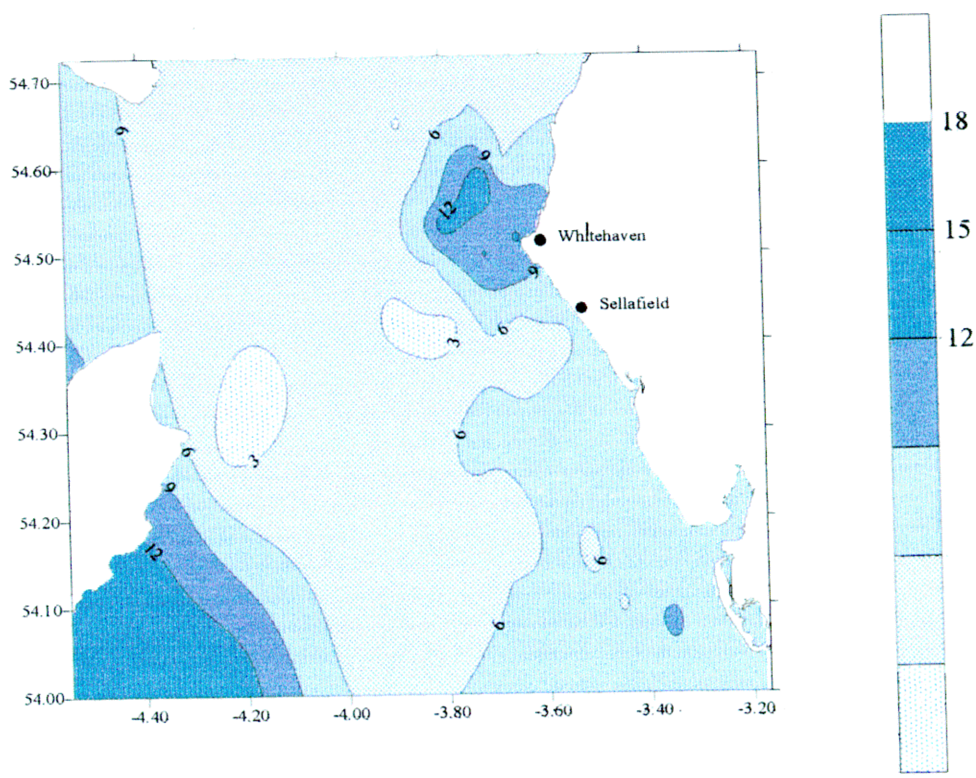

Figure 29. Cumbria coast survey May 1997. SRP µg/litre.

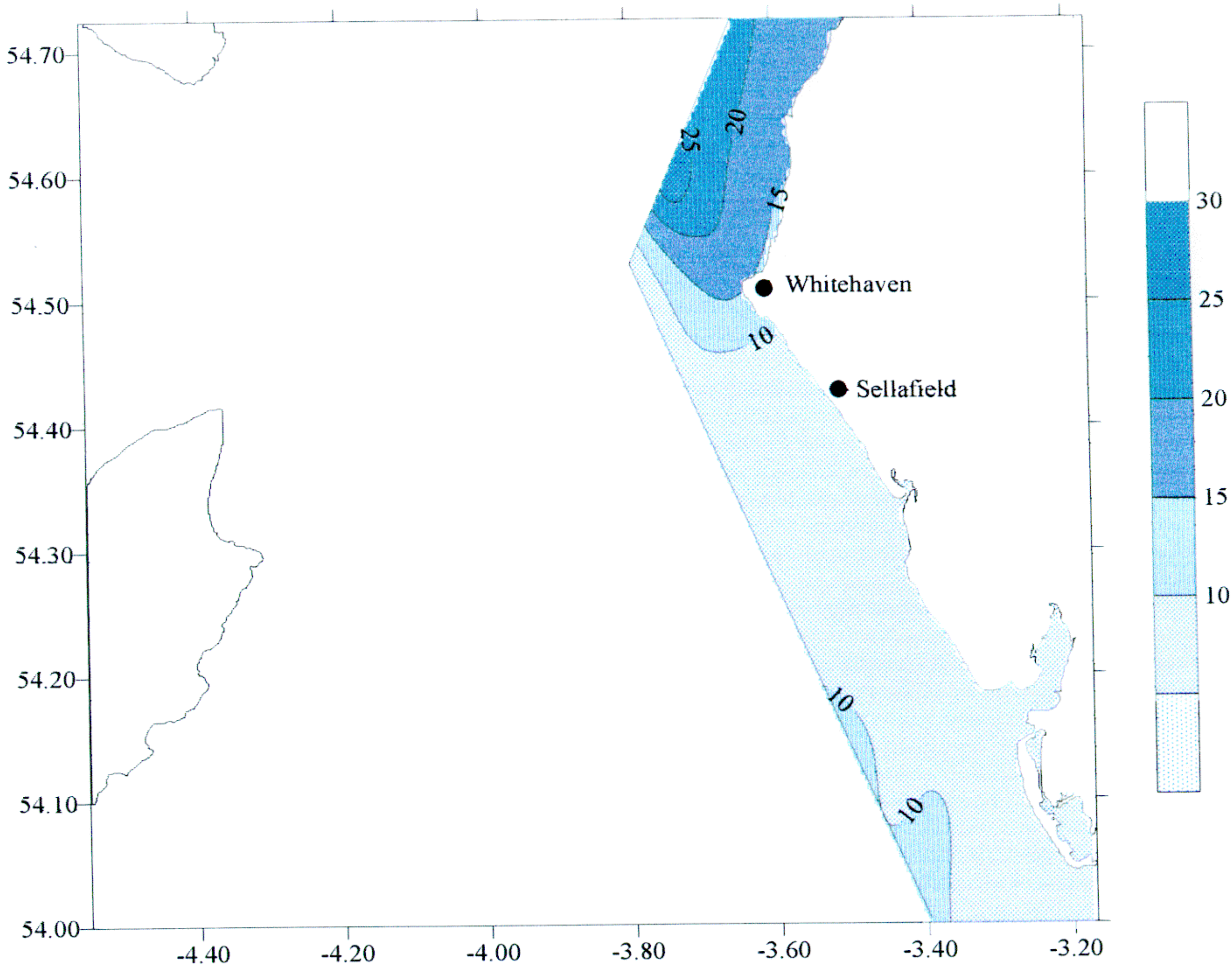

Figure 30. Cumbria coast survey June 1997. Phosphate µg/litre

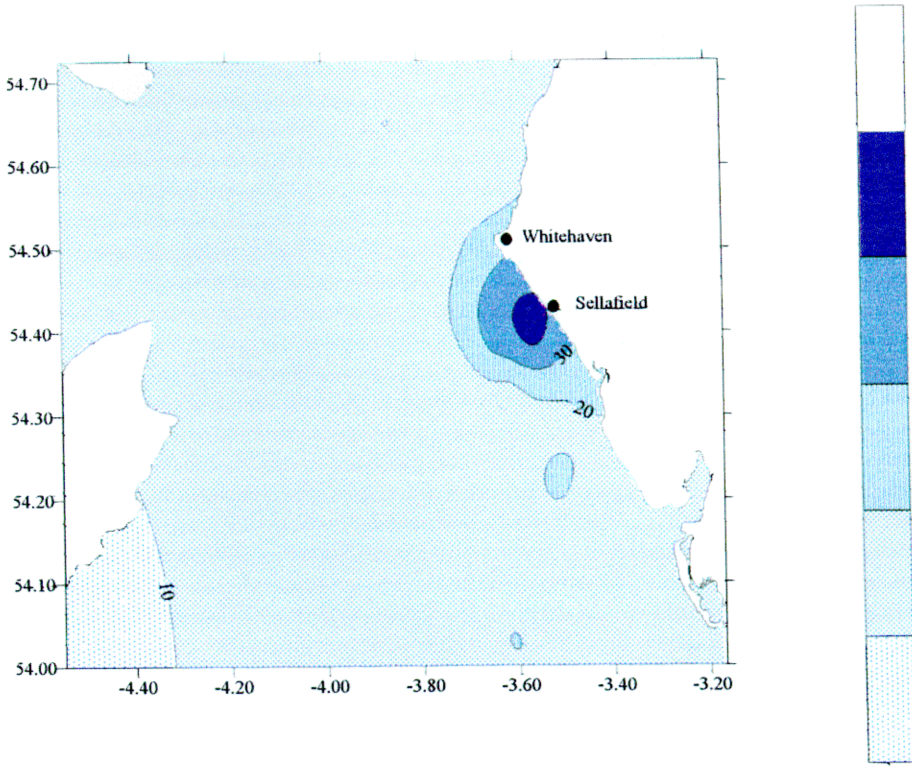

Figure 31. Cumbria Coast Survey July 1997. SRP µg/litre.

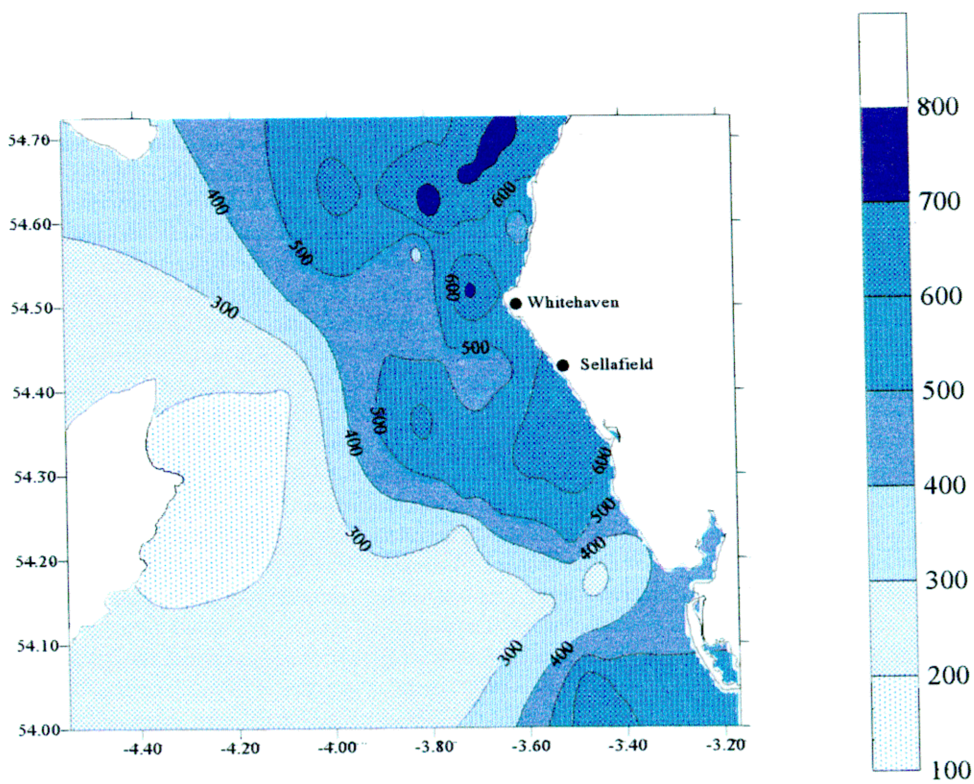

Figure 32. Cumbria Coast Survey March 1997 Silicate µg/litre.

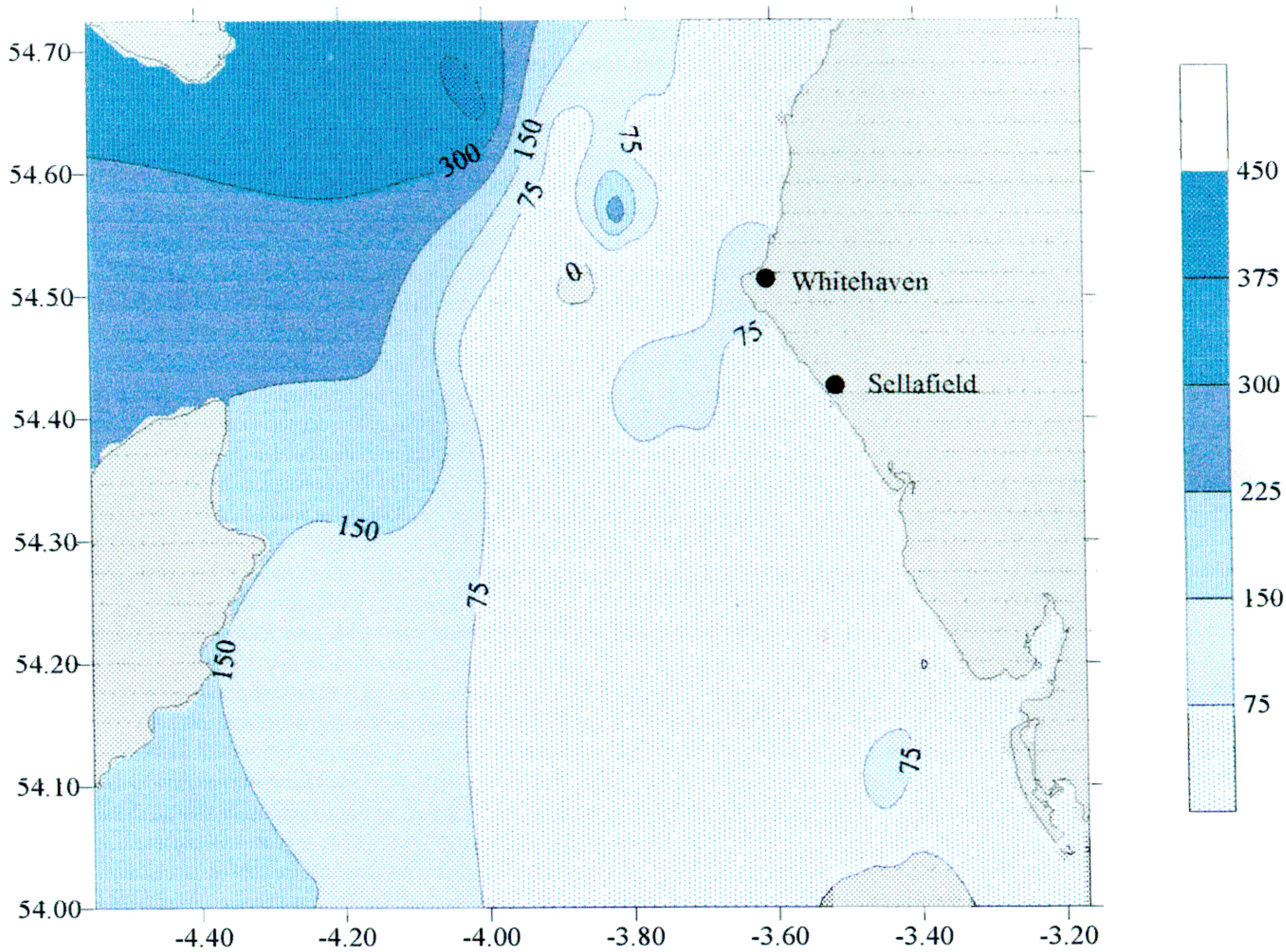

Figure 33. Cumbria Coast Survey May 1997. Silicate µg/litre

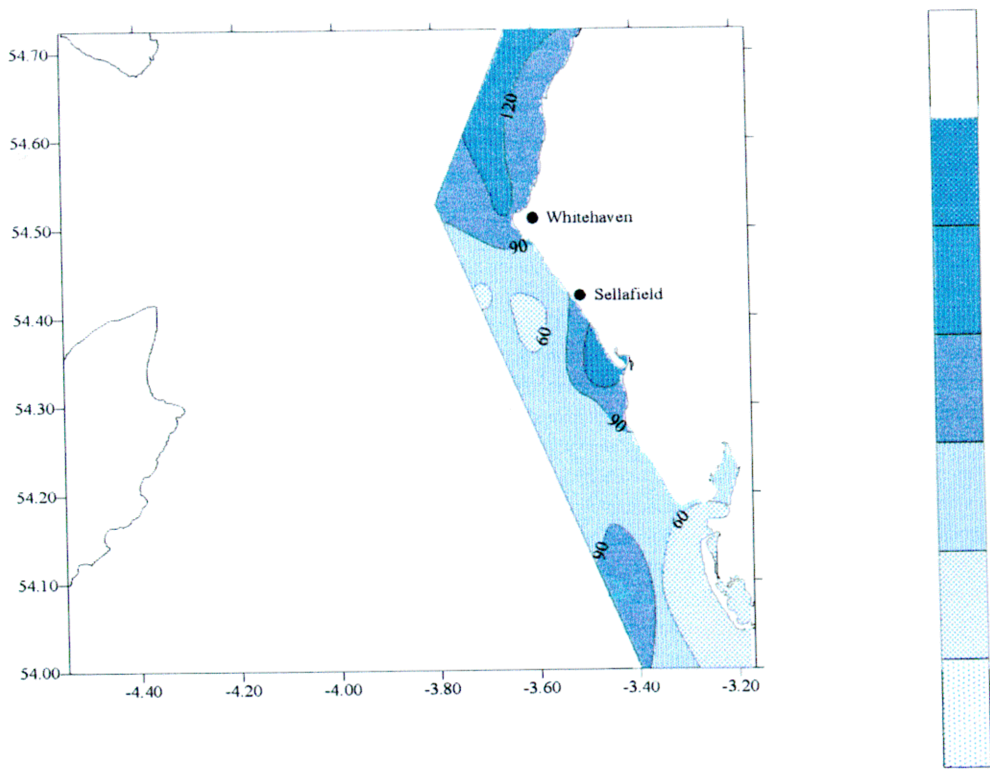

Figure 34. Cumbria coast survey June 1997. Silicate µg/litre

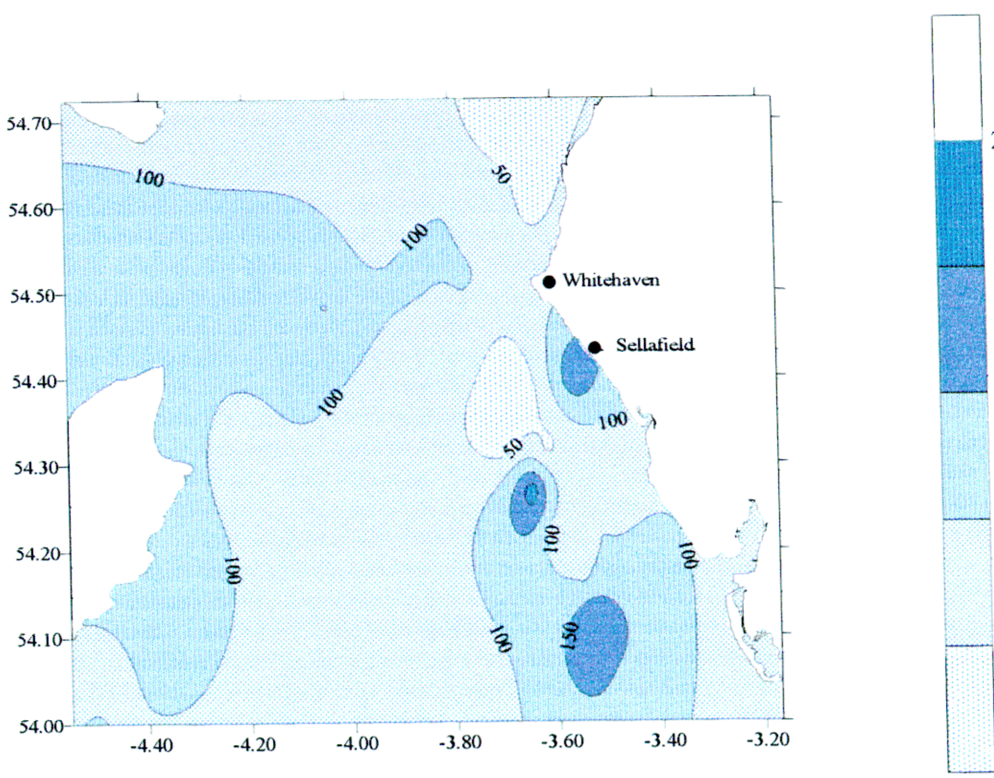

Figure 35. Cumbria Coast Survey July 1997. Silicate µg/litre.

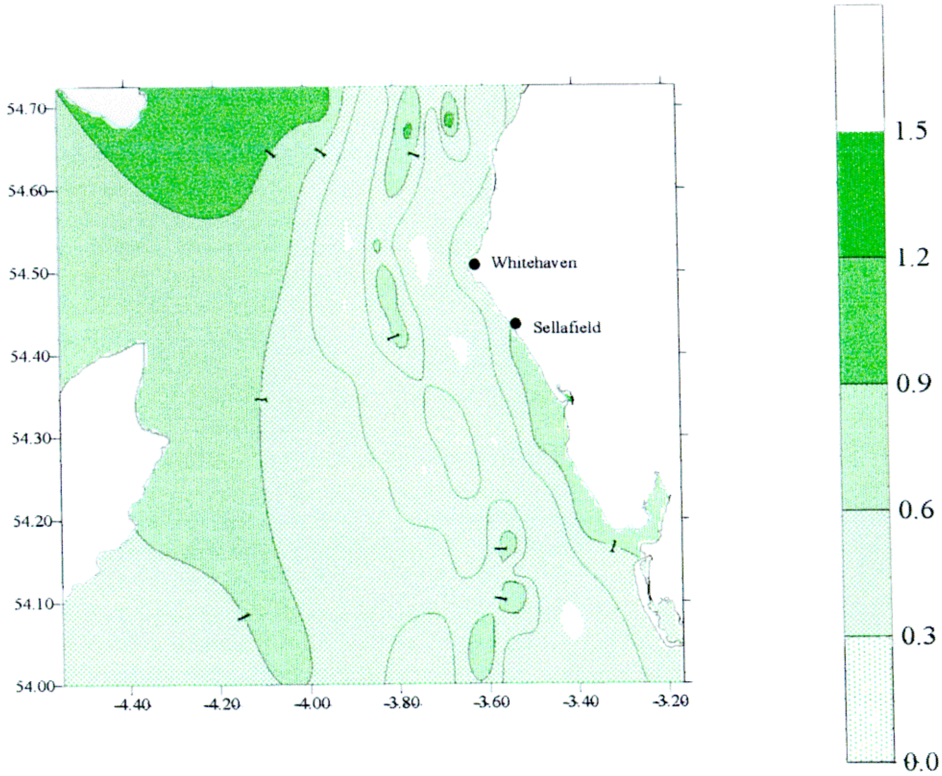

Figure 36. Cumbria Coast Survey March 1997. Chlorophyll a µg/litre (UNESCO)

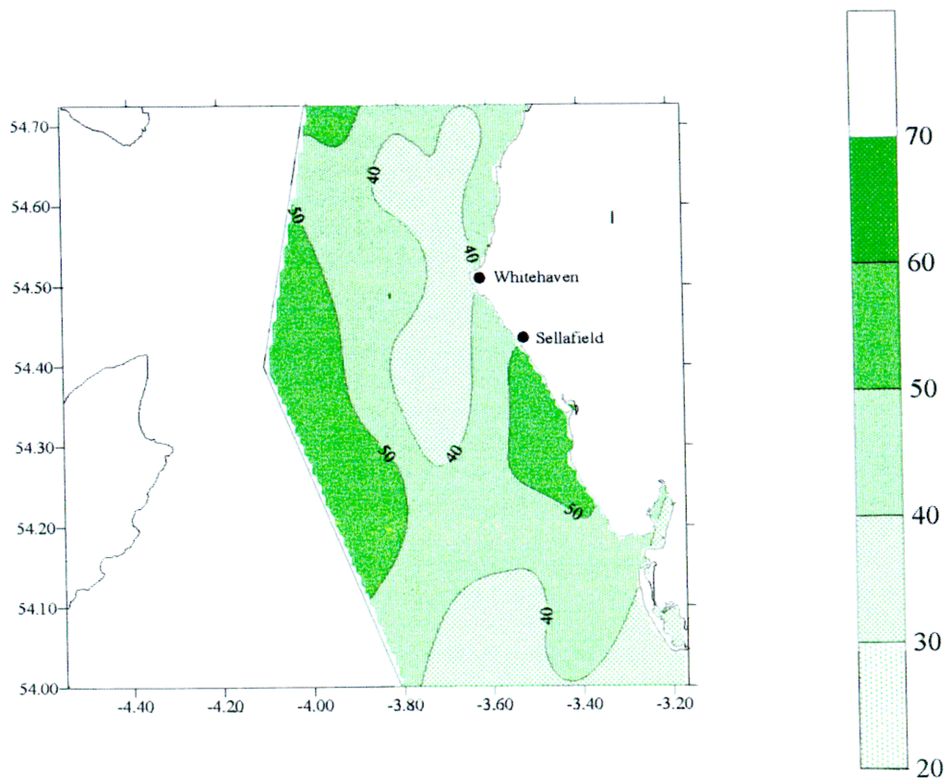

Figure 37. Cumbria Coast Survey March 1997. Standing Crop (Chlorophyll mg/m2).

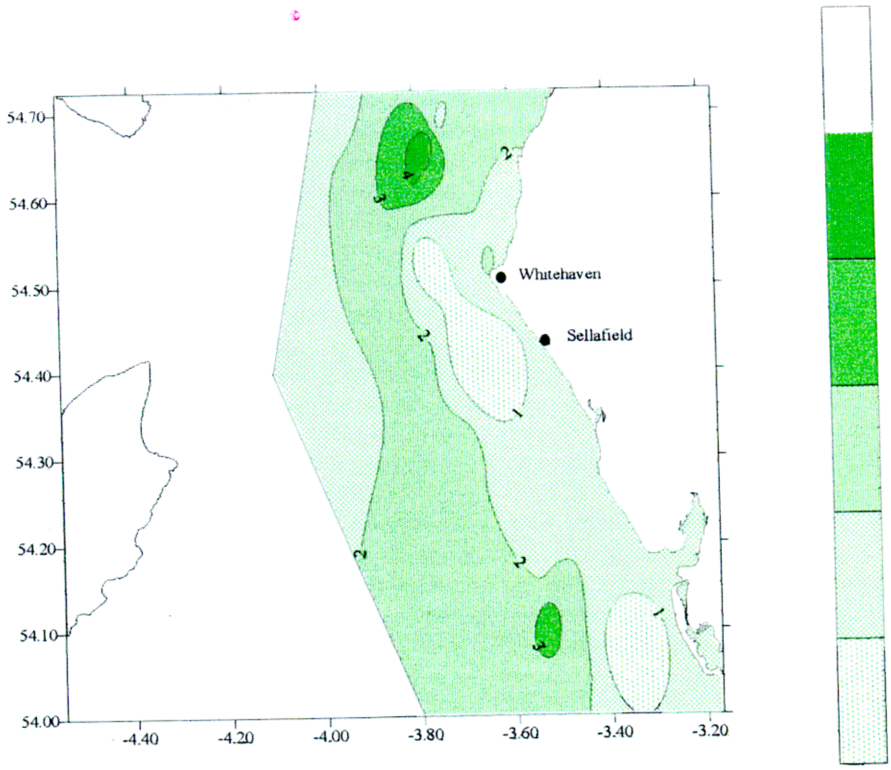

Figure 38. Cumbria Coast Survey March 1997. Standing Crop divided by depth (Chlorophyll a mg/m3).

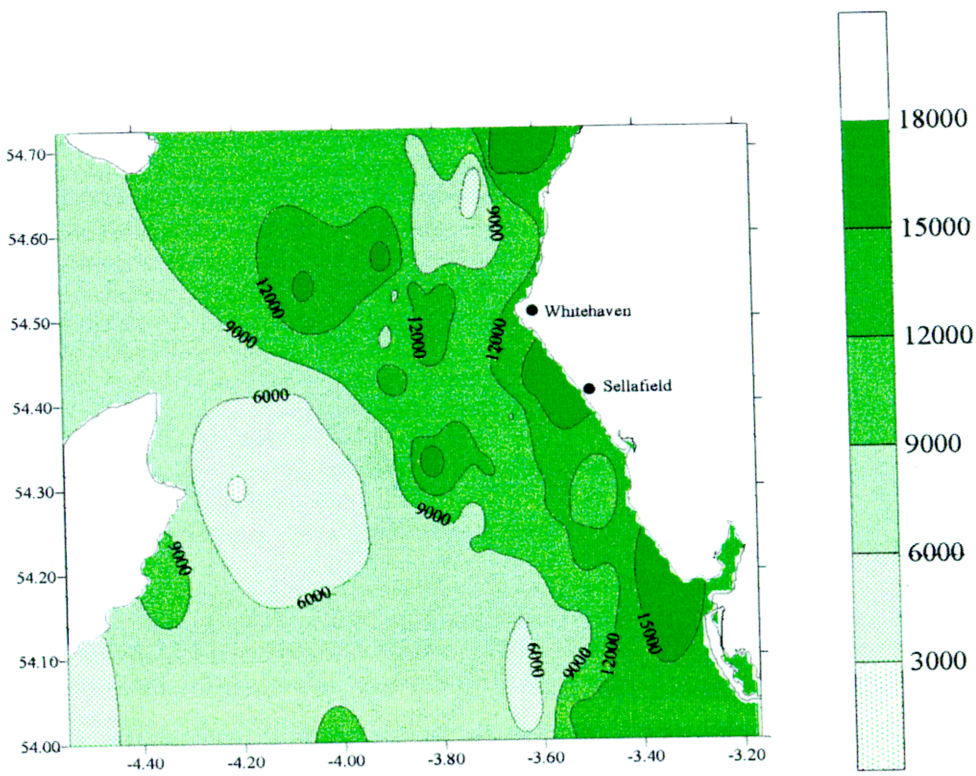

Figure 39. Cumbria Coast Survey March 1997. Total phytoplankton (cells/litre).

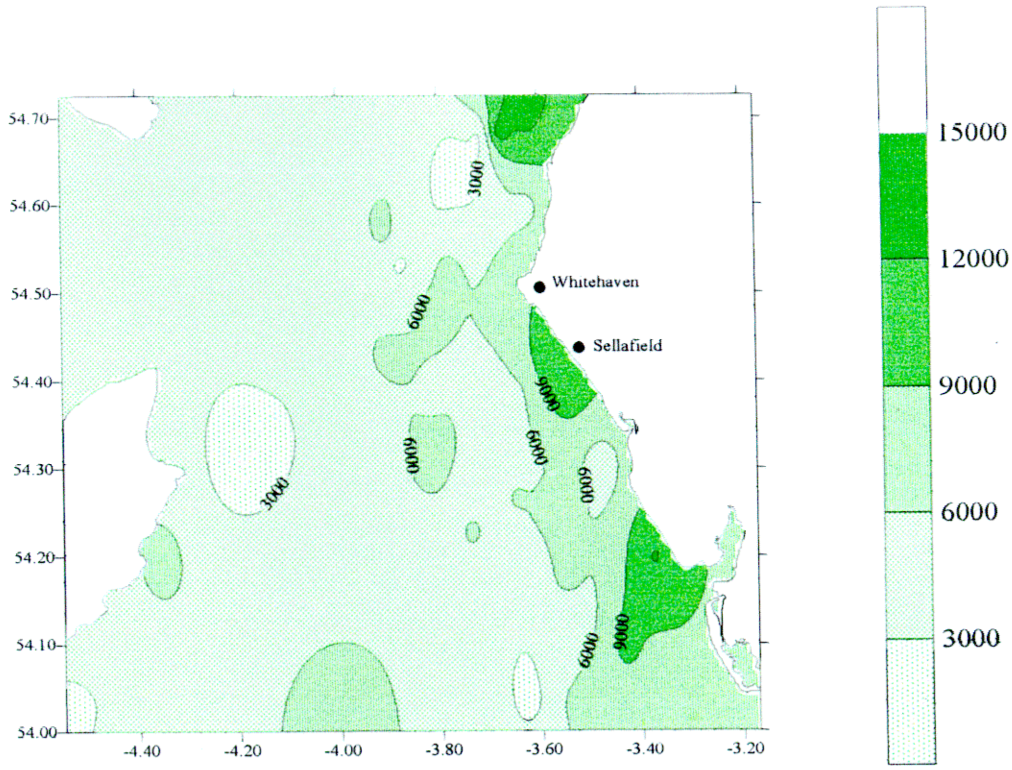

Figure 40. Cumbria Coast Survey March 1997. Total Diatoms (cells/litre).

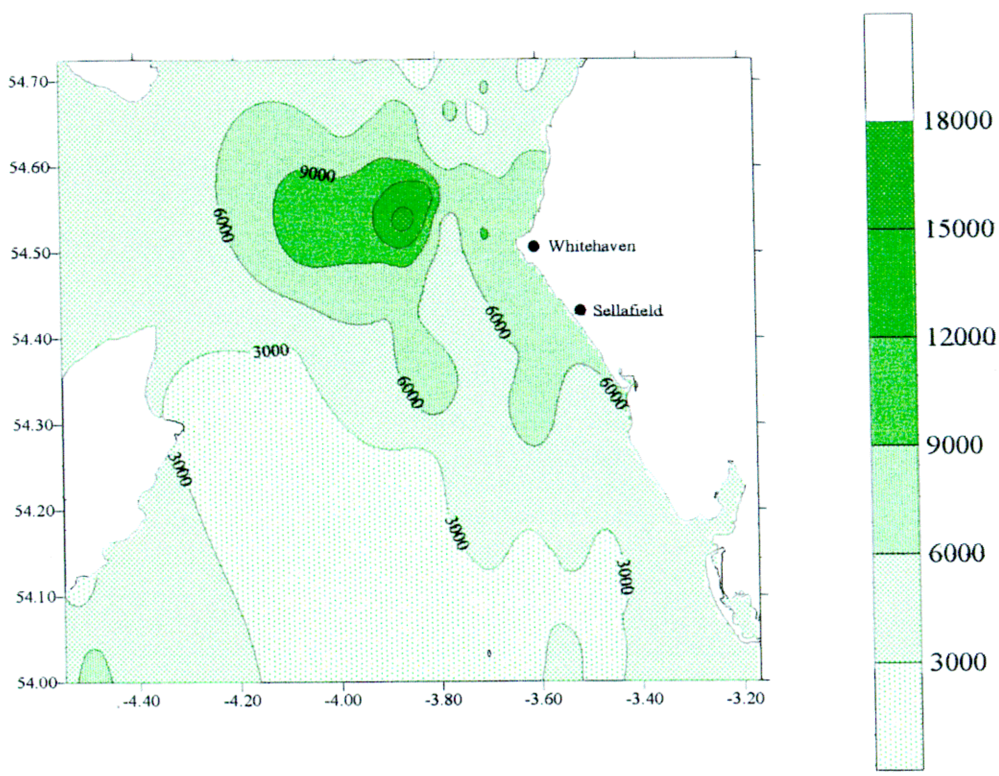

Figure 41. Cumbria Coast Survey March 1997. Total small flagellates/monads (cells/litre).

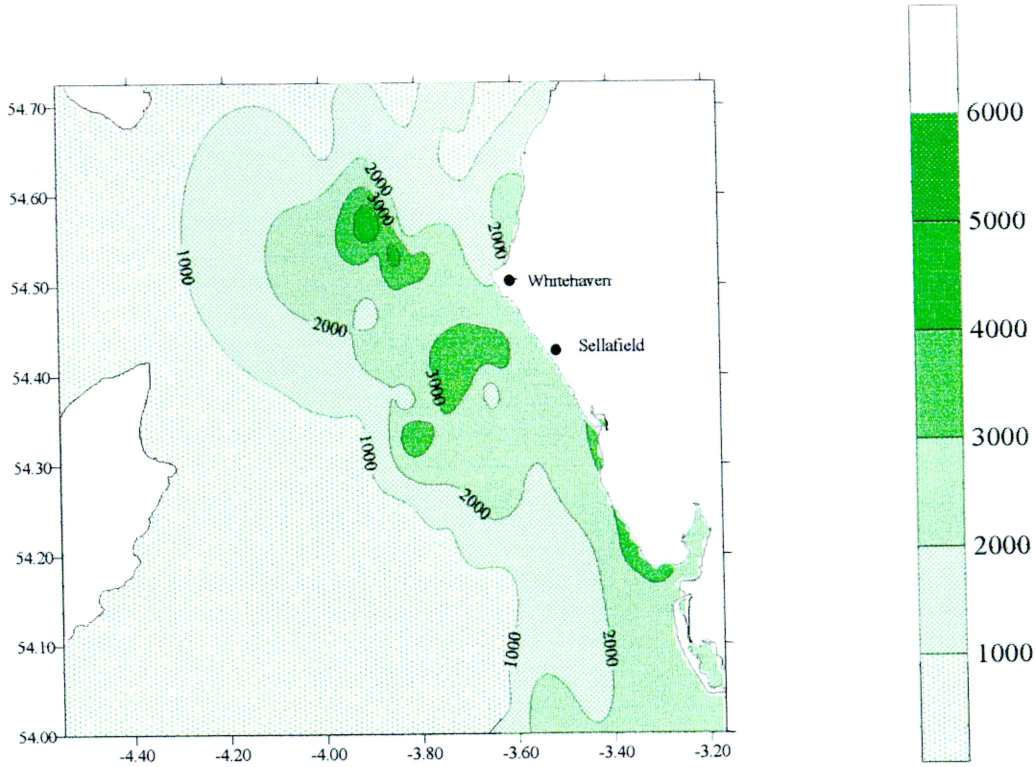

Figure 42. Cumbria Coast Survey March 1997. Total Dinoflagellates (cells/litre).

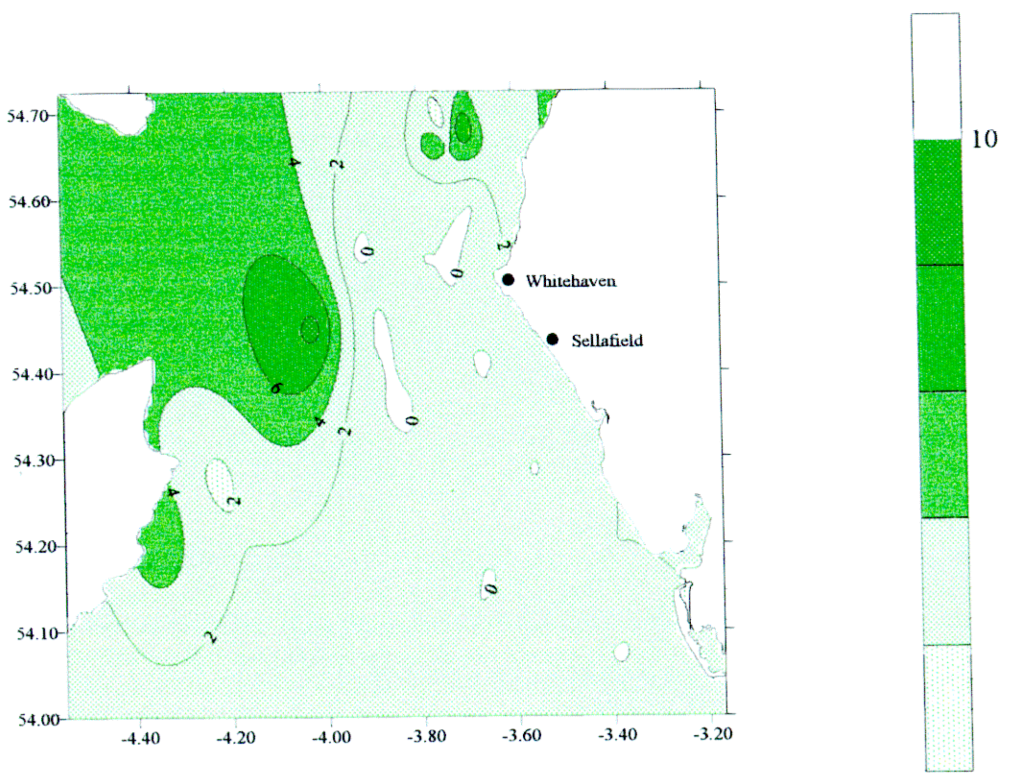

Figure 43. Cumbria Coast Survey May 1997. Chlorophyll µg/litre (UNESCO)

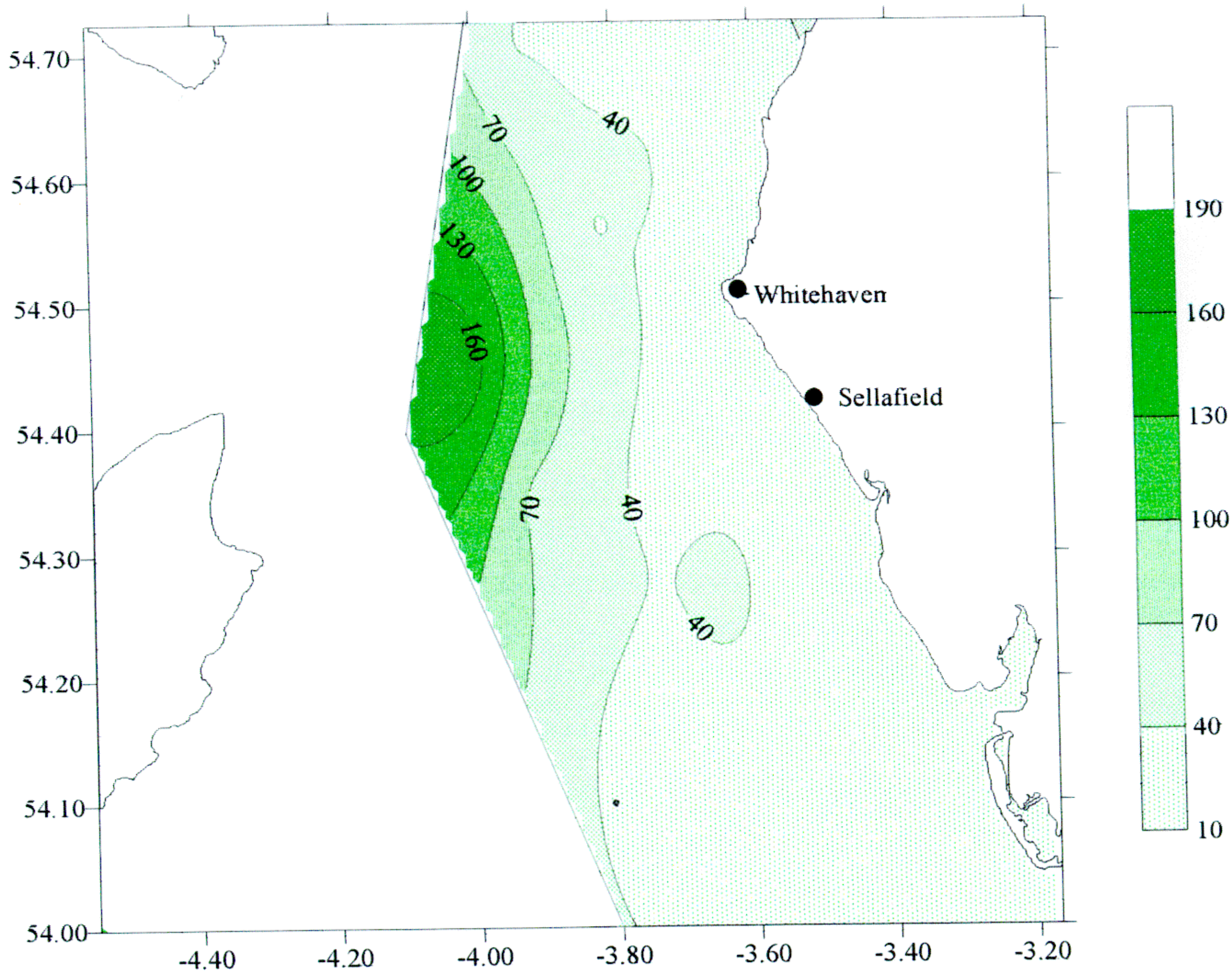

Figure 44. Cumbria Coast Survey May 1997. Standing Crop (Chlorophyll a mg/m2)

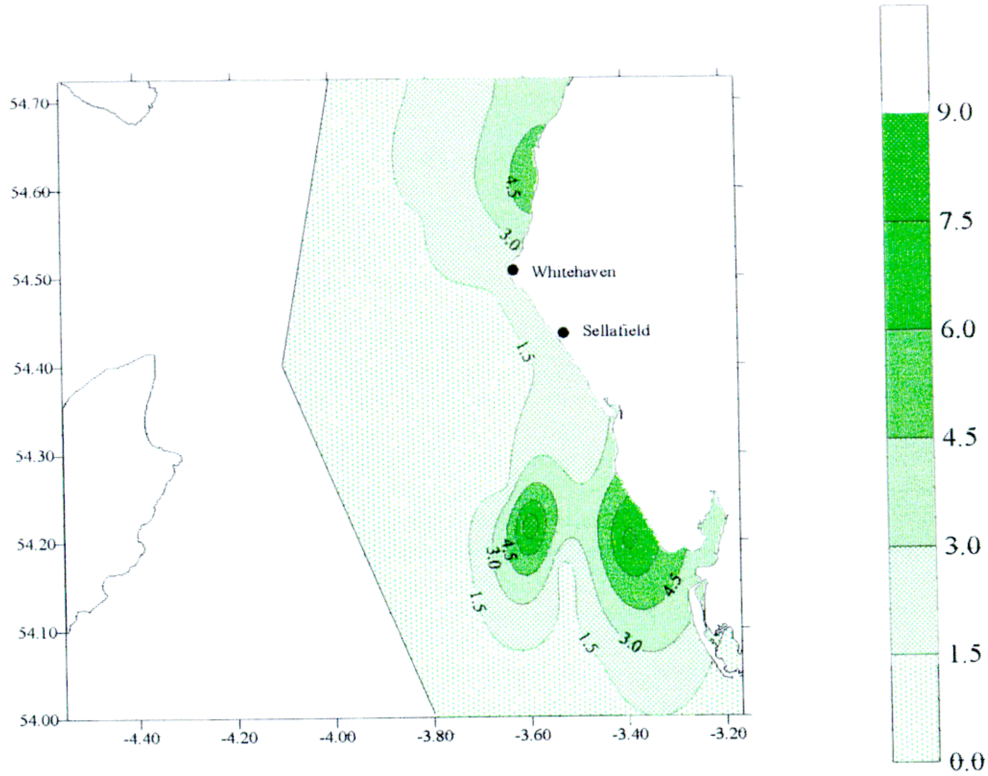

Figure 45. Cumbria Coast Survey May 1997. Standing Crop Divided By Depth (Chlorophyll mg/m3)

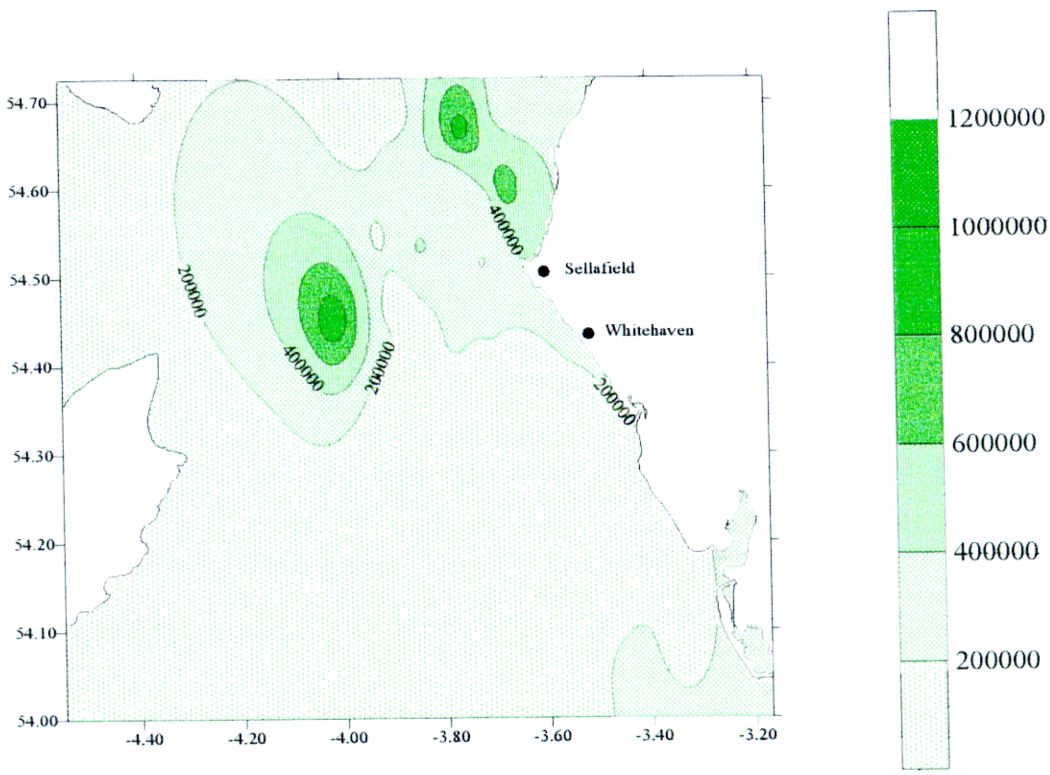

Figure 46 Cumbria Coast Survey May 1997. Phaeocystis globosa (cells/litre).

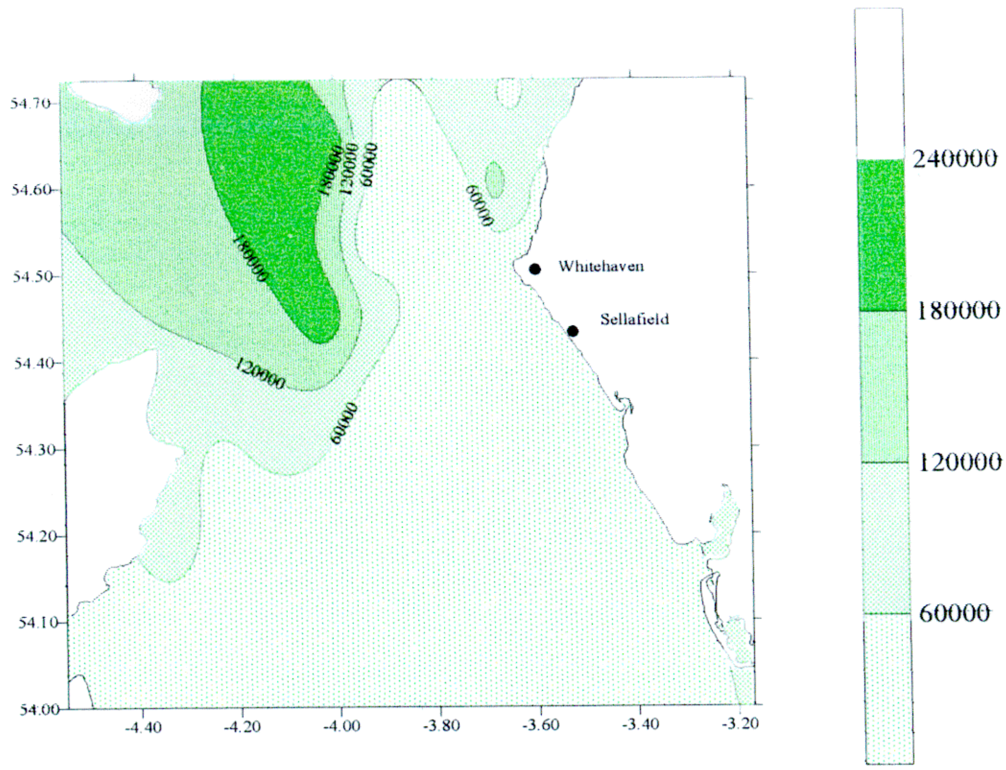

Figure 47. Cumbria Coast Survey May 1997. Total diatoms (Cells/litre).

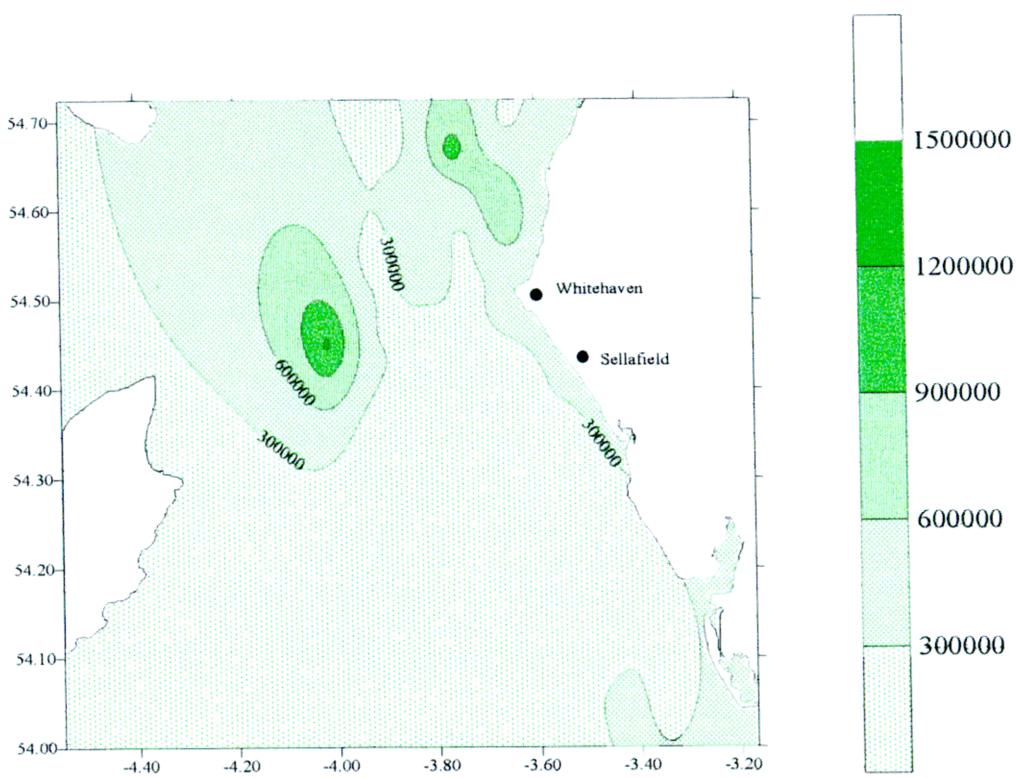

Figure 48. Cumbria Coast Survey May 1997. Total Phytoplankton (cells/litre)

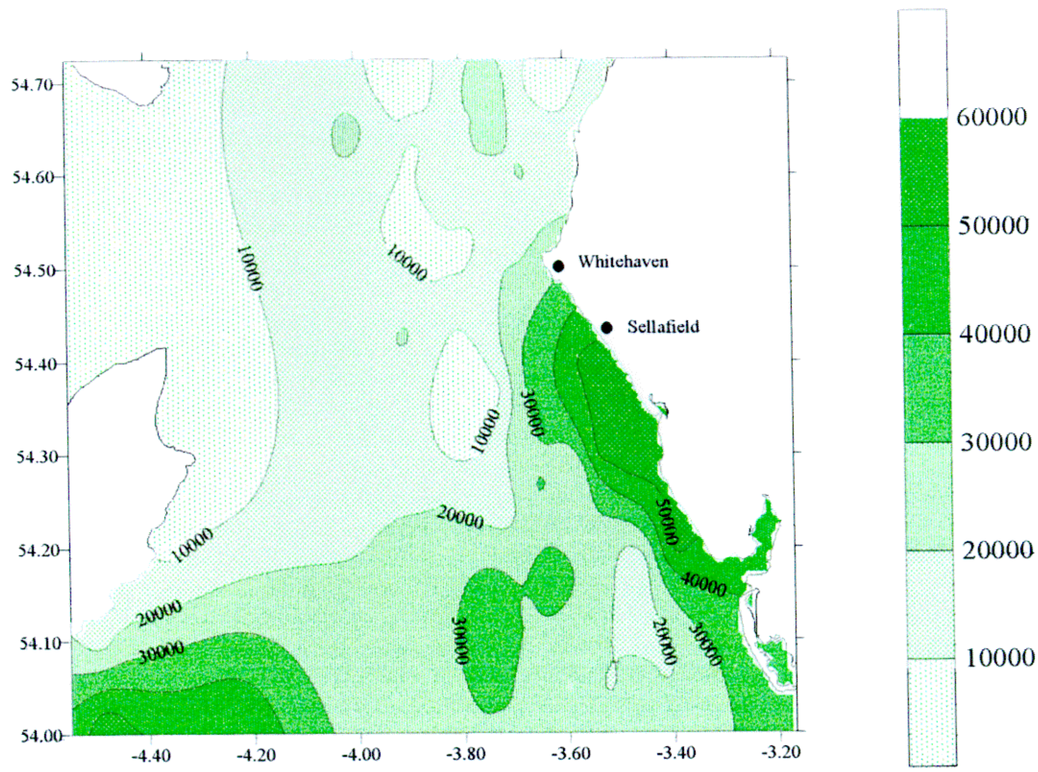

Figure 49. Cumbria Coast Survey May 1997. Total monads small flagellates (cells/litre).

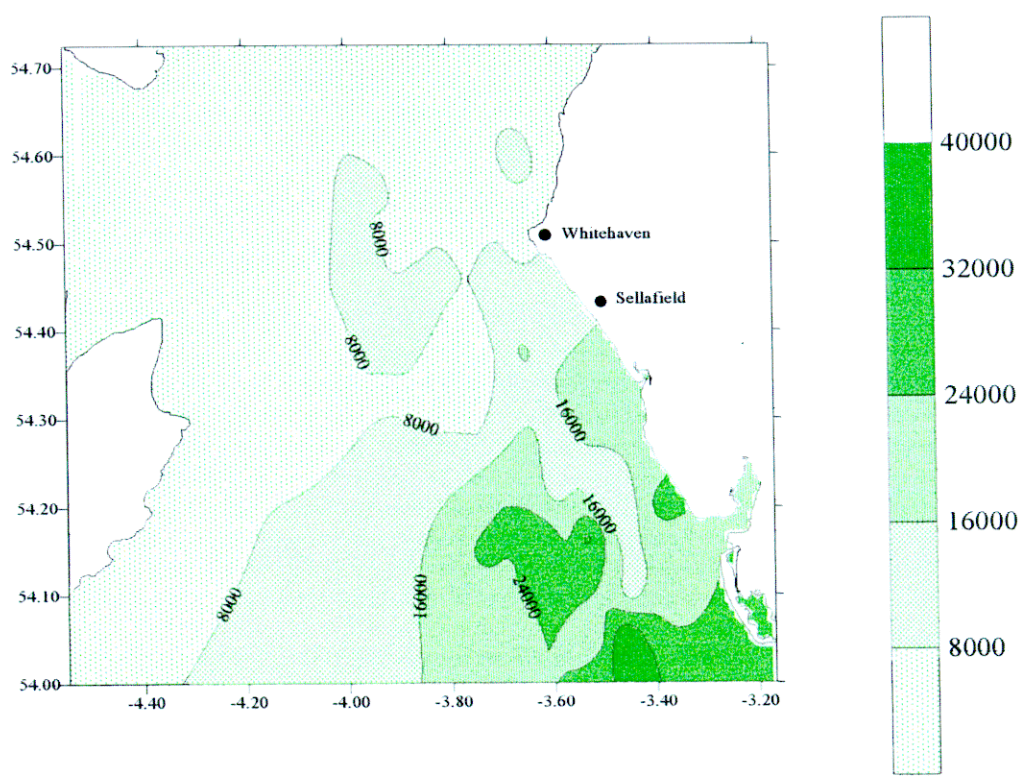

Figure 50. Cumbria Coast Survey May 1997. Total dinoflagellates (cells/litre).

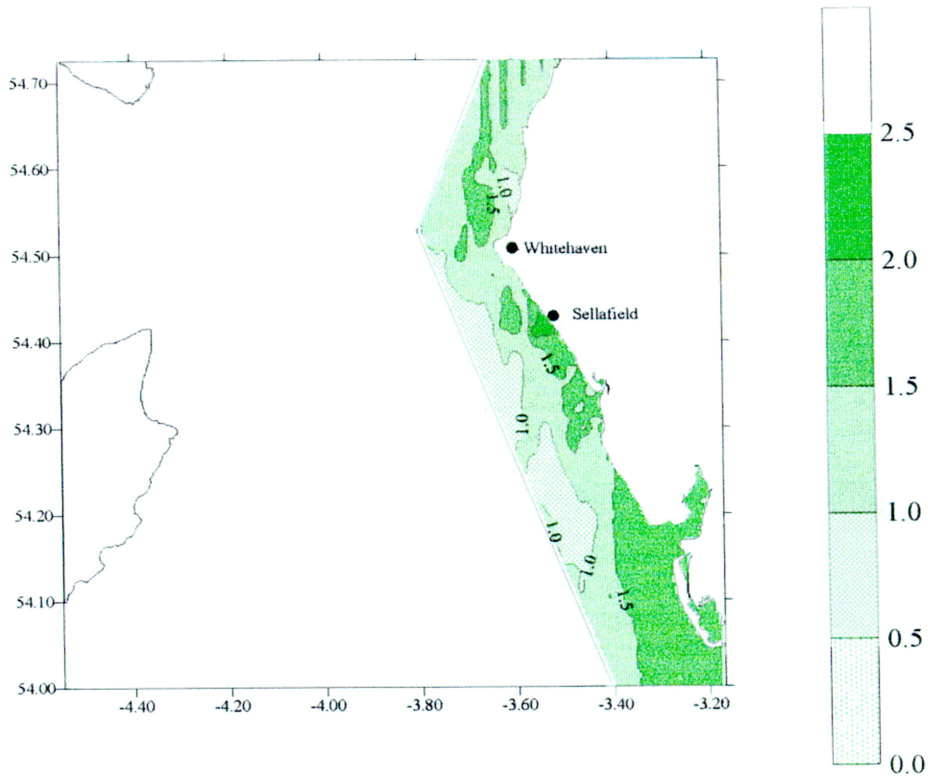

Figure 50b. Cumbria coast survey June 1997. Chlorophyll µg/litre.

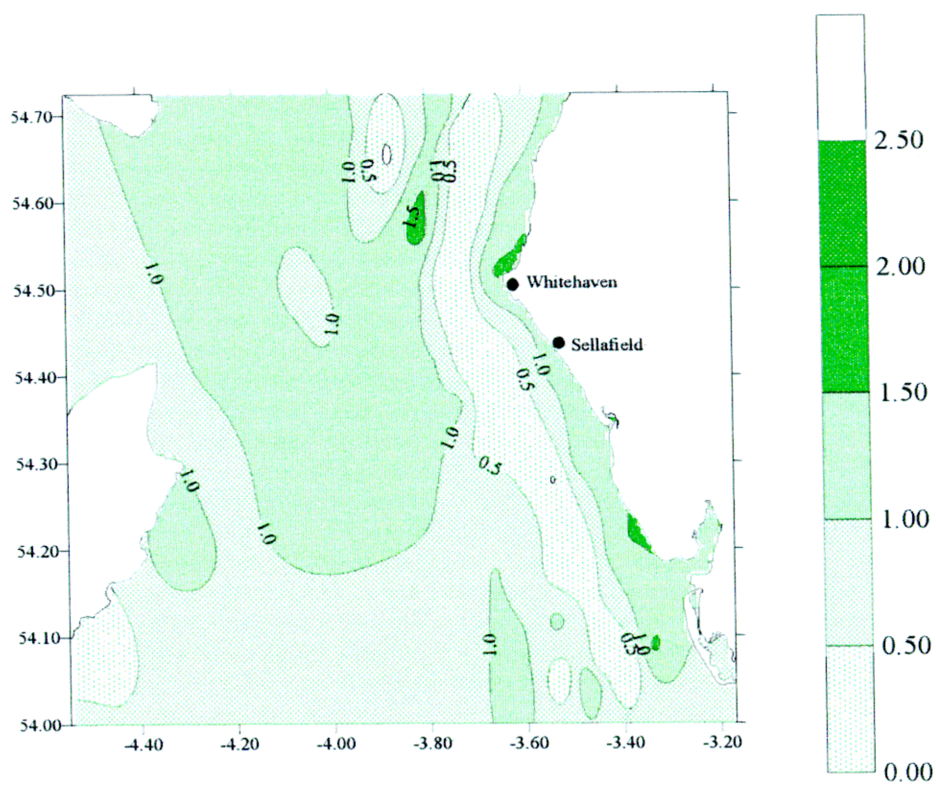

Figure 51. Cumbria Coast Survey June 1997. Chlorophyll µg/litre (UNESCO)

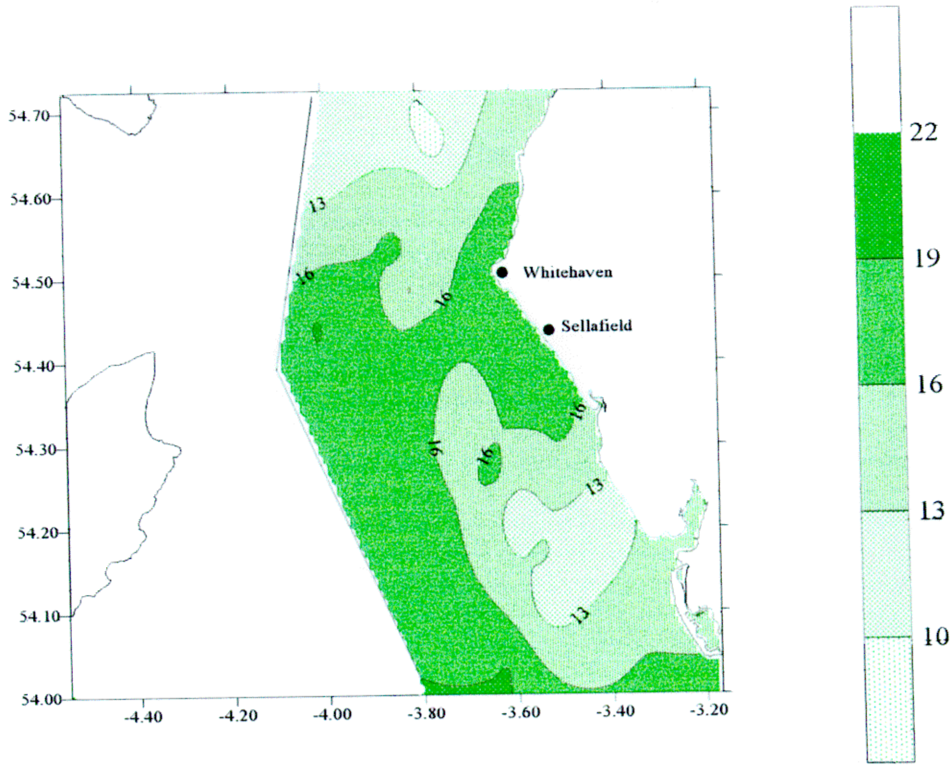

Figure 52. Cumbria Coast Survey July 1997. Standing Crop (chlorophyll a mg/m2)

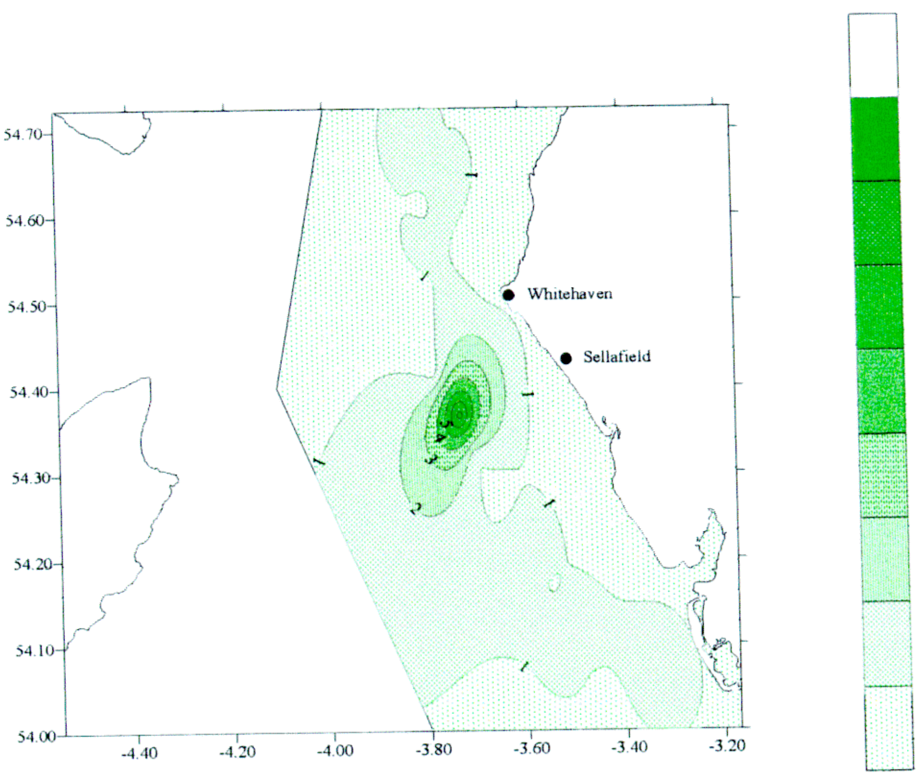

Figure 53. Cumbria Coast Survey July 1997. Standing Crop Divided By Depth (Chlorophyll a mg/m3)

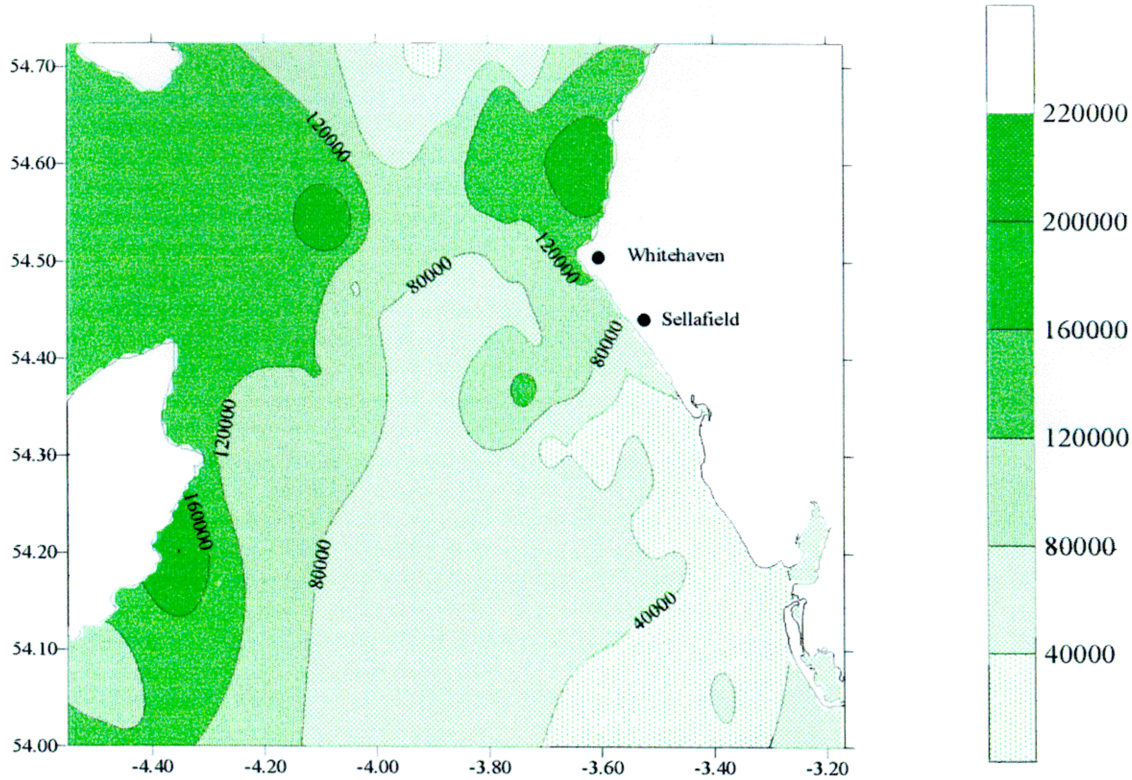

Figure 54. Cumbria Coast Survey July 1997. Total monads/small flagellates (cells/litre).

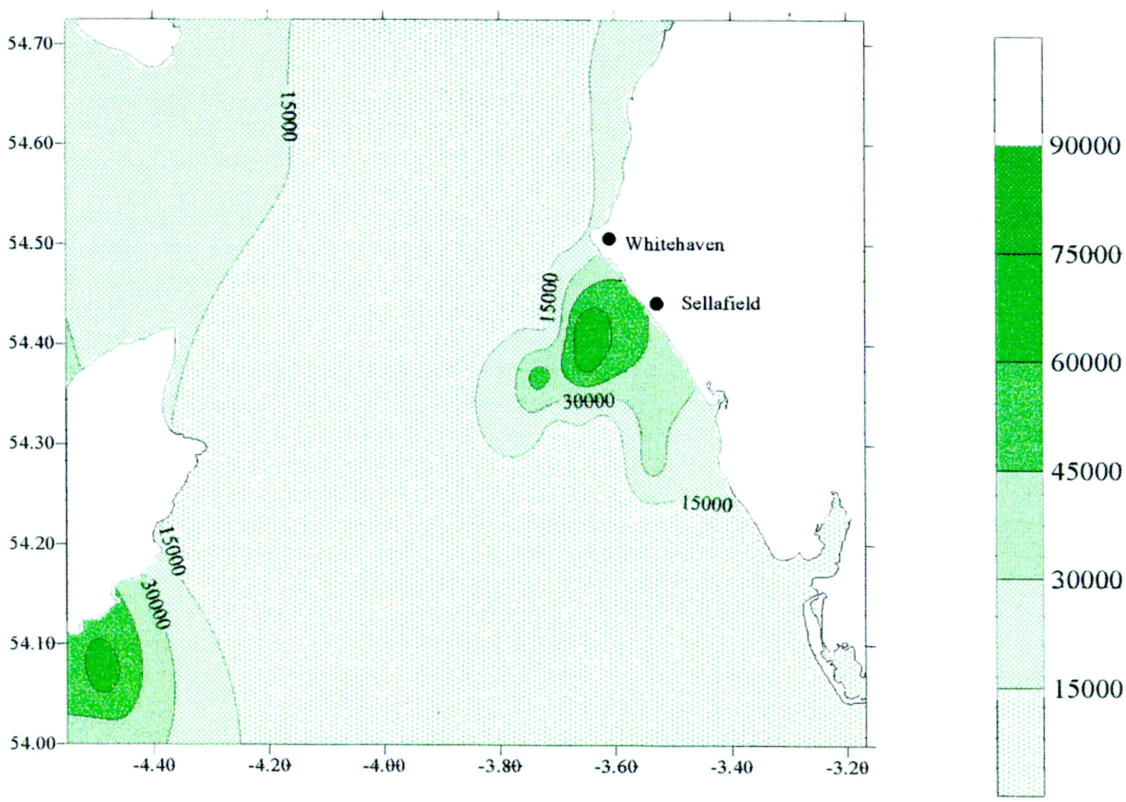

Figure 55. Cumbria Coast Survey July 1997. Total Diatoms (cells/litre).

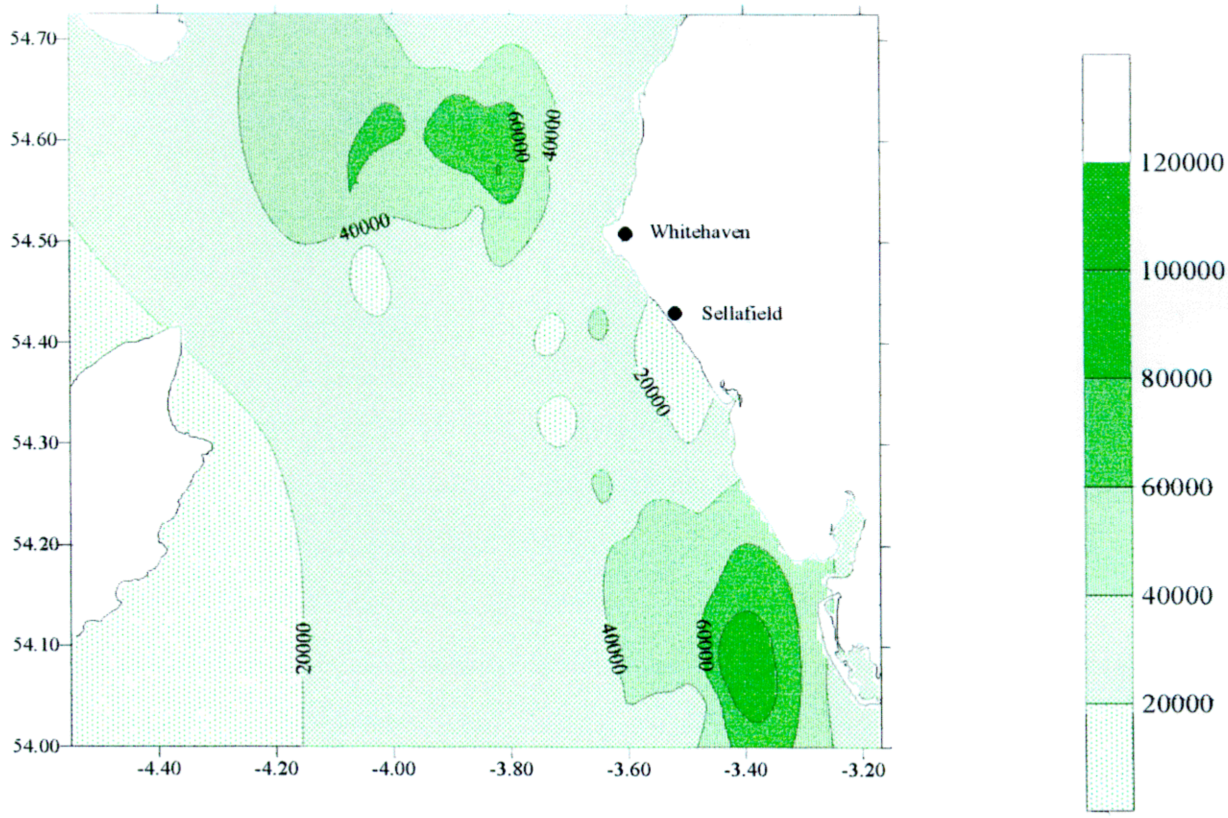

Figure 56. Cumbria coast survey July 1997. Total Dinoflagellates (cells/litre).

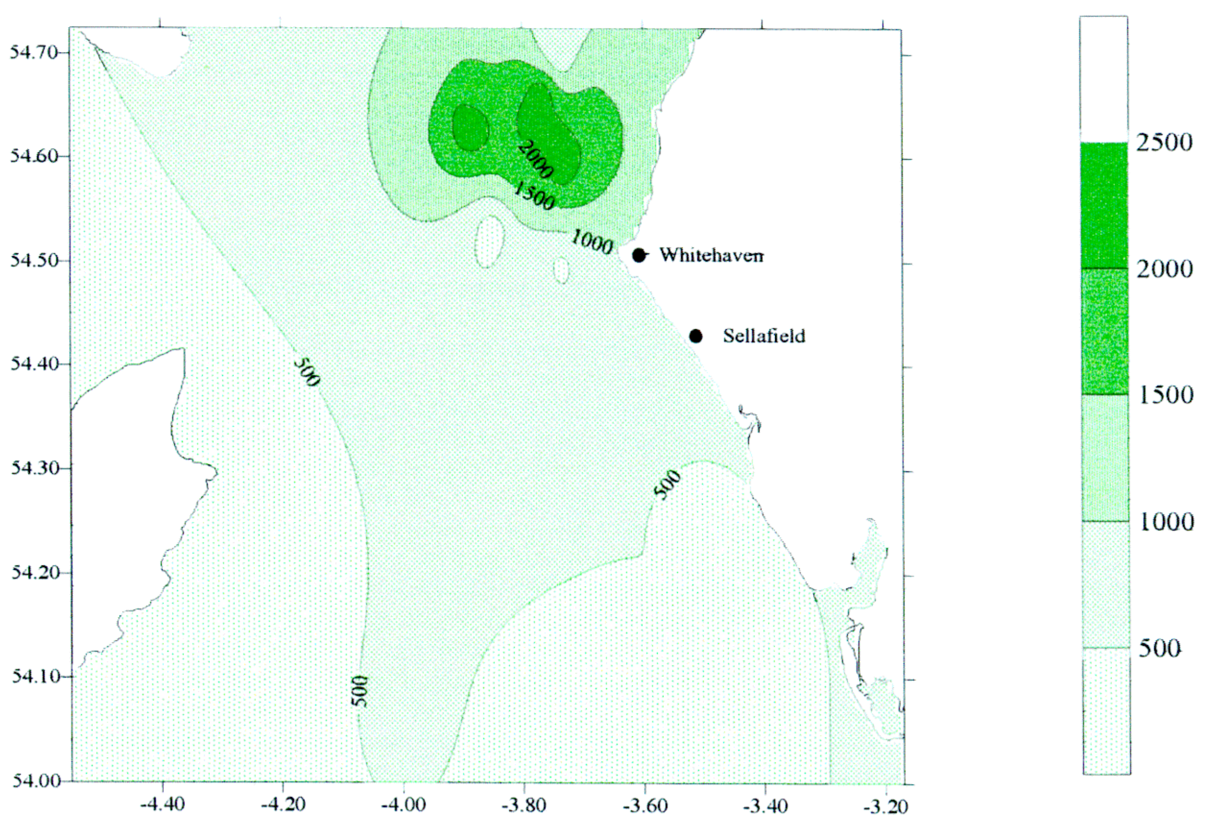

Figure 57. Cumbria coast survey July 1997. (Dinophysis acuta/accuminata (cells/litre).

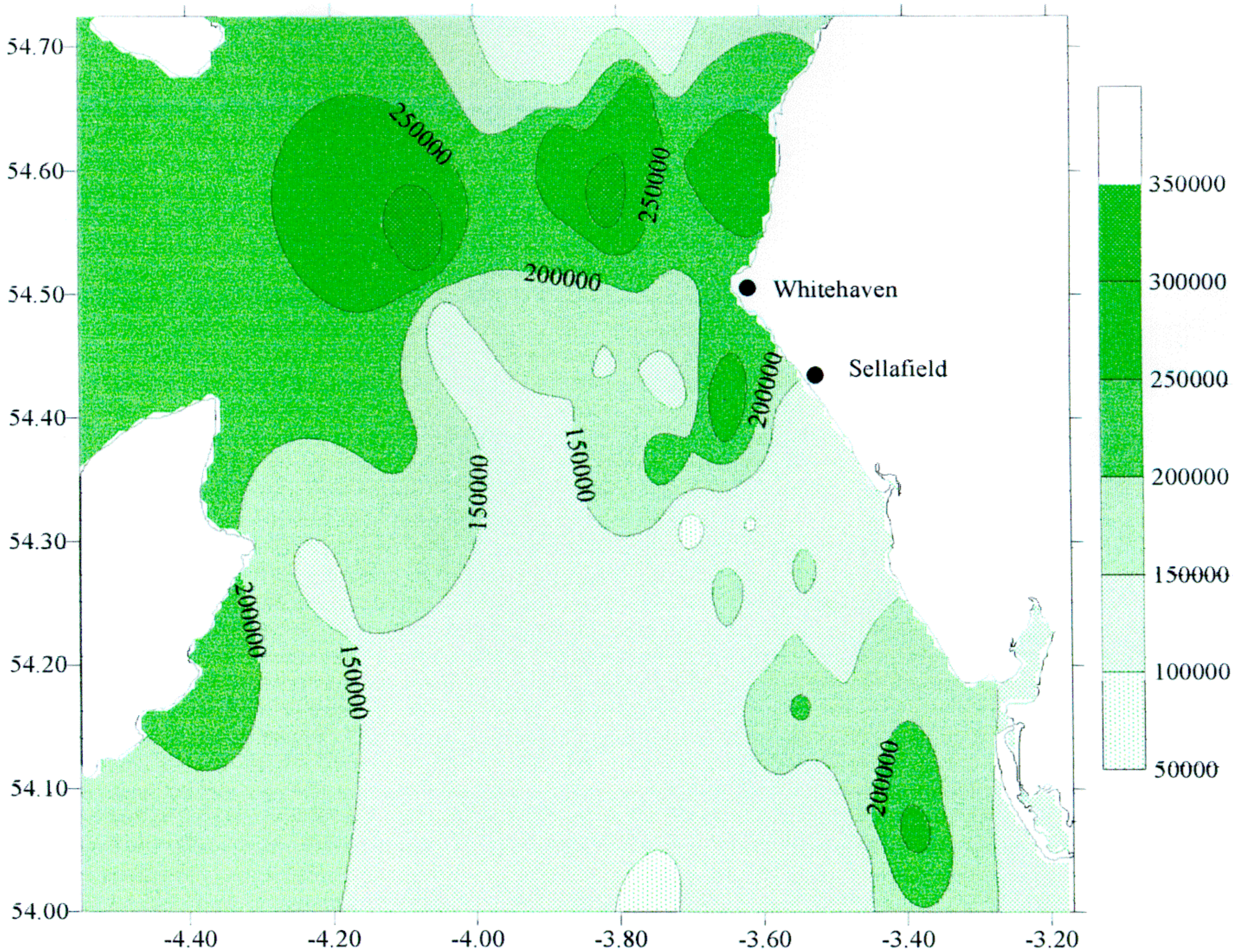

Figure 58. Cumbria coast survey July 1997. Total phytoplankton (cells/litre).

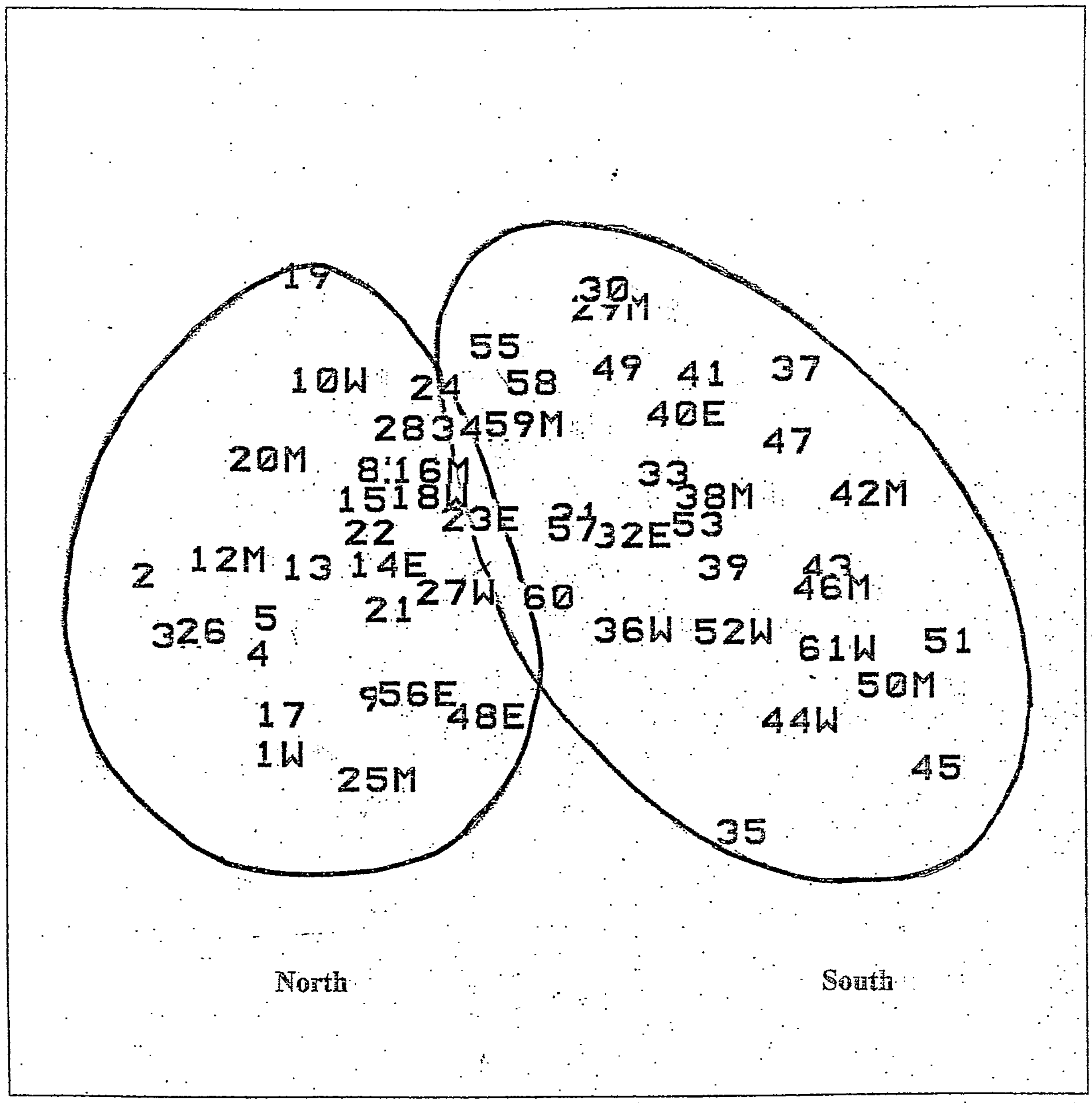

Figure 59. MDS Ordination of Spring Phytoplankton Data and Sampling Site Locations. (Stress = 0.13)

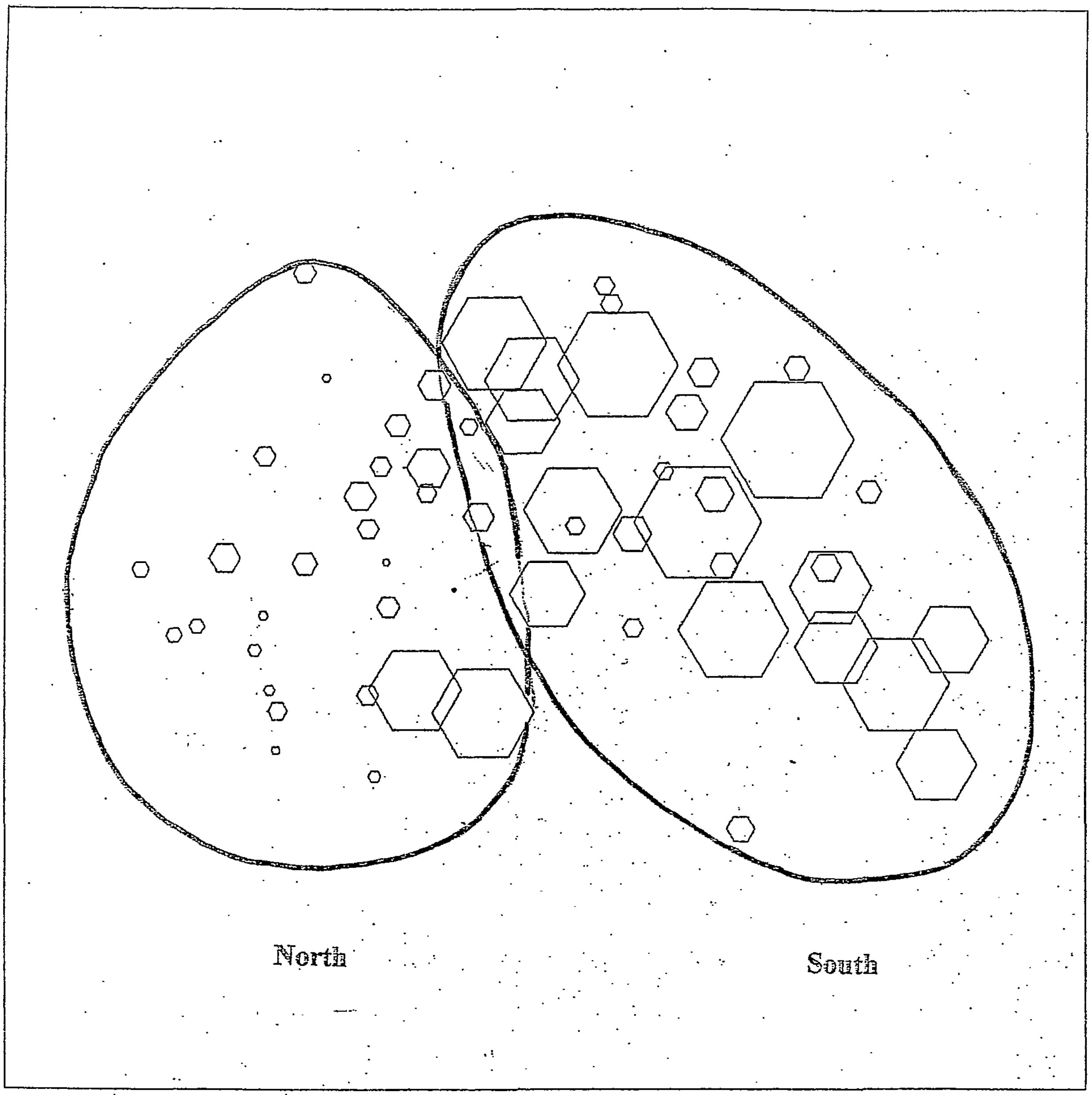

Figure 60. MDS Ordination between spring phytoplankton data and winter nitrite concentrations. Hexagon diameters are proportional to winter concentrations of nitrite. (Stress = 0.13).

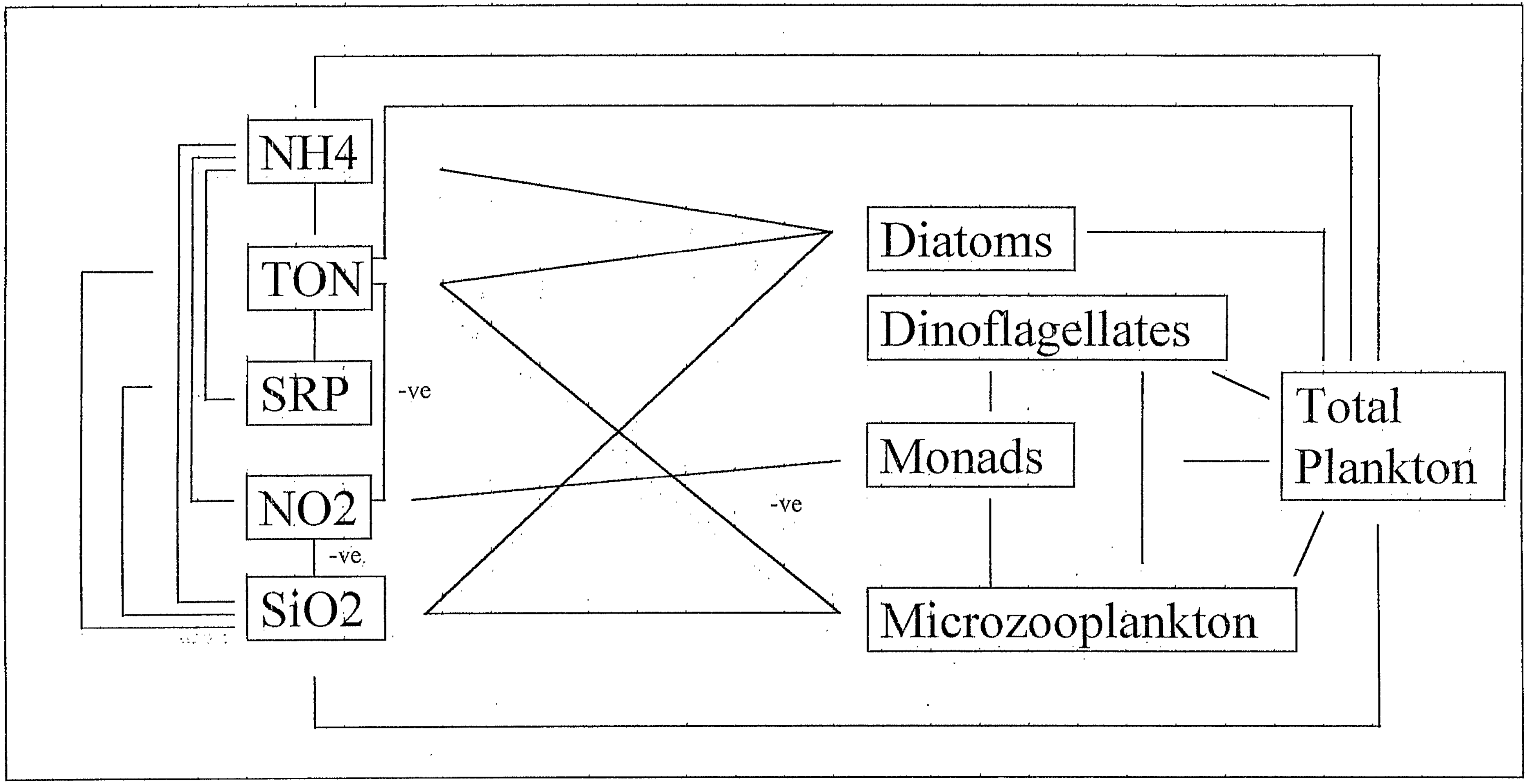

Figure 61. The Relationship between Significant (P=<0.05) Correlation Coefficients of Major Taxonomic Groupings and Nutrient Salts. Eastern Irish Sea March 1997.
(All Correlations are positive unless indicated)

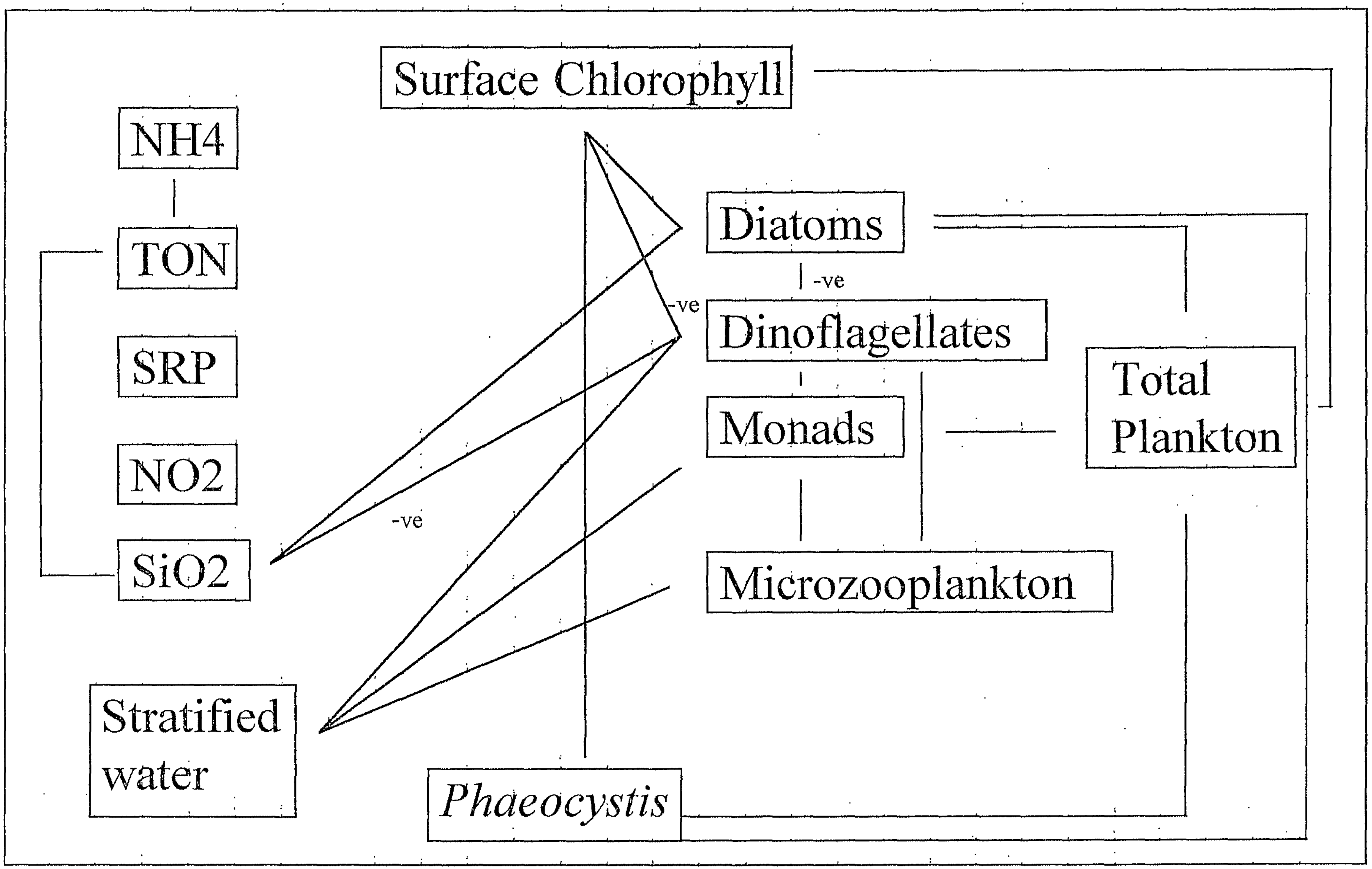

Figure 62. The Relationship Between Significant (P= <0.05) Correlation Coefficients of Major Taxonomic Groupings and Nutrient Salt Concentrations. Eastern Irish Sea May 1997. (All correlation coefficients are positive unless indicated)

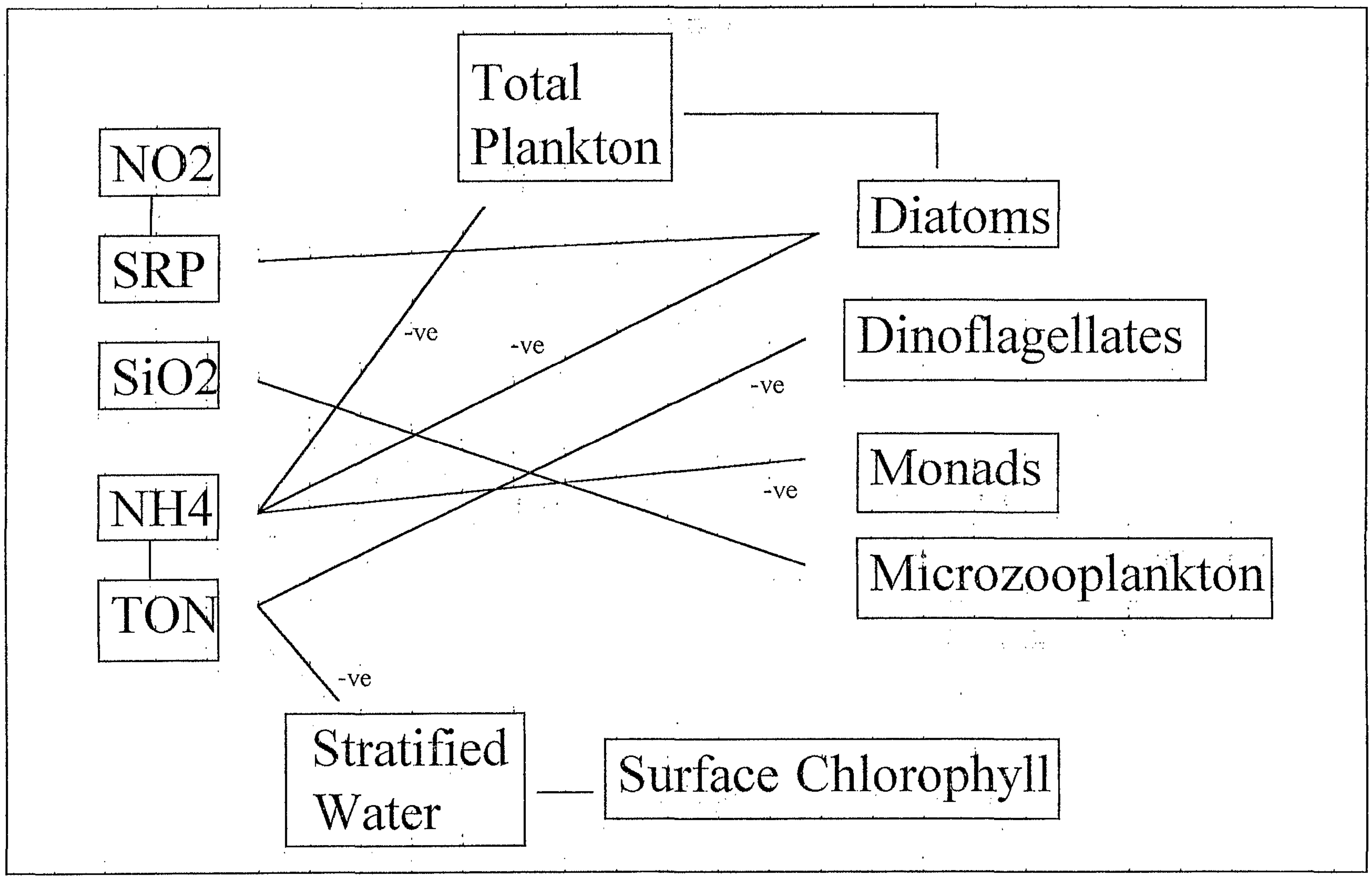

Figure 63. The Relationship between Significant (*P*= <0.05) Correlation Coefficients of Major Taxonomic Groupings and Nutrient Salt Concentrations. Eastern Irish Sea July 1997. (All correlation are positive unless indicated)

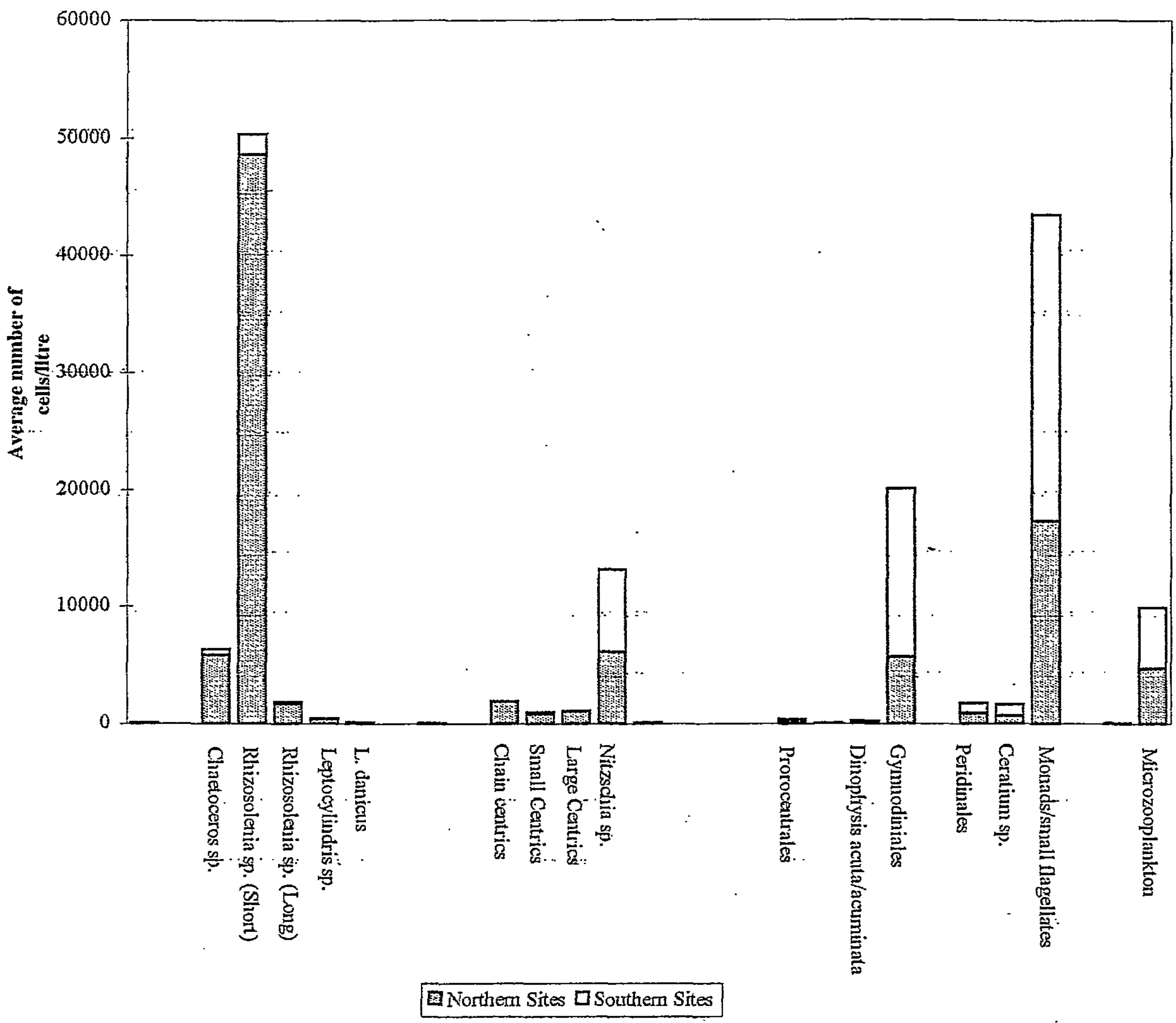

Figure 64. Average abundances of major taxonomic categories at northern and southern sites during May 1997 (*Phaeocystis globosa* counts have been omitted from this graph).

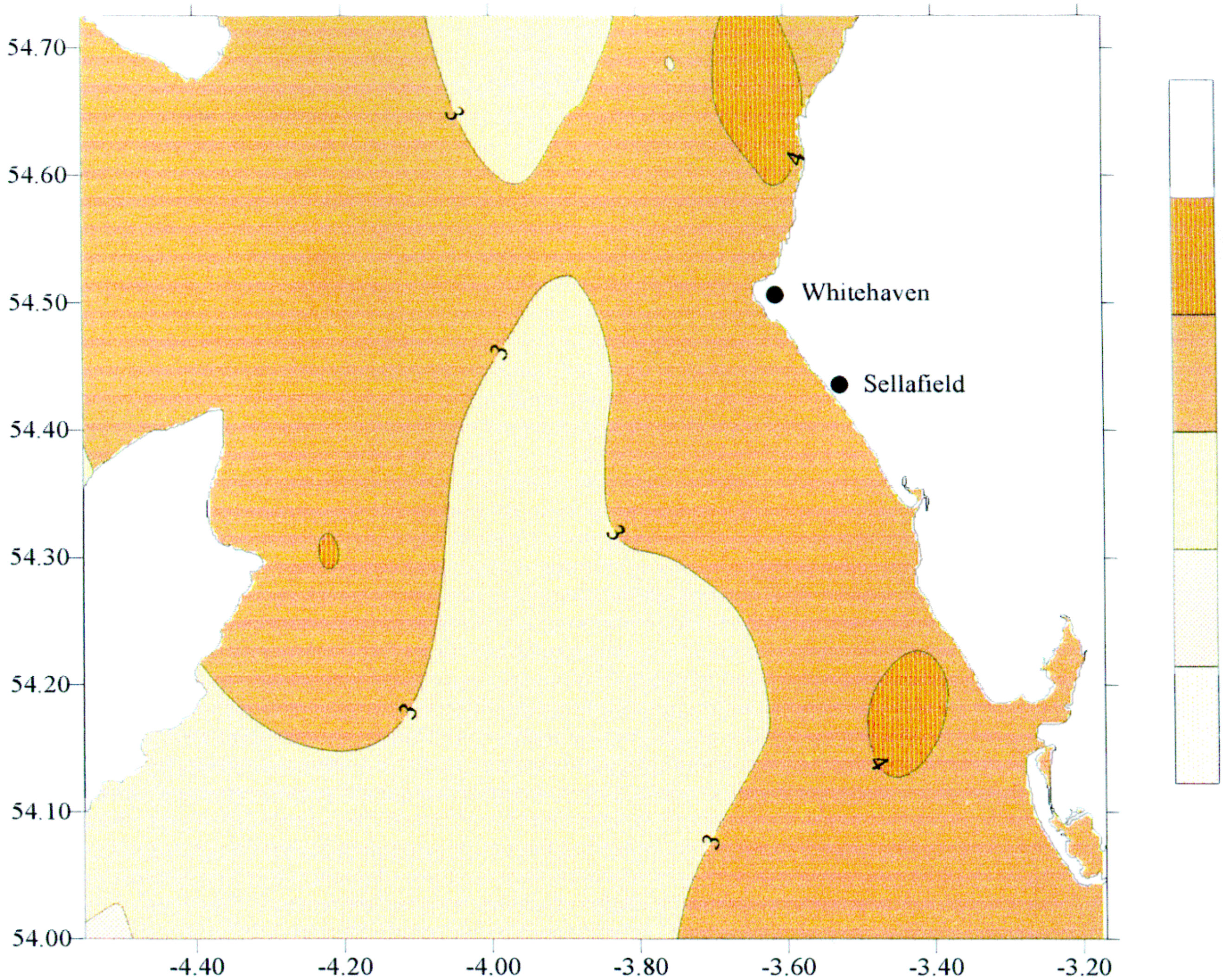

Figure 65. Cumbria Coast survey March 1997. N:Si ratio (μg-at/litre)
Areas with an N:SI ratio greater than 2 are indicative of waters subject to future eutrophication.

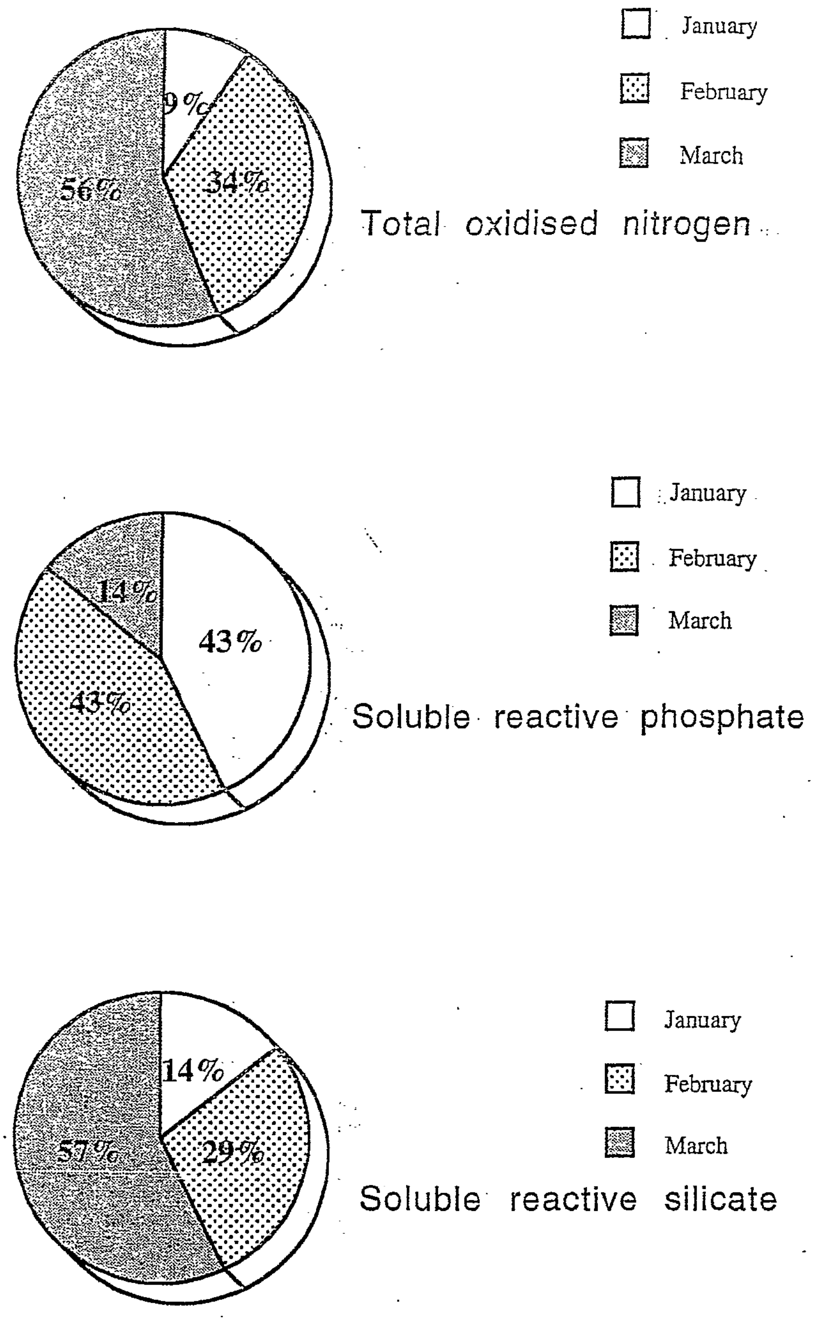

Figure 66. Month of nutrient salt maximum. Data taken from the long term monitoring studies at Port Erin Marine Laboratory's Cypris Station approximately 4km west of Port Erin, Isle of Man.

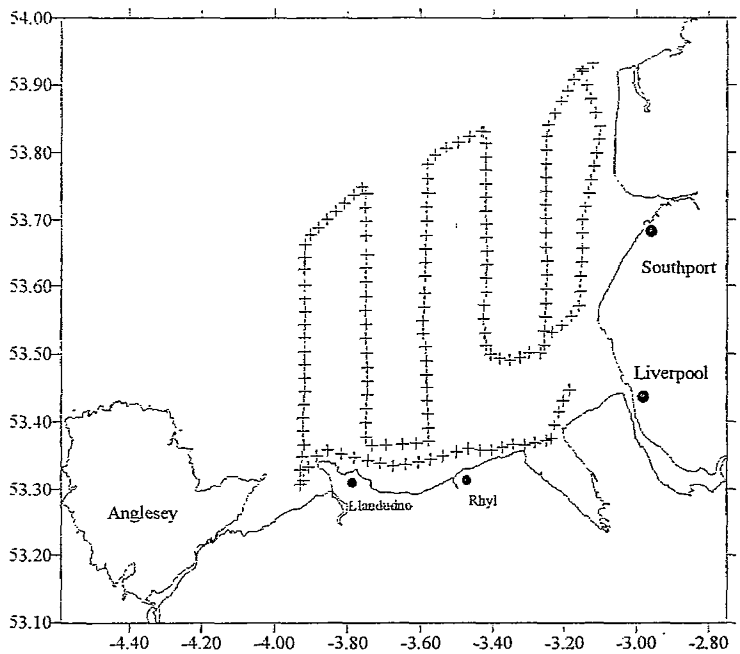

Figure 67. Liverpool Bay Survey January 1997. Sampling positions.

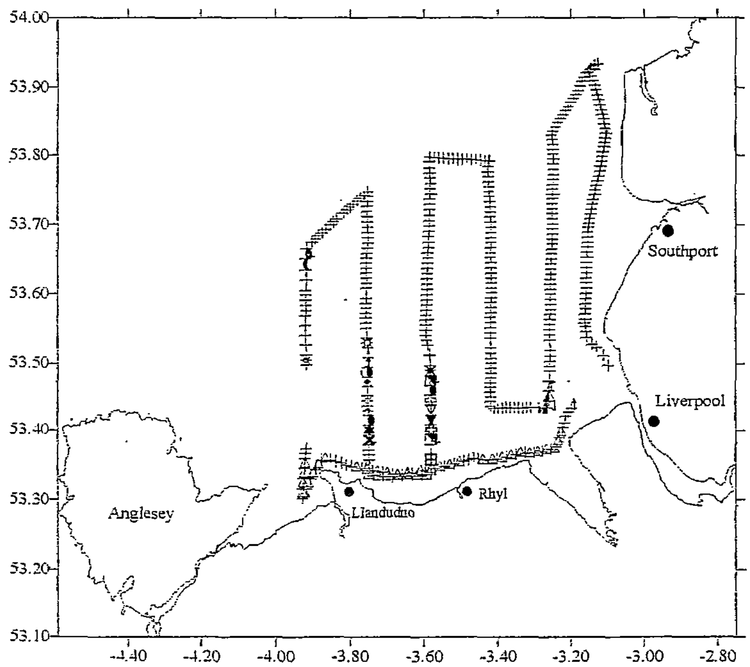

Figure 68. Liverpool Bay Survey April 1997. Sampling positions

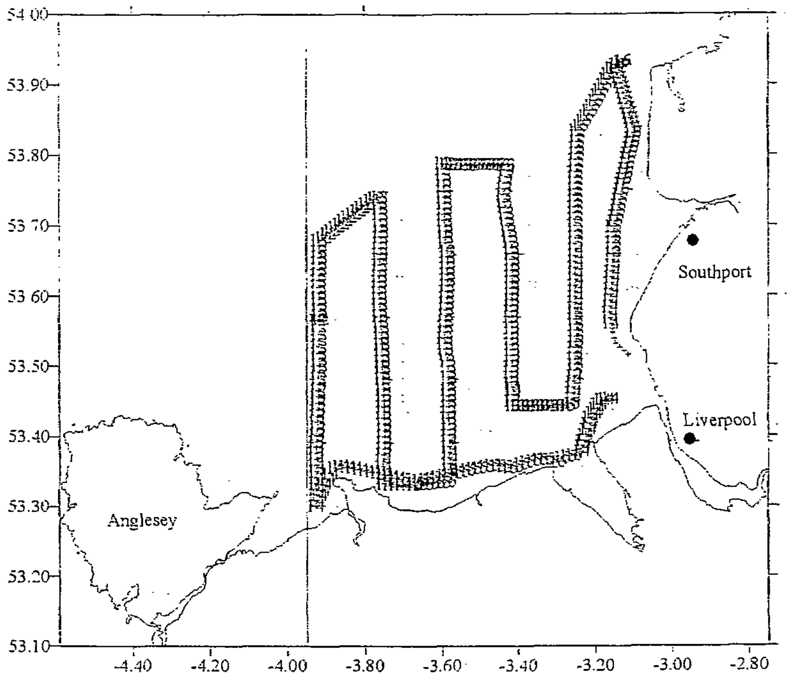

Figure 69. Liverpool Bay Survey June 1997. Sampling Positions.

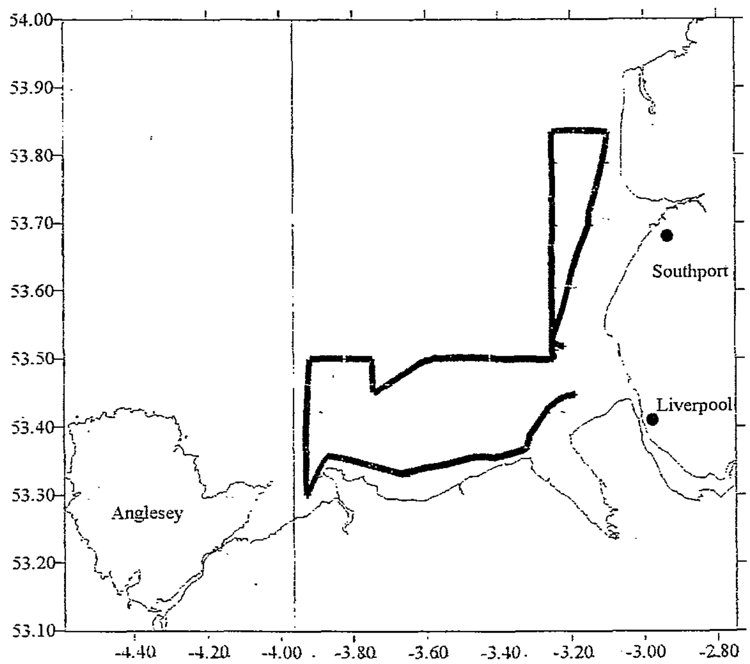

Figure 70. Liverpool Bay Survey November 1997. Sampling positions.

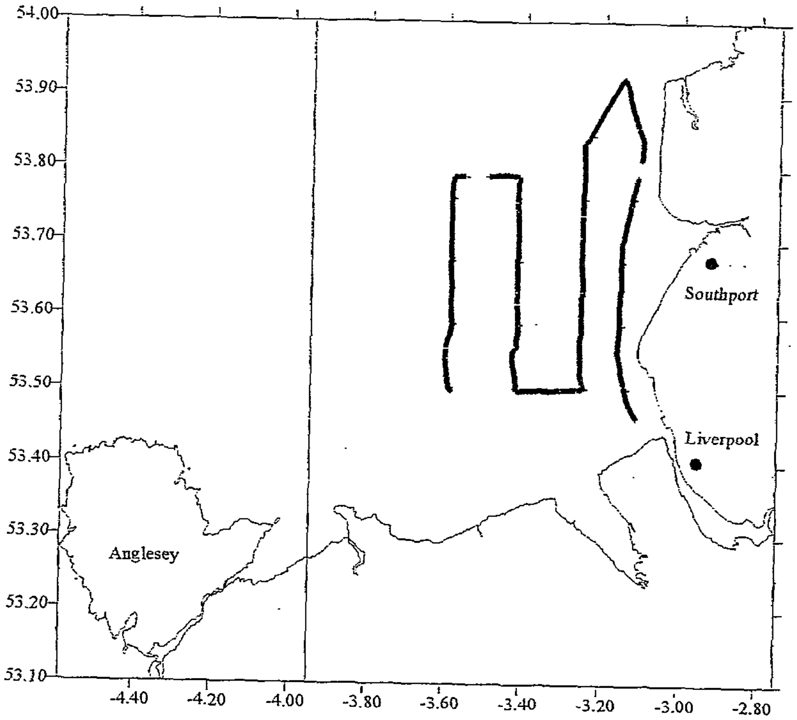

Figure 71. Liverpool Bay Survey December 1997. Sampling Positions.

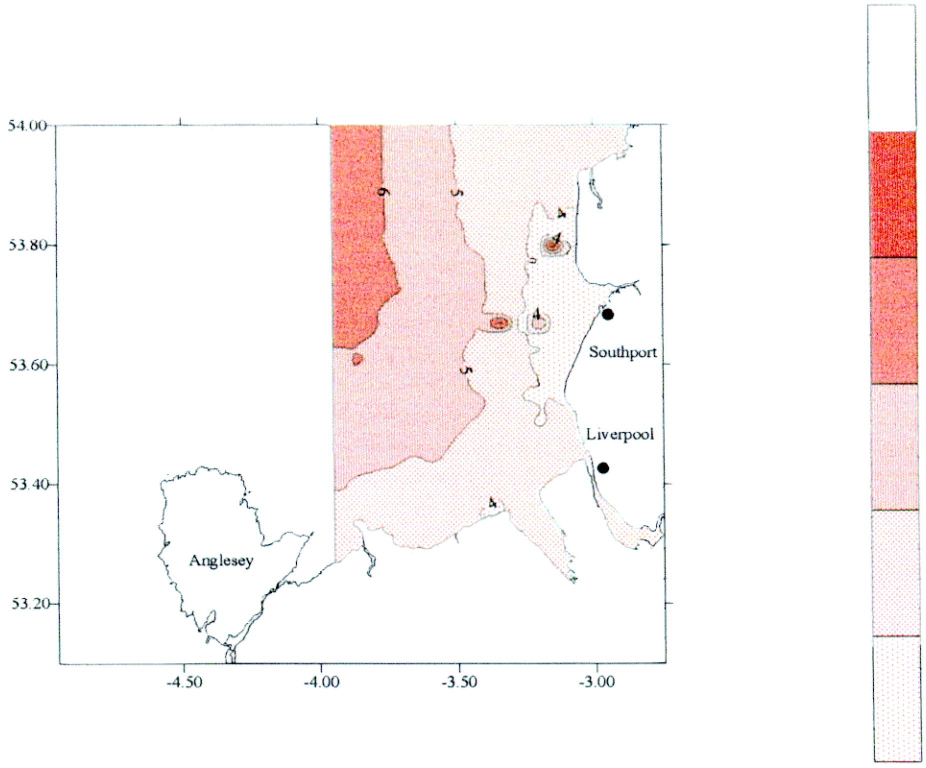

Figure 72. Liverpool Bay Survey January 1997. Temperature (Degrees Celsius).

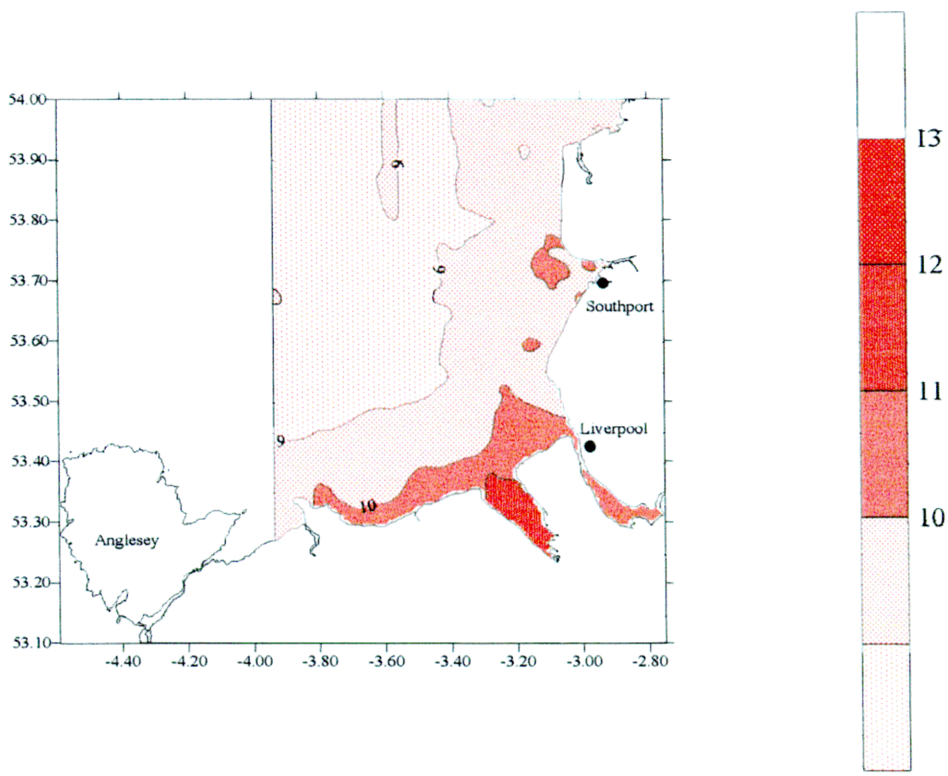

Figure 73. Liverpool Bay Survey April 1997. Temperature (Degrees Celsius).

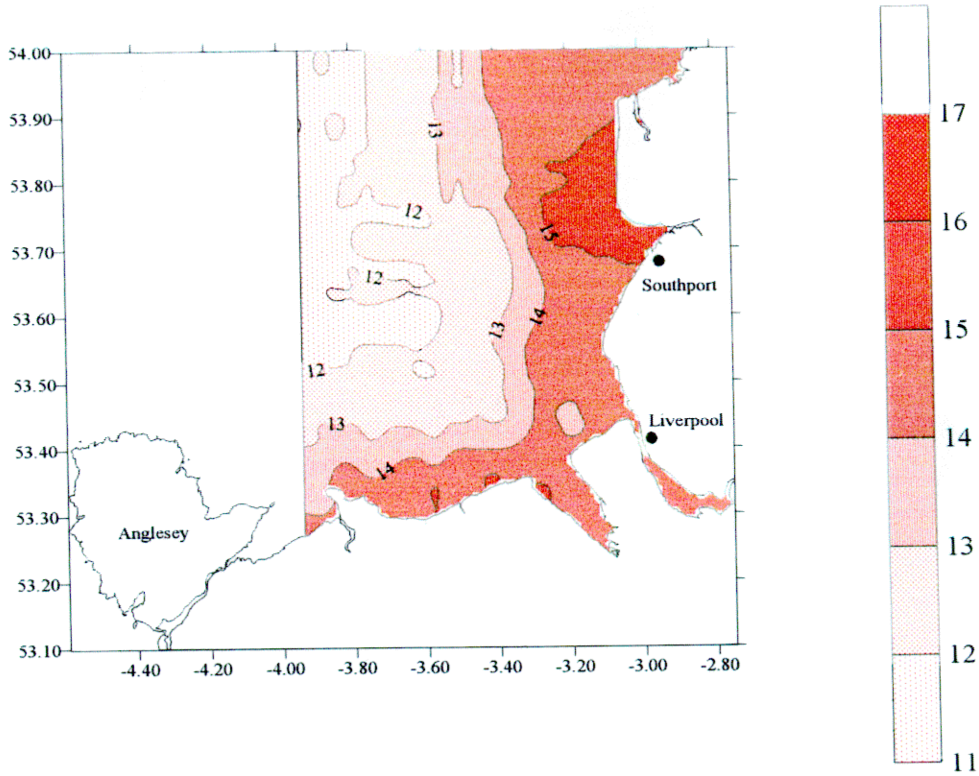

Figure 74. Liverpool Bay Survey June 1997. Temperature (Degrees Celsius)

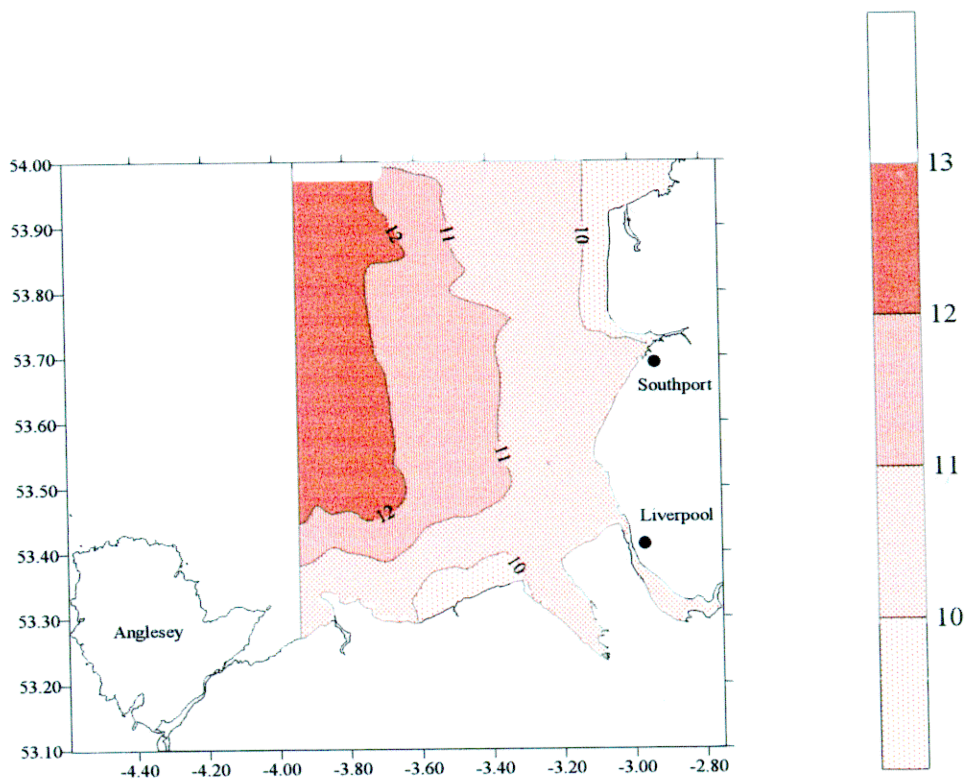

Figure 75. Liverpool Bay Survey November 1997. Temperature (Degrees Celsius).

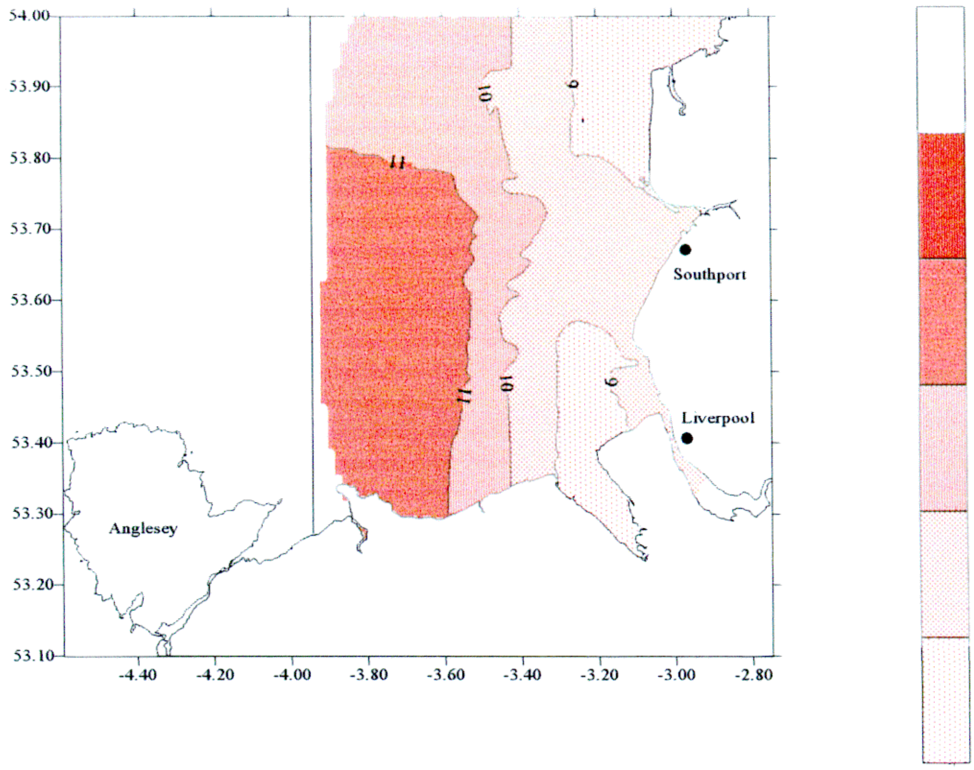

Figure 76. Liverpool Bay survey December 1997. Temperature Degrees Celsius.

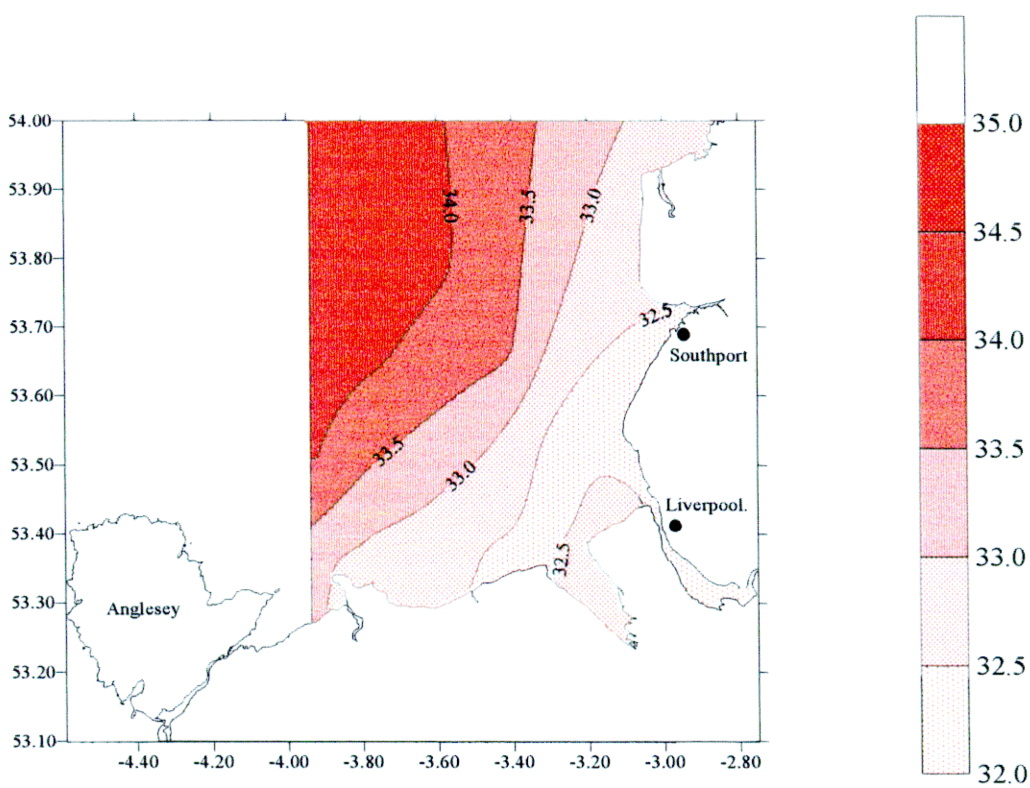

Figure 77. Liverpool Bay Survey January 1997. Salinity.

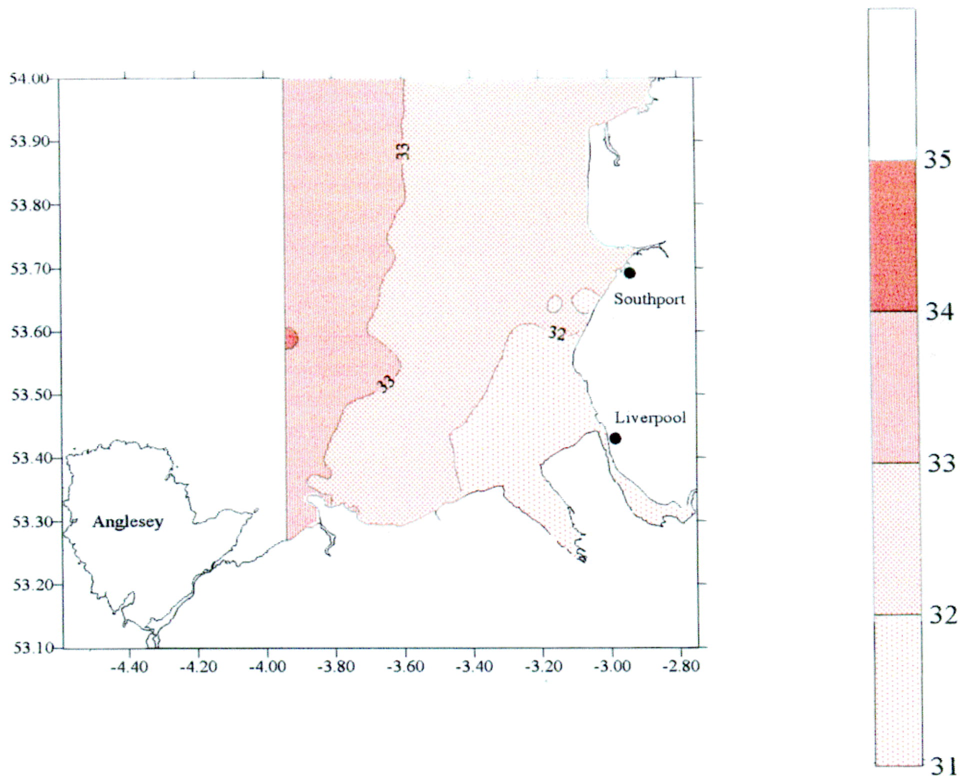

Figure 78. Liverpool bay Survey April 1997. Salinity.

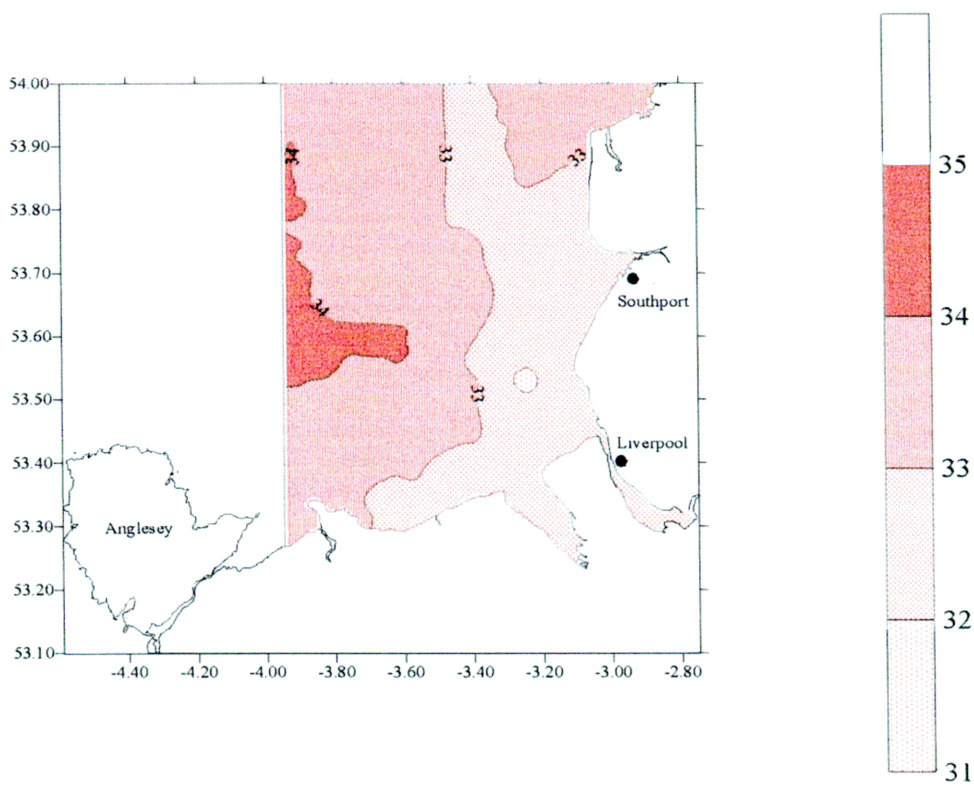

Figure 79. Liverpool Bay Survey June 1997. Salinity.

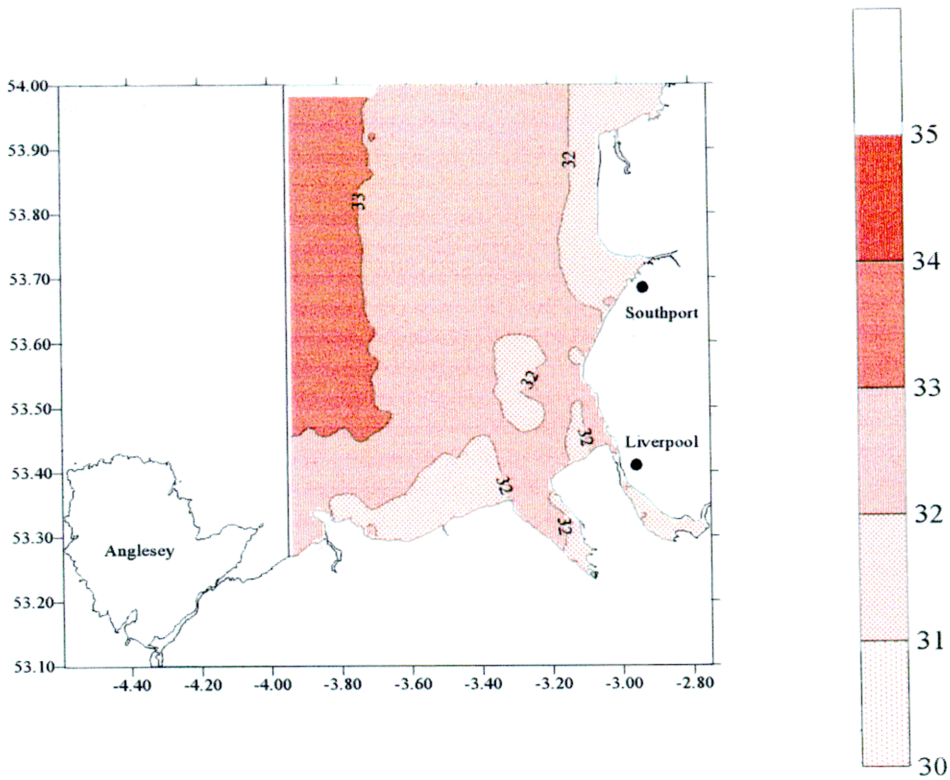

Figure 80. Liverpool Bay Survey November 1997. Salinity

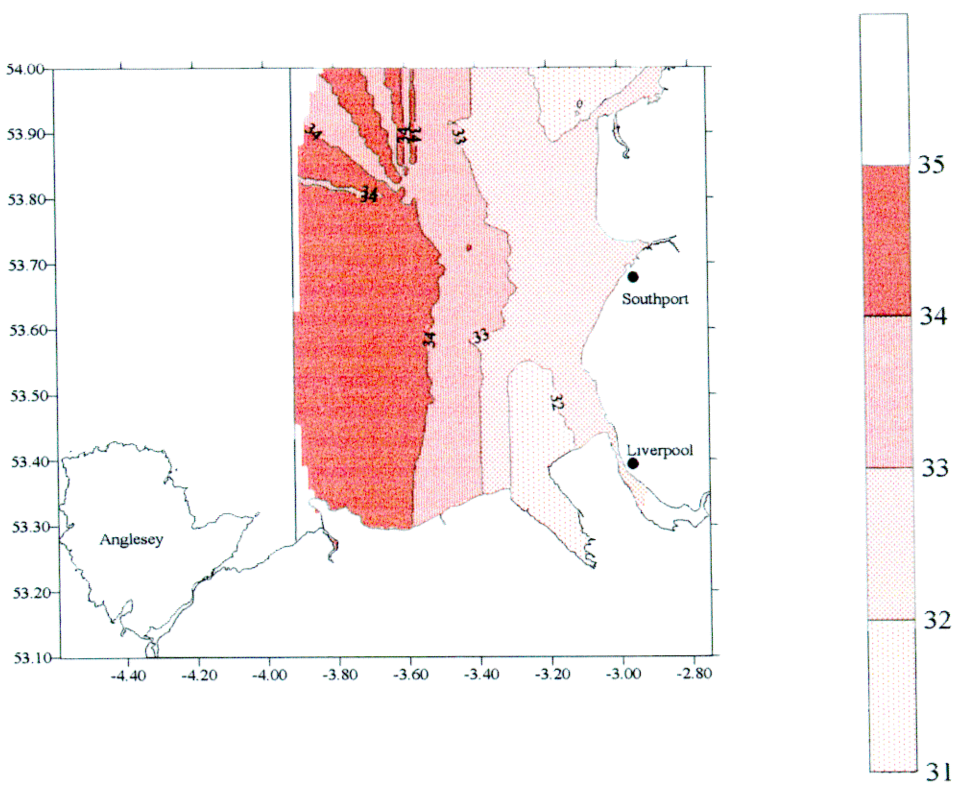

Figure 81. Liverpool Bay Survey December 1997. Salinity.

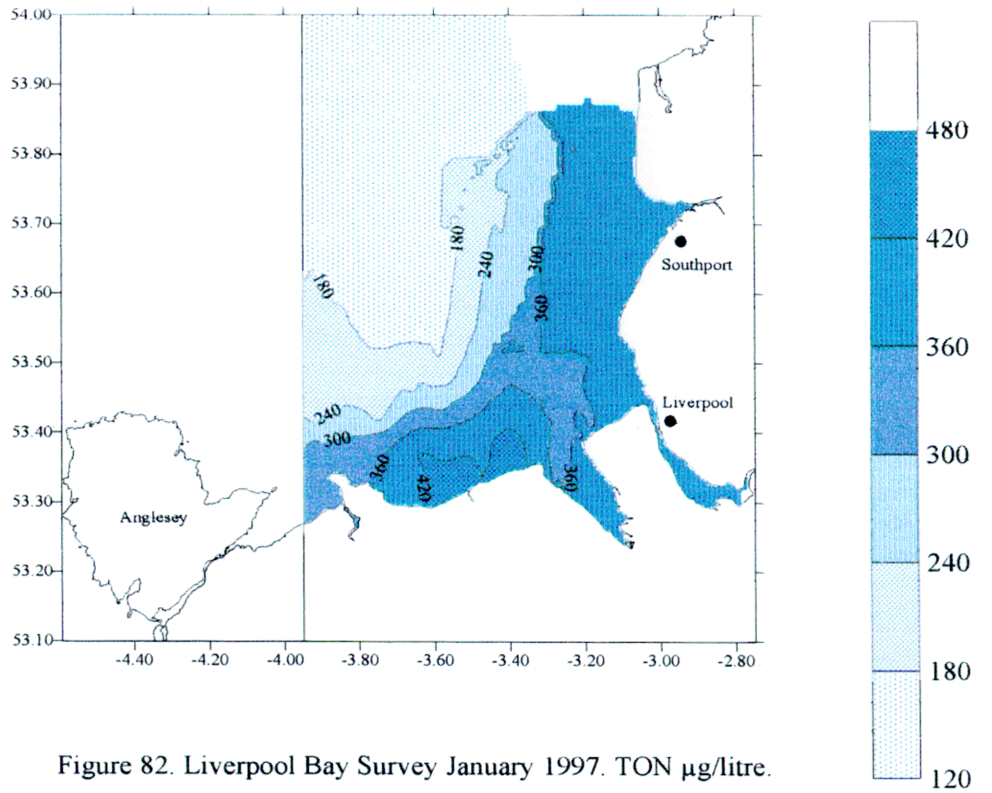

Figure 82. Liverpool Bay Survey January 1997. TON µg/litre.

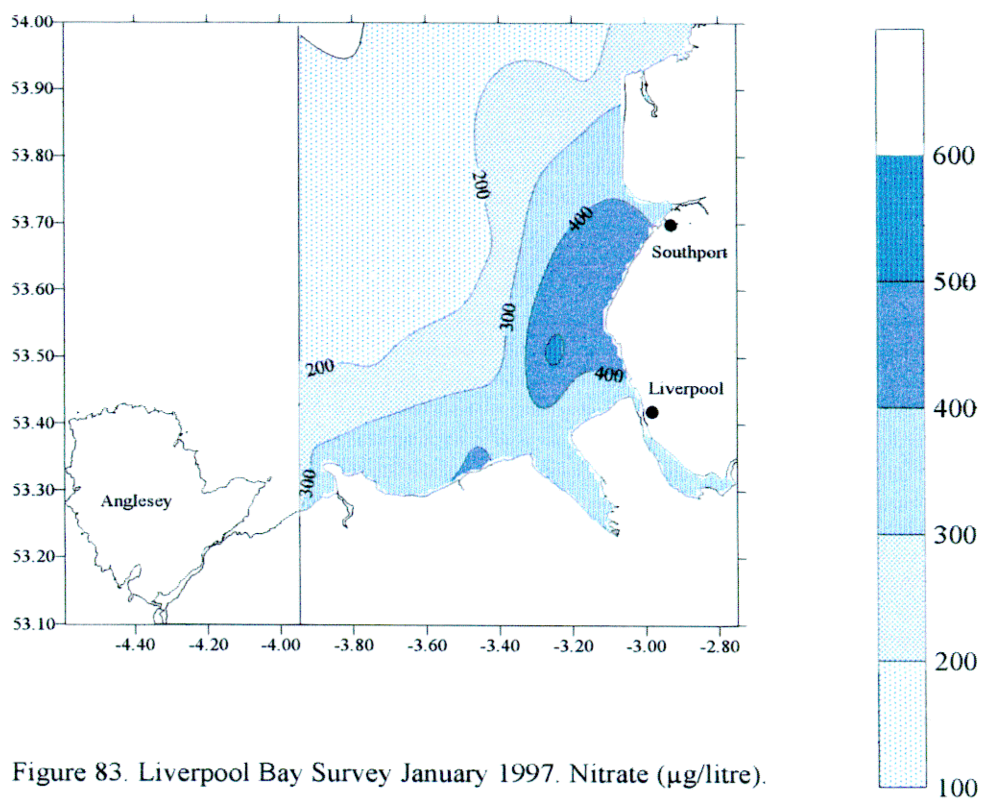

Figure 83. Liverpool Bay Survey January 1997. Nitrate (µg/litre).

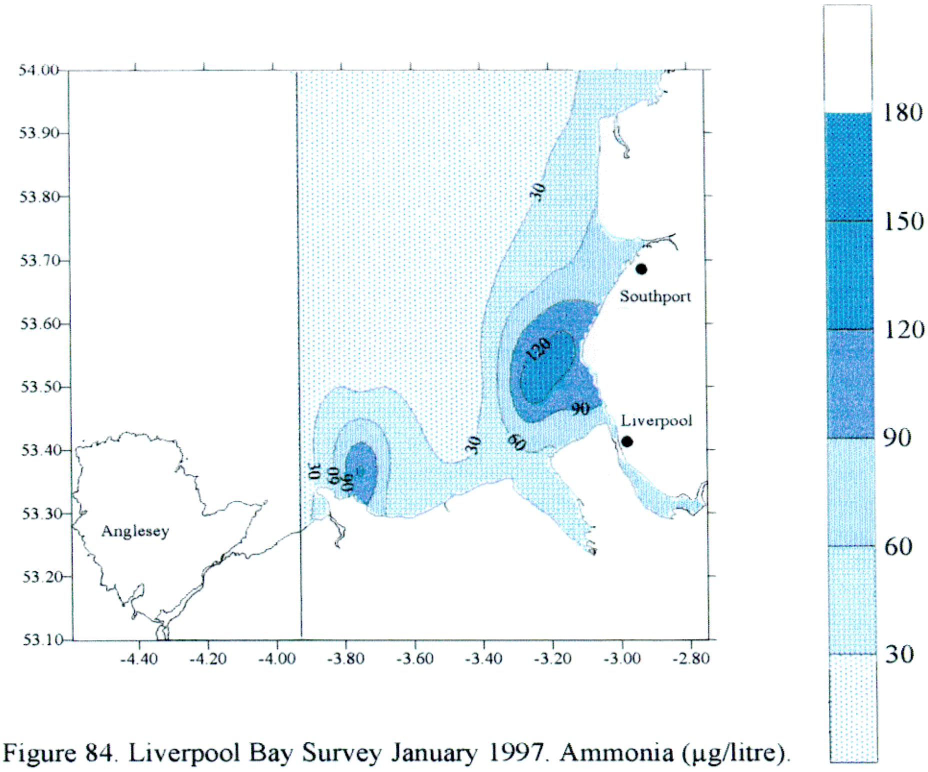

Figure 84. Liverpool Bay Survey January 1997. Ammonia (µg/litre).

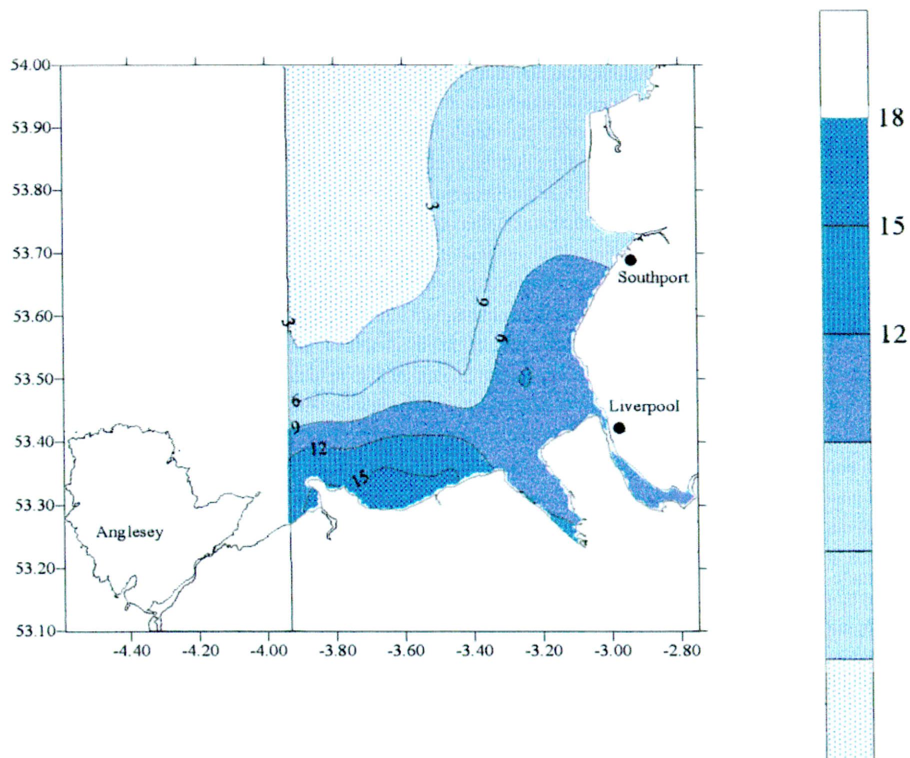

Figure 85. Liverpool Bay Survey January 1997. Nitrite (µg/litre).

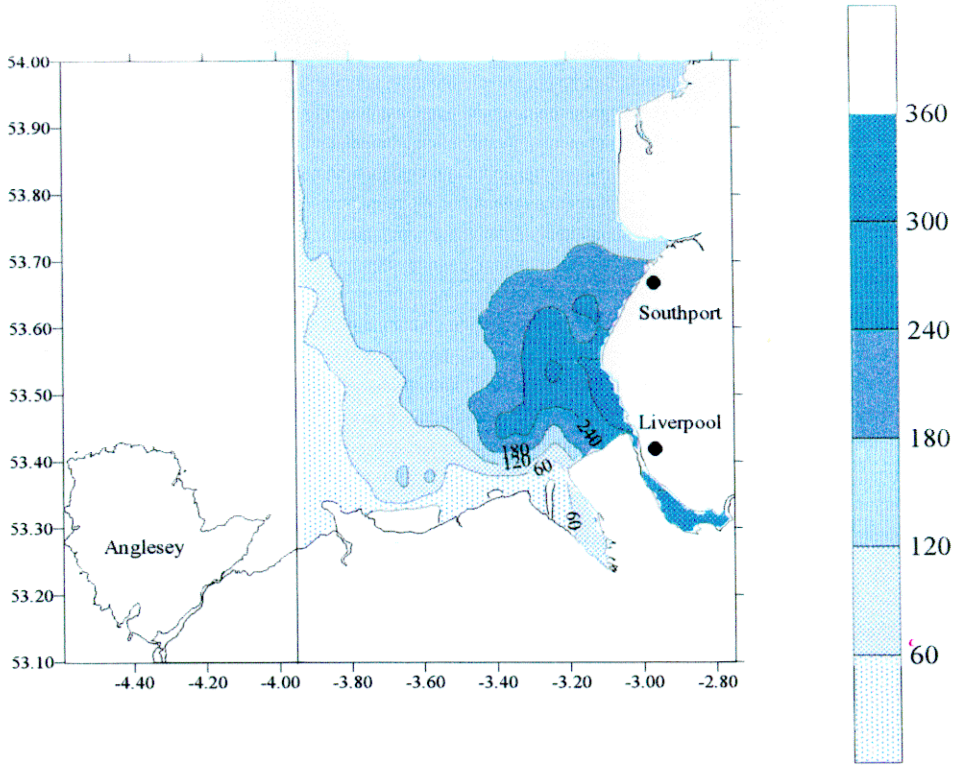

Figure 86. Liverpool Bay Survey April 1997. TON (µg/litre).

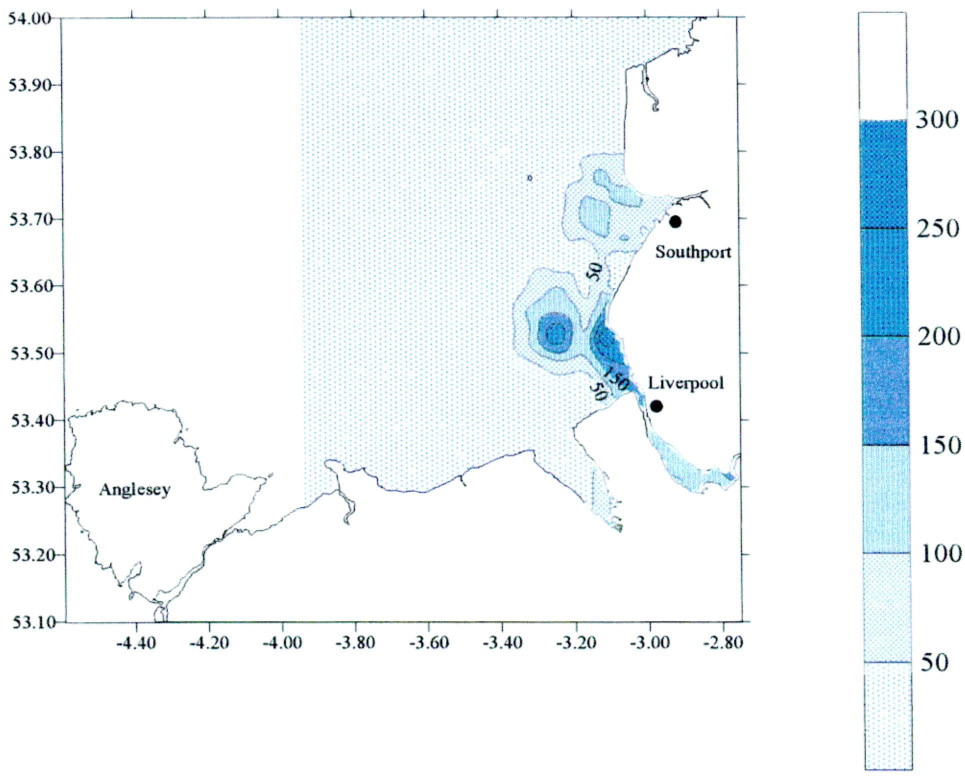

Figure 87. Liverpool Bay Survey June 1997. TON (µg/litre).

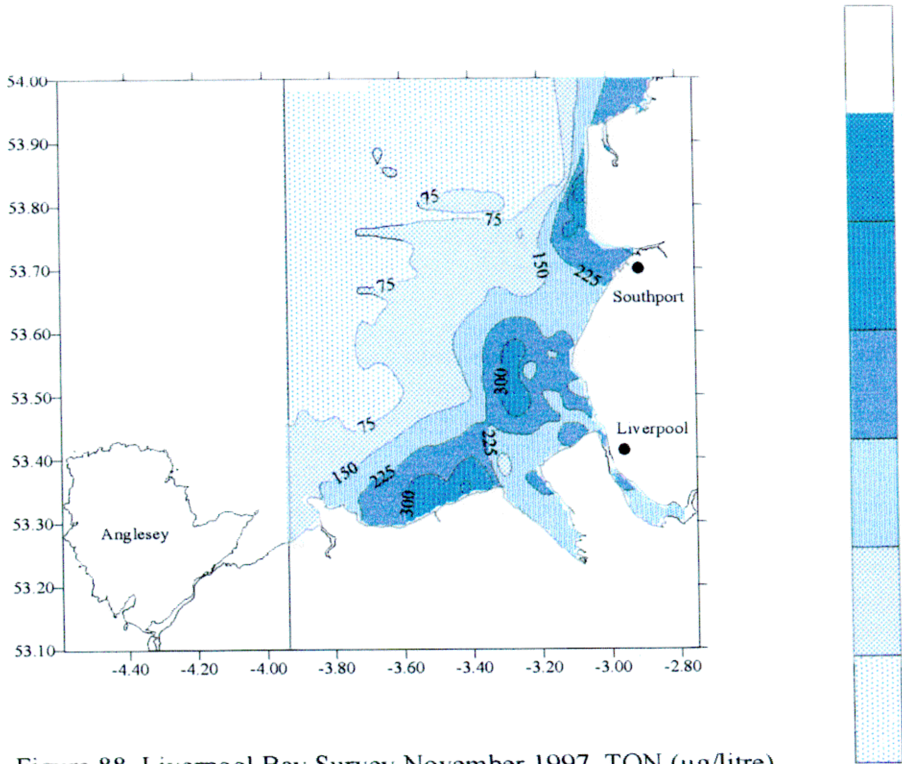

Figure 88. Liverpool Bay Survey November 1997. TON (μg/litre)

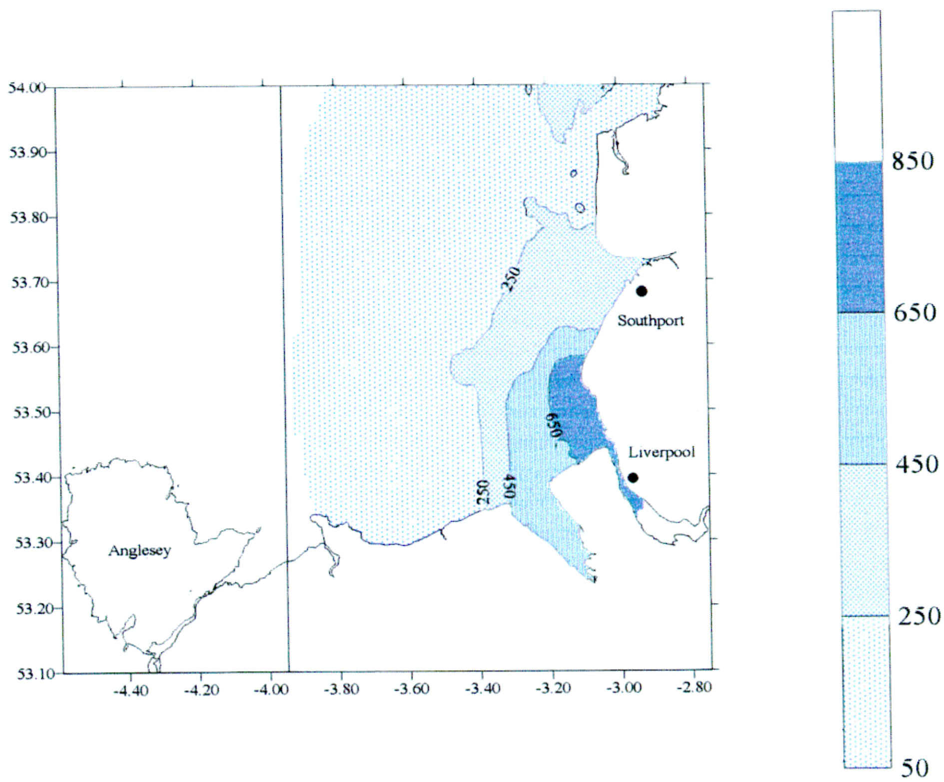

Figure 89. Liverpool Bay Survey December 1997. TON (μg/litre).

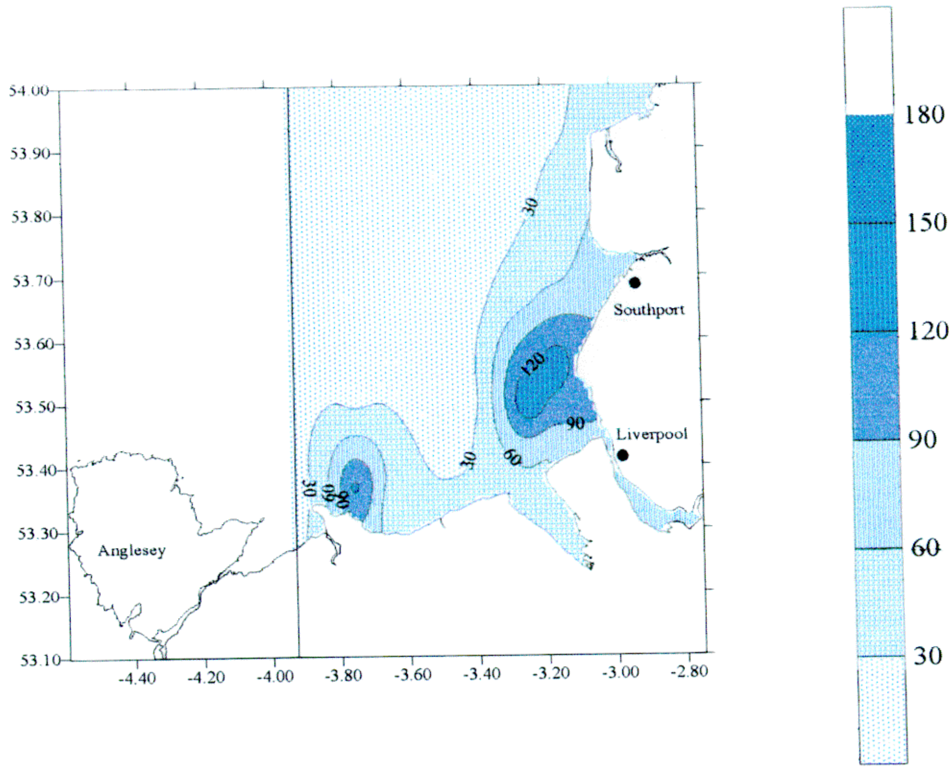

Figure 90. Liverpool Bay Survey January 1997. Ammonia (µg/litre).

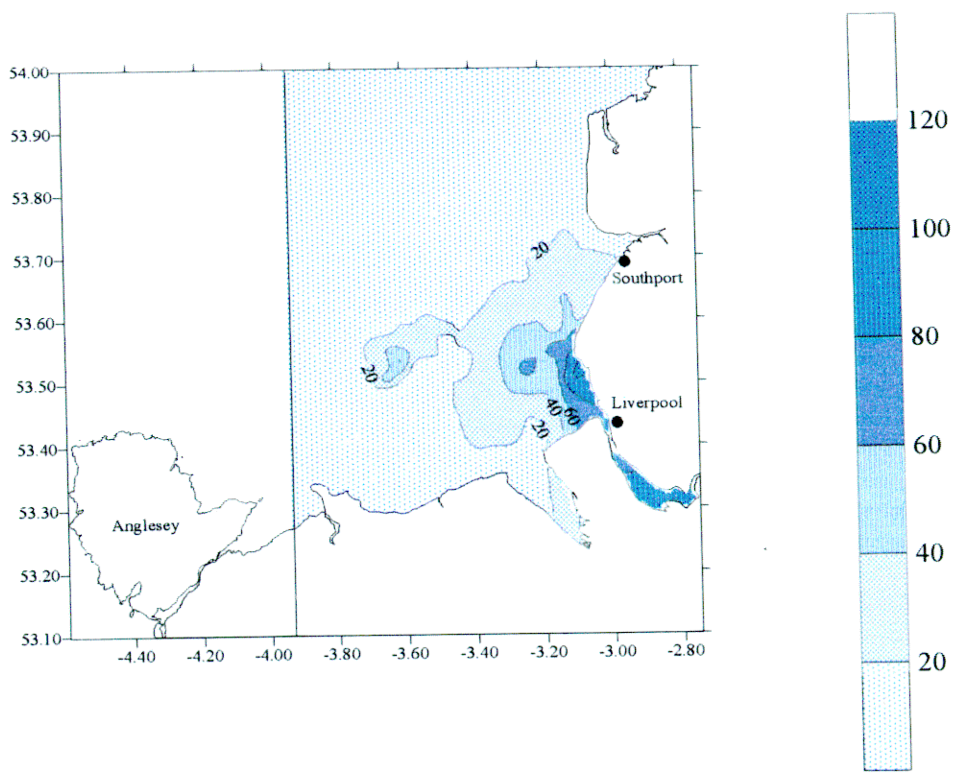

Figure 91. Liverpool Bay Survey April 1997. Ammonia (µg/litre).

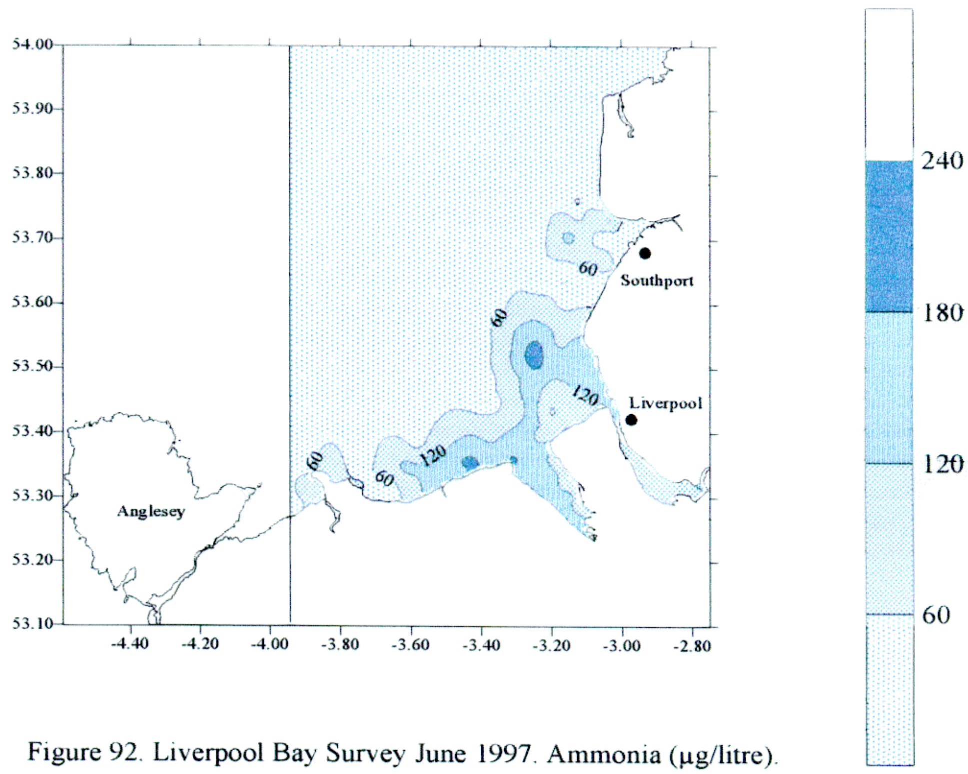

Figure 92. Liverpool Bay Survey June 1997. Ammonia (μg/litre).

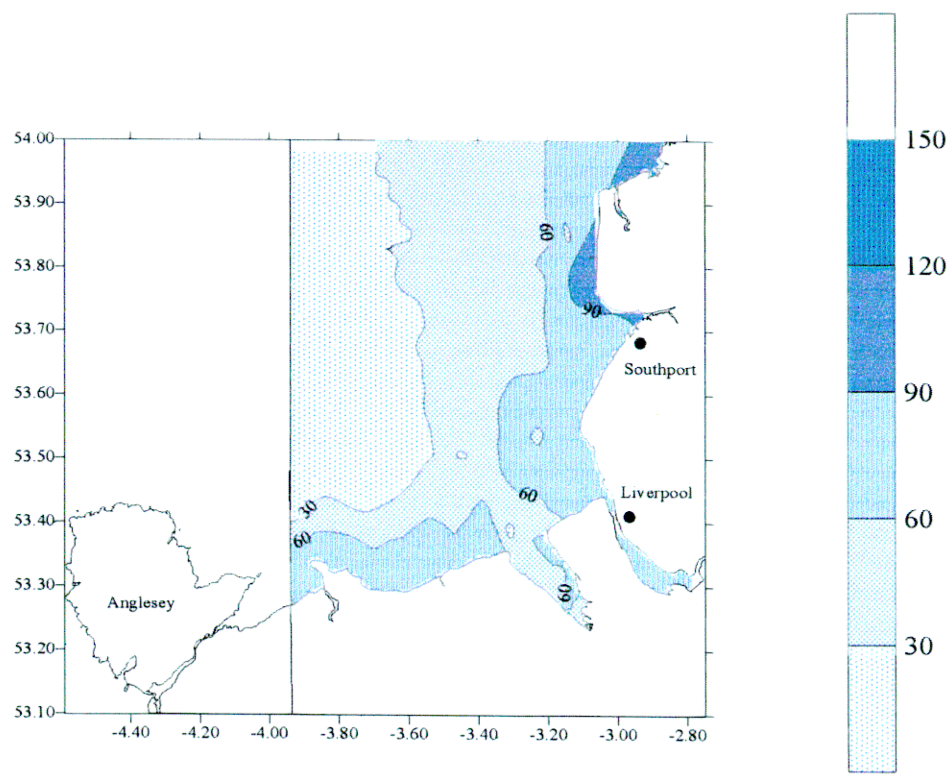

Figure 93. Liverpool Bay Survey November 1997. Ammonia (μg/litre).

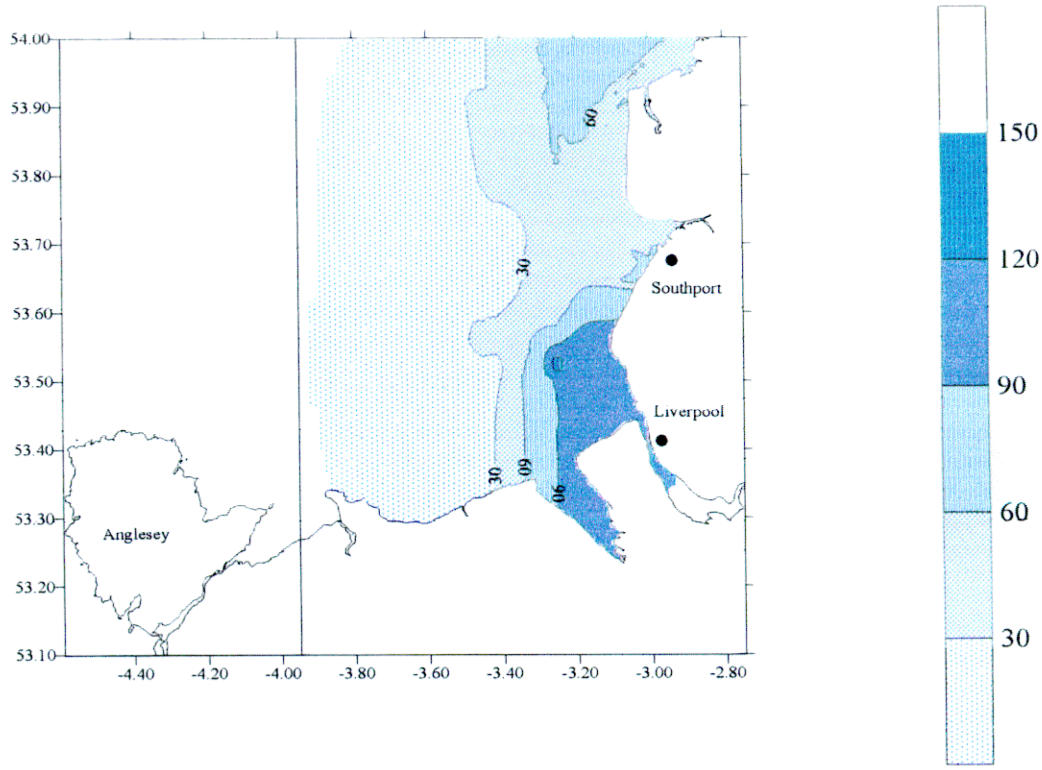

Figure 94. Liverpool Bay Survey December 1997. Ammonia (µg/litre).

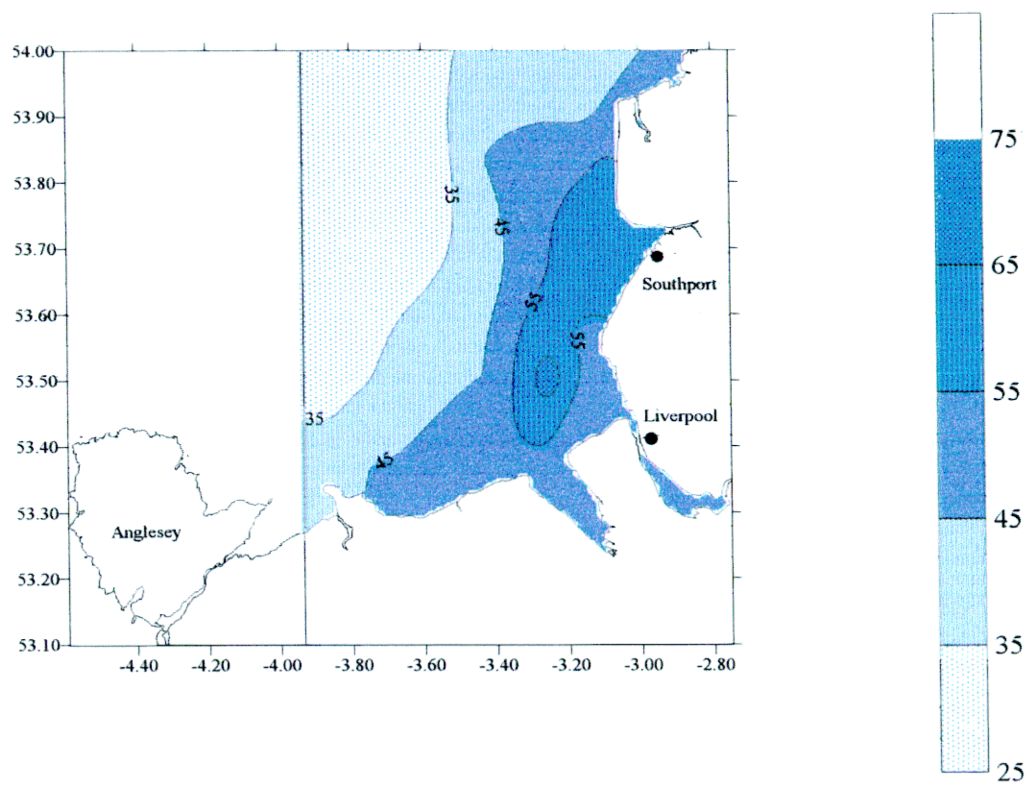

Figure 95. Liverpool Bay Survey January 1997. SRP (µg/litre).

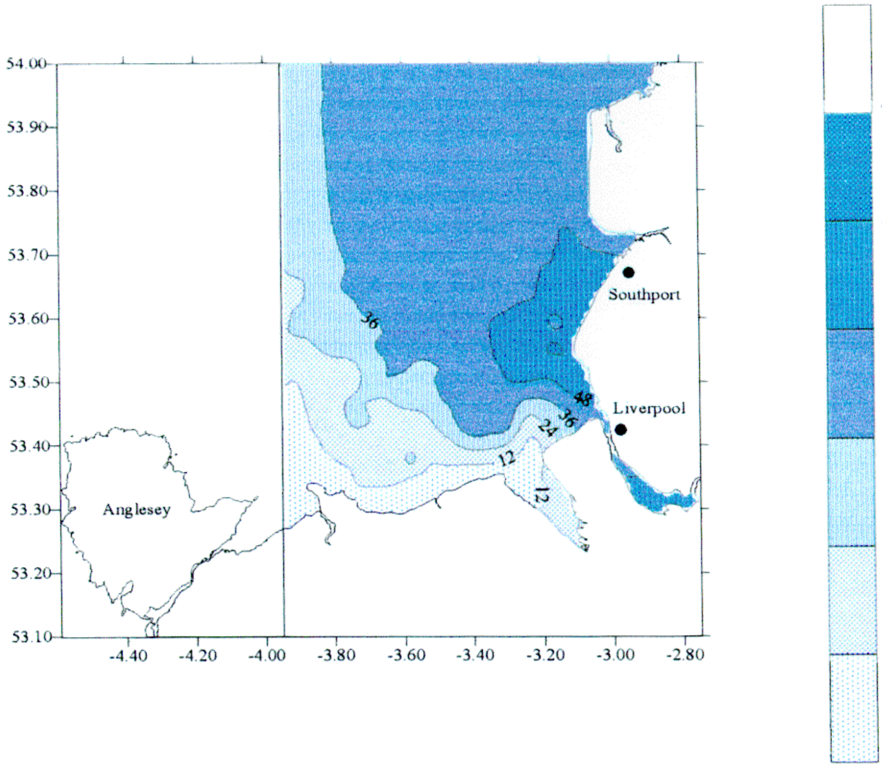

Figure 96. Liverpool Bay Survey April 1997. SRP (µg/litre)

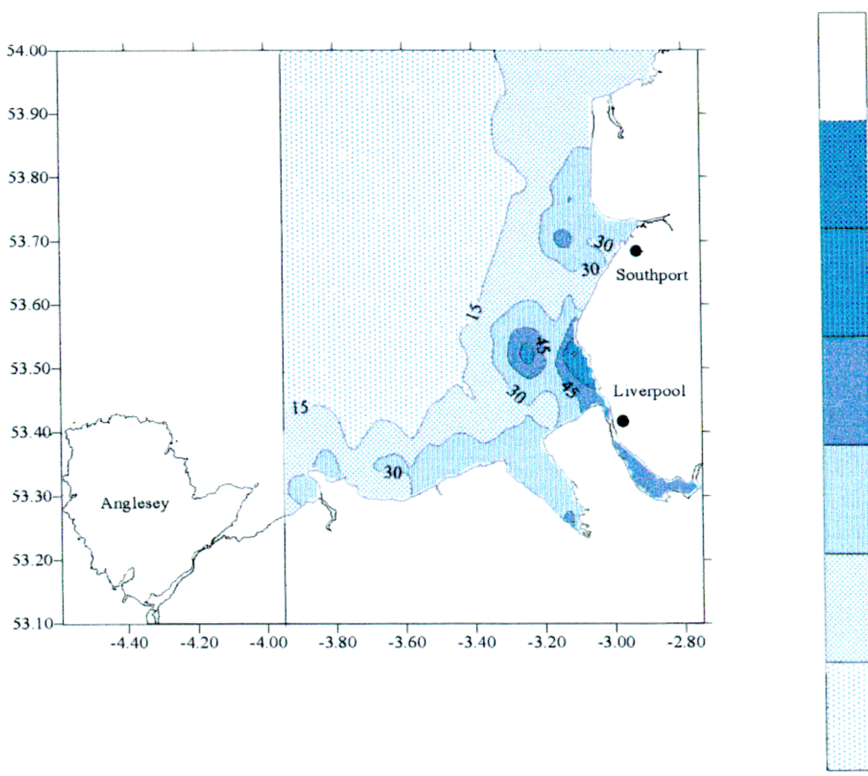

Figure 97. Liverpool Bay Survey June 1997. SRP (µg/litre).

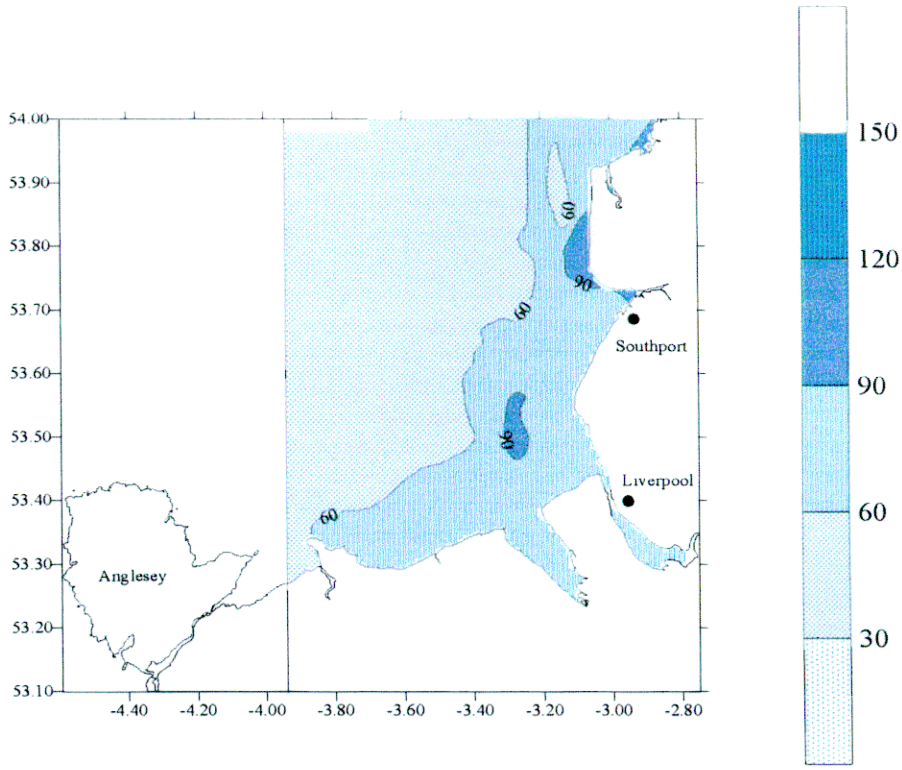

Figure 98. Liverpool Bay Survey November 1997. SRP (μg/litre).

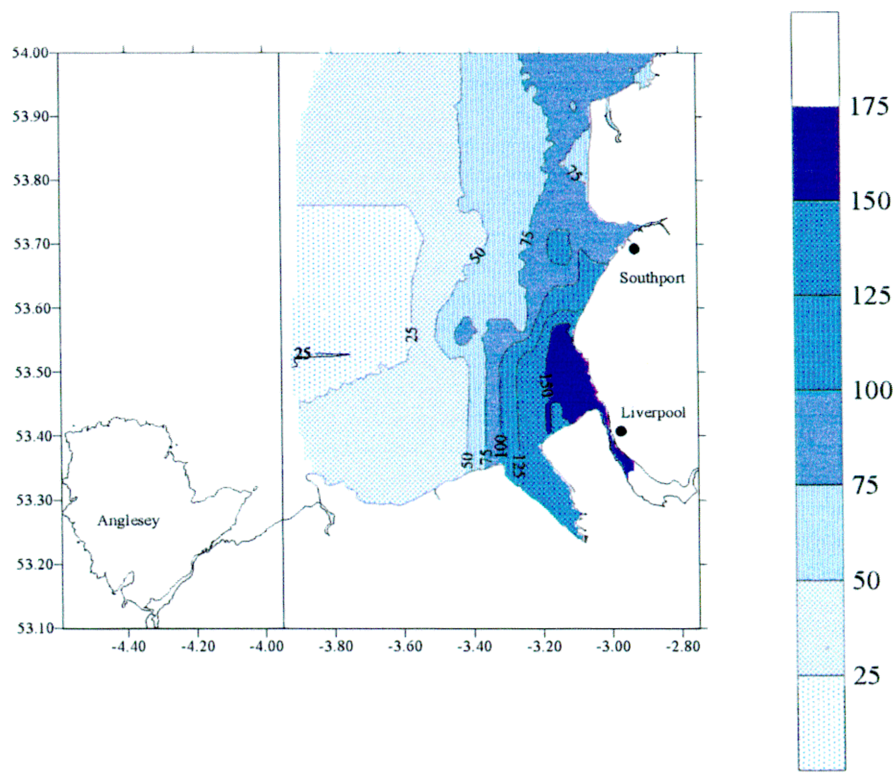

Figure 99. Liverpool Bay Survey December 1997. SRP (μg/litre).

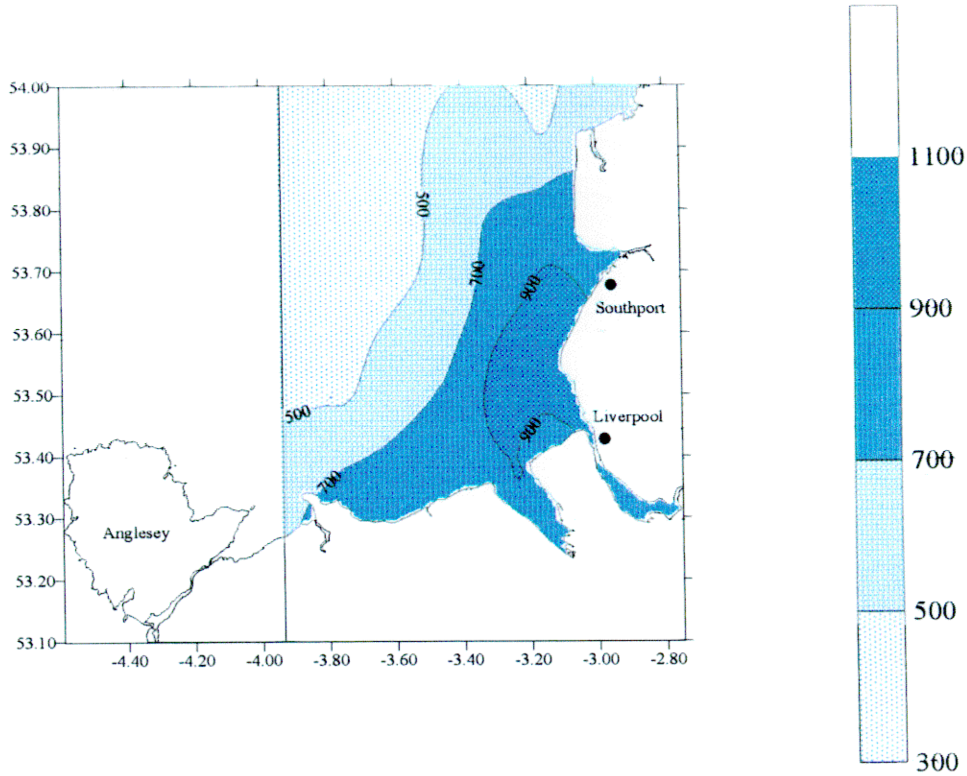

Figure 100. Liverpool Bay Survey January 1997. Silicate (µg/litre)

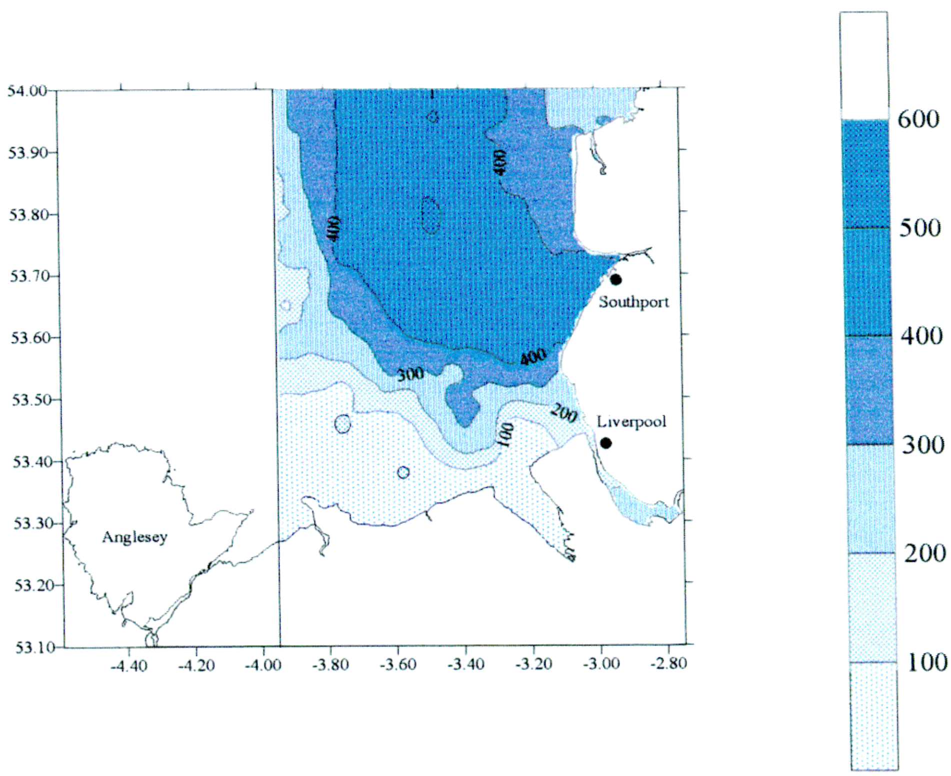

Figure 101. Liverpool Bay Survey April 1997. Silicate (µg/litre).

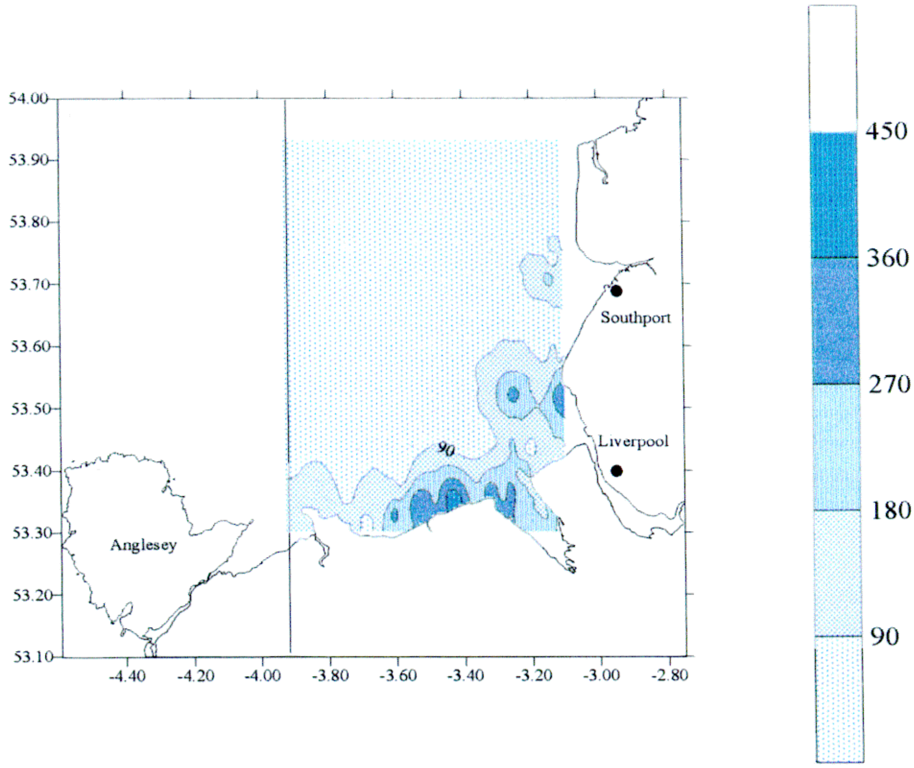

Figure 102. Liverpool Bay Survey June 1997. Silicate (µg/litre).

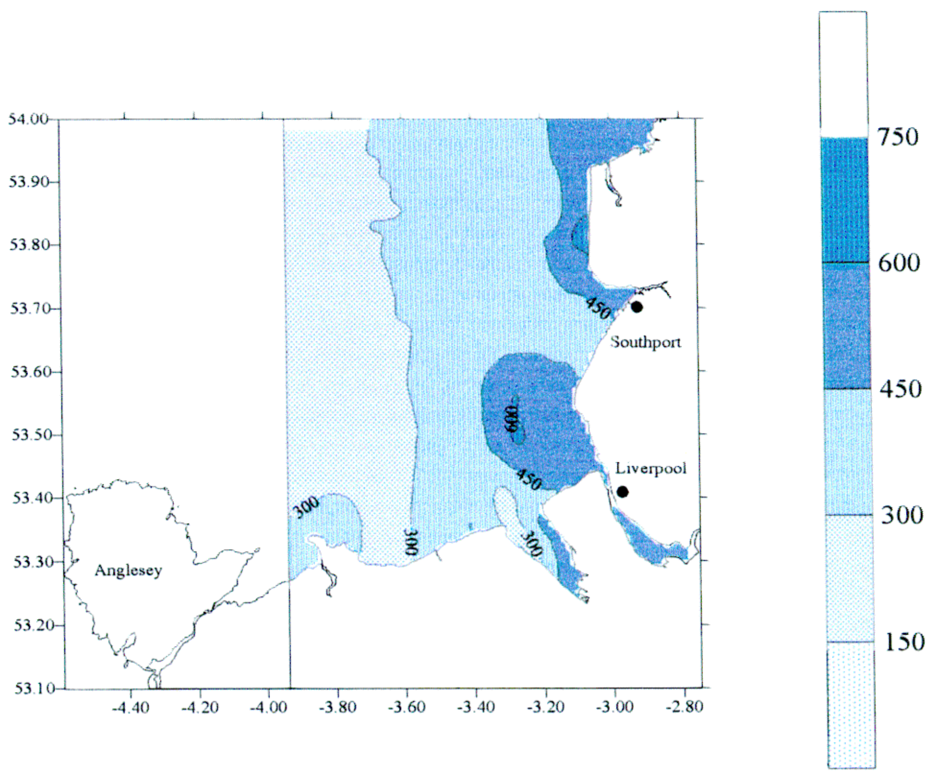

Figure 103. Liverpool Bay Survey November 1997. Silicate (µg/litre).

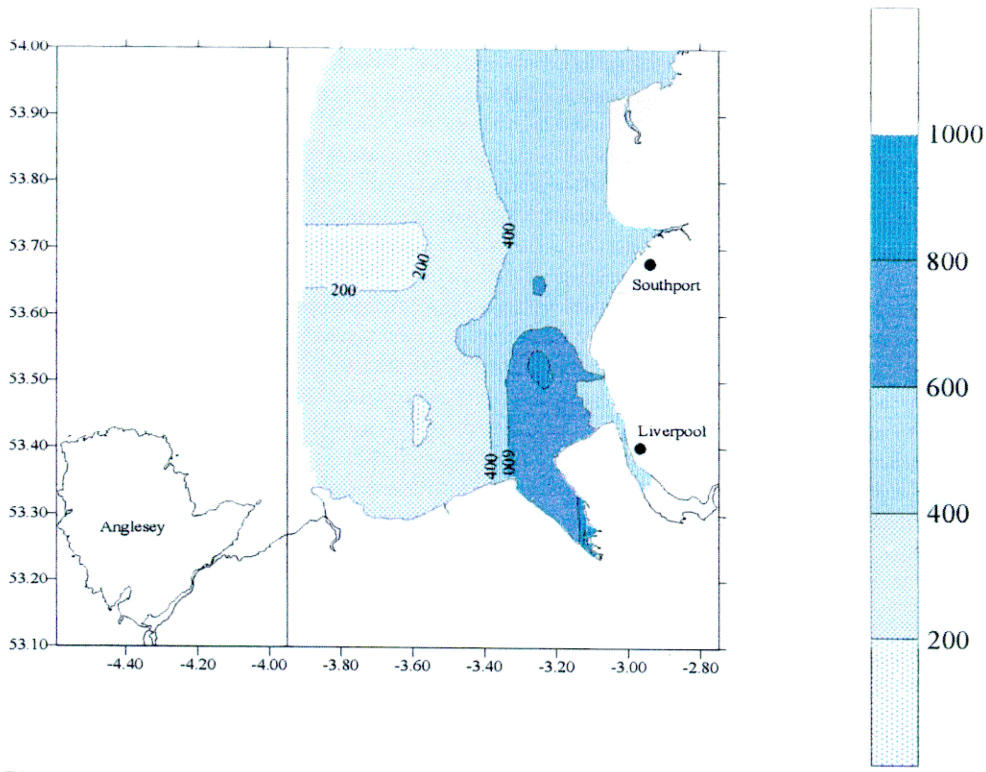

Figure 104. Liverpool Bay Survey December 1997. Silicate (μg/litre).

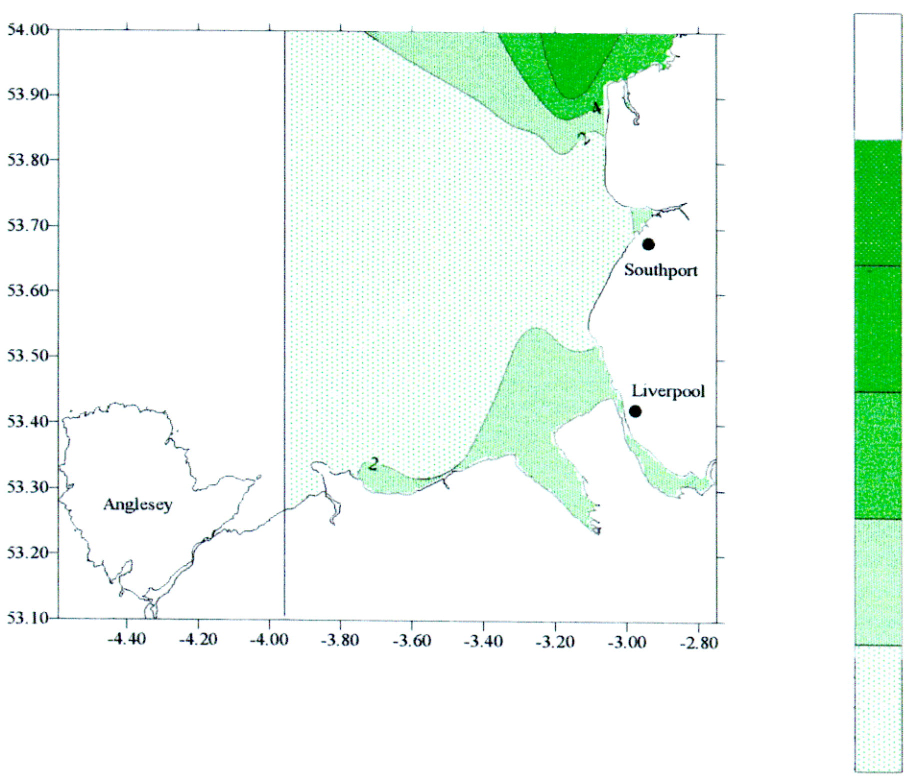

Figure 105. Liverpool Bay Survey January 1997. Chlorophyll a (μg/litre).

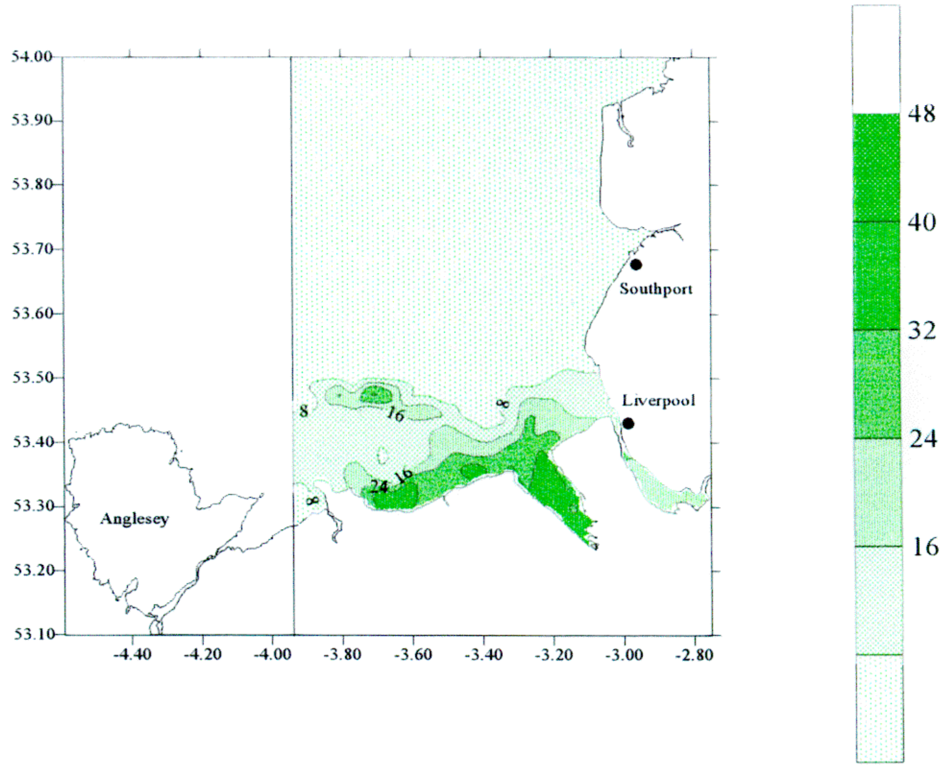

Figure 106. Liverpool Bay Survey April 1997. Chlorophyll a (µg/litre).

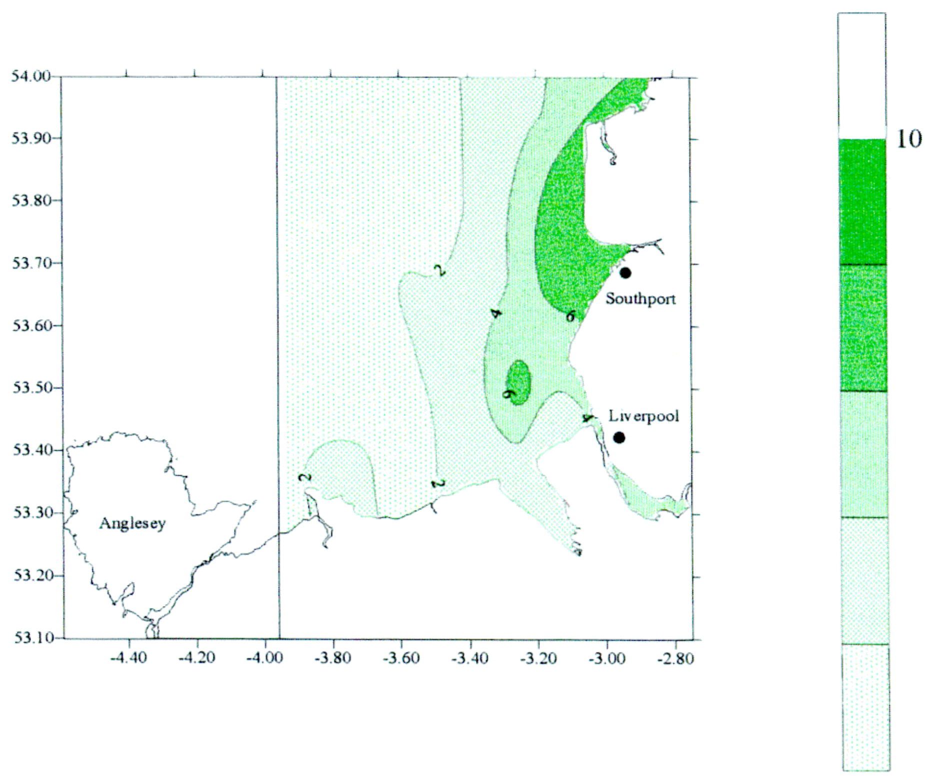

Figure 107. Liverpool Bay Survey June 1997. Chlorophyll a (µg/litre).

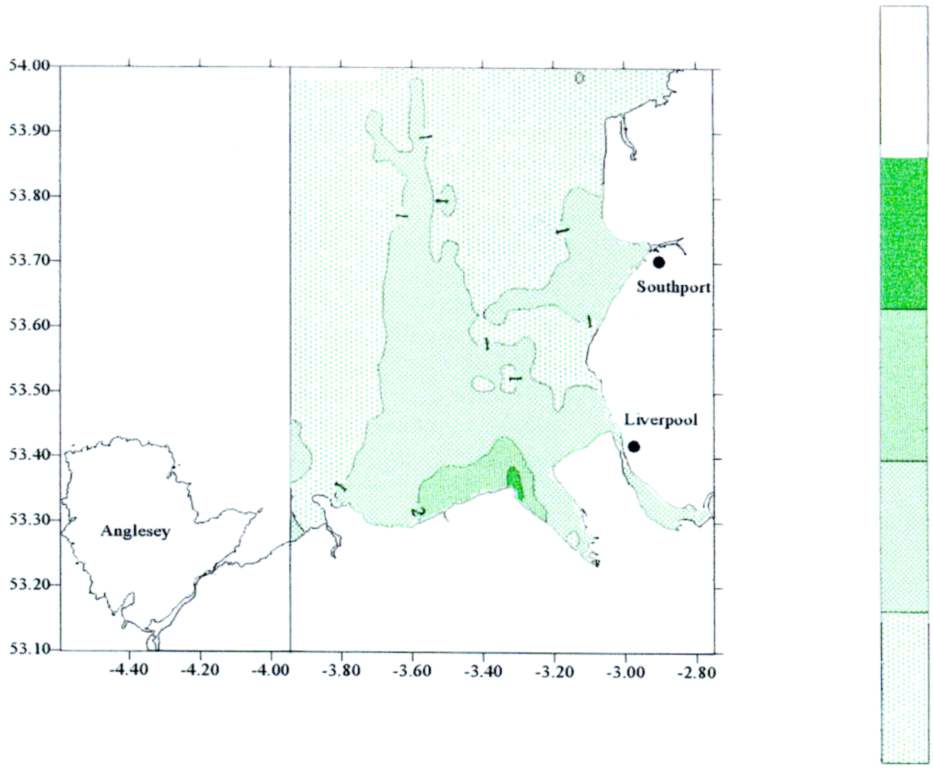

Figure 108. Liverpool Bay Survey November 1997. Chlorophyll (μg/litre).

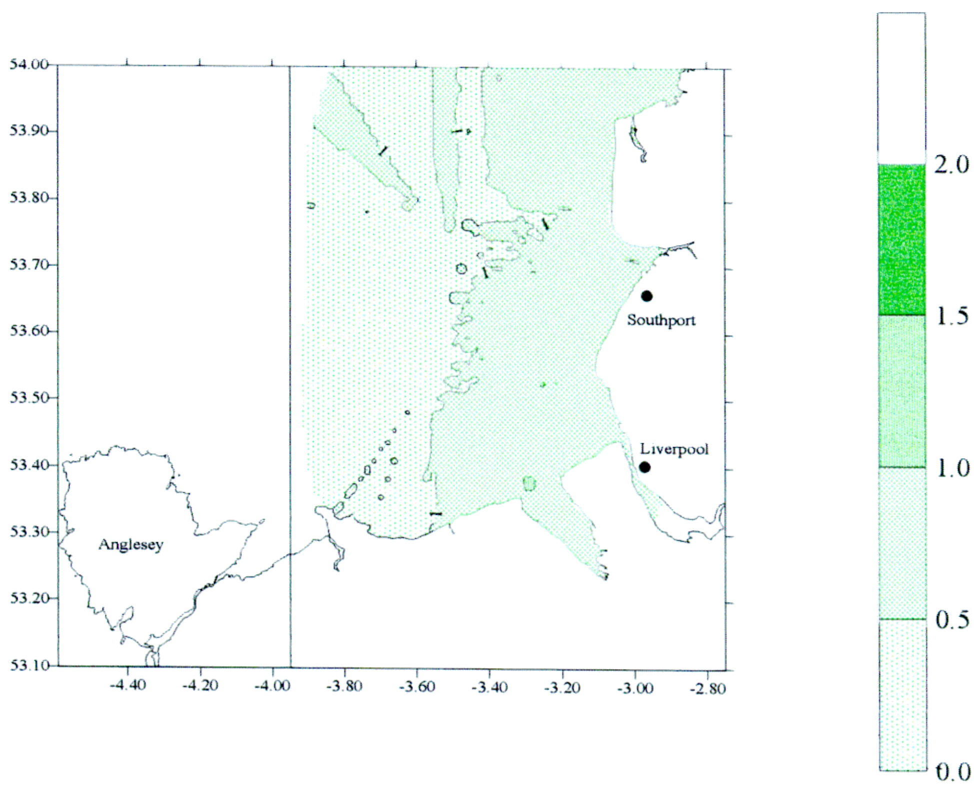

Figure 109. Liverpool Bay Survey December 1997. Chlorophyll a (μg/litre).