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The Distribution of Phytoplankton and Nutrients in the North East Irish Sea during 1996.

University of Liverpool

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The Distribution of Phytoplankton and Nutrients in the North East Irish Sea During 1996.

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Statement of Use
This report summarises the findings of collaborative research between the Environment Agency and Port Erin Marine Laboratory on nutrient and phytoplankton distributions in the north east Irish Sea during 1996. The information within this document is for use by EA staff and others involved in the research and management of coastal waters with respect to hyper-nutrification and eutrophication.

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Nutrient and Phytoplankton Distributions in the North-East Irish Sea

Executive Summary

Objectives of this research have been to monitor the distribution and concentrations of nutrient and phytoplankton abundances in the north-eastern Irish Sea. Specific aims have been to identify areas potentially at risk from the adverse effects of excessive nutrient discharges from sewage and industrial outfalls. Although any such exercise is constrained by the infrequent sampling dates, certain conclusions can be made, albeit tentatively.

The industrial discharges from Albright & Wilson (Whitehaven) and BNFL (Sellafield) are readily apparent in the data presented. Soluble reactive phosphorus (SRP) concentrations have been recorded at elevated concentrations around Whitehaven during 1995 (Allen *et al.* 1996) and 1996 (herein). Nitrogenous compounds have also been recorded above background coastal concentrations along the coastal margin adjacent to Sellafield for these time periods. At present these waters exceed the guidelines of the Comprehensive Studies Task Team (with regard to winter observations of DAIN and DAIP) for High Natural Dispersion Areas. Some concern must also be registered with reference to concentrations of summer surface chlorophyll concentrations which exceeded the 10 µg/l threshold (outlined by the CSTT) during May. The relatively high chlorophyll concentrations reported adjacent to Sellafield for May were reflected in increased phytoplankton counts. A comparison between winter nutrients and summer phytoplankton suggests that winter TON and silicate may best explain the phytoplankton community structure.

Discharges of orthophosphate from Albright & Wilson are expected to decrease over the next few years, however discharges of nitrogenous and phosphorus concentrations from BNFL are likely to increase as throughput increases and new operations commence in 1998/99. This again raises some cause for concern, and may result in some adjustment of the N:Si ratios which, as can be seen from Figure 49, are already indicating that waters extending from the Solway Firth to the Ravenglass estuary may be prone to future eutrophication. Such reductions in N:Si may actively alter the phytoplankton community structure favouring non-siliceous organisms with the possibility of increased occurrences of nuisance algae.

The discharge of nutrients into Liverpool Bay stems mainly from the rivers Mersey, Ribble and Dee. On all sampling occasions from the present study nutrients were recorded to be of greatest concentrations around the Mersey and Dee estuaries. Nutrient concentrations exceeded the criteria outlined by the CSTT at almost all locations within the Liverpool Bay during the winter sampling period and must cast doubt upon the provisional classification of this region as a 'Less Sensitive Area'. Further evidence of detrimental or "adverse effects" are provided by high summer surface chlorophyll concentrations which exceed the recommended 10 µg/l threshold for prolonged periods (levels of 28 µg/l were recorded for May and 25 µg/l for August). The winter N:Si ratio suggests that these waters are prone to eutrophication. Although no evidence of nuisance algae has been reported from the current study, Liverpool Bay has been prone to blooms of *Phaeocystis pouchetii* in recent years. The high abundances of *Dinophysis* sp. reported for 1996 also warrant further investigation into the spring/summer phytoplankton community as species of this genus are a known threat to public health and fisheries alike.

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1. Introduction

This report is the product of collaborative work between Port Erin Marine Laboratory (PEML) and the Environment Agency (EA, North West Region) during 1996. The aim of the work was to examine spatial and temporal changes in nutrient concentrations in the north-eastern Irish Sea and any associated changes in the phytoplankton community structure. This is the second year of the collaboration and continues on from that published for 1995 (Allen *et al.* 1996).

Nutrient studies in the Irish Sea have been undertaken by scientific staff at PEML since the 1950's. Work carried out by D.J.Slinn at PEML has demonstrated that concentrations of dissolved inorganic forms of both phosphorus and nitrogen (see Figures 1a-d) have increased considerably since the 1950's and 60's (Slinn *et al.* 1990, Shammon *et al.* 1996). 4 regions in the north eastern Irish Sea off the Wirral and West Cumbrian coast are candidate Less Sensitive Areas (LSA's) under the European Union's Urban Waste Water Treatment Directive (UWWTD).

The UWWTD recognises the category of LSA's where under appropriate conditions, discharges of sewage may only require primary treatment. To help identify LSA's, the UK government introduced the concept of High Natural Dispersion Areas (HNDA's). These are defined areas around candidate discharges. The criteria for confirming that primary treatment into a HNDA will satisfy the requirement of the UWWTD are considered in detail in the Comprehensive Studies Task Team (CSTT) report (1997). Designated HNDA's must prove by comprehensive studies that discharges cause no deleterious effects and that primary treatment alone is adequate. If the relevant water companies can prove that primary treatment is adequate, the UK Government can apply to the EU for LSA status to be approved.

Provisions within the EU directive allow member states to identify coastal regions that would not be adversely affected by discharges of primary treated sewage. The absence of these "adverse effects" must be demonstrated by a "comprehensive study". Although the directive does not define adverse effects nor the context of the comprehensive study it does provide safeguards through Article 6 and Article 15. Under these articles areas identified as being 'Less Sensitive' must:

1) Receive primary treatment to specified standards (Article 6.2).

2) Prove by comprehensive studies that any such discharge will not adversely effect the environment (Article 6.2).

3) Be reviewed at intervals of not more than four years (Article 6.4).

4) Be subject to scrutiny by the commission who may make appropriate proposals to the Council (Articles 6.2 & 6.3).

5) Be monitored once designated (Article 15.3).

The safeguards outlined in the directive go some-way in providing a framework for the designation of LSA's. Further definitions regarding the *nature* of adverse effects and comprehensive studies have been provided by the Marine Pollution Monitoring Management Group and the Groups Co-ordinating Sea Disposal Monitoring's task team. These guidelines are outlined in the report of the Comprehensive Studies Task Team (CSTT 1997).

The candidate LSA's that the current study is concerned with include parts of the Cumbrian Coast (Workington North, Workington South & Braystones) and the North Wirral (Liverpool Bay). Should designation become confirmed, secondary treatment will not be provided. The Cumbrian Coast candidate LSA's receive land based nutrient inputs from two major industrial sources and several river catchments. The Liverpool Bay also receives additional inputs from agricultural sources and from sewage sludge. The relatively high resident times (of up to one year) of waters in the Eastern Irish Sea (Dickson & Boelens 1988) adds to the concern of the ability of these anthropogenic inputs to disperse.

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. A distinction must be made between eutrophication and hypernutrification. A water body may not be eutrophic but can have elevated levels of winter nutrient concentrations, if these nutrient concentrations exceed 12 mmol DAIN m^{-3} in the presence of at least 0.2 mmol DAIP m^{-3} then the water body is termed hypernutrified (CSTT 1997). 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 increased mortality of benthic organisms, increased abundances of nuisance algal blooms and the loss of benthic fisheries.

Predicting the effect of nutrient changes upon phytoplankton populations is very difficult as the causal relationships between phytoplankton stocks and eutrophication are not clearly understood. Different water bodies around Europe have been shown to respond in different ways to cultural eutrophication. Although the Prymnesiophyte *Phaeocystis pouchetii* has not conclusively been associated with increased nutrient enrichment of coastal waters it seems most likely that this is the case (Lancelot *et al.* 1987). Blooms of *Phaeocystis pouchetii* were first reported in Dutch coastal waters in 1978 and have occurred on an annual basis ever since. Increased reports of blooms of this species have been recorded for the North Sea in recent years (Batje & Michaelis 1986, Riegman *et al.* 1992) and also from regions within the Irish Sea (Irish Sea Study Group 1990, Jones & Haq 1963). Increased reports of toxic algal species such as the dinoflagellates *Dinophysis acuta, D.accuminata,* and *D.norvegica* have also been linked to changing nutrient ratios of coastal waters having severe implications for both public health and shell fisheries. Within the entrance to the semi-enclosed Baltic Sea, blooms of the nuisance flagellate *Chrysochromulina polyepsis* occurred on a massive scale in 1988 (Rosenberg *et al.* 1988). Within Norwegian coastal waters, blooms of the unarmoured dinoflagellate *Gyrodinium aureolum* have caused the death of thousands of farmed fish since it was first reported in 1966 (Tangen 1977). In the Black Sea long term decreases in the Si:P ratio has been associated with an increase of blooms of the dinoflagellate *Prorocentrum cordatum* (Bodeanu & Userelu 1979). Marchetti's (1992) study of the semi-enclosed Adriatic Sea highlighted a connection between dense blooms of diatoms and dinoflagellates with eutrophication from the Po Delta, this lead to deoxygenation of bottom waters and the production of surface scums.

The nutrient status of semi-enclosed water masses obviously plays an important role in phytoplankton community structure, however, other studies have shown that physical parameters such as the degree of mixing in the water column may play an equally important role (Pingree *et al.* 1976).

1.1 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 north eastern Irish Sea are from the River Eden (25%), BNFL Sellafield (12%) and from sewage sludge disposal (30%). Individual sewage outfalls in the area are of minor importance by comparison with a total of all major outfalls in the area accounting for approximately 9% 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 Irish Sea are dominated by the industrial outfall of Albright & Wilson at Whitehaven. Allen *et al.* (1996) calculated that Albright & Wilson were responsible for 59% of the total phosphorus loading discharged into the north east Irish Sea. This contribution currently represents approximately 47% of total inputs (EA 1996 data). The sum of all sewage outfalls is responsible for around 11% and all rivers for 7% (dominated by the River Eden) 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 that of Gowen *et al.* (1995) and Gowen & Bloomfield's (1996) studies 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.

Table 1

Estimated nutrient loads from the English coast directly to coastal waters of the north-east Irish Sea (north of Blackpool 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 1996), 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. The rivers Ribble and Mersey are outside the immediate area of study and figures are included for comparison only. Sewage figures are based on flows and the composition of 'standard sewage' based on total nitrogen (as N) or phosphorus (as P).

	N	**P**
Industrial		
Albright & Wilson (Whitehaven)	-	1543
BNFL Sellafield	1500	65
Rivers		
Eden	3211	157
Derwent	838	11
Leven	403	9
Kent	601	6
Lune	983	10
Wyre	337	23
Total north-east rivers	6373	216
(Ribble)	(7065)	(996)
(Mersey)	(11346)	(1838)
Sewage direct to coastal waters		
Workington/Whitehaven area	280	94
Millom	60	20
Barrow-in-Furness	165	55
Morecambe	116	39
Blackpool	471	157
Total coastal sewage	1092	365
Sewage Sludge from NWW	3900	1100
Total of all major inputs to north-east Irish Sea	**12 865**	**3289**

2. CUMBRIAN COAST SURVEYS

2.1 Sampling Protocol and Methodology

2.1.1 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 maxima), mid-May (spring phytoplankton maxima) and mid July (post peak summer sample). PEML sampled on an offshore grid and the EA sampled on an inshore grid (see figures 3a & 3b). 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. A fourth sampling trip was undertaken by the EA during September (inshore grid) and the data are included in this report. Actual sampling dates are as follows;

Inshore Grid	Offshore Grid
28/2/96	26/2/96
14/5/96	13/5/96
16/7/96	17/7/96
14/9/96	---

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 3a) 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.

2.1.2 Sampling and Analytical Methods

Sampling and analytical methods remained the same as for the 1995 sampling program as outlined in Allen *et al.* (1996). The analytical methods outlined below are for the PEML samples only. EA analysed samples (for Cumbria coast, Liverpool Bay and 'NORSAP' triangle surveys) 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 surface water 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 manufacture. 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.

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 were 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). A SuperCalc ® template written by P. Edwards was used for this purpose.

Samples collected on the inshore grid included, nutrients (Skalar Auto-analyser) and fluorescence (Meerestecknik-Electronik Fluorometer), no phytoplankton data is available for the inshore grid. 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 C. 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.

2.1.3 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.

2.2 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 3a/b, 99, 100, 101, 102 & 103) 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 is available for both inshore and offshore grids for the Cumbrian coast surveys, PEML (offshore grid) data is plotted first.

Multivariate statistical analysis and associated plots were carried out using PRIMER version 4.0 (Plymouth Marine Laboratory). The ANOVA of replicate phytoplankton samples were analysed using SPSS for Windows version 6.0 (Microsoft). Details of statistical treatment are the subject of a separate section of this report.

3.Cumbria Coast Surveys

3.1 Results

This section describes the results obtained for both the PEML and EA cruises for 1996. A full list of figures is given at the rear of the report.

3.1.1 Physical Patterns

Sea Surface Temperatures (SST's) showed a general east-west trend across the study area on all sampling occasions. During February coldest temperatures were found adjacent to the English coastline and warmest temperatures were found to the south-west of the sector, off the south-east coast of the Isle of Man. Temperatures across the region at this time of year were between 5 and 7 degrees Celsius (Figures 4a & 4b). Temperatures during May showed less variation than those reported for February. The east-west trend reported during the winter sampling period still persisted although by this time highest SST were found inshore. Lowest SST's were recorded in waters adjacent and to the north of the Isle of Man. A cooler water 'plume' was also found running south from the Ravenglass estuary (Figure 5a). Temperatures during May ranged between 8.5 and 10 degrees Celsius. Summer SST's once more portrayed a general east-west gradient with highest temperatures reported between the southern part of the Solway Firth and Sellafield. Elevated SST's were reported along the coast adjacent to and to the south of, the Dudden estuary. Highest SST's during July were found off S^t Bees Head (see Figures 6a & 6b). Temperatures during July ranged between 13 and 17 degrees Celsius. Inshore waters during September were approximately 16°C (Figure 7).

Surface water salinities showed an increasing trend from the north-east to the south-west of the study area on all sampling occasions (see Figures 8a-11). Lowest surface salinities were found around the Solway Firth and extended along the English coast. Highest surface salinities (>34) were found to the south-west of the Isle of Man. Penetration of low surface salinity waters was greatest during February and May and was much more reduced during July.

Stratification of the water column can restrict the degree of mixing between surface and bottom waters. 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 that the water column was stratified in some areas of the north-eastern Irish Sea on all sampling occasions. An assessment of the degree and nature of stratification is given by the Simpson stratification parameter (after Simpson *et al.* 1978). A stratification parameter of less than -9 is suggested to imply stratified waters (Fogg *et al.* 1995). During February an area to the centre of the study region (see Figure 12) was shown to be stratified, closer examination of the CTD data showing this to be a haline anomaly caused by reduced surface water salinity. This haline effect continued during May where larger areas of the north-east Irish Sea were shown to be stratified (see Figure 13). Regions of unstratified water during May were found to the south-east of the study area, an area to the south of S^t Bees Head and also to the north of the region between the Solway Firth and Burrow Head. Stratification during July was shown to be caused by both elevated SST's and reduced surface water salinities. A region to the south of 54.5N (decimal latitude) consisted of thermally stratified waters whilst to the north of this region waters were stratified due to both haline and temperature effects (see Figure 14).

3.1.2 Distribution of Nutrients

During the winter and spring surveys (February and May) the majority of dissolved available inorganic Nitrogen (Figures 15a & 15b) was present as Nitrate. All dissolved nitrogenous compounds follow a very similar trend. Nitrate concentrations during February showed a northeast-southwest trend with highest concentrations (180-340µg/litre) found along the Cumbrian coast between the Solway Firth and Ravenglass estuary (Figure 25). Nitrite concentrations during this time followed a similar trend as for nitrate. Highest concentrations were found in waters south of Sellafield and to the north of Whitehaven. Highest concentrations of ammoniacal nitrogen during February was found north of S^t Bees Head offshore from Workington (~17µg/litre. Figures 24a & b).

Concentrations of Nitrate during May showed a very similar trend to that reported for February with highest concentrations (>75µg/litre) found between the Solway Firth and S^t Bees Head , Nitrite followed a similar pattern. A nitrate maxima was also noted to the south-east of the Isle of Man (a plot of TON is given in figures 16a & 16b). An apparent small localised elevation in nitrite was noted to the north of St Bees Head. Ammoniacal nitrogen showed a more patchy distribution during May than those reported for February, concentrations of up to 130µg/litre are reported from around St Bees Head (inshore grid only). Although the distribution of nitrate concentrations between February and May show a good correlation, February concentrations were considerably higher across the region than for May suggesting that the May samples were collected after the onset of increased phytoplankton growth leading to the decline in nitrate concentrations.

During July the majority of dissolved inorganic nitrogen was present as ammoniacal nitrogen. Concentrations of total inorganic nitrogen during this time reached approximately 80µg/litre while ammoniacal nitrogen had maximum concentrations of approximately 50µg/litre. There was poor agreement between the inshore (EA) and offshore (PEML) TON data (Figures 17a &17b) Highest concentrations as recorded by the EA were located in waters adjacent to Sellafield where concentrations reach approximately 10µg/litre. PEML data suggest highest inshore concentrations were found in waters between Sellafield and a region to the south of the Ravenglass estuary. All forms of nitrogen at this time are present at very low concentrations. Nitrite concentrations during July were especially low often being below detectable limits. Maximum nitrate concentrations during July were recorded near to the Ravenglass estuary and also in an area to the south-east of the Isle of Man (concentrations ~18µg/litre). The study area can be split into three regions regarding July nitrate concentrations. A low nitrate region found to the north of the region between the Solway Firth (extending south to St Bees Head) and the Burrow Head. A second low nitrate concentration region being located to the south of the Dudden estuary. A third region of higher nitrate values is found in the middle of the study area, concentrations here are generally low but a plume is identified from the Sellafield area where concentrations reach approximately 12µg/litre.

Maximum concentrations of soluble reactive phosphate (SRP) are found along the Cumbrian coast on all sampling occasions (Figures 18a-20b). Maximum winter concentrations were found around Whitehaven/St Bees Head and along the Cumbrian coast south of Sellafield (Figures 18a & 18b). Winter SRP concentrations show a marked east-west trend with highest values being found along the English coast decreasing to the south-west, lowest concentrations (<20µg/litre) were reported to the south-east of the Isle of Man. Data from the inshore grid showed phosphate concentrations to be highest to the north of St Bees Head close to Whitehaven (500µg/litre).

May concentrations of SRP are considerably lower than those reported for February. At this time offshore concentrations are generally low (1-10µg/litre). Maximum spring SRP concentrations were found between Whitehaven and an area just south of the Ravenglass estuary with highest levels being reported in waters just off Sellafield (Figure 19). A further SRP maxima was found to the north-east of the Isle of Man (~17µg/litre). The considerable reduction in SRP concentrations between February and May reinforce the notion that the May samples are most likely to have been collected after the onset of major phytoplankton production in the region. During July, SRP concentrations were found to be highest along the Cumbrian coast south of Whitehaven. Highest concentrations during this time (which exceed those reported for May) are found in waters adjacent to Sellafield. SRP concentrations at this location are close to those reported for February (~45µg/litre). Data from the inshore grid are in good agreement with PEML data and identify a second SRP 'hot-spot' in waters adjacent to Whitehaven (see Figures 20a & b).

Silicate concentrations during February showed an east-west trend with highest concentrations (~600µg/litre) being found in the Solway Firth and along the Cumbrian coast (~500µg/litre) decreasing to the south-west of the study area. Lowest February concentrations were reported from the south-east of the Isle of Man. A localised reduction in winter silicate concentration was noted in the coastal region off Sellafield (PEML data). Data from the inshore grid are at odds with those presented by PEML since the apparent decrease in coastal silicate noted around Sellafield were not found by EA investigations. EA's data suggests this region to have the highest concentration of silicate along the Cumbrian coast during this sampling period (Figures 21a & b).

May silicate concentrations show a more patchy distribution than those recorded for February. Data from the inshore grid suggest maximum silicate concentrations (~200µg/litre) to be found off Whitehaven. Lowest silicate concentrations were found south of the Ravenglass estuary extending to ~3.8° N (decimal longitude) and also to the north of S^{t} Bees Head. Three areas of high silicate concentration (~180µg/litre) were noted, the first in a region just south of S^{t} Bees Head extending west to ~4.0° N (decimal longitude), the second extending into the Solway Firth and a third in a region to the south-east of the Isle of Man (Figures 22a & b). Lowest recorded silicate concentrations were found during July (Figures 23a & b). At this time much of the waters adjacent to the Cumbrian coast recorded lower concentrations than offshore locations. Exceptions to this being a region extending south from S^{t} Bees Head to just north of the Dudden estuary. Maximum silicate concentrations (115µg/litre) were found to the east of the Isle of Man.

Data for September are only available from the inshore grid. Coastal SST during this time were approximately 16°C and surface water salinities of around 34 were recorded. No data for TON, SRP and nitrate are available. Inshore nitrite concentrations were relatively low during September with highest concentrations (~1.90µg/litre) found north of the Ravenglass estuary. Ammoniacal nitrogen concentrations were similar to those reported for July with maximum concentrations of ~2.0µg/litre being reported.

Information on the vertical distribution of nutrients is available from the offshore grid only. During February all nutrients with the exception of silicate show similar concentrations in surface and bottom samples. Silicate concentrations were highest in surface samples to the north and south of the region. Samples located to the middle of the sampling area show highest concentrations in bottom waters. This central area has been identified as being stratified due to haline effects. During May surface/bottom differences were more marked, but highest concentrations were now in bottom waters.

Silicate concentrations were however higher in surface samples at some sites, these being to the north of the region where waters were stratified due to haline effects. During July some differences in vertical distribution were observed. Silicate, nitrite and TON were generally at higher concentrations in bottom waters whilst SRP and Ammonia were generally highest in surface waters. The elevated bottom water silicate and TON concentrations are generally associated with areas of thermal stratification.

3.2 The Distribution of Phytoplankton, Chlorophyll *a*, and Standing Crop

3.2.1 February 1996

The distribution of chlorophyll *a* did not always suggest the same trends in primary production as indicated by phytoplankton counts, this may be due to poor accuracy at low chlorophyll *a* levels. Pearson correlation coefficients between February chlorophyll *a* and the distribution of major phytoplankton groupings showed positive significant ($P<0.01$) correlations between the distribution of winter diatom counts and chlorophyll *a* ($P=0.007$). A significant positive correlation was also recorded between winter chlorophyll *a* and winter nitrate concentrations ($P=0.003$).

Surface chlorophyll *a* distributions during February were generally low (<1.5µg/litre) indicating very low phytoplankton biomass across the whole area (Figures 26a & b). Highest levels of productivity (as indicated by chlorophyll *a*) were found towards the Solway Firth. Inshore chlorophyll levels (EA data) were of the same order of magnitude as those reported by PEML. Marginally higher concentrations from the inshore grid were noted in waters around Sellafield.

Standing stock figures represent the phytoplankton biomass summed over the whole water column (see Figure 27). 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 standing crop (as mg/m^2) during February showed a region of elevated phytoplankton biomass to the centre of study area and also in the region of the Solway Firth. 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 (see Figure 28), here the data has been averaged over 1m depth intervals. Such an exercise gives an average indication of phytoplankton biomass throughout the water column. It can be seen from Figure 28 that this gives a different indication of phytoplankton biomass when compared to either surface chlorophyll *a* or total water column standing crop. Although still relatively low (< 3.5 mg/m^3 averaged over 1m depth intervals), highest standing crop levels are now found to the north of the region towards the Solway Firth.

The abundances of diatoms, dinoflagellates, small monads/flagellates and total phytoplankton are mapped for the region and are presented in Figures 29-32. It can be seen that total phytoplankton abundances (expressed as cells/litre) are low throughout the north-eastern Irish Sea during February. Maximum abundances are found to the middle of the study area (~20000 cells/litre). Monads and small flagellated algae (<15µm) dominated the phytoplankton and are the main influence on the distribution of total phytoplankton counts (Figure 31). A breakdown of the averaged phytoplankton data (diatoms & dinoflagellates only) for February shows that diatom and dinoflagellate species are poorly represented at this time of year with no individual species exceeding 900 cells/litre (Figure 52).

3.2.2 May 1996

The distribution of chlorophyll *a* showed significant positive correlations (Pearson correlation coefficient) with the total abundances of diatoms and monads/small flagellated algae ($P=0.009$ & $P=0.004$ respectively). The distribution of total phytoplankton abundance and surface chlorophyll *a* did not show any such associations however. No significant correlations were found between May phytoplankton counts and any spring nutrient concentrations.

The distribution of spring chlorophyll *a* suggests that the phytoplankton biomass had increased significantly compared to the February data. Elevated levels of chlorophyll *a* were recorded along much of the Cumbrian coast, highest concentrations however were recorded offshore to the south of the region where surface chlorophyll *a* levels reached 14µg/litre (Figures 33a & b). High levels of chlorophyll *a* (>8µg/litre) were also recorded in waters adjacent to Sellafield and also midway between the Solway Firth and Burrow Head. Surface chlorophyll *a* concentrations from the inshore grid are reasonably well correlated with the PEML data. Chlorophyll *a* maxima from the inshore grid are reported in waters between S^t Bees Head and the Ravenglass estuary and also in waters towards the Solway Firth.

Standing crop figures for May (Figure 34) suggest that the surface chlorophyll *a* maxima noted above extended throughout the water column with levels exceeding 260mg/m^2. These high standing crop values were found to the south of S^t Bees Head and extend offshore to approximately 4.0° N. The expression of standing crop as a function of depth (Figure 35) showed a distinctive northwest-southeast profile with highest levels recorded in waters adjacent to Sellafield..

The concentrations of diatoms, dinoflagellates, monads/small flagellates and total phytoplankton are mapped for the region and are represented in figures 36-39. Total phytoplankton concentrations are highest in waters to the east of the Isle of Man, where total concentrations exceed 800 000 cells/litre. Highest total phytoplankton cell concentrations along the Cumbrian coast were found between Sellafield and an area south of the Ravenglass estuary where concentrations exceeded 300 000 cells/litre. Such concentrations are typical of temperate latitude coastal waters during spring.

Diatoms represented the greatest proportion of the total phytoplankton population during May (Figure 37). Highest abundances were recorded in waters to the east of the Isle of Man and in coastal waters around the Ravenglass estuary. The high diatom productivity noted around the Isle of Man is reflected in the abundances of monads/small flagellates where concentrations of up to 300 000 cells/litre were recorded. Maximum dinoflagellate concentrations were found offshore midway between the Cumbrian coast and the Isle of Man and also in the Solway Firth where total abundances of up to 7000 cells/litre were noted.

Averaged species abundances for May (Figure 53) show that the diatoms are the dominant constituent of the phytoplankton flora. *Chaetoceros* and *Rhizosolenia* sp. being the most abundant. Monads/small flagellated algae are also represented by high average abundances. The nuisance algae *Phaeocystis pouchetii* was recorded from the north of the region with abundances of up to 100 000 cells/litre being found offshore from S^t Bees Head and also towards the Solway Firth (Figure 40).

3.2.3 July 1996

No significant correlations existed between the distribution of surface chlorophyll *a* and phytoplankton counts for the summer sampling period. A significant correlation (P=0.001) did exist between July surface chlorophyll and July silicate concentrations. The distribution of surface chlorophyll during the summer sampling (Figures 41a & b) period shows an underlying east-west gradient. Generally highest concentrations were found to the west of the region (chlorophyll *a* = 2-3µg/litre) whilst the coastal waters appeared to have had decreased phytoplankton biomass (chlorophyll *a* <1.0ug/litre). An exception to this decreased coastal production was noted in a region between just south of S^t Bees Head and the Dudden estuary with maximum chlorophyll *a* concentrations in this region being located around the Ravenglass estuary (chlorophyll *a* = 2-3µg/litre). Data from the inshore grid (EA data) show levels of chlorophyll *a* concentration to be similar as those found by PEML, although there is some disagreement between the distribution of chlorophyll *a* between the two data sets.

Phytoplankton standing crop showed two areas where productivity appeared to have been relatively high, one to the north of the region towards the Solway Firth and a second extending westwards from S^t Bees Head and the Ravenglass estuary into the middle of the study area (see Figure 42), this second region coincides with the region of stratified waters Maximum phytoplankton standing crop for July did not exceed 150mg/m^2. When the phytoplankton standing crop is expressed as a function of depth (i.e. water column values are averaged over 1m depth intervals) it can be seen that average water column productivity was greatest in regions around the Solway Firth and Sellafield (Figure 43).

The distribution of diatoms, dinoflagellates, monads/small flagellates and total phytoplankton are mapped for the region and are presented in figures 44-47. Total phytoplankton concentrations were greatest in waters adjacent to Sellafield (~300 000 cells/litre) and towards the Solway Firth. Total phytoplankton concentrations decrease offshore and are relatively low towards the west of the region (<100 000 cells/litre). Significant positive correlations existed between summer total phytoplankton and ammoniacal nitrogen (*P*=0.008). A comparison between winter nutrient concentrations and summer (July) phytoplankton counts showed significant positive correlations between total phytoplankton counts and all winter nitrogenous compounds (Inorganic nitrogen, nitrate and nitrite) suggesting a causative link between these variables and summer phytoplankton productivity. A breakdown of the phytoplankton into the general phytoplankton groups also showed a strong relationship between winter nitrogenous compounds and summer diatom abundances (*P*= 0.00-0.006). Highest concentrations of diatoms were found (the distribution of which closely followed that of total phytoplankton counts) in waters adjacent to Sellafield (~250 000 cells/litre) and the Solway Firth (>150 000 cells/litre). Dinoflagellate abundances were greatest towards the middle of the study (in stratified waters) area where maximum abundances reached ~35 000 cells/litre. Abundances of dinoflagellates in waters adjacent to Sellafield were also relatively high (see Figure 46). The distribution of small cells (<15µm) is somewhat more patchy than for either diatom or dinoflagellate distribution. Highest concentrations of these monads/small flagellates were found offshore with maximum abundances being found to the Southwest of the study area (~100 000 cells/litre).

Average species densities for July are given in Figure 54. It can be seen that diatoms have decreased in abundance across the region when compared to the May data. Dominant diatom species during July include *Leptocylindrus* sp. (mainly *L.danicus*), *Nitzschia* sp., *Chaetoceros* and *Rhizosolenia* sp. (in order of importance) It can also be seen from Figure 54 that small monads/flagellated algae had significantly increased in abundance during July with average densities of over 30 000 cells/litre. Dinoflagellates had also increased in abundance during July with Gymnodiniales and Peridiniales being the most dominant forms.

The abundance of microzooplankton showed maximum concentrations during the summer (>5000 cells/litre) and were significantly correlated with the distribution of the small monads/ flagellated algae (*P*=0.002) suggesting a possible predator-prey relationship.

3.2.4 September 1996

Surface chlorophyll *a* values for September are only available from the inshore grid. It can be seen from Figure 48 that highest concentrations of chlorophyll *a* are located south of the Ravenglass estuary where concentrations reached ~3.5μg/litre. No phytoplankton data for September is available.

3.3 Analysis of Phytoplankton Community Structure and Environmental Variables

3.3.1 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.

3.3.2 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 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).

3.3.3 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.

3.3.4 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.

3.3.5 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.

3.3.6 Standard Procedure

Phytoplankton species abundance and environmental data for each sample date was converted to a standard format use 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).

3.4 Results of Statistical Analysis

3.4.1 February 1996

Cluster and MDS analysis undertaken on the February phytoplankton data showed no clear grouping, all sites having a similar floral assemblage and abundance of species. Outliers on plots were transit sites (B,C,D,F,H,I) and sites 61W and 52W, these sites had relatively high abundances of diatoms. An MDS stress of 0.236 was indicated so no further analysis was undertaken.

3.4.2 May 1996

Phytoplankton communities in May showed the most noticeable trends in community structure of any sampling date as identified by MDS (see Figures 50 & 51). An MDS stress of 0.165 applied to the plot was used later in BIOENV. Two groups were identified according to the similarity of species abundances. Six outliers were identified these representing transit sites A,B,E,G,H & I. The transit sites were then removed and the ordination run again producing an MDS stress of 0.159 . The two groups identified reflect sites from the North (group 1) and South (group 2) of the sampling area. A dissimilarity breakdown of these data showed that the average similarity between samples was 53.5%. *Rhizosolenia* sp. (short) and *Chaetoceros* sp. were most important in discerning groups of samples from each end of the spectrum and represented 37.5% and 30.36% of the dissimilarity respectively. Monads/small flagellates and the diatom genus *Thalassiosira* were next in order of importance for describing the differences between groups of samples accounting for approximately 7% of the variation each.

The patterns in phytoplankton communities identified from the ordination exercise were used in the BIOENV procedure to identify which physical or chemical variables that best describe the distribution of the phytoplankton communities. Winter (February) nutrient and spring (May) salinity and temperature variables were run against the spring phytoplankton data. It is likely that winter nutrient concentrations will reflect levels initially available, before any modification by the plankton flora. The BIOENV procedure conducted on all sites (including transit sites) suggested little relationship between spring phytoplankton and winter nutrients concentrations. The maximum correlation (Harmonic-weighted Spearman) was achieved with a combination of silicate and salinity (r=0.308). A second BIOENV analysis was run on the data, this time the transit sites (identified by MDS as being outliers) were removed. Once more all correlation coefficients were relatively low with a maximum correlation achieved with a combination of TON and silicate (r=0.229). Salinity had the highest correlation coefficient of any single determinant (r=0.227) followed by nitrate, SRP, silicate, nitrite, ammoniacal nitrogen and temperature (in order of significance). Correlation coefficients for the determinants other than salinity were very low (r=<0.07). An MDS ordination between spring phytoplankton and winter TON showed that sites within group 1 had higher concentrations of winter TON than those of group 2. Figure 51 represents the proportion or concentration of TON at these sites. The size of the circles in Figure 51 are proportional to the winter TON concentrations (larger circle represent higher TON concentrations).

3.4.3 July 1996

Cluster and MDS analysis undertaken on the July phytoplankton data showed no clear grouping suggesting that sites during this time had similar species assemblages. Outliers on the MDS plots included transit sites A, B, H, & I. An MDS stress of 0.238 was indicated and so no further analysis was carried out.

3.5 Comparison of Phytoplankton Replicate Counts

Triplicate phytoplankton samples were collected at most sampling stations on the off-shore grid during the winter (February) and spring (May) sampling occasions. It was hoped that such an exercise would show the degree of within-site variation of phytoplankton abundances and species composition. Each replicate group was enumerated independently starting with set 1 through to set 3. The phytoplankton counts of each sampling site was expressed by three independent phytoplankton counts and any within-site variation in species composition and/or abundance could thus be calculated. A one way analysis of variance without replication (ANOVA) was then run on the data using SPSS for Windows version 6.

3.5.1 Results of ANOVA

Appendix B shows the site identifiers and significance level for the results of the ANOVA for the winter and spring phytoplankton replicates. The null hypothesis (H_0) for each site is 'that all samples come from normally distributed populations with the same means and variances' and is tested by an F-test. The H_0 is accepted where F is less than the upper 5% point ($P= 0.05$) in published tables and the H_0 is rejected when F is larger than the tabulated value (Pearson and Hartly 1966).

3.5.2 February 1996

It can be seen from Appendix B that the ANOVA for the winter (February) phytoplankton data suggests that variance between replicate samples is often high with 17 of the 36 sites showing significant ($P>0.05$) differences.

3.5.3 May 1996

All sampling sites counted for phytoplankton species abundances during the spring (May) sampling period showed no significant differences between replicate samples (see appendix B) as indicated by the ANOVA.

3.5.4 Interpretation of ANOVA data

Several possible explanations exist as to why the winter phytoplankton replicates showed such a high degree of variation. Firstly, the variation may possibly be a result of taxonomic differences produced by the fact that a few of the samples were counted by different taxonomists. If these sites are disregarded from the overall interpretation then 13 sites are still suggested to have a high degree of variation, so it seems unlikely that there is any taxonomic bias to the data.

A closer examination of the phytoplankton counts for each of the replicates shows some interesting trends. Almost without exception the counts from the first set of replicates are greater than either the second or third sets, suggesting a possible dissolution anomaly. It appears from the data that long term storage of phytoplankton counts in acidified Lugol's solution may explain the high degree of within-site variation. All species groupings appear to have been affected though diatom and monads/small flagellates appear to have been affected the most. This idea of increased dissolution is further explained when the data for the May (spring) ANOVA is considered. Here no or very little within-site variation occurred. The spring phytoplankton samples were stored in **non**-acidified Lugol's.

A comparison of the total phytoplankton abundance data (figure 29) and the distribution of sites where high levels of variation occurs also aids interpretation. There is a fairly high level of agreement between the regions of increased algal biomass and decreased variation between replicates. This suggests post-collection dissolution may be greatest in samples where phytoplankton biomass is low. The possible dissolution of silica from the samples caused by the acidified iodine may have lead to the exacerbated dissolution of diatoms from the samples. At some concentration the dissolution of silica may become reduced owing to a buffering effect caused by this addition of silica to the solution from the diatom frustules. This may also explain why samples collected from waters of elevated plankton biomass show less with-in site variation than those collected from reduced productivity waters. As yet these suggestions remain unqualified and further work needs to be done in order to understand the problems of phytoplankton preservation. It is recommended that for future collection and storage that **non**-acidified Lugol's solution be used until a suitable alternative can be found.

The enumeration of phytoplankton data also needs to be made as soon as possible after collection in order to minimise any problems caused by dissolution. It has been suggested (I.G.Polikarpov *pers.comm.*) that this should ideally be done within four weeks of collection.

3.6 Cumbria Coast Surveys

3.6.1 Summary

3.6.2 Major Spatial and Temporal Trends

Sea surface temperatures, salinity and nutrients showed an east west trend on all sampling occasions. Winter SST's were positively correlated with salinity whilst spring and summer SST's were negatively correlated. By May the penetration of low salinity waters into the region was much reduced. The influence of freshwater discharges from the Solway Firth on salinity, nitrate and silicate were most noticeable during winter and spring. Phosphate concentrations were generally highest between Whitehaven /S^t Bees Head and the Ravenglass estuary on all sampling occasions, these results are on the whole in agreement with those published by Allen *et al.* (1996) for 1995. Nitrate and silicate concentrations were positively correlated across the region during May and July. By July silicate and nitrate concentrations were generally highest to the west of the region although localised elevations in nitrate were noted in waters close to the Ravenglass estuary.

The spring increase in phytoplankton growth was greatest in waters adjacent to the Cumbrian coast. Highest concentrations of chlorophyll *a* during May were noted around Sellafield (EA data) and in waters to the south of the Solway Firth (PEML data). Information from the phytoplankton standing crop for May showed highest productivity to be found in waters around Sellafield running to the south and west of the study area. Levels of all nutrients were reduced during May and July. An exception to these reduced nutrient concentrations during July was noticed in regard of SRP concentrations during July, waters adjacent to Sellafield at this time having concentrations closer to those reported for the winter sampling period.

Concentrations and trends of nutrients during February are generally in good agreement with results of long term monitoring stations (Shammon *et al* 1996) situated along the 54°N parallel. Generally, comparisons indicate that nutrient concentrations of sites located to the south west of region (transit sites) are typical of more open waters of the Irish Sea.

Diatoms were generally the most dominant phytoplankton group on all sampling occasions. Winter phytoplankton data suggests that monads/small flagellates were the most dominant organisms, these data may be unreliable however owing to dissolution problems of the preserved samples. Phytoplankton concentrations were highest in May and July. Diatom concentrations during May were highest in waters to the south east of the Isle of Man and also in waters between Sellafield and the Ravenglass estuary. The high phytoplankton concentrations reported to the south east of the Isle of Man consisted of very high abundances of monads/small flagellates (~300 000 cells/litre).

Results from 1995 (Allen *et al.* 1996) showed that spring (May) phytoplankton communities were often dominated by small cells and dinoflagellates especially at more southern locations. No evidence from the present study proposes this to be so for 1996 and suggests the 1995 data may be a reflection of that climatically unusual year.

Maximum dinoflagellate abundances during May were found offshore between the Cumbrian coast and the Isle of Man and also in the waters south of the Solway Firth. During July phytoplankton abundances were greatest in waters adjacent to Sellafield and towards the

Solway Firth. These assemblages consisted primarily of diatoms and dinoflagellates. Increased abundances of microzooplankton were also recorded during the summer sampling period.

MDS results of the spring phytoplankton data show two distinct clusters distinguishing phytoplankton communities from the north and south of the sampling grid (figure 50). A closer examination of the phytoplankton data shows that the northern sites are generally more abundant in *Chaetoceros, Thalassiosira, Phaeocystis* and small flagellates/monads while the southern sites are dominated by *Rhizosolenia* (long) monads/flagellates and increased numbers of dinoflagellates. A comparison between winter nutrients and spring phytoplankton suggests that winter TON & silicate, and summer salinity may best explain the differences in the phytoplankton community structure (Figure 51). Results from 1995 (Allen *et al.* 1996) also identified winter concentrations of TON as a possible causative factor in discriminating phytoplankton community structure.

Agreement between the distribution of total phytoplankton cell counts and chlorophyll *a* concentrations were generally good. Strongest correlations between such variables was found for Cumbrian coastal waters during May and July. Elevated chlorophyll *a* levels adjacent to the Isle of Man during July were not reflected in total phytoplankton counts. This may be due to high numbers of smaller algae (<15µm) which would have been excluded from total phytoplankton counts.

Restrictions on any sampling program such as the one presented exist. The present study has concentrated on monitoring phytoplankton, nutrients, (etc.) for surface waters only and variations in these parameters will inevitably exist with depth owing to biological migration and water column characteristics (stratification, depth of photic zone, etc.). The results obtained will therefore depend upon sampling depth, time of sampling and the degree of mixing within the water column.

3.7 Evidence of Impact of Nutrient Inputs

Riverine inputs of nutrients are most evident during winter especially for nitrate, SRP and silicate. As reported in Allen *et al.*(1996) it is impossible to determine the influx of nutrients with water movements from the contour diagrams produced. The effects of industrial discharges of nutrients is apparent on all sampling occasions. The impact of phosphate discharged from Albright & Wilson at Whitehaven was evident on all sampling occasions. However elevated concentrations of SRP were also reported from waters in the proximity of the Sellafield outflow during May and July, a phenomenon not reported for the 1995 sampling period. The influence of BNFL Sellafield on the discharge of nitrogenous compounds is most evident during February and July where elevated levels of TON were found adjacent to the discharge area. The discharge regimes of both BNFL Sellafield and Albright & Wilson at Whitehaven may influence results especially if the rate of discharge varies.

Any change in the community structure and abundance of phytoplankton cells which could clearly be associated with nutrient inputs or physical parameters is clearly a complex issue since such relationships are often interrelated and seasonally variable. During May and July high abundances of diatoms (and total phytoplankton cells) were noted offshore from Sellafield to the Ravenglass estuary, however, to conclusively state that such high abundances are associated with nutrient inputs as opposed to physical parameters (e.g. stratification, temperature etc.) would be wrong since it is virtually impossible to distinguish between such relationships given the limited number of sampling dates. Results produced from the statistical (BIOENV) procedure on winter nutrient and spring phytoplankton and physical data suggest that winter TON and silicate concentrations may best explain any changes in the spring phytoplankton community structure.

Increased phytoplankton cell counts were observed around Sellafield during May and July. These elevated counts are reflected in surface chlorophyll *a* and standing stock concentrations during these times. A breakdown of the phytoplankton into constituent groups revealed that diatoms were the most abundant organisms present in these waters. During May the genera *Chaetoceros* and *Rhizosolenia* were the most dominant whilst *Leptocylindrus danicus* and *Rhizosolenia* sp. were the most dominant during July. Yoder *et al.* (1994) identified *Rhizosolenia* species as being associated with hydrographic fronts of elevated nutrient status. Previous studies have shown that some *Rhizosolenia* species may be able to adjust their buoyancy and migrate vertically between surface waters and nutrient enriched deeper waters (Villereal *et al.* 1993). Concentrations of *Leptocylindris danicus* have been suggested to be directly correlated with dissolved inorganic phosphorus and may also be capable of triggering red tides (Chen 1993).

Any variation in distribution of total phytoplankton counts and chlorophyll *a* concentrations could be explained by degradation of chlorophyll in the water column, it being known that the chlorophyll content can vary according to the condition and age of the phytoplankton cell. It should be noted also that only cells greater than 5μm were counted in the present study, high densities of smaller cells (e.g. blue-green algae) would therefore give chlorophyll peaks not reflected in actual counts.

Guidelines from the Comprehensive Studies Task Team (CSTT 1997) of the Marine Pollution Monitoring Management Group suggest an area to be adversely affected by nutrient inputs if winter observations of dissolved available inorganic nitrogen (DAIN) are greater than 12mmol/m^{-3} (170μg/litre) in the presence of at least 0.2 mmol/m^{-3} (6.2μg/litre) dissolved available inorganic phosphate (DAIP); or there are observations of summer chlorophyll concentrations of greater than 10 mg/m^{-3} (=> 10μg/litre). Background winter concentrations of N & P are similar to the levels considered by the CSTT as being indicative of hypernutrification (NSTF 1993). It is therefore not unexpected that the concentration of these nutrients in coastal waters exceed the CSTT guidelines.

Data collected during March showed that DAIN levels were above the limits outlined by the CSTT across most of the sampling region (DAIN levels varied from 100-298μg/litre and DAIP varied from 14-40 μg/litre). Surface chlorophyll *a* concentrations during May exceeded 10μg/litre at a few sites. Data from the inshore grid showed concentrations exceeding 10μg/litre adjacent to Sellafield during this time. Another region to the south-east of the Isle of Man was reported from the offshore grid as having high (>10μg/litre) surface chlorophyll *a* concentrations. As only two summer sampling trips were undertaken it is possible that surface chlorophyll in excess of 10μg/litre may have been present in other locations and at other occasions during the summer. Surface chlorophyll *a* concentrations during the July sampling period were below 10μg/litre at all sampling sites.

It has recently been suggested by the CSTT that a molar N:Si ratio of >2 in winter is indicative of waters liable to become eutrophic. This ratio becomes 0.47 when nitrogen is expressed as μg/l N and silicon as μg/l SiO_2 (NRA 1996). It can be seen from Figure 49 that the coastal waters extending from the south of the Solway Firth to the Ravenglass estuary have winter N:Si ratios in excess of 0.47 and are therefore suggested to be liable to eutrophication. A second region to the south-east of the Isle of Man also exceeds this threshold.

3.8 Occurrence of Nuisance Phytoplankton Blooms

Evidence of severe phytoplankton blooms has been reported in the north-east Irish Sea in recent years (M.B.C.C 1995, 1996, 1997). Results from the current study show that the nuisance algae *Phaeocystis pouchetii* (Prymnesiophyceae) was present in waters offshore between S^{t} Bees Head and the Solway Firth with concentrations of up to 100 000 cells/litre being reported. Although thought to be non-toxic this algae can produce surface scums which when washed ashore can be unpleasant to bathers and beach users. The potentially toxic dinoflagellates *Dinophysis acuta* and *Dinophysis acuminata* were reported but at concentrations thought not to be problematic or threatening to shellfisheries. Other studies in the Irish Sea did report high concentrations of these toxic dinoflagellate species. Shammon *et al.* (1996) recorded cell counts of 500 and 2400 cells/litre of *D.acuminata* and *D.acuta* respectively, from the Cypris station (approximately 5 km west of Port Erin, Isle of Man). Such concentrations of these toxic species would be notifiable and require action under Environmental Agency monitoring procedures (M.Mills *pers .comm.*). The high abundances of the diatom *Chaetoceros* sp. noted during May around Sellafield could also be regarded as a nuisance algae. Species of this genus have long siliceous spines (setae) attached to the diatom frustule, these can become lodged in fish gills when high abundances of this genera are found, leading to increased fish mortality rates.

3.9 Future Considerations

The designation of Less Sensitive Areas under articles 6 and 15 of the European Union's Urban Waste Water Treatment Directive must take into account the current state of the local marine environment and its response to sewage inputs. The directive does not, however, take into consideration discharges of inorganic nutrients from industrial sources. The north east Irish Sea receives significant inputs of nitrogen and phosphorus from two industrial sources. BNFL Sellafield is a major point source of oxidised nitrogen, current consent limits allow discharges of 4080 te/N per annum, however, this consent limit has not been utilised. Latest estimates for the period up to 2005 are for an actual discharge of 2400-2800 te/N/yr.. Despite these estimates the actual discharge for 1996 was approximately 1500 te/N (EA 1996 figures). The input of nitrate from Sellafield is, however, set to increase in the near future as the THORP nuclear reprocessing plant comes into full production.

Information from Albright & Wilson at Whitehaven suggests discharges of phosphate from the plant will decrease (or have already decreased) from pre-1992 levels. The discharge is currently responsible for over 45% of the total phosphorus input into the region (estimated from NRA figures). The phosphorus discharges from Albright & Wilson Whitehaven currently run at approximately 1500 te/P. Results presented in the current study have highlighted elevated levels of SRP adjacent to Sellafield during May and July 1996. Phosphate discharges from Sellafield have decreased slightly in recent years from approximately 72 te/P/yr. in 1994 to approximately 65 te/P/yr. in 1996 (EA 1996 data). Sources of phosphate at Sellafield are; Tri-butyl-phosphate (TBP), a solvent used in the separation of actinides (~ 50-60 te/PO_4); detergents, used in laundry processes (~5-7 te/PO_4) and from the sewage treatment works (~ 5 te/PO_4). Discharges of PO_4 are expected to increase towards 1998/9 owing to the introduction of other treatment processes.

The effect increased anthropogenic sources of nutrients will have on the coastal marine environment in the north east Irish Sea can only be tentatively considered as more specific consideration and detailed modelling of each outfall would be required. It is likely that the ratio of major nutrients entering the region will change over the next few years. The effect such changes in nutrient concentrations may have on the phytoplankton communities is considered below.

Increased discharges of N and P into the north east Irish Sea are likely to alter the ratios of N:P, N:Si and P:Si in these waters. Justic *et al.* (1995) suggest such changes in nutrient ratios may have a considerable impact on phytoplankton community structures. Elevated N:Si and Si:P levels could force changes in the species composition and food web dynamics with an increased risk of novel and toxic phytoplankton blooms and altered nutrient recycling pathways (Conley *et al.* 1993). Higher Si:P ratios are thought to favour diatom communities rather than flagellated algal communities, increasing N:Si ratios may have the opposite effect (Ryther & Officer 1981). Capriulo *et al.* (1993) stated that increasing N:P and N:Si ratios may favor smaller algal species. Diatoms require dissolved silicate (DSi) for growthAny increase in N:Si is likely to favor the growth of non-silica dependant species. Conley *et al.* (1993) state that the frequency of changes in species composition and dominance by non-diatom phytoplankton communities will undoubtedly increase as DSi concentrations are depleted with eutrophication. The nutrient composition of treated wastewater is never the same as that of the coastal waters in which they are discharged (Hallegraeff 1995). There is considerable concern (Officer & Ryther 1980, Ryther & Dunstan 1971) that such altered nutrient ratios in coastal waters may favour blooms of nuisance flagellated algae species which can in exceptional circumstances replace the normal spring and autumn blooms of the siliceous diatoms.

The aim of this collaborative research project between the EA (North-West Region) and PEML has been to identify spatial and temporal trends in the nutrient and phytoplankton concentrations in the north east Irish Sea. Particular emphasis has been placed on the influence of known discharge sites and sources of nutrient enrichment into the region. It was hoped that the study might elucidate information on the causal relationships between environmental parameters and summer phytoplankton communities. Whilst the research presented goes some way in explaining such phenomenon, the results are by no means conclusive. This is the second year of the collaboration and the work will continue over the following year (1997). It is hoped that problems encountered with phytoplankton preservation will be remedied during the 1997 sampling periods enabling more robust statistical procedures to be used that may aid interpretation of the complexities of nutrient and phytoplankton dynamics. The 1997 sampling protocols will remain fundamentally the same as for 1996 with replicate counts being taken for both phytoplankton and nutrient samples.

Further work on this study in the coming year will add to the base of knowledge presented in Allen *et al.* (1996) and herein which will give some indication of inter-annual variation and will increase the reliability of any conclusions drawn from this research. Results presented for 1995 (Allen *et al.* 1996) were from a climatically unusual year and showed some variability with the data presented here, future work will help in understanding the affects of such variables as climate on summer nutrient and phytoplankton relationships.

4 CUMBRIA COAST SURVEY : CONCLUSIONS

- On all sampling occasions SRP concentrations were highest around Whitehaven and S^t Bees Head. These results are in agreement with those published in Allen *et al.* (1996) for the 1995 sampling dates. Elevated spring and summer concentrations of SRP were also reported around Sellafield.

- Winter and spring concentrations of nitrate are highest between the Solway Firth and the Ravenglass estuary. Maximum summer nitrate concentrations were found off the Ravenglass estuary.

- Winter (March) levels of Dissolved Available Inorganic Nitrogen (DAIN) varied between 100-298µg/litre and winter levels of Dissolved Available Inorganic Phosphorus (DAIP) varied between 14-40µg/litre. Under the guidelines of the CSTT such concentrations suggest that waters across the majority of the sampling region are hypernutrified.

- Water column stratification was apparent in regions of the north-east Irish Sea on all sampling occasions. Winter (haline) stratification was strongest to the middle of the study area. Summer (haline and thermal) stratification was also found. Waters to the north of the region being stratified to both haline and thermal effects whilst waters to the south of 54. 30 (decimal latitude) were stratified due to thermal effects.

- Vertical variations in nutrient concentrations were found during May and July. During May highest concentrations of all nutrients were found in bottom waters . During July silicate and nitrate concentrations were highest in bottom waters whilst SRP and ammonia were generally highest in surface waters. Increased concentrations of TON and silicate in bottom waters during July were generally associated with thermally stratified waters.

- A comparison between summer phytoplankton cell abundance and all winter nitrogenous compounds showed very strong positive correlations (*P.*= 0.000-0.006). No such associations were noted between winter nutrients and spring planktonic indices.

- Summer chlorophyll *a* concentrations were highest along the Cumbrian coast particularly around Sellafield and the Ravenglass estuary. Highest concentrations during May reached approximately 14µg/litre in waters around Sellafield (EA data) and in offshore waters west of the Dudden estuary (PEML data). During July highest concentrations were found around the Ravenglass estuary and in waters east of the Isle of Man (chlorophyll *a* = approximately 3µg/litre). Highest values exceeded the CSTT guidelines but were localised in extent and did not appear to be sustained throughout the summer.

- Diatoms were the dominant representatives of the phytoplankton flora during May and July. *Chaetoceros* sp. and *Rhizosolenia* sp. were the dominant species during May. *Leptocylindrus danicus, Nitzschia* sp., *Chaetoceros* sp. and *Rhizosolenia* sp. were the most dominant during July. Small monads/flagellated algae, dinoflagellates and microzooplankton were all recorded in increased abundances during July. The nuisance algae *Phaeocystis pouchetii* (Prymnesiophyceae) was also recorded in high abundances during May.

- The statistical analysis of phytoplankton community structure and environmental variables suggests winter silicate and TON concentrations may best explain spring phytoplankton distributions.

- Phytoplankton samples collected during February may have been subjected to post-collection dissolution. Results of the ANOVA run on phytoplankton replicate counts suggest that acidified Lugol's solution may not be a suitable preservation medium for long term storage of phytoplankton samples.

- The results presented in this study have continued and built upon those presented by Allen *et al.* (1996). Continuing surveys during 1997 will concentrate further on the relationships between nutrients and phytoplankton community dynamics.

5 LIVERPOOL BAY SURVEYS

5.1 Results

5.1.1 Physical Patterns

As with all the SURFER plots presented in this report attention must be made to the exact sampling positions of the surveys. SURFER interpolates between sampling points and extrapolates contours where there is no data. The reader is therefore, referred to figures 99-103 for exact sampling positions.

Sea surface temperatures (SST) showed a general southeast-northwest trend within the Liverpool Bay on all sampling occasions. During March coldest SST (~4.5 °C) were recorded to the east of the study area in waters close to the mouth of the River Dee (see Figure 55). Warmer waters were noted to the west of the sampling area (~6.5°C). During April warmest SST were found adjacent to the Liverpool Bay coastline and decreased offshore (see Figure 61). Coastal SST during this time were approximately 8°C (max.) whilst those recorded further offshore were approximately 6°C. July and August SST (see Figures 68 & 93) show a very similar pattern as for those found during April with highest SST found adjacent to the coast, SST for July and August are in the same temperature range (15-19°C) although during August warmer waters extended further offshore. During November SST were warmest to the north-west of the region (see Figure 92) where temperatures reached 10°C, coolest SST were found to the south-east of the region.

Surface water salinities showed a very similar trend to temperature distributions on all sampling occasions (see Figures 56, 62, 69, 81 & 93). Lowest surface water salinities were found in coastal waters, particularly around the Mersey and Dee estuaries. Penetration of low surface salinity waters was greatest in March, April and November and lowest in July and August.

5.2 Nutrient Distributions

5.2.1 Nitrogenous Compounds

During March, April and July the majority of total inorganic nitrogen was present as ammoniacal nitrogen. Highest concentrations of ammoniacal nitrogen during March were found in waters around the Dee estuary (see Figure 60) where concentrations of up to 180 µg/litre were recorded. TON levels for the same period were also found to be highest off the Dee estuary with levels of up to 700 µg/litre (see Figure 59). These high values of ammoniacal and TON decreased westwards with minimum concentration found in waters to the north of Great Ormes Head. (<200µg/litre TON, <40µg/litre ammoniacal nitrogen). Nitrite levels during March were relatively low compared to either TON or ammoniacal nitrogen. Highest concentrations were recorded around the Dee estuary (10µg/litre) and decreased westwards.

Levels of TON (see Figure 63) and ammoniacal nitrogen during April were of the same order of magnitude as during March and showed a similar east-west trend. Highest concentrations of all nitrogenous compounds (nitrite, ammoniacal nitrogen and nitrate) were found off the Mersey estuary with TON concentrations of between 600-760 µg/litre and ammoniacal nitrogen concentrations of up to 200µg/litre. Nitrite levels were slightly higher than those reported for March at around 30µg/litre (Figure 64). All these variables decreased to the north and west of Liverpool Bay.

Highest levels of nitrate and nitrite concentrations continued to be found in the south-east region of Liverpool Bay during July (see Figures 70 & 71). Nitrite levels had decreased to levels similar to those found during March. Maximum nitrite concentrations of approximately 14µg/litre were found in the regions of the Dee and Mersey estuaries. Maximum nitrate concentrations of up to 48µg/litre were also found around these estuaries during July. Ammoniacal nitrogen showed a general north-south trend, concentrations between the west of the Dee estuary and Colwyn Bay were <150µg/litre and represent the highest concentrations in the south of the region (see Figure 72). An isolated ammoniacal nitrogen maxima was identified towards the north-west of the region during this time with concentrations reaching >250µg/litre.

Nitrate, nitrite and ammoniacal nitrogen were all reported in highest concentrations off the Mersey estuary during August (see Figure 82, 83 & 84) Nitrate concentrations of up to 180µg/litre were found whilst nitrite concentrations had maximum levels no greater than 45µg/litre. These values were the lowest reported for any sampling date. Maximum concentrations of ammoniacal nitrogen were around 65µg/litre.

During November the southeast-northwest trend reported for nitrogenous compounds in Liverpool Bay was still apparent. TON had increased considerably from the summer sampling periods with concentrations as high as 600µg/litre being recorded. (see Figure 94). These levels were comparable to those reported for March and April. Maximum concentrations were again recorded in waters around the Dee estuary and those close to the eastern Liverpool Bay coastline. Ammoniacal nitrogen and nitrite levels followed the same distribution as for TON with concentrations of up to 150µg/litre and 50µg/litre respectively.

5.2.2 Phosphorus Compounds

Soluble reactive phosphate (SRP) during March were highest off the Dee estuary and decreased towards the west of the study area. Maximum concentrations during this period reached 55µg/litre (Figure 57). SRP levels during April had maximum concentrations (95µg/litre) in waters around the Mersey estuary and decreased north and westwards with highest values of <15µg/litre being found in waters running westwards from the River Ribble (Figure 65).

SRP concentrations during the summer sampling periods (July & August) were on the whole similar to those reported for March and April. Maximum levels during July were found in the south-east of the study area (60µg/litre) and decreased to the north and west of the bay (Figure 73). These 'seasonally high' levels continued during August and the distribution remained the same as for July. Maximum concentrations during the late summer (August) were found in isolated waters off the Mersey estuary where they reached approximately

90μg/litre (Figure 85). The distribution of SRP during November was similar to those reported for all previous sampling occasions with lowest concentrations (~10μg/litre) being recorded to the north-west of the study area. Regions of increased SRP concentration extended further north than for the previous sampling dates. Maximum concentrations of 90μg/litre were recorded (see Figure 95).

5.2.3 Silicate

Silicate levels during March reached a maximum concentration of 900μg/litre around the Dee estuary and decreased towards the north of the region (Figure 58). Silicate concentrations during April had decreased compared to those reported for March. Highest concentrations of 450μg/litre were found off the Mersey estuary (Figure 66). July silicate distributions were similar to those reported for April with maximum concentrations of 500μg/litre being recorded from waters near to the Mersey estuary and also off Prestatyn (Figure 74). Lowest silicate concentrations of any sampling date were recorded during August (Figure 86). The silicate maxima recorded off Prestatyn in July continued during August albeit with reduced concentrations (230μg/litre). The overall distribution of silicate during August had changed when compared to the previous sampling dates. Highest overall silicate levels were found in waters north of approximately 53.5N (decimal latitude). Silicate concentrations had recovered considerably during November with maximum concentrations once more found in waters to the south-east of the sector particularly off the Dee and Mersey estuaries and extended northwards along the eastern coast of Liverpool Bay. November concentrations were the highest of any sampling date with maximum levels reaching 1200μg/litre (Figure 96).

5.3 Chlorophyll *a* and Phytoplankton data

Chlorophyll data for March was not available. April chlorophyll *a* data showed significant positive correlations ($P. < 0.05$) with the distribution of winter (March) nitrogenous compounds. Highest surface chlorophyll *a* concentrations were found in waters around the Dee and Mersey estuaries where levels of up to 28μg/litre were recorded. These high surface chlorophyll concentrations reflect the increased algal production of the vernal bloom. Waters in the coastal region south of Morecambe Bay to the Afon Clywd all show chlorophyll *a* concentrations greater than 7μg/litre (Figure 67).

The distribution of surface chlorophyll during July was similar to those reported for April although concentrations were generally lower. The elevated chlorophyll *a* levels reported around the Dee and Mersey estuaries continued to be the highest for the study area with maximum concentrations of 12μg/litre. Concentrations decreased to the north and west of the region (Figure 75)

August concentrations were also highest around the Dee and Mersey estuaries although maximum concentrations had increased to 25μg/litre (Figure 87). Lowest levels of chlorophyll *a* from any sampling date were reported during November. Concentrations during this time within the whole of Liverpool Bay did not exceed 1.5μg/litre (Figure 97). The apparent increase in surface chlorophyll concentrations during August are suggested to reflect the onset of the autumn bloom.

Phytoplankton data was only available for July and August sampling dates. It can be seen from Figure 76 that total phytoplankton counts during July were relatively low with maximum abundances of up 37 000 cells/litre being recorded. The higher concentrations were found adjacent to the Dee and Mersey estuaries and along the Fylde coast south of Morecambe Bay. Phytoplankton abundances generally showed good agreement with the distribution of winter nutrients and decreased to the north and west of the region. A breakdown of the phytoplankton data into constituent diatom and dinoflagellate groups showed that the diatom abundances generally followed those of the total phytoplankton with maximum abundances of 34 000 cells/litre being recorded (Figure 77). Dinoflagellate abundances were relatively high during July (Figure 78). Maximum abundances of up to 14 000 cells/litre were found around the Dee and Mersey estuaries and also in a region running northwards from the Afon Clwyd. The potentially toxic dinoflagellate genus *Dinophysis* was reported in high concentrations (~1000 cells/litre) to the north of the Afon Clwyd and also in waters close to the River Ribble (Figure 79)[1].

Phytoplankton appeared to have increased in abundance during August with concentrations of up to 550 000 cells/litre being recorded in the mouth of the Dee estuary (Figure 88). A breakdown of these data demonstrated that the majority of the flora was represented by diatoms, the distribution of which closely followed that of the total phytoplankton (Figure 89). Dinoflagellate abundances during August were also relatively high with concentrations of up to 45 000 cells/litre being found near the Afon Clwyd and in waters offshore of the River Ribble (Figure 90). The Dinoflagellates were represented by species of *Ceratium*, Prorocentrales, *Peridinium*, *Dinophysis*, and Gymnodiniales (in order of abundance). The potentially toxic *Dinophysis* sp. were reported in very high numbers in waters west of the River Ribble where abundances of up to 4500 cells/litre were recorded (Figure 91).

6. LIVERPOOL BAY SURVEYS: SUMMARY

6.1 Major Spatial and Temporal Trends

Physical parameters (SST & surface salinities) showed a general southeast-northwest trend within Liverpool Bay on all sampling occasions. Warmest SST were found offshore during March, April and November and inshore during July and August. Surface water salinities were greatest offshore on all sampling dates. The penetration of low salinity waters was greatest during March, April and November and lowest in July and August. The influence of freshwater run-off via the Dee, Mersey and Ribble estuaries on silicate, salinity and nutrients was also apparent on all sampling occasions. The gradual cooling of waters during autumn and winter results in minimum SST during March and April. By the spring, increased insolation increased the SST throughout the spring and summer. The proximity of land and the shallow waters within the Bay result in distinct seasonal changes of coastal and offshore SST. During winter and early spring there is a strong negative correlations ($P. < -0.05$) between SST and surface water salinities. The increased insolation during spring warms the

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[1] Species of the genus *Dinophysis* particularly *D.acuta* & *D.acuminata* have been reported from UK coastal waters in recent years and are thought to have been responsible for outbreaks of toxic shellfish poisoning. As no speciation of this genus were made in the current study no conclusions can be made regarding the potential threat of *Dinophysis* in Liverpool Bay during 1996.

coastal waters faster than those offshore so that by late spring/summer the SST are strongly positively correlated with surface water salinity.

Levels of nitrate and silicate generally reflect a combination of coastal inputs and patterns of phytoplankton growth, being more depleted in areas of increased chlorophyll concentrations during April particularly. The spring increase in surface plankton production, as indicated by chlorophyll *a* values, was associated with the major estuaries of Liverpool Bay. This was most prevalent for the Dee and Mersey estuaries where chlorophyll *a* values of up to 28μg/litre were recorded. Levels of inorganic nitrogen were especially low during the summer sampling periods when compared to the winter concentrations. Nutrient levels for March and April were generally higher than those reported for July and August. This possibly suggests that these samples were collected prior to the onset of major phytoplankton production.

The nutrient concentrations within the Bay are highest during winter before the onset of the spring bloom. After the Bloom had started silicate and nitrogenous compounds decreased in concentration over most of the Liverpool Bay. Concentrations were still relatively high however around the Mersey estuary suggesting some possible anthropogenic inputs. During the winter and spring sampling occasions (November & March) the distribution of nutrients appear to predominantly be controlled by physical parameters operating within the Liverpool Bay. The high nutrient loadings during winter are associated with less saline waters discharging from the Mersey, Dee and Ribble estuaries, consequently nutrient concentrations decrease offshore.

As mentioned previously, highest chlorophyll *a* concentrations were reported for April. Previous studies within the Liverpool Bay have shown that the major period of spring phytoplankton production occurs during May and June (Foster *et al.* 1982,). It is therefore quite possible that chlorophyll *a* values may have increased between April and July . No data is available for this time period so no firm conclusions can be drawn. Chlorophyll *a* concentrations continued to be relatively high during July and August particularly around waters associated with the Dee and Mersey estuaries where concentrations greater than 25μg/litre (August) were reported.

Spatial distributions of phytoplankton, nutrients and chlorophyll indicated by this work are described for surface samples only. Such an approach can be highly restrictive. Variations in these parameters will occur with depth due to physical stratification and biological migration. Consequently the results obtained and described will depend to some extent on sampling depth, time and the degree of mixing within the water column.

6.2 Evidence of Impact of Nutrient Inputs

Nutrient discharges into Liverpool Bay generally arise from two main sources. The first is from agricultural runoff, fertiliser applications in excess of those that can readily be taken up by crops are washed from the land within in the major river catchments and subsequently find there way to the marine environment, additionally industrial discharges of silicate from at least

one point source within the Mersey catchment are known. The second major source of nutrient enrichment into Liverpool Bay is via the discharge of domestic sewage which can be high in concentrations of nitrogenous compounds, particularly ammoniacal nitrogen (Taylor & Parker 1993). Evidence of riverine inputs, particularly silicate, phosphate and nitrogenous compounds were most obvious in winter and early spring around the Mersey and Dee estuaries. The distribution of these variables on all sampling occasions was however highest around the south-east of the Bay. This suggests that the Mersey, Dee and possibly the Ribble estuaries continue to enrich the nutrient pool of Liverpool Bay throughout the year.

The distribution of phytoplankton abundances reflect those of the nutrients reported previously. The distribution of chlorophyll *a* also indicated that waters discharged from the Mersey and Dee estuaries had higher levels of primary productivity than for other regions within the bay on all sampling dates. Although no evidence of nuisance algal species were reported from the current study, reports of the colonial flagellate *Phaeocystis pouchetii* have been reported within Liverpool Bay in recent years (Savidge and Kain 1990, Spencer 1988). Although thought to be non-toxic, *Phaeocystis pouchetii* can produce extensive surface scums which if washed ashore can be aesthetically unpleasant. The dinoflagellate genus *Dinophysis* was reported from Liverpool Bay in relatively high abundances during July and August with concentrations of up to 4500 cells/litre reported. Which species of *Dinophysis* found is not known from the current study, however representatives of this genus have been known to cause shellfish poisoning in other coastal sites around the UK. Environment Agency guidelines suggest that if certain species of *Dinophysis* (namely *D.acuminata, D.acuta* & *D.norvegica*) are present at densities of more than 100 cells/litre then action should be taken.

Guidelines set out by the Comprehensive Studies Task Team (1997) of the Marine Pollution Monitoring Management Group suggest an area to be adversely affected by nutrient inputs if;

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

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

Winter nutrient concentrations exceed the above criteria at just about all the sampling sites with DAIN ranging from 162-600µg/litre and DAIP from 33-50µg/litre within Liverpool Bay. This suggests that waters within the Bay are adversely affected by nutrient inputs. Evidence from surface chlorophyll data for July and August suggest that regions of Liverpool Bay are adversely affected under the remit of the guidelines outlined above. Chlorophyll *a* concentrations around the Dee and Mersey estuaries during this time ranged from 10-25µg/litre.

N:Si ratios of greater than 0.47 (µg/litre) were recorded in waters north of Afon Clwyd and those adjacent to the Mersey (Figure 98).

7. LIVERPOOL BAY SURVEYS: CONCLUSIONS

- Under the guidelines of the Comprehensive Studies Task Team (1997) of the Marine Pollution Monitoring Management Group (MPMMG) waters around the Mersey and Dee estuaries are adversely affected by nutrient inputs. The most likely source of these nutrients are from riverine inputs of agricultural fertiliser and sewage discharges. The high levels of winter DAIN and DAIP in conjunction with the high summer chlorophyll *a* concentrations indicate that Liverpool Bay should not be classified as a 'Less Sensitive Area'.

- On all sampling occasions nutrient concentrations (SRP, silicate and nitrogenous compounds) were highest around the Dee and Mersey estuaries.

- Positive correlations ($P. < 0.05$) exist between winter nutrient concentrations (TON, silicate and SRP) and both chlorophyll *a* and phytoplankton cell counts during April, July and August.

- Chlorophyll *a* concentrations were highest in the south-east of Liverpool Bay (particularly around the Dee and Mersey estuaries) on all sampling occasions. Highest concentrations were recorded during April, where concentrations around the Mersey and Dee estuaries reached 28µg/litre. During July and August concentrations remained relatively high with levels of up to 25µg/litre recorded adjacent to these major estuarine waters.

- No conclusive evidence of severe blooms of nuisance algae were reported on any of the sampling dates. However, abundances of the dinoflagellate genus *Dinophysis* were found in high numbers during July and August. No conclusions can be made regarding this potentially toxic algae owing to lack of taxonomic information in the present study. Evidence from other sources suggest that *Phaeocystis* blooms occured along the north Wales coast and Liverpool Bay during spring. A bloom of the toxic dinoflagellate *Dinophysis acuta* was also found in waters off Colwyn Bay during July (M.B.C.C 1997).

8 NORSAP TRIANGLE SURVEY

8.1 Introduction

The 'NORSAP' (Northern Seas Action Plan) triangle was sampled by the R.V. Coastal Guardian over a two day period on the 28/29 August 1996. The cruise followed the 54° N parallel from the Isle of Man to the Cumbrian coast and then south to approximately 53.5° N (decimal longitude) and back to the Isle of Man (see Figure 115). Sea surface temperature, salinity, nutrient, chlorophyll *a* and phytoplankton samples were taken and the results are presented below. As with all the contour plots produced in this report, attention must be made to the position of sampling points as the 'SURFER' package extrapolates between data points.

8.2 Results

8.2.1 Physical Patterns

Temperature showed an east-west trend across the sampling area with highest temperatures (17°C) found along the Cumbrian and Lancashire coasts. Lowest temperatures (14°C) were found towards the Isle of Man (Figure 104). Salinity was negatively correlated with temperature, lowest salinities being found in coastal waters (~32) and highest salinities (Figure 105) found towards the Isle of Man (~35). No CTD casts were taken , thus no information on the vertical structure of the water column is available.

8.2.2 Distribution of Nutrients

The distribution of all nitrogenous compounds show similar patterns for the region. Total oxidised nitrogen (TON) concentrations were highest to the south east of the study area towards Liverpool Bay (see Figure 106). TON concentrations at this location exceeded 100µg/litre. Nitrite concentrations showed an identical distribution to those of TON with highest concentrations found towards Liverpool Bay (~20µg/litre). Ammoniacal nitrogen (see Figure 107) was also found in highest concentration towards Liverpool Bay (~26µg/litre) and decreased toward the north west of the study area. The results presented from the NORSAP survey are in broad agreement with those from the Liverpool Bay survey for August.

Soluble reactive phosphate (SRP) concentrations were found to be highest towards the south-east of the study area (see Figure 108). Highest concentrations (~120µg/litre) were found towards Liverpool Bay. These concentrations exceed those reported for the August Liverpool Bay survey. The Liverpool Bay survey was undertaken two weeks before the NORSAP survey which may account for the discrepancies between the two data sets.

Silicate concentrations showed a general east-west trend with highest concentrations generally found to the west of the region (see Figure 109). Maximum concentrations (~300µg/litre) were found to the north of the region. These results are in general agreement with those reported for the Liverpool Bay survey during August.

8.2.3 Distribution of Phytoplankton and Chlorophyll *a*

Highest chlorophyll *a* concentrations are located to the south-east of the study area towards the Liverpool Bay (see Figure 110). Highest concentrations (~4.0µg/litre) are comparable to those recorded from the Liverpool Bay survey during August. The distribution of chlorophyll *a* and phytoplankton are well matched. Maximum phytoplankton (total) abundances were again located to the south-east of the sampling region (~100 000 cells/litre, see Figure 111). A breakdown of the phytoplankton into major groupings shows that the peak abundances recorded towards Liverpool Bay are dominated by dinoflagellates and diatoms, away from this region phytoplankton are much less abundant. a peak in the monad and small flagellated algae distribution was recorded west of the river Ribble and north of the Conwy Bay, concentrations of these algae at these sites reached approximately 70 000 cells/litre (Figures 112-114).

8.3 NORSAP TRIANGLE: SUMMARY

The influence of nutrient discharges from the Dee and Mersey estuaries reported from the August Liverpool Bay survey are apparent in the NORSAP survey data. All nitrogenous and phosphorus compound have maximum concentrations towards the Liverpool Bay. Both the concentrations of chlorophyll and abundances of phytoplankton are greatest towards Liverpool Bay. No evidence of nuisance phytoplankton blooms are noted although abundances of the genus *Dinophysis* were reported in numbers exceeding 100 cells/litre (see footnote on page 30).

8.4 NORSAP TRIANGLE: CONCLUSIONS

- All nutrient concentrations are highest towards the south-east of the study area.
- Chlorophyll *a* and phytoplankton data suggest highest algal biomass to be towards Liverpool Bay.
- No evidence of nuisance phytoplankton blooms are reported.
- Chlorophyll *a* concentrations are within limits outlined by the Comprehensive Studies Task Force.

9 THE DISTRIBUTION OF NUTRIENTS AND PHYTOPLANKTON IN THE EASTERN IRISH SEA DURING 1996.

9.1 Summary of Major Conclusions

- Winter levels of DAIN and DAIP recorded from both the Cumbria coast and Liverpool Bay surveys during 1996 showed elevated levels of coastal nutrients caused by nutrient discharges to these. Evidence provided by the nutrient data collected from the surveys indicate that these waters fail to comply with the guidelines provided by the Comprehensive Studies Task Team and exceed the limits outlined for LSA's. Liverpool Bay is more adversely affected under the CSTT guidelines than the waters off the Cumbrian coast with maximum winter DAIN levels approximately twice as high as those recorded for the Cumbrian coast.

- Results from the Cumbria Coast surveys suggest that concentrations of SRP were highest around Whitehaven and S^{t} Bees Head on all sampling occasions. Winter and spring concentrations of nitrate were highest between the Solway Firth and the Ravenglass estuary. The influence of Albright & Wilson at Whitehaven and BNFL Sellafield discharges into the region are readily apparent on most sampling occasions. These results are in good general agreement with those presented for 1995 (Allen *et al.* 1996). Results from the Liverpool Bay surveys show nutrient concentrations to be highest around the Dee and Mersey estuaries at all times.

- Concentrations of chlorophyll *a* recorded during the summer months exceeded the 10µg/litre threshold (as outlined by the CSTT) along the Cumbria coast and within Liverpool Bay. These data reinforce the aforementioned conclusion that these waters should not be classified as 'Less Sensitive Areas'. Summer chlorophyll *a* concentrations along the Cumbria coast reached a maximum of ~14µg/litre in waters adjacent to Sellafield and in waters west of the Dudden estuary, however, chlorophyll values declined during the summer months. Summer chlorophyll *a* concentrations within Liverpool Bay were found to be highest around the Dee and Mersey estuaries where concentrations reached 28µg/litre, these elevated levels of surface chlorophyll *a* were sustained throughout the spring and summer.

- Results from the Cumbria Coast survey suggest that water column stratification was apparent on all sampling occasions. Winter (Haline) stratification was strongest to the middle of the study area. Summer (haline and thermal) stratification was also found, waters to the north of the region being stratified to both haline and thermal effects whilst waters to the south of 54.3° N (decimal longitude) were stratified to thermal effects.

- Comparisons between winter nitrogenous concentrations and summer phytoplankton data showed very strong positive correlations (*P*= 0.000-0.006) from both the Liverpool Bay and Cumbria Coast surveys. The statistical analysis (BIOENV) produced for the Cumbria coast data suggests that variations in the spring phytoplankton community structure may best be explained by variations in winter TON and silicate concentrations.

- Evidence of severe nuisance algae blooms were reported, the Prymnesiophyte *Phaeocystis pouchetii* was recorded in concentrations of up to 100 000 cells/litre from the northern sector of the Cumbria Coast survey area during May. Blooms of Phaeocystis were also reported from waters in and around the Mersey and Liverpool Bay and the north Wales coast during spring (M.B.C.C 1997). A single bloom of the dinoflagellate *Dinophysis acuta* was reported from waters around Colwyn Bay during July.

Acknowledgements

The authors would like to thank the crews of the research vessels Roagan (PEML) and Coastal Guardian (EA). Joanne Forster and John Hateley (EA) are acknowledged for their assistance with sample collection. Mathew Mosely (PEML) is also thanked for his assistance with sampling at sea and for help in the preparation of the SURFER plots.

Appendix A

Sampling locations and site identifiers for the Cumbria coast surveys.

Offshore grid (PEML)

Site	Latitude	Longitude
A	54:06.19	04:31.08
B	54:12.08	04:21.33
C	54:18.10	04:13.18
D	54:21.27	04:05.14
1W	54:41.96	03:57.67
2	54:42.08	03:50.72
3M	54:41.96	03:45.87
4	54:41.94	03:42.10
5	54:42.04	03:37.26
6E	54:41.95	03:41.95
7	54:40.86	03:43.77
8M	54:40.42	03:46.88
9	54:39.74	03:52.43
10W	54:39.06	03:59.74
11	54:38.03	03:52.05
12M	54:37.58	03:48.04
13	54:36.78	03:42.04
14E	54:36.00	03:37.02
15	54:35.40	03:43.96
16M	54:34.58	03:49.48
17	54:34.01	03:54.08
18W	54:32.82	04:04.16
19	54:32.43	03:53.63
20M	54:32.30	03:51.30
21	54:32.02	03:47.59
22	54:31.71	03:43.50
23E	54:31.34	03:39.44
24	54:29.77	03:45.90
25M	54:29.22	03:49.48
26	54:28.28	03:54.80
27W	54:27.11	04:01.71
28	54:26.56	03:54.39
29M	54:25.80	03:47.51
30	54.25.40	03:42.72
31	54.25.06	03:38.60
32E	54:24.67	03:33.77
33	54:23.75	03:39.19
34M	54:22.83	03:22.83
35	54:22.10	03:49.87
36W	54:21.15	03:55.64
37	54:20.34	03:49.12
38M	54:19.46	03:42.67
39	54:18.81	03:36.14
40E	54:18.16	03:29.39
41	54:17.37	03:34.63
42M	54:16.75	03:39.33
43	54:16.12	03:44.41
44W	54:15.30	03:50.57
45	54:14.73	03:44.98
46M	54:13.96	03:36.75
47	54:13.10	03:30.58
48E	54:12.32	03:23.36
49	54:11.43	03:28.64
50M	54:10.73	03:33.35
51	54:10.03	03:88.93
52W	54:09.20	03:44.58
53	54:08.31	03:38.60
54M	54:07.42	03:32.14
55	54:06.47	03:26.23
56E	54:40.55	03:20.25
57	54:05.05	03:23.16
58	54:04.18	03:27.28
59M	54:03.87	03:28.98
60	59:02.91	03:33.96
61W	54:02.16	03:37.95
F	54:02.11	03:43.93
G	54:01.76	04:01.79
H	54:01.96	04:12.54
I	54:02.10	04:30.37

Appendix B

Two-Way ANOVA without replication results.

February

Site	Sig.*P*	
A	0.395690	*
C	0.028627	
E	0.005972	
1W	0.005055	
3M	0.116873	*
6E	0.048497	
8M	0.242504	*
10W	0.342197	*
12M	0.266074	*
14E	0.007230	
16M	0.030561	
18W	0.006863	
20M	0.259330	*
23E	0.036026	
25W	0.072931	*
27W	0.058313	*
29M	0.011557	
32E	0.066706	*
34M	0.020381	
36W	0.022044	
38M	0.128710	*
40E	0.066649	*
42M	0.099364	*
44W	0.076813	*
46M	0.017140	
48E	0.002885	
50M	0.053072	*
52W	0.006155	
54M	0.049625	
56E	0.095300	*
59M	0.103481	*
61W	0.044943	
F	0.000914	
G	0.054412	*
H	0.003914	
I	0.022856	

May

Site	Sig.*P*
1W	0.007600
3M	0.003321
8M	0.003321
10W	0.016802
12M	0.000091
14E	0.003537
16M	0.001506
18W	0.017502
20M	0.000652
23E	0.000201
25M	0.045312
27W	0.000964
29M	0.000056
32E	0.000046
34M	0.000708
36W	0.000817
38M	0.000144
40E	0.000455
44W	0.000121
46M	0.000915
48E	0.000052
50M	0.000062
52W	0.000066
54M	0.000058
56E	0.000781
59M	0.000486
61W	0.000059

N.B. Sites marked * suggest significant differences (*P.>0.05*) in species composition between replicates.

Appendix C

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 colonies were also noted.

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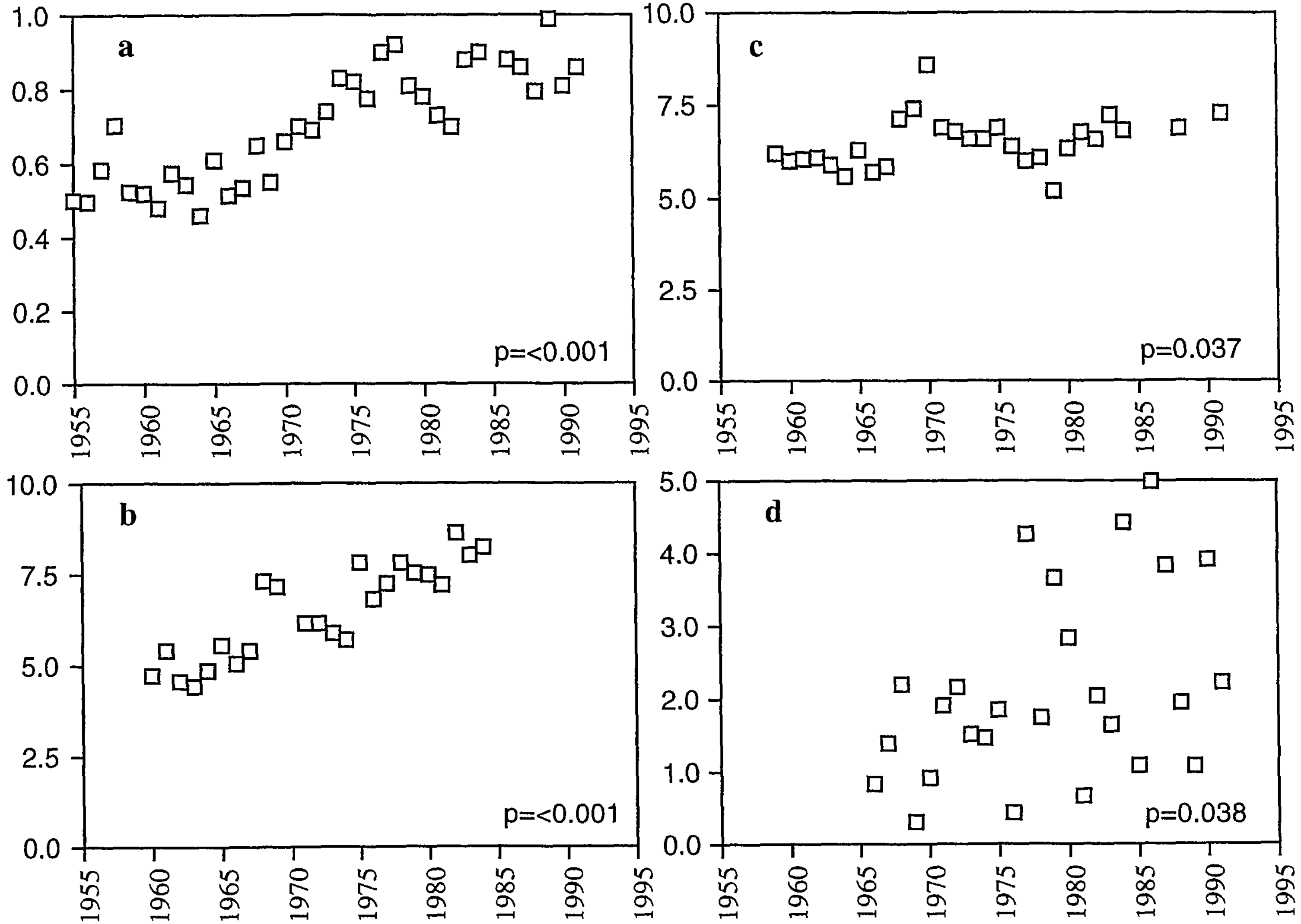

Fig. 1 **a** to **c** Time series of median nutrient concentrations for January-February, a) soluble reactive phosphate, b) total oxidised nitrogen, c) dissolved silicate, µmol/l as P, N and Si respectively. **Fig 1d** Time series of median chlorophyll concentrations for May-June, µg/l. P values are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

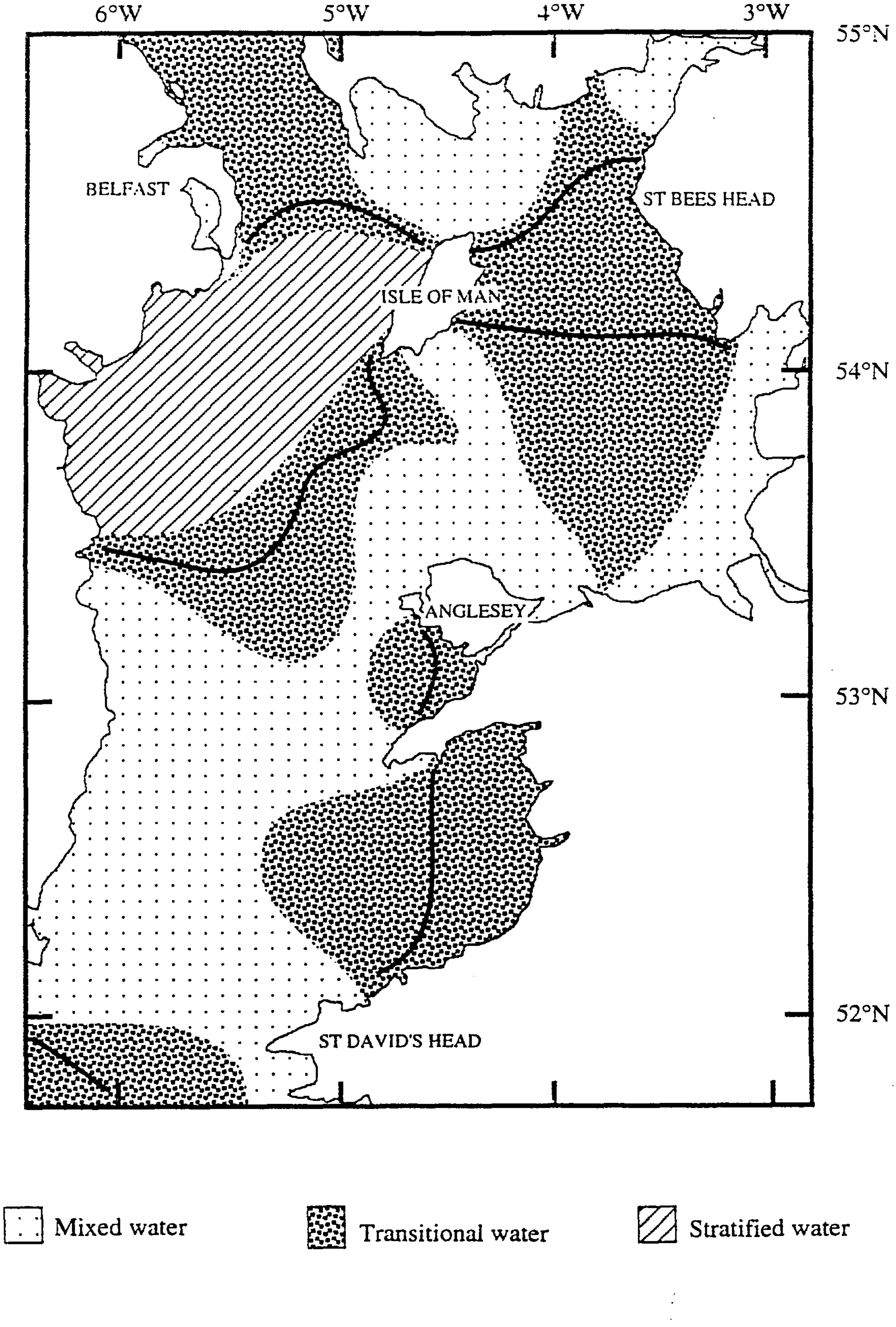

Figure 2. Summer hydrographic conditions in the Irish Sea as predicted from the numerical model of Pingree & Griffiths (1978), showing areas of mixed, transitional and stratified water and frontal regions. The approximate position of the fronts is indicated by bold lines (From Brand & Wilson 1996).

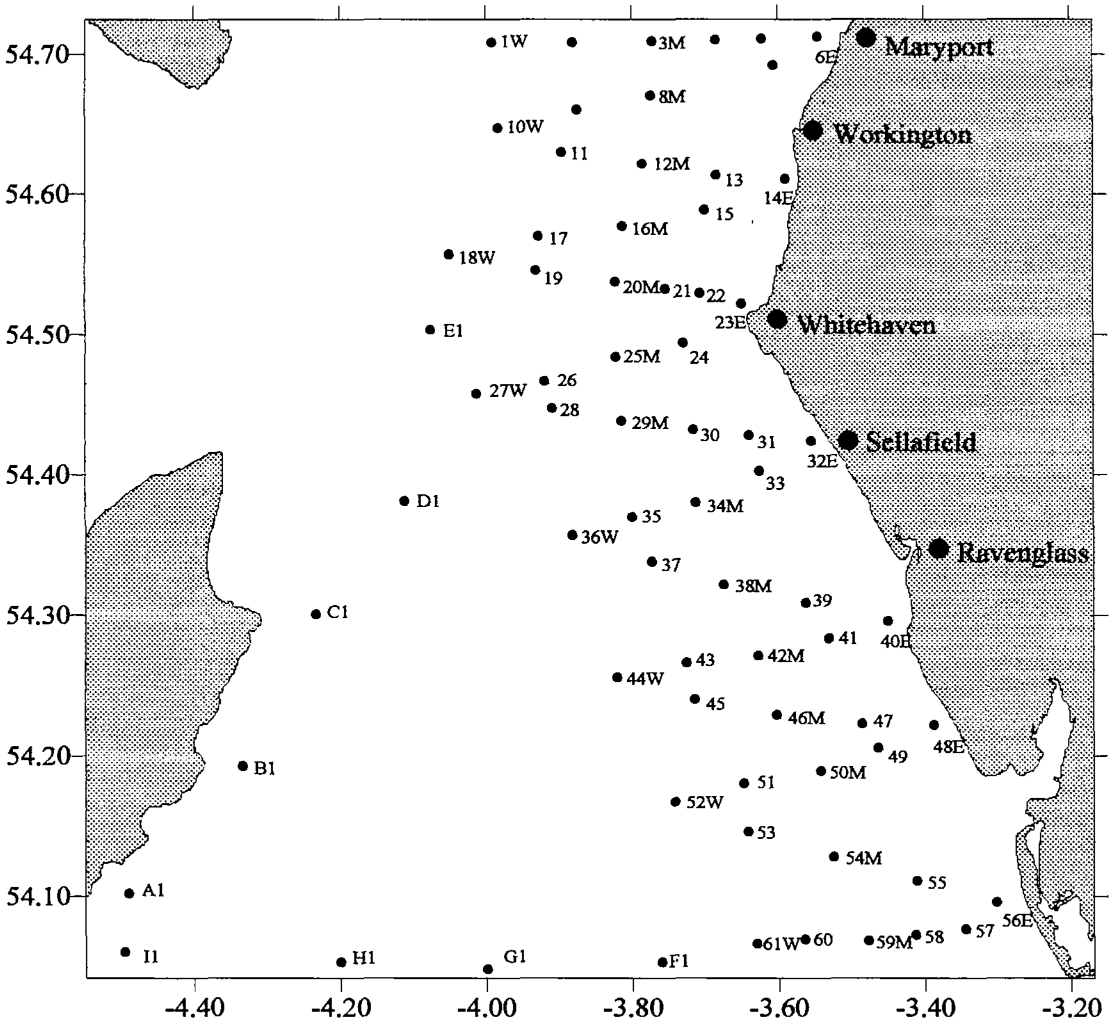

Figure 3a. Cumbria coast surveys. Nominal sampling positions and site identifiers. PEML Samples-Offshore grid

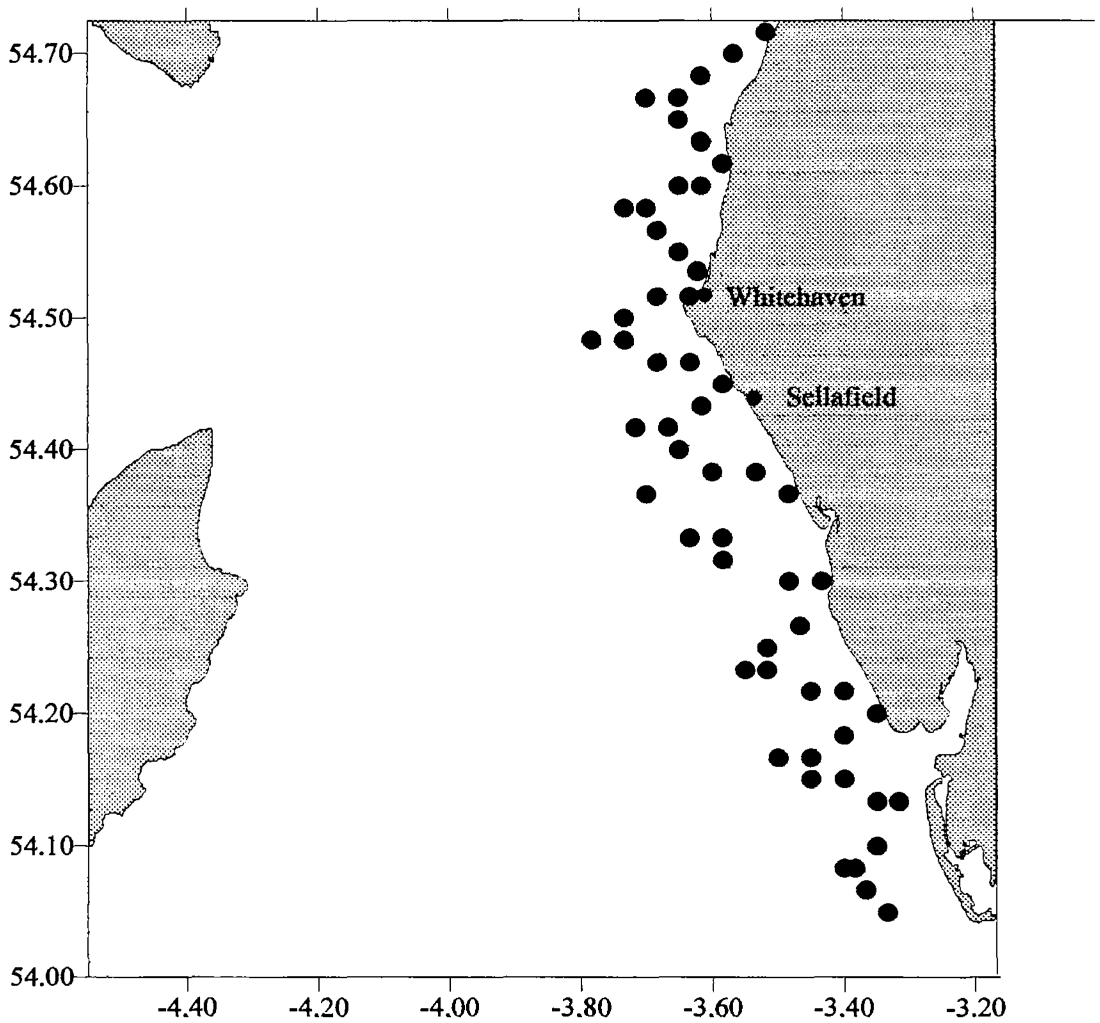

Figure 3b. Discrete sampling sites for (EA) inshore-grid locations. Skalar samples were taken every 10 seconds between discrete sampling sites.

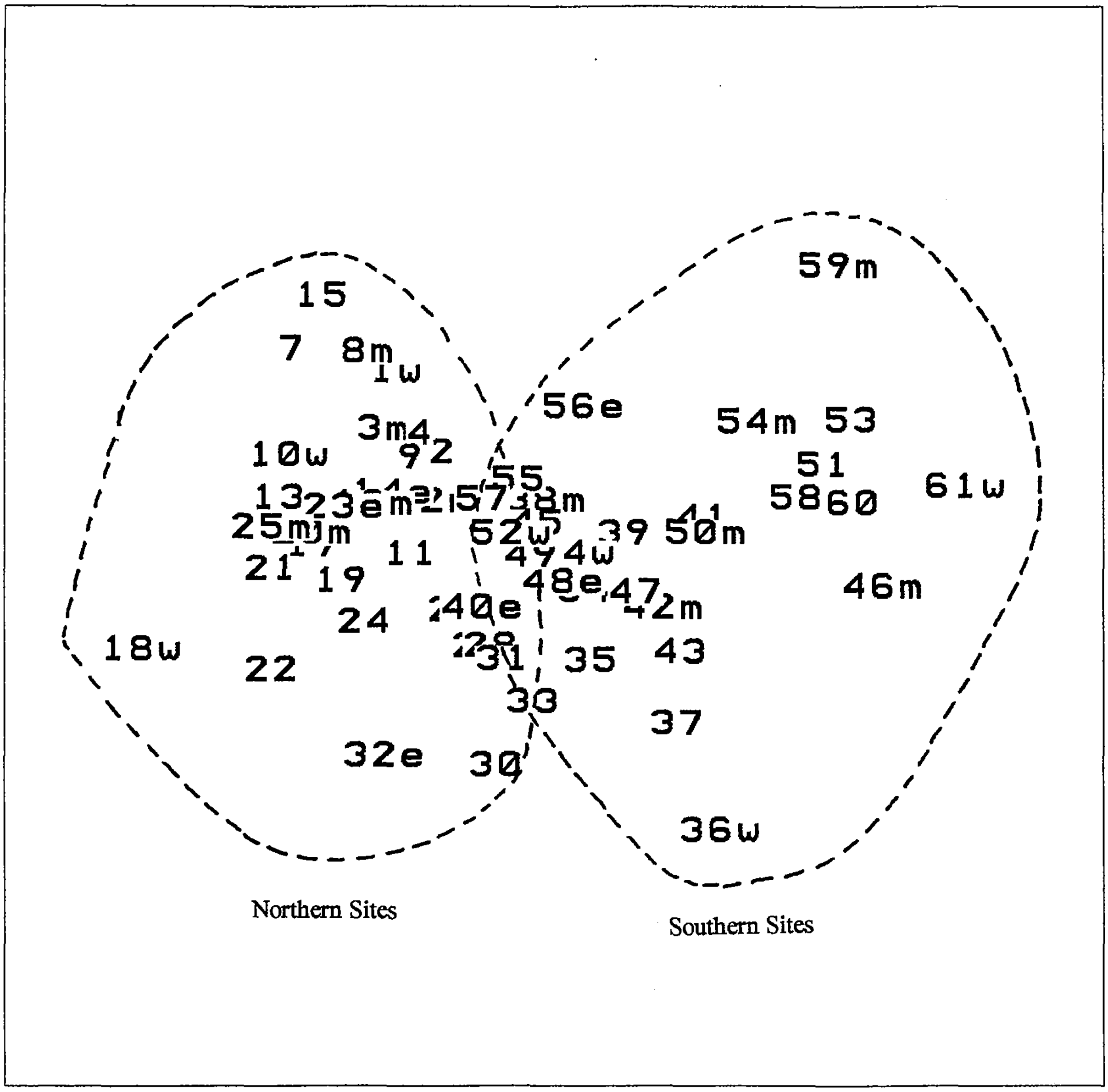

Figure 50 MDS ordination of spring phytoplankton data and sampling site locations
Stress = 0.165

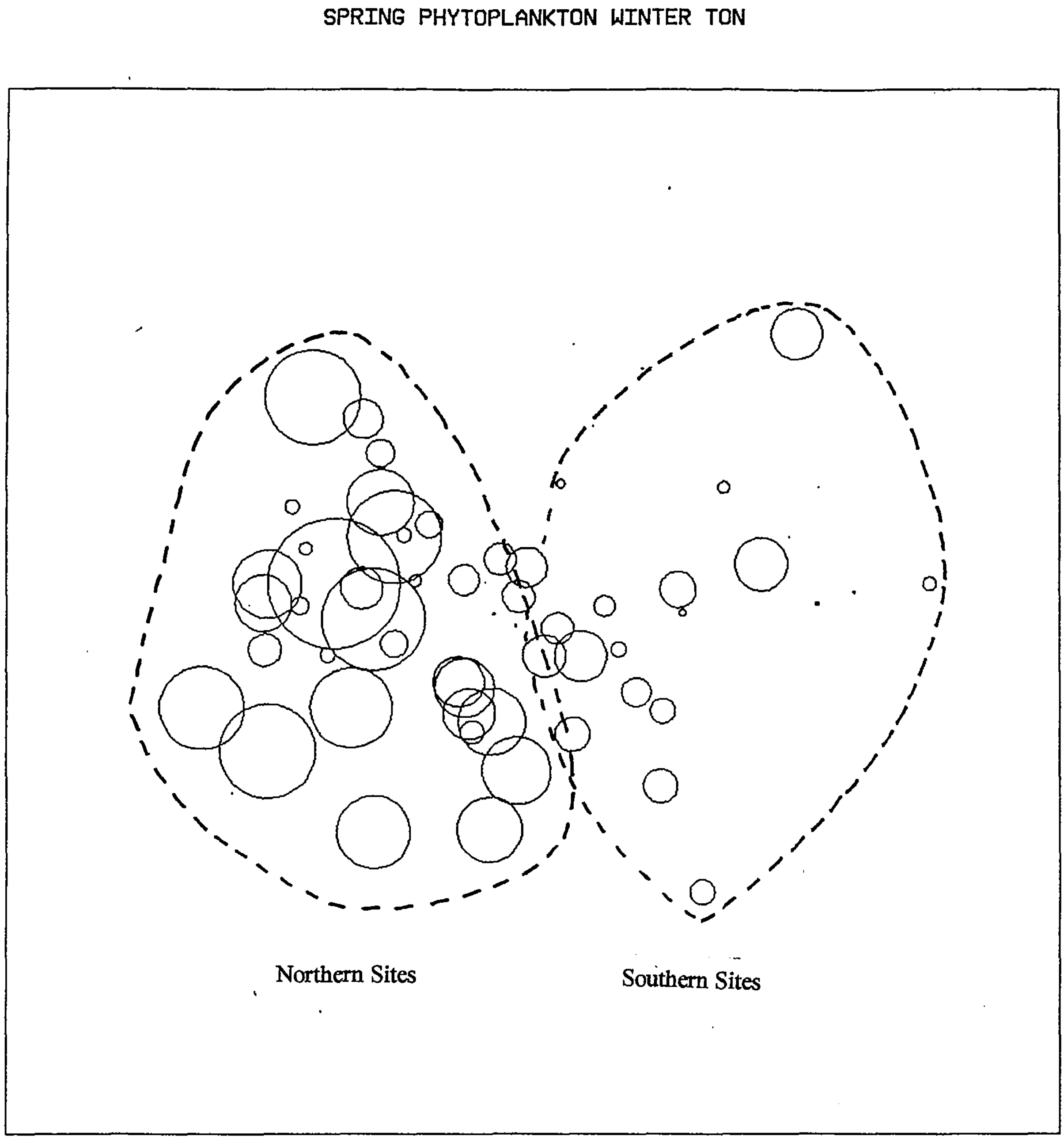

Figure 51. MDS ordination between spring phytoplankton data and winter total oxidised nitrogen (TON). Circle diameters are proportional tp winter concentrations of TON. Northern sites represent group 1, southern sites group 2.
Stress = 0.159.

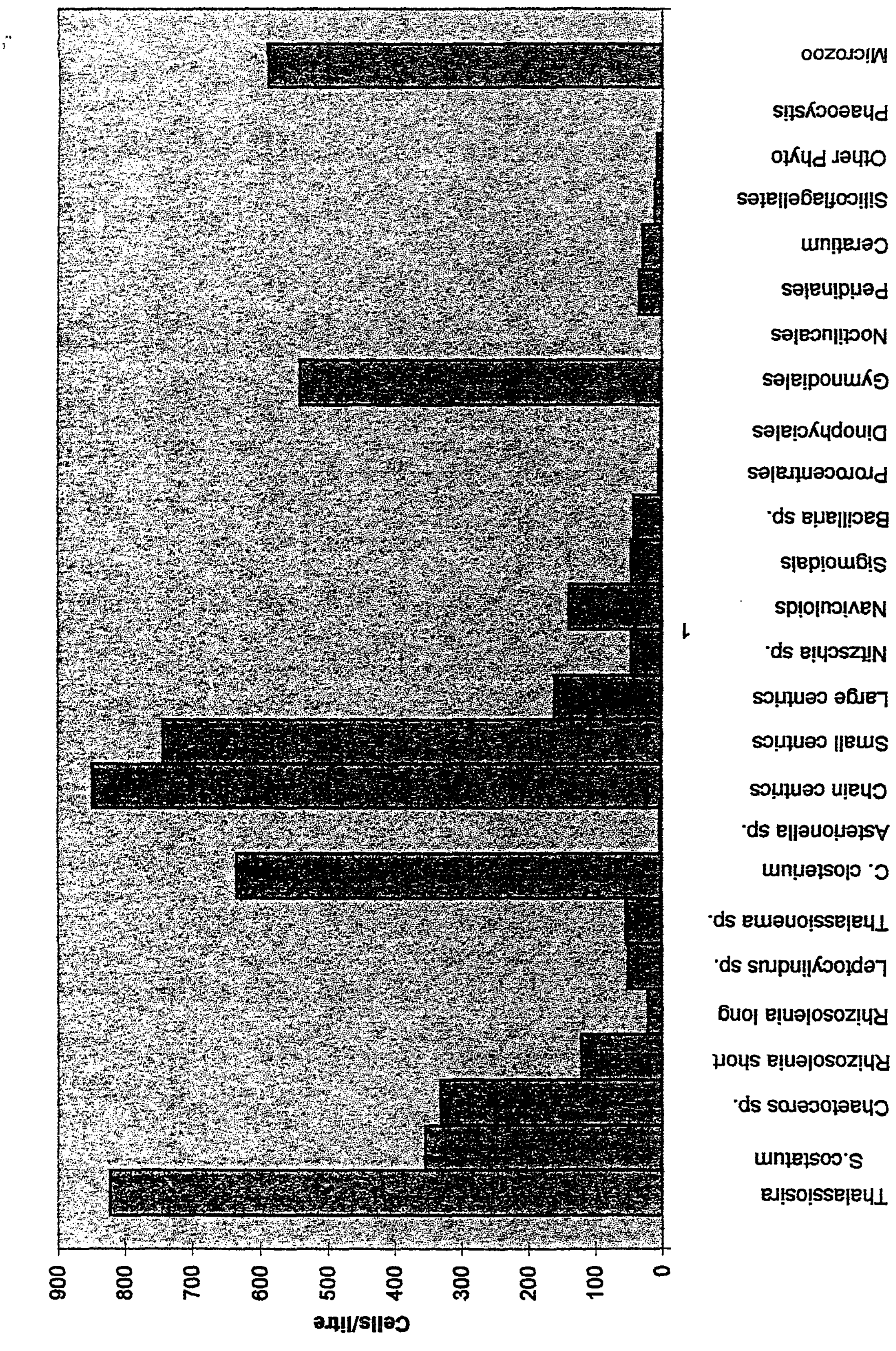

Figure 52. Cumbria coast survey February 1996. Average phytoplankton species abundances.

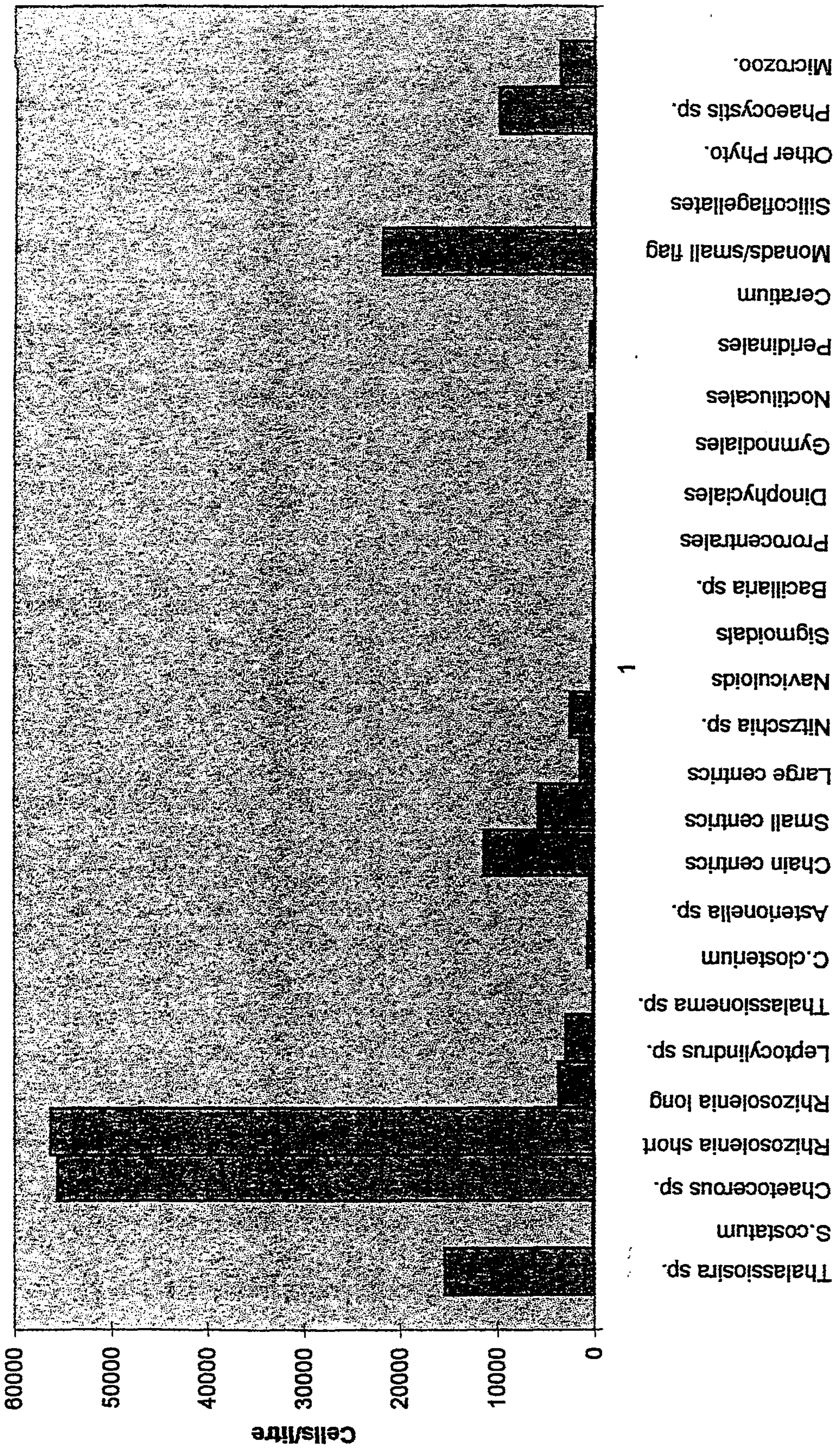

Figure 53. Cumbria coast survey May 1996. Average phytoplankton species abundances.

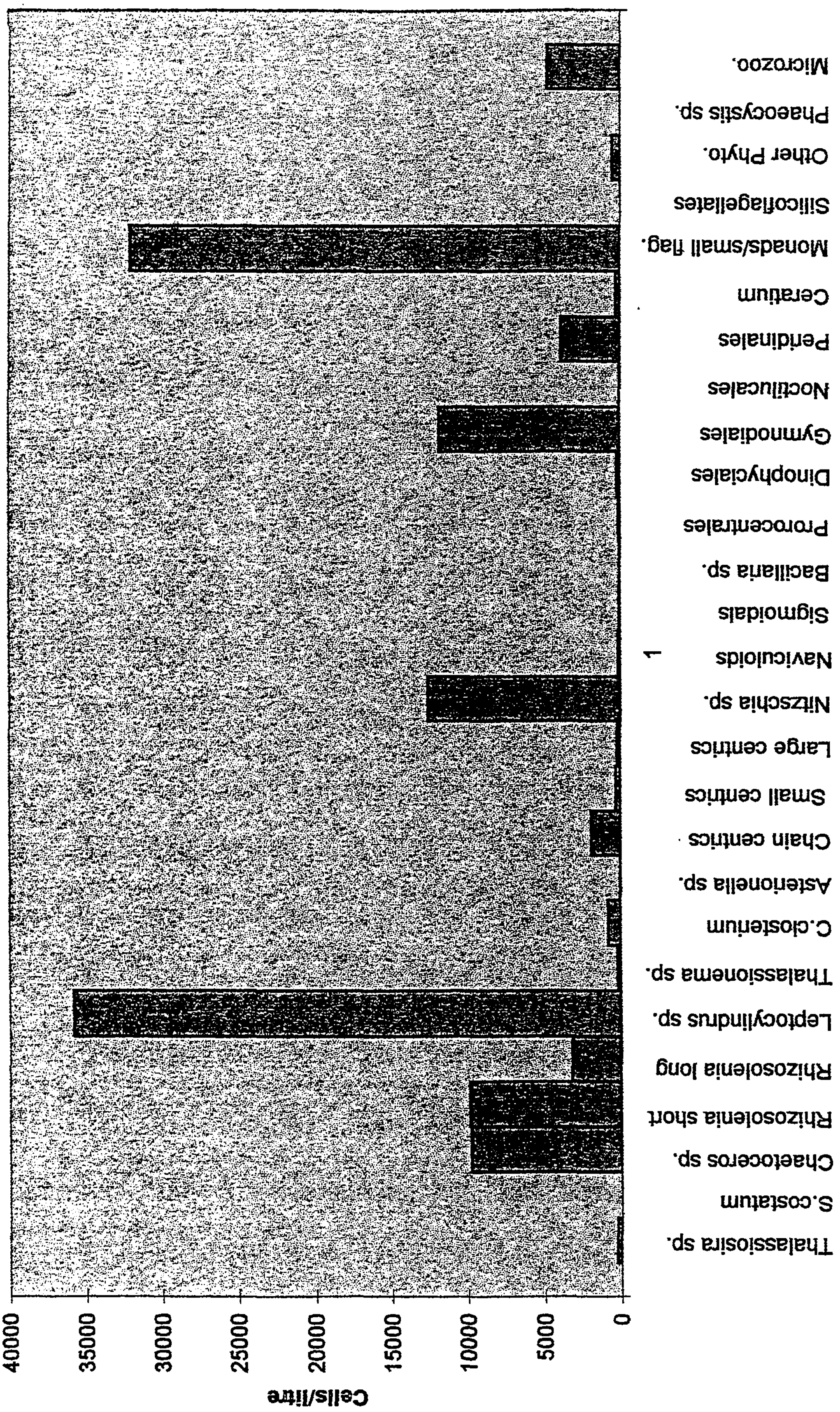

Figure 54. Cumbria coast survey July 1996. Average phytoplankton species abundances.

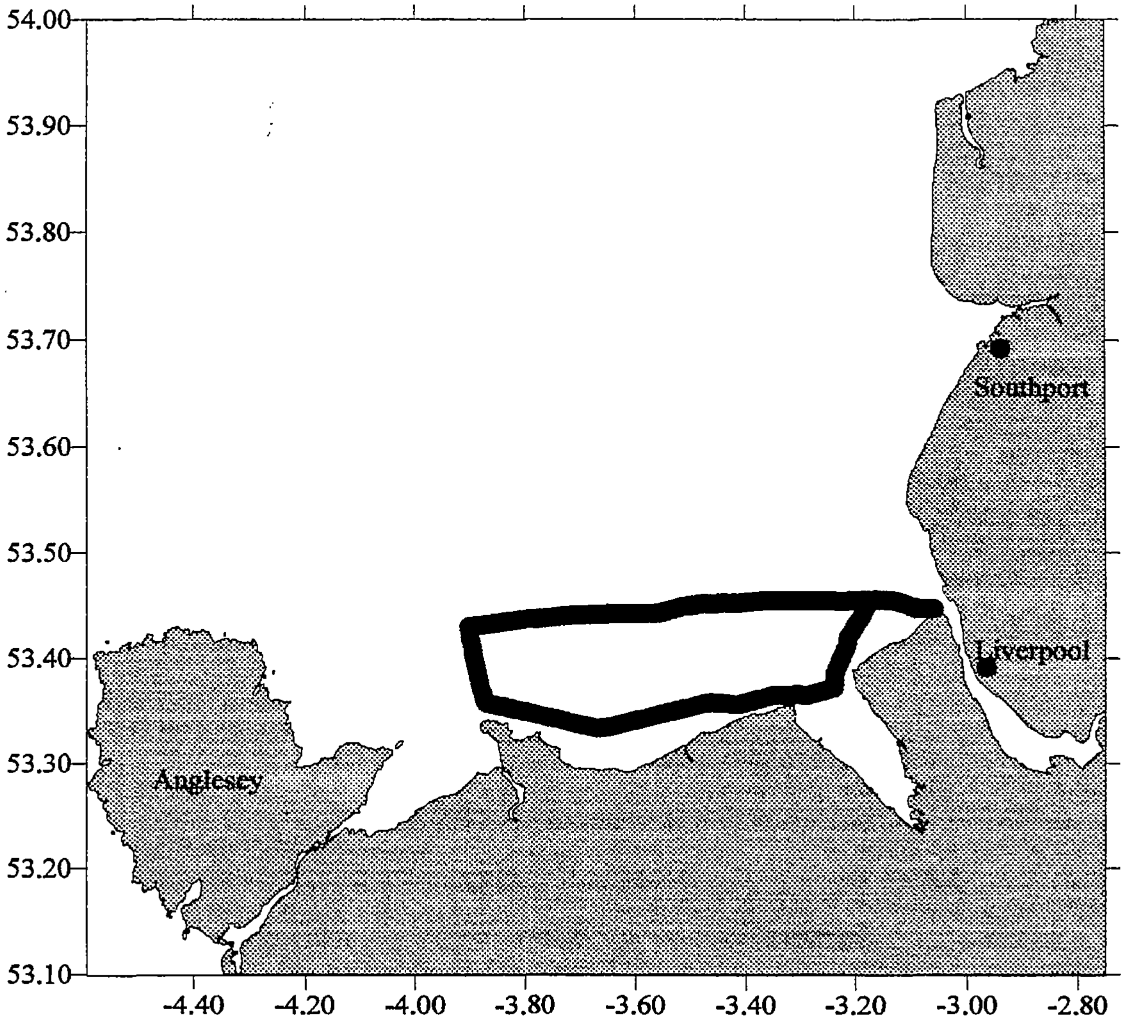

Figure 99. Liverpool Bay survey March 1996. Sampling positions.

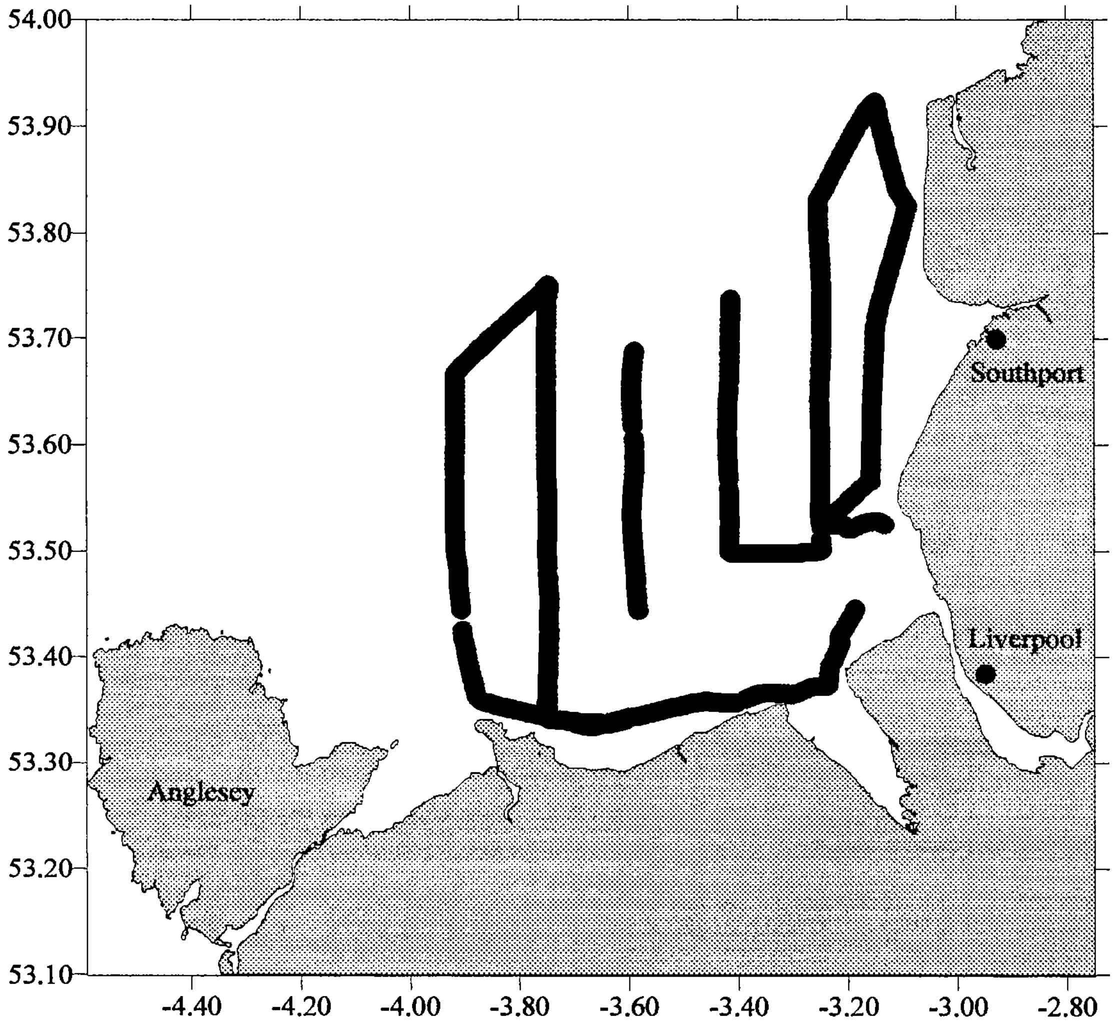

Figure 100. Liverpool Bay survey April 1996. Sampling positions.

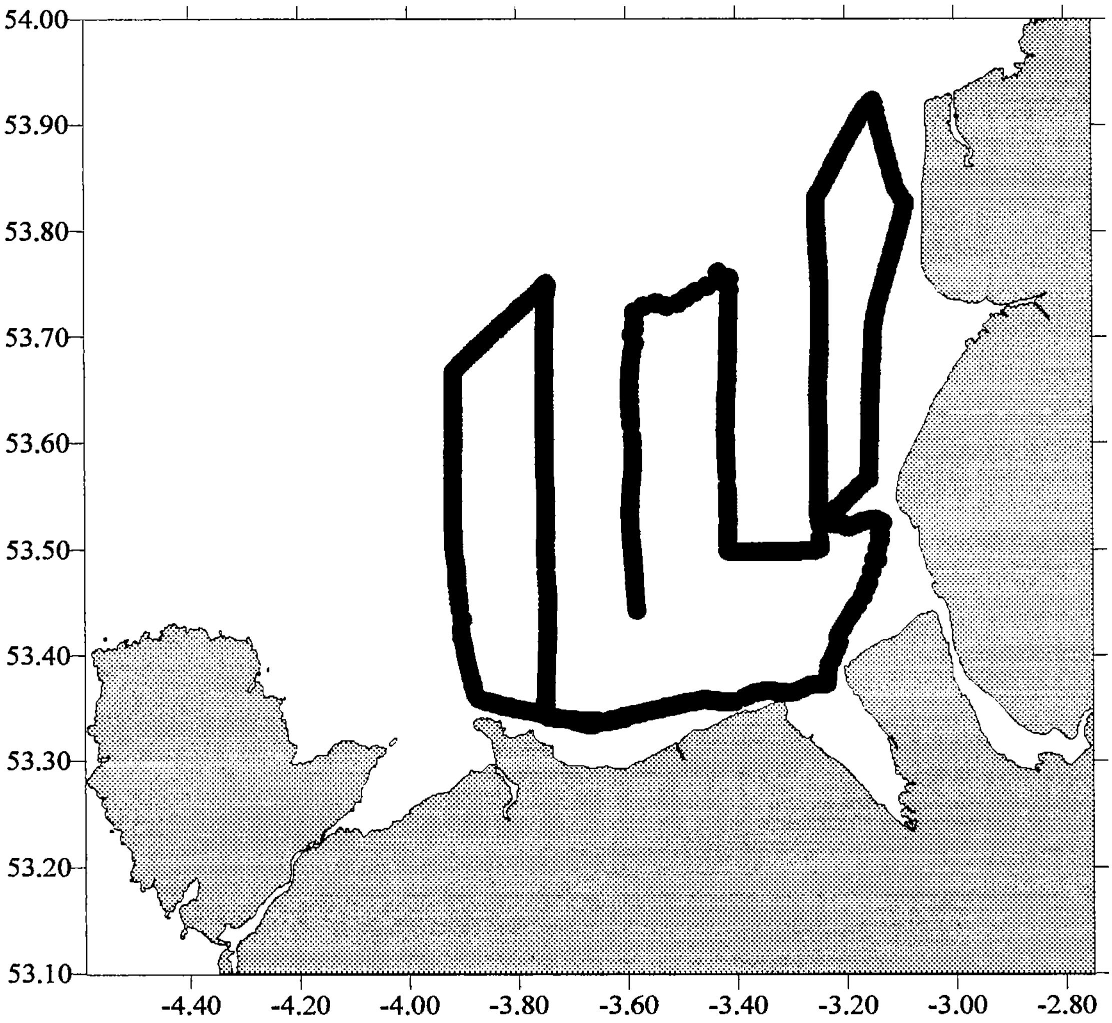

Figure 101. Liverpool Bay survey July 1996. Samplng positions.

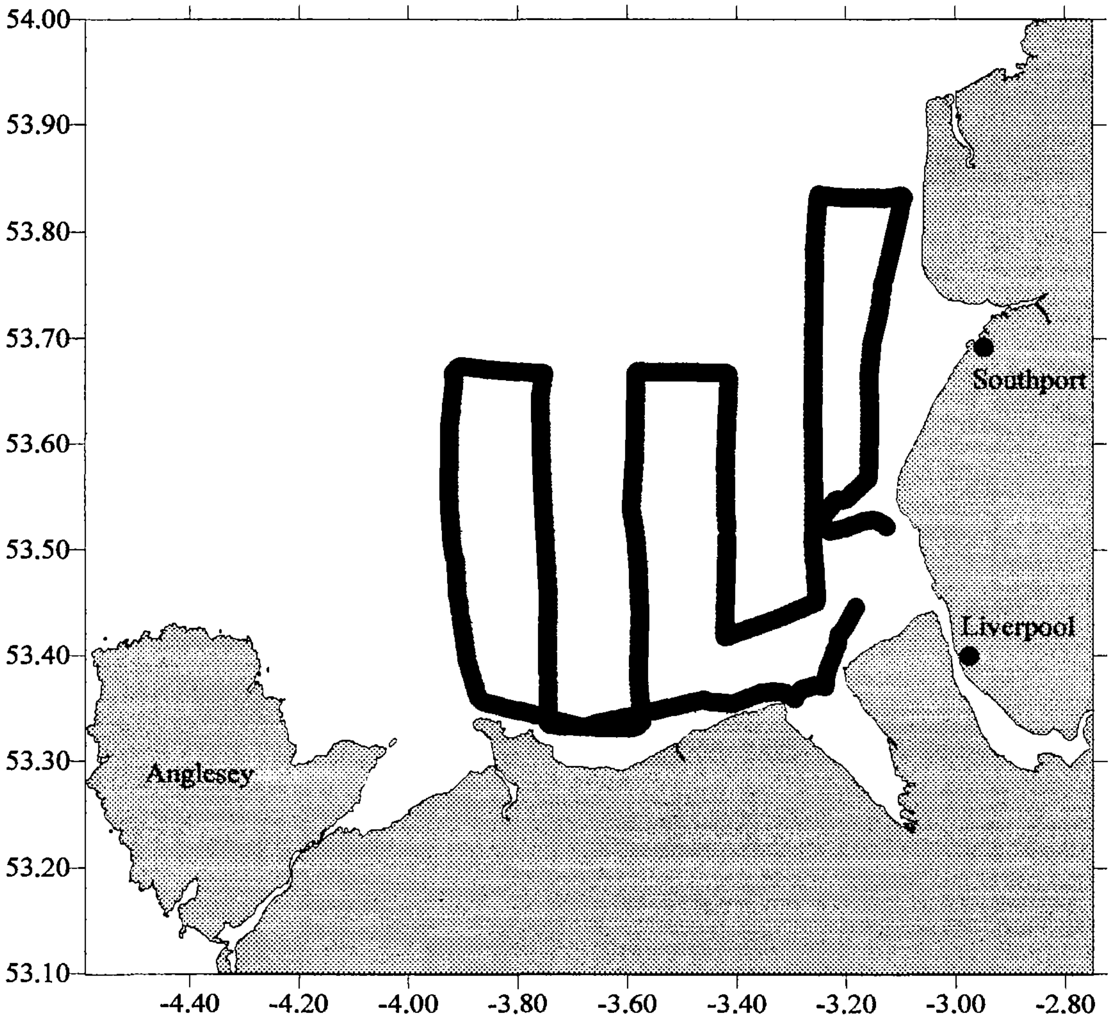

Figure 102. Liverpool Bay survey August 1996. Sampling positions.

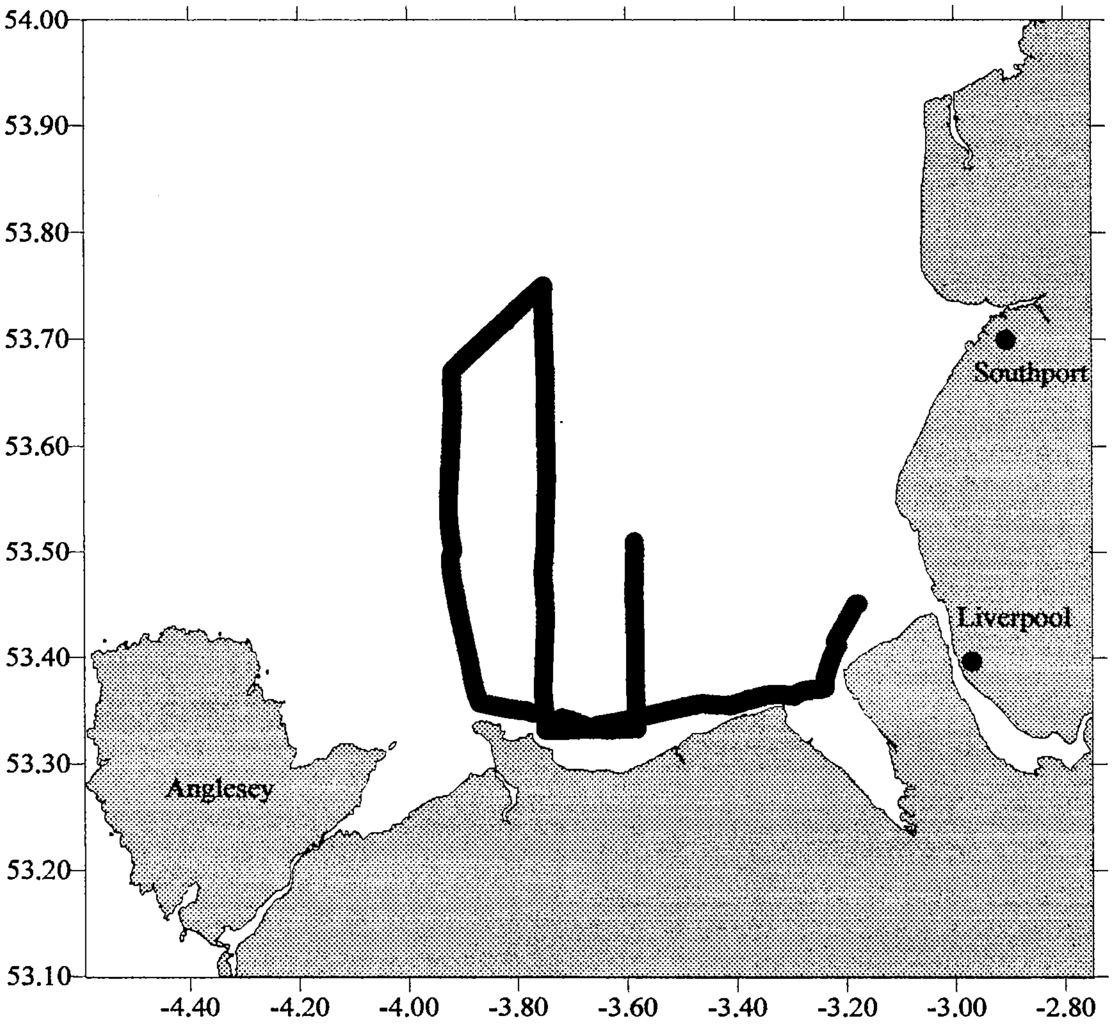

Figure 103. Liverpool Bay survey November 1996. Sampling positions.