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The trophic status of two northern Irish Sea loughs

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Abstract. Studies were conducted on nutrient cycling in two coastal embayments; Strangford Lough and Belfast Lough, in order to classify these coastal waters in compliance with the European Union Urban Waste Water Treatment and Nitrates Directives. Analysis of the data suggests that Strangford Lough is nitrogen-limited throughout much of the growing season with chlorophyll-a levels comparable to the open Irish Sea. In contrast, much of Belfast Lough is never nitrogen-limited and, with chlorophyll-a levels at times exceeding 50 µg/l, is exhibiting symptoms of eutrophication.

Keywords: Belfast Lough; Eutrophication; Nutrients; Strangford Lough.

Introduction

Belfast and Strangford Loughs lie on the east coast of Northern Ireland (Fig. 1). They are the subject of routine monitoring carried out by the Department of Environment (Northern Ireland) — DOE (NI) — in order to meet local and United Kingdom national coastal water classification requirements, and in accordance with certain European Union Directives, have been the subject of intensive surveys over the last two years to determine their response to anthropogenic nutrient inputs.

There have been several studies of the nutrient status of Belfast and Strangford Loughs, though none of these have dealt specifically with this subject in relation to the requirements of the above-mentioned Directives. Early work on Belfast Lough by Lett & Adeney (1908) found indications of nutrient enrichment demonstrated by excessive growth of the green alga *Ulva latissima*. Similar results were also found by Parker et al. (1988) who recorded elevated levels of productivity in the inner lough coupled with increased concentrations of nitrate-nitrogen. Rosell (1989) considered that much of this N-elevation was due to an industrial source and that the inner lough, at least, was showing signs of eutrophication. Maxwell (1978) found a distinct gradient decreasing seawards to Irish Sea background levels superimposed upon the typical winter peak and summer low of nutrients. He suggested that the inner lough was showing signs of pollution and that small diatom blooms occurring in the lough were due to nutrient enrichment.

There is little published work which refers to nutrient levels in Strangford Lough, although unpublished reports by Savidge (1988) and Shearman (1988) have indicated the presence of gradients of soluble reactive phosphate (SRP) and nitrate (NO_3) decreasing seawards in winter with a reverse pattern appearing in the summer.

In 1991 the EU introduced legislation dealing with the trophic status of estuaries and coastal waters (Anon. 1991a, b). The EU Urban Waste Water Treatment Directive (91/271/EEC) deals with the relationship between eutrophication and urban waste water discharges. A similar directive specifically relates to eutrophication resulting from nitrate inputs (Nitrates Directive 91/676/EEC).

In simple terms, these directives state that where a water body is found to be eutrophic or sensitive, certain management strategies must be implemented. The Urban Waste Water Treatment Directive (UWWT) requires that suitable treatment must be introduced for qualifying sewage works (i.e. those with a Population Equivalent > 10 000) if the waters to which they discharge are classified as 'sensitive'. Similarly, the Nitrates Directive requires that appropriate controls on agricultural inputs of nitrate must be put in place within the catchment area of any water body classified as 'polluted'. The definitions of 'sensitive' or 'polluted' refer principally to the potential for adverse effects to occur, caused by eutrophication arising from elevated nutrient inputs.

Belfast and Strangford Loughs are broadly similar in terms of catchment area and basic physical dimensions, but there are some fundamental differences in structure and catchment land use (Table 1). The aim of the present research is to definitively classify these two water bodies under the two directives detailed above in order that appropriate management actions may be taken. This paper presents a preliminary analysis of the results obtained to date. As the purpose of this paper was to

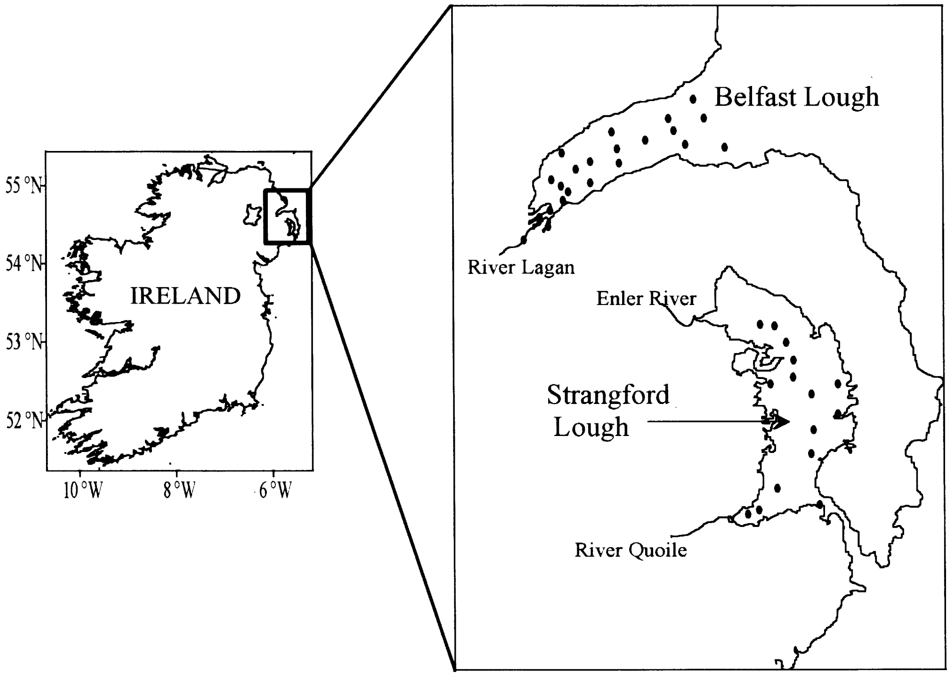


Fig. 1. Map of Belfast and Strangford Loughs showing the location of sampling stations.

present results in the context of the above EU Directives, the bulk of what is presented below will deal with nitrogen as the nutrient of concern.

Material and Methods

Field sampling

Sampling was started in Belfast and Strangford Loughs in September 1992 and July 1993, respectively, at stations chosen to maximise spatial coverage (Fig. 1). Surveys were carried out approximately fortnightly during the months of April to October, monthly for November to March, and supplementary sampling was carried out during April and May to ensure that the main spring growth period was adequately recorded. At each station a Global Positioning System fitted aboard the survey vessel was used to fix position. A computer-linked Seacat SBE19-03 CTD (Seabird Electronics Inc., Washington, USA) was used to measure salinity, which was determined using the Practical Salinity Scale (Anon. 1985). This enabled real-time display of the salinity/temperature profile, and water sampling where vertical stratification was indicated. A 300-mm-diameter Secchi disk was also used at each station to measure light penetration. Water samples were taken at the surface and bottom at all stations, with additional mid-depth sampling as required when the water column was stratified. Water samples were immediately filtered, using Millipore pre-filters and 0.45 µm membrane filters, into three vials, to be used for analysis for SRP and Silicate, Ammonia and Total Oxidizable Nitrogen (NO_3-N + NO_2-N(TON)), respectively. The remaining water was filtered onto Whatman GF/F filters for subsequent chlorophyll-a analysis. All samples were maintained in the dark, in cool boxes containing ice packs. On return to the laboratory, samples to be analyzed for Ammonia, TON and Chlorophyll-a were stored at – 20°C, while samples for SRP and Silicate were maintained at 4 °C and analyzed within 24 hours.

Table 1. Physical characteristics of Belfast and Strangford Loughs.

	Belfast Lough	Strangford Lough
Catchment (km^2)	900	771
Volume (10^6 m^3)	1 060	1 251
Max. depth (m)	23	59
Mean depth (m)	8.94	11.78
Intertidal area (km^2)	8	46
FW runoff (10^6 m^3 yr^{-1})	1 022	510
Sewered population (10^3 p.e.)	790	100
Flushing time (d)	1.8	1.6

Table 2. Mean and range values of winter and summer nutrient, chlorophyll-a and secchi depth data - Belfast and Strangford Loughs.

		Inner Belfast Lough		Outer Belfast Lough		Strangford Lough	
		Winter	Summer	Winter	Summer	Winter	Summer
	Mean	8.45	9.31	3.28	1.64	1.25	0.61
SRP-P	Min.	1.74	0.97	1.06	0.10	0.77	0.19
(µmol/l)	Max.	27.77	33.23	6.61	21.48	6.23	1.29
	Mean	130.32	63.30	38.95	10.70	11.14	1.81
NO_3-N	Min.	27.20	6.00	0.00	0.00	1.29	0.00
(µmol/l)	Max.	363.00	301.30	74.14	49.00	38.80	11.93
	Mean	74.05	134.37	31.05	21.70	2.01	0.93
NH_3-N	Min.	9.07	5.93	2.57	0.00	0.00	0.00
(µmol/l)	Max.	380.14	605.00	92.71	271.50	7.46	5.44
	Mean	39.76	6.45	14.40	1.92	9.02	2.63
SiO_2	Min.	10.57	0.00	6.05	0.00	1.12	0.20
(µmol/l)	Max.	121.03	54.00	31.22	18.07	20.57	22.60
	Mean	1.53	1.66	2.00	2.29	4.33	5.54
Secchi depth (m)	Min.	0.30	0.75	0.50	0.75	1.50	1.50
	Max.	3.50	3.00	3.75	4.75	7.00	10.00
Chlorophyll-a	Mean	1.27	13.17	1.27	10.32	0.75	1.91
(µg/l)	Min.	0.24	1.39	0.10	0.42	0.26	0.20
	Max.	7.29	60.20	8.84	58.00	3.70	14.79

Monitoring was also carried out on the tributary rivers whose catchments drain directly to Belfast and Strangford Loughs. The rivers were sampled on a fortnightly basis, in conjunction with the marine survey, for similar physical and chemical parameters.

Sample analysis

Nutrient analysis used the following colorimetric techniques; SRP method as described by Murphy & Riley (1962); Total Phosphate by Eisenreich et al. (1975); Silicate as described by Golterman et al. (1978); Ammonia analysis as described by Scheiner (1976), modified for saline determination (Dinsmore pers. comm.); TON by the method of Grasshoff (1976) modified for the Traacs Analyser 800 System by the Bran and Lüebbe Method No. 369-88E (Anon. 1989). Water samples for chlorophyll-a determination were analyzed using the standard fluorescence technique, including acidification step, by the method as described by Tett & Wallis (1978).

Data analysis

Flow figures for the ungauged rivers discharging to the loughs were based upon flow data from rivers monitored by DOE (NI) and a scaling factor was used to account for differences in catchment area. Monthly loads of nitrate in the rivers were calculated using the method of Smith et al. (1982), which employed the simplified method of multiplying monthly total flows by mean monthly concentrations calculated from fortnightly observations. For SRP, the log load *vs* log flow relationship was used (Smith 1977).

For loads from the sewage treatment works, a flow weighted mean concentration was multiplied by flow data calculated for inputs monitored in fulfillment of Paris Commission requirements (Anon. 1994a). A similar process was used for obtaining loads from industrial sources. The PC based-contouring package Surfer (Version 6 Golden Software Inc. Co. USA) was used to produce contour plots from some of the data.

Results

Salinities in Strangford Lough ranged from approximately 32.5 to 34.5, and in Belfast Lough from 31.0 to 33.5. Significant reduction in surface salinity was seen only at sites immediately adjacent to the larger freshwater sources. There was a modest seasonal effect on salinity in both loughs, with salinities at the lower end of the range observed between September to March, after which values rose to the highest observed levels by late July. Water column stratification was generally weak and transient, or altogether absent, in both systems.

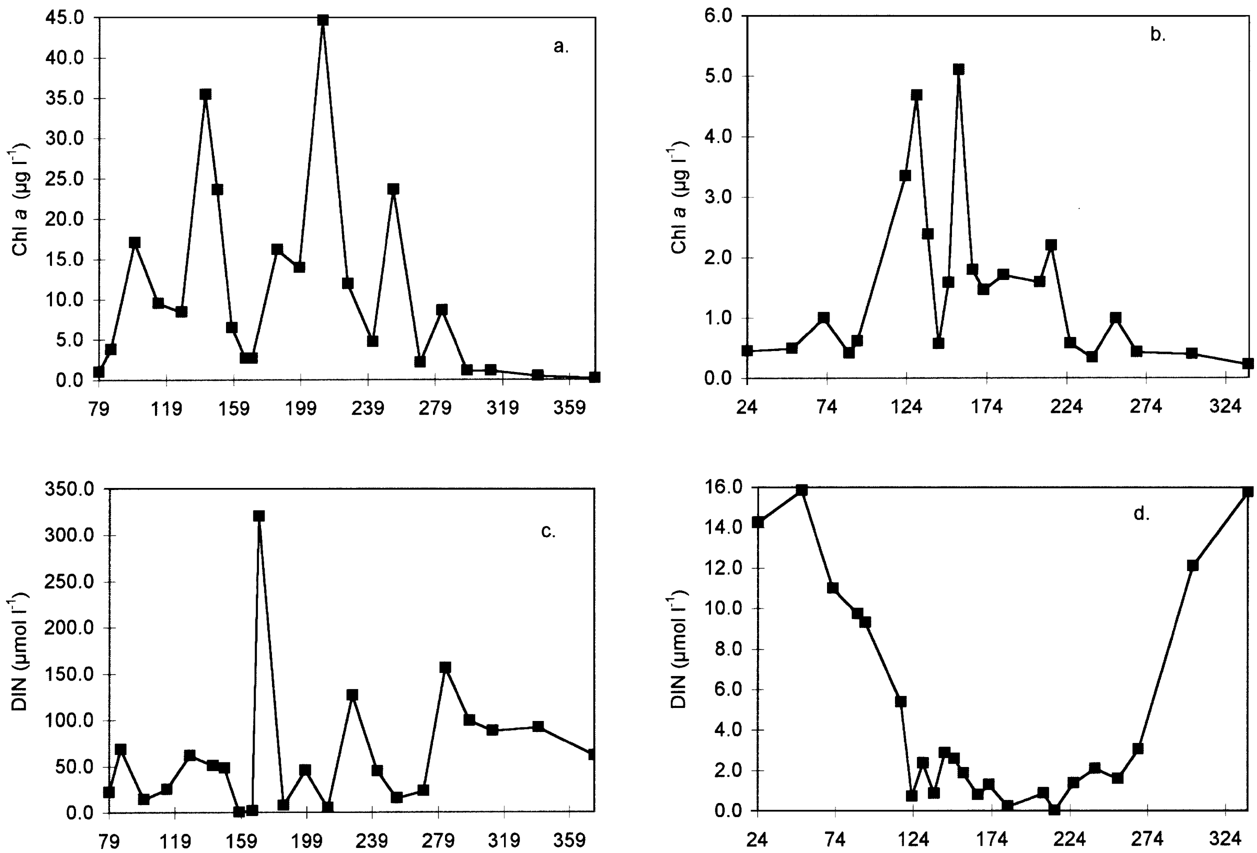


Fig. 2. a, b. Time series plots of chlorophyll-a concentrations in (a) Belfast and (b) Strangford Loughs. 1995 data for sites 8 (Belfast) and 10 (Strangford).
c, d. Time series plots of DIN concentrations in (c) Belfast and (d) Strangford Loughs. 1995 data for sites 8 (Belfast) and 10 (Strangford).

Summary data for nutrient and chlorophyll-a concentrations, and for secchi depth, for the entire sampling period appear in Table 2. It should be noted in reference to this Table that sites at the inner/outer Belfast Lough boundary have been incorporated in the 'outer lough' data, since low summer NO_3-N and NH_3-N values were recorded at some of these sites on isolated sampling occasions. These values are not representative of typical observations, and coincided with high chlorophyll-a levels.

These data demonstrate the reduction in nutrient levels during the growing season in Strangford Lough. This pattern was not repeated in Belfast Lough, with the exception of silicate. Nutrient and productivity levels in Belfast Lough were markedly higher than those in Strangford.

Fig. 2a, b show time-series plots of chlorophyll-a concentration for a single site in each lough for 1995. Strangford Lough typically exhibited a double 'spring' peak in growth, followed by a short 'summer' period when nutrient levels dropped, and with a small, brief 'autumn' growth period prior to increased nutrient levels during the winter season (Fig. 2b). During 1995, the lough showed a chlorophyll-a maximum of approximately 7 µg/1 in early May (site 11), followed in June by a secondary maximum of approximately 5 µg/l (sites 10 and 15). The autumn chlorophyll-a peak occurred in late September and reached a maximum of aproximately 15 µg/l (site 15), although values were more typically around 1 µg/l. Productivity in Belfast Lough followed a similar double spring peak, followed by a smaller autumn peak, but the autumn bloom was relatively larger and more prolonged than that in Strangford Lough. The spring chlorophyll-a peak in Belfast Lough occurred in mid-May with a maximum in excess of 50 µg/l at certain sites in the inner lough (Fig. 2a). An as yet unexplained anomalous phytoplankton bloom occurred in early August, during which chlorophyll-a levels exceeded those in the spring peak, reaching levels of 60 µg/l at sites in the inner lough. The typical autumn maximum was recorded in mid-September at about 20 µg/l.

There was a marked difference in the seasonal

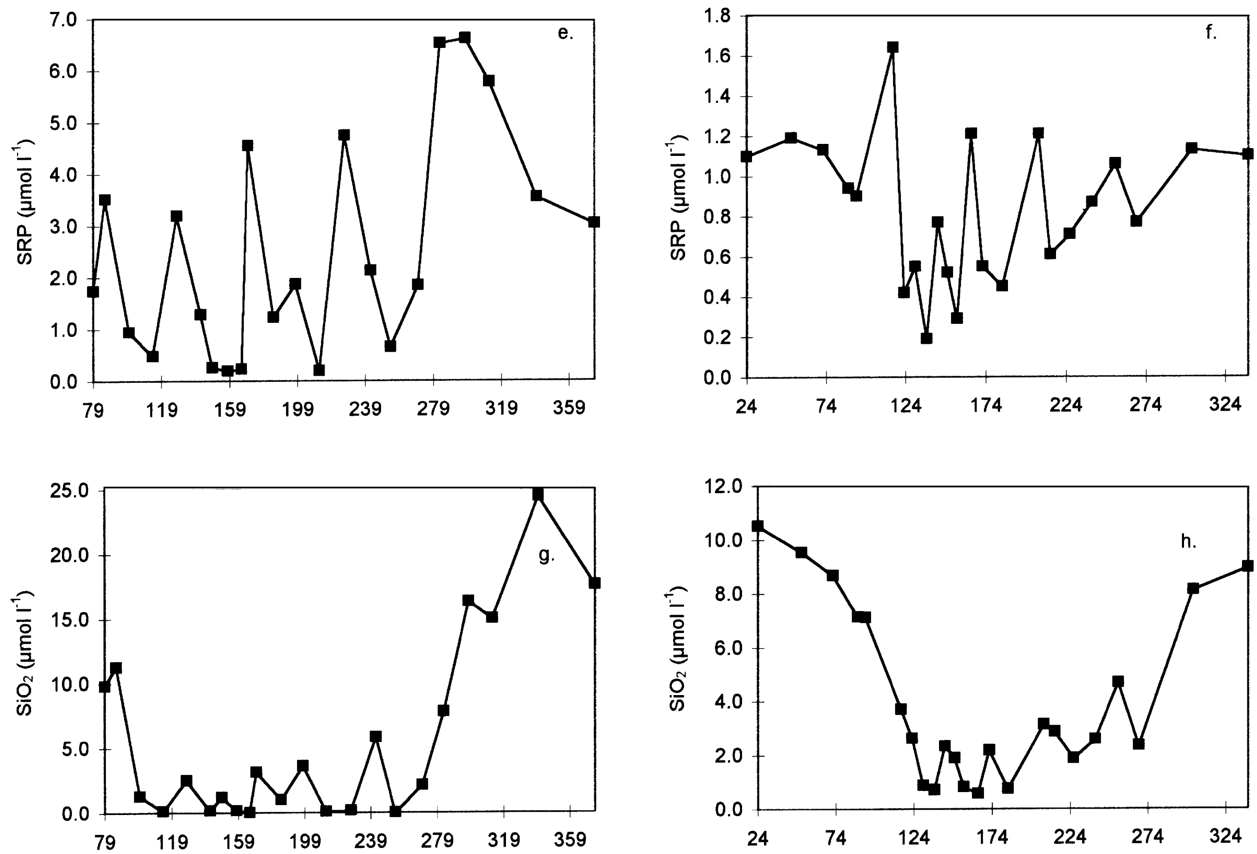


Fig. 2. e, f. Time series plots of SRP concentrations in (e) Belfast and (f) Strangford Loughs. 1995 data for sites 8 (Belfast) and 10 (Strangford).

g, h. Time series plots of silicate concentrations in (g) Belfast and (h) Strangford Loughs. 1995 data for sites 8 (Belfast) and 10 (Strangford).

cycle of dissolved inorganic nitrogen (DIN; TON + NH_3-N) levels in the two systems (Fig. 2c, d). Strangford Lough exhibited a large seasonal effect with maximum levels found in the winter, which diminished to a minimum during the summer months. Belfast Lough, however, did not show any such seasonality (Fig. 2c). DIN levels fluctuated randomly throughout the year, and did not appear to be linked to chlorophyll-a events.

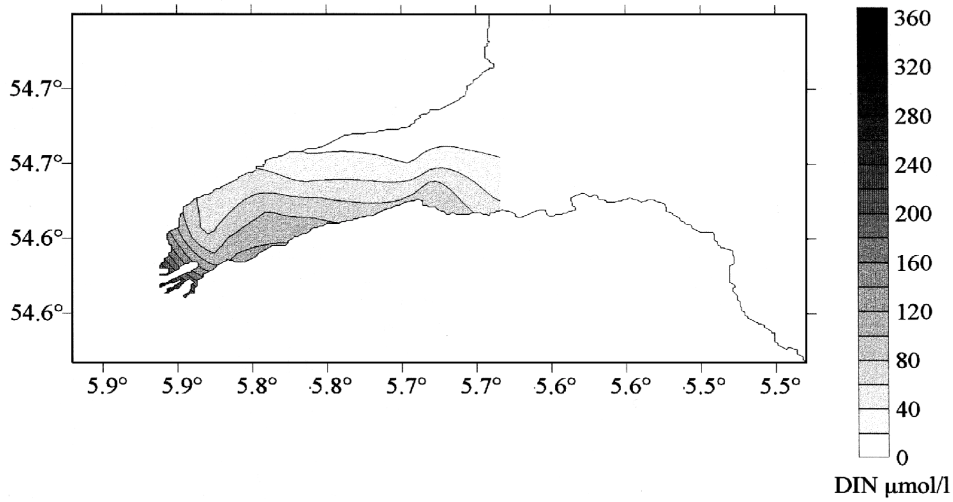
SRP and silicate levels followed similar patterns in both loughs (Fig. 2 e-h), with maximum levels recorded in the winter months. During the growing season the data for silicate and, to some extent, SRP, showed evidence of an inverse relationship with chlorophyll-a concentrations. However, there were a number of, as yet, unexplained anomalies in this pattern.

As shown in Table 3, the annual load of nitrogen differs substantially between the two loughs. Belfast Lough receives almost 3,5 times the total nitrogen load that reaches Strangford, of which more than 60 % is from a single industrial source. In contrast, the primary source of nitrogen to Strangford Lough is direct runoff from the land.

During the winter, both loughs exhibited a similar pattern of a decreasing seaward gradient of DIN (Fig. 3a, b). Summer DIN concentrations in the two

Table 3. Partitioning of nitrogen load to Belfast and Strangford Loughs.

	Load (tonnes/yr)	% of total load
Belfast Lough		
River Lagan	801	12
Other rivers and direct runoff	294	4
Urban streams	66	1
Sewage Treatment Works	1 482	22
Industry	4 149	61
Total	6 792	100
Strangford Lough		
Sewage Treatment Works	229	12
Other rivers and direct runoff	1 752	88
Total	1 981	100



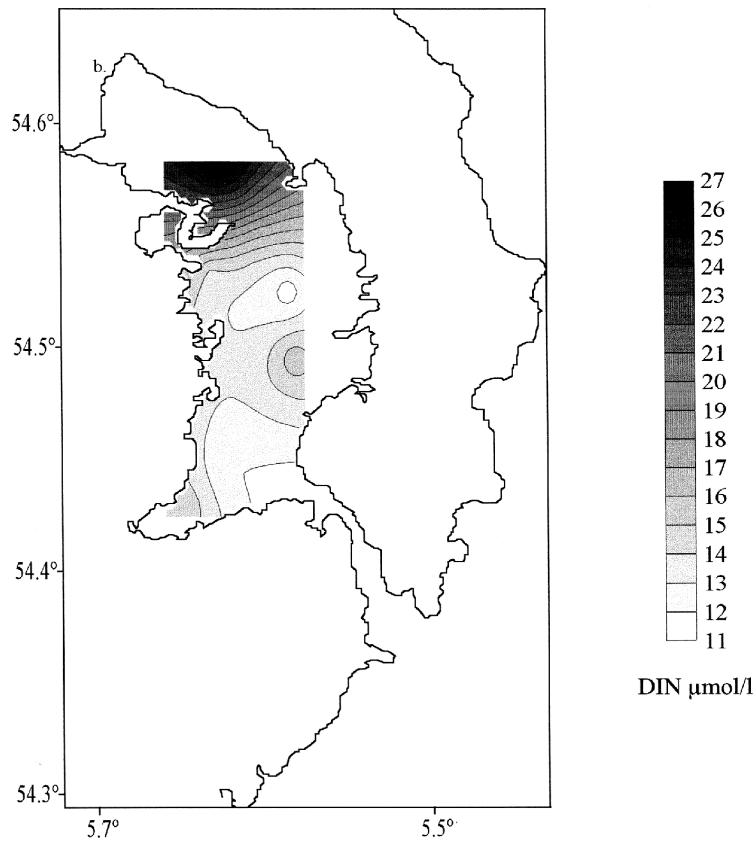


Fig. 3. Contour plots of winter DIN concentrations in (a) Belfast and (b) Strangford Lough. Data for 10 January 1996 (Belfast) and 25 January 1995 (Strangford).

systems showed a contrasting pattern of spatial distribution (Fig. 4a, b). Belfast Lough continued to maintain a strong decreasing seaward gradient, similar to the winter season, while the reverse situation existed in Strangford Lough, with the inner lough almost totally depleted of DIN and a small increasing seaward gradient in evidence.

Spatially, peak spring productivity levels varied throughout each lough (Fig. 5a, b). The highest levels in Belfast Lough occurred in the inner reaches of the lough. In Strangford, productivity was highest in the south of the lough.

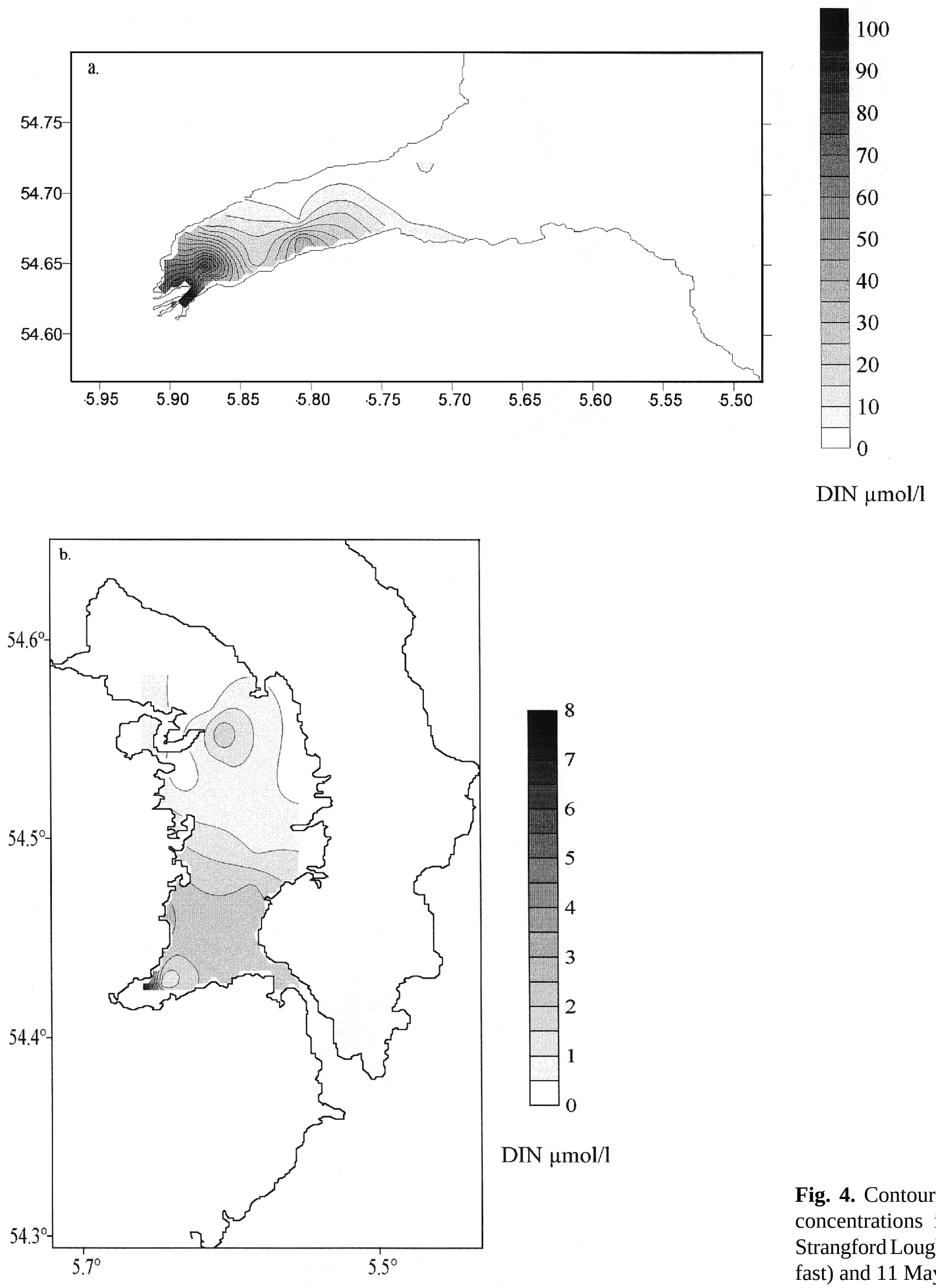


Fig. 4. Contour plots of summer DIN concentrations in (a) Belfast and (b) Strangford Lough. Data for 23 May (Belfast) and 11 May 1995 (Strangford).

Discussion

Belfast Lough is essentially an enclosed embayment with a gradual increase in depth towards the open, well-mixed waters of the North Channel, whereas Strangford Lough has only a restricted entrance to the open sea and has a deep central channel. This feature results in increased tidal speed throughout much of the lough. Freshwater inputs to each lough are small, the main sources being the River Lagan in Belfast Lough and the Enler and Quoile Rivers in Strangford (Fig. 1). In terms of catchment land use there is a contrast between the two systems. The catchment of Belfast has a sewered population of ca. 750 000, this being about half the total

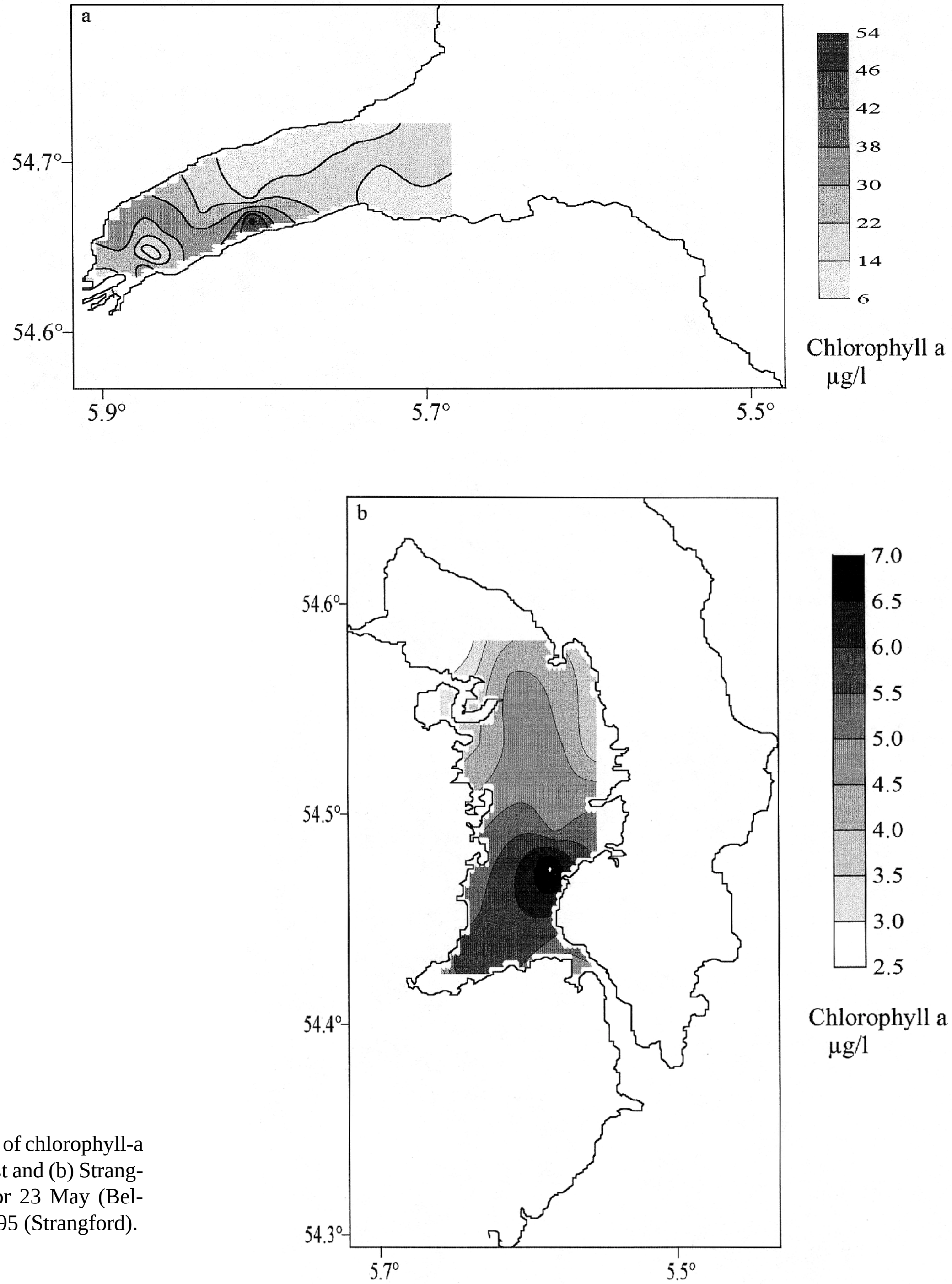


Fig. 5. Contour plots of chlorophyll-a maxima in (a) Belfast and (b) Strangford Lough. Data for 23 May (Belfast) and 11 May 1995 (Strangford).

population of Northern Ireland. The harbour is the site of major process industries and operates as an important commercial port. In contrast, the Strangford catchment is primarily agricultural, comprising a mixed land use from horticulture in the north to rough grazing in the south west corner, and has a population of 100 000.

The difference in land usage is illustrated clearly by the resultant nitrogen loads to the loughs and consequent levels of productivity. Belfast Lough receives of the order of 0.6 tonnes N $(10^6\ m^3)^{-1}$ $month^{-1}$ and this figure varies little throughout the seasonal cycle. This pattern reflects the dominating influence of industrial sources on the nitrogen loads to the system. Strangford Lough, however, receives considerably smaller loads of nitrogen which vary seasonally, falling in the order of 0.16 tonnes N (10^6 m^3)$^{-1}$ month^{-1}. This peaks at 0.53 tonnes N (10^6 m^3)$^{-1}$ month^{-1} at the time of maximum freshwater runoff, indicating the relative importance of variable freshwater flow over the more constant industrial input operating in Belfast Lough.

The pattern of inputs described above, in conjunction with the productivity cycle, inferred from chlorophyll-a concentration data, provides evidence of the limiting factors influencing the two systems. Productivity in Belfast Lough generally fluctuated independently of DIN levels (Fig. 2a, c), suggesting that alternative factors are limiting within the system. These may include other key nutrients, specifically silicate, or physical parameters, such as light availability. However, Strangford Lough exhibited a much closer inverse relationship between DIN and productivity levels (Fig. 2b, d), implicating nitrogen as the limiting factor here.

The UWWT Directive defines eutrophication as "the enrichment of water by nutrients, especially by compounds of nitrogen and phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable balance of organisms present in the water concerned". Eight criteria used to assess eutrophic status were defined by the DOE (NI) (Anon. 1993), namely:

(1) Nitrate-N concentrations significantly enhanced relative to background;
(2) Occurrence of exceptional algal blooms;
(3) Duration of algal blooms;
(4) Oxygen deficiency;
(5) Changes in fauna;
(6) Changes in macrophyte growth;
(7) Occurrence of Paralytic Shellfish Poisoning (PSP);
(8) Formation of algal scums.

Clearly Belfast Lough meets, at least in part, criteria a, b, g and h above. Data presented here demonstrate elevated nitrate-N concentrations within the lough, compared to background Irish Sea levels. Winter nitrate-N levels of approximately 8.9 μmol/l were recorded in the Irish Sea by Foster (1984). These compare well with winter nitrate levels of 9.6 μmol/l found by the present study at the entrance to Belfast Lough. However, levels in the lough were considerably elevated at the inner sites; concentrations of around 50 μmol/l were typical, though levels > 300 μmol/l were routinely recorded at stations in the harbour. Biological effects which may be attributable to these elevated N-levels were observed; blooms of *Phaeocystis* spec., a species which causes nuisance algal scums, are regularly observed in early summer (Service, pers. obs.). Routine toxic algal monitoring by DANI has identified the presence of *Alexandrium* spec. in the lough since 1994. Paralytic Shellfish Poisoning toxins have also been found in exploited shellfish within the lough (McCaughey & Campbell 1992), together with cysts of the causative organism in the lough sediments (Tylor et al. 1995). The other indicators are less easy to define; the lough is dredged regularly with the effect that the benthic fauna is routinely disturbed, although Parker (1980) observed that the inner lough was showing signs of benthic enrichment. Macroalgal mats are scarce, but this may be due to the lack of a suitable substratum for their attachment.

Strangford Lough shows none of the symptoms of eutrophication and meets none of the criteria listed above. However, some caution must be employed with respect to this classification in the inner lough, where the residence may be 20 times greater than in the southern reaches (Anon. 1994b). During the summer months there is almost complete nitrogen removal in the upper reaches due to either algal uptake or denitrification on the extensive mudflats in the north of the lough. Studies on the role of denitrification in mediating DIN levels in the water column overlying the tidal mud flats in Strangford and Belfast Loughs are underway. Preliminary results (Livingstone & Smith 1995) indicate that the potential exists for this process to have a major role in controlling DIN levels in these water bodies. These authors were able to demonstrate that this process is temperature-dependent and most likely to exert its influence in the summer months. The possibility does exist, however, that large inputs of nutrients to this area at times of optimal growing conditions could stimulate excessive algal growth, and this needs to be taken into account when deciding future management practices for the lough.

Conclusions

Such management strategies for these water bodies must be designed to reflect their potential vulnerability to the different sources of N. Thus, in the case of Belfast Lough, the main focus will be to reduce the influence of point source discharges. For Strangford Lough, the principal management strategy will be catchment-based, and will need to take account of changing patterns of land use. Agricultural practices, and especially issues surrounding fertilizer usage, will be central to such management plans.

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