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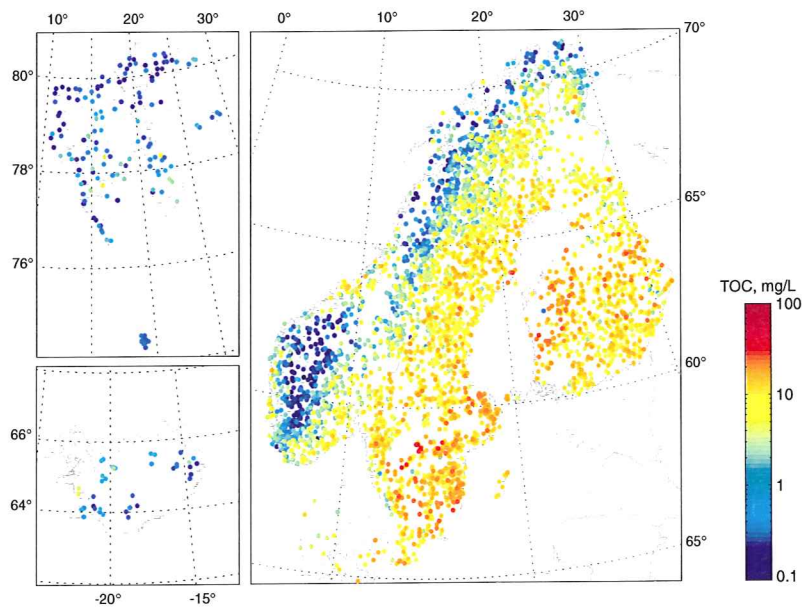
Chemistry of lakes in the Nordic region - Denmark, Finland with Åland, Iceland, Norway with Svalbard and Bear Island, and Sweden

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Abstract

This report presents the first common evaluation of water chemistry in the Nordic countries (except for the Faroe Islands and Greenland): Denmark, Finland including Åland, Iceland, Norway including Svalbard and Bear Island, and Sweden. The Nordic countries exhibit large gradients in many chemical constituents in lake water, from Iceland in the west, Svalbard and Bear Island in the north via Denmark to Sweden, Finland and Norway, due to large differences in geology, hydrology, vegetation and air pollution. The data are interpreted relative to these factors.

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1. innsjøer	1. lakes
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Preface

This project is a continuation of the NMR-project "Nordic Lake Survey 1995" (Henriksen *et al.* 1997, Henriksen *et al.* 1998, Skjelkvåle *et al.* 1999). The Nordic Lake Survey was used to assess the status of the Nordic lakes with respect to general water quality, heavy metals and critical loads for sulphur.

This report presents the first common evaluation of water chemistry in all the Nordic countries (except for the Faroe Islands and Greenland). This includes Denmark, Finland including Åland, Iceland, Norway including Svalbard and Bear Island, and Sweden. The Nordic countries exhibit large gradients in many chemical constituents in lake water, from Iceland in the west, Svalbard and Bear Island in the north, Denmark in the soputh, to Sweden, Finland and Norway, due to large differences in geology, hydrology, vegetation and air pollution. In the report we have interpreted the concentrations and fluxes in the lakes relative to these factors.

The project was financially supported by NMD (Nordiska arbetsgruppen för miljöövervakning och -data) which is a working group under NMR (Nordic Council of Ministers)

As a part of the project we held a meeting in Iceland 2-6 September 2000, with an excursion to Icelandic lakes. We appreciate this opportunity to see some of the lakes included in the project and to discuss the results in the field at the sites. We believe that this project is very important for the work of harmonising monitoring methods of lakes within the Nordic countries, and for future Nordic co-operation.

Oslo, 1 November 2001

Brit Lisa Skjelkvåle

Contents

Summary

Lakes and watercourses are important ecosystems in the Nordic countries as there are about 133 000 lakes larger than 4 ha (0.04 km2). The waterbodies cover 19% of the total land area in Finland, 8.5 % in Sweden, 5% in Norway, 1% in Denmark and 1.5% in Iceland.

The purpose of this report is to evaluate the chemistry of the lake populations for the whole Nordic area. The report use data from the Nordic Lake Survey in 1995 (4973 lakes in Denmark, Finland, Norway and Sweden), a lake survey in Iceland in 1997 to 1998 (39 lakes), a lake survey at Svalbard and Bear Island (147 lakes and 15 streams sampled 1990-92) and a lake survey in Åland in 1997 (9 lakes). Together these data represent a unique opportunity to evaluate the chemistry of the lake populations for the whole Nordic area.

The Nordic region comprises a wide variety of physical and chemical conditions in lakes and rivers. There are major differences in bedrock geology, from slow weathering Precambrian bedrock of the Fennoscandian shield (Finland, Norway, Sweden) to high weathering sedimentary rocks in Svalbard/Bear Island, volcanic rocks in Iceland and quaternary deposits in Denmark. There is a wide range in precipitation (from 100 to 5000 mm yr^{-1}) depending on distance from the sea and on topography. Weathering rate in combination with precipitation are the most important factors determining the concentrations of base cations (Ca, Mg, Na, K), bicarbonate, sulphate and fluoride, and to a certain degree also silica and phosphorous. In areas with the same type of bedrock geology and thus similar weathering rates, there are lower concentrations in the high precipitation areas than in low precipitation areas due to dilution.

Soil cover regulates the concentrations of organic carbon (TOC), and nutrients correlated with organic carbon, such as organic nitrogen. Agricultural activity and input of anthropogenic nitrogen through precipitation are the most important factors for concentrations of nitrate and ammonia in the Nordic lakes.

The common Nordic lake-chemistry database provides an extensive basis for evaluation of lake resources with respect to international pollution risks in the Nordic region. Regional lake surveys are necessary for accumulating knowledge of the past and present status of freshwater resources, thus giving a valuable basis for future decisions. Thus they provide important baseline information with respect to large-scale and long-term changes in lakes, caused by factors such as acidification, climate change and land use. Lakes are more common in the Nordic countries than in most other parts of Europe. Lake water resources are of great importance today, and their importance will inevitably grow in the future. The need for extensive knowledge of the present status of the lake populations in all of Europe will most likely increase, and the approach used in the Nordic countries could well form the basis for future co-operative projects within Europe.

1. Introduction

Lakes and watercourses are important ecosystems in the Nordic countries (in this context we consider these countries to be: Denmark, Finland including Åland, Iceland, Norway, Sweden, Svalbard and Bear Island). In these areas there are about 133 000 lakes above 4 ha (0.04 km^2) in size (Henriksen *et al.* 1998). Water bodies cover 19% of the total area in Finland, 8.5 % in Sweden and 5% in Norway. In Denmark there are very few lakes (about 700) and they cover about 1% of the total area. In Iceland there are 1841 lakes larger than 0.1 km^2. These lakes cover about 1.5% of the land area (Adalsteinsson, 1990), corresponding to about 2300 km^2 of the land area. There are no official register of the numbers of lakes in Svalbard and Bear Island (Bjørnøya), but a conservative estimate is that there is about 100 lakes > 0.1 km^2 at Bear Island and about 500 at Svalbard.

The majority of lakes in the Nordic region are small, except for a few very large lakes (Vänern and Vätteren in Sweden, Enare in Finland and Mjøsa in Norway).

Both the physical and chemical properties of the lakes differ across the region. The results from the Nordic lakes survey in 1995 (Henriksen *et al.* 1998) showed that the lake water chemistry in the Northern European countries (with the exception of Denmark) is dominated by low ionic strength (dilute) water, with low concentrations of nutrients (nitrogen and phosphorus compounds). This is mainly due to low weathering rates, low intensity of agriculture and low population density. There are differences in the lake water chemistry over the Nordic due to differences in hydrology, precipitation chemistry and amount, soil cover, and vegetation. From west in Norway to east in Finland, there is a gradient from high to low precipitation, and from mountain areas with thin and patchy soils to forested areas with thick soils. This is reflected in clear water lakes with low input of nutrients, base cations and alkalinity in the western areas to coloured lakes with higher concentrations in the eastern areas.

The lakes in Denmark are influenced by different soil and bedrock mineralogy than the other countries in the survey, and there is also much more intensive agricultural activity in their catchments. The Danish lakes generally have much higher ion concentrations and high concentrations of nitrogen and phosphorus.

Table 1. Number of lakes and lake size distribution in the countries (see **Figure 1**)

	0.04-0.1	0.1-1	1-10	10-100	>100	total > 0.04	total >0.1
Bear Island*							103
Denmark	365	269	69	6	0	709	
Finland	14 717	12 311	2 164	276	47	29 515	
Iceland		1 648	176	17	0	1 841	
Norway	21 218	16 417	2 139	164	7	39 945	
Sweden	35 802	20 484	3 599	379	24	60 288	
Svalbard*							501
Åland	8	35	4	0	0	47	
Sum	72 110	51 164	8 151	842	78	132 345	604

* Data for lake size distribution not available.

1.1 Background and aims of the project

In the autumn 1995 Finland, Norway and Sweden initiated a joint Nordic Lake Survey using standard protocols giving criteria for selecting lakes and analytical procedures (Henriksen *et al.* 1996). Subsequently the project was expanded to include Denmark, Russian Kola, Russian Karelia, Scotland and Wales (Henriksen *et al.* 1998). Together these surveys covered a land area of ca. 1 300 000 km^2, corresponding to about 13% of the total area of Europe. Excluding European Russia the area represents 28% of Europe. The total number of lakes (> 0.04 km^2) in the study area is about 155 000, and of these 5 690 lakes (3.7%) were sampled in this survey.

The individual national lake surveys have been presented in several publications; Finland by Mannio *et al.* 2000, Norway by Skjelkvåle *et al.* (1996), and Sweden by Wilander *et al.* (1998). In addition joint publications on trace metals in lake water in the Nordic countries has been published by Skjelkvåle *et al.* 1998, 2001.

After the Nordic Lake Survey 1995 was completed an extensive lake survey was carried out in Iceland. This survey included 39 lakes larger than 1 km^2 (>16% of the total lake population) and 7 lakes smaller than 1 km^2. At Svalbard and Bear Island, 147 lakes and 15 streams was sampled during the period 1990-92 (Lien *et al.* 1995) to assess critical loads and critical load exceedances for the area. The chemistry data as such was not evaluated at that time. For Åland data for 9 lakes (out of 47) sampled in 1987 were available. Together with the Nordic Lake Survey 1995 these additional three sets of data present a unique opportunity to evaluate the chemistry of the lake populations for the whole Nordic area.

Figure 1. Map showing the area covered by the survey.

2. Lake selection, sampling and analytical methods

It is not achievable to monitor all lakes in an area; therefore a sample has to be drawn from the population. The lake surveys of Finland, Norway and Sweden were carried out based on statistical selection of national lake registers. This technique was not applied for the Iceland, Denmark, Svalbard, Bear Island and Åland. Thus, conclusions about the conditions in these areas are not necessarily completely representative for the lake populations. For each area descriptions for the lake selection methods are presented below.

Iceland

For Iceland, lakes selected for chemical sampling were mostly lakes listed for the Ecological Survey of Icelandic Lakes (ESIL) project (Malmquist *et al.* 2000). The criteria for ESIL lakes were lakes different in relation to water origin, type of bedrock, geographical location, altitude and depth. The project focuses on lakes (ca. 100 lakes) larger than 1.0 km^2 (193 in Iceland). The total number of lakes larger than 0.1 km^2 is estimated to be 1841, and these cover an area of 1300 km^2 (Adalsteinsson 1990). For this project samples were collected in 39 lakes during the period August to September 1997 and 1998.

Sampling procedures, variables chosen for analyses and analytical procedures followed the Nordic Lakes Survey protocols (Henriksen *et al.* 1996). Temperature, pH, conductivity and alkalinity were measured at the sampling site. One liter of lake water was collected and frozen for the variables SO_4, Cl, F, Ca, Mg, Na, K, Fe, SiO_2 and Al, and a 0.5 L lake water sample was collected in acid-washed glass bottle and preserved with sulphuric acid (5 ml 8M H_2SO_4) for total nitrogen (Tot-N), total phosphorus (Tot-P), NO_3-N, NH_4-N, and PO_4-P. All samples were analysed at the laboratory of the Norwegian Institute for Water Research.

Data on bedrock geology for Iceland were taken from the ESIL database (Malmquist *et al.* 2000). Data on altitude, size and lake depth were from the Hydrological Service´s database on lakes (Adalsteinsson 1989). Data on drainage area, discharge and co-ordinates for location were kindly prossessed for this study by The Hydrological Service, National Energy Authority in Iceland.

Svalbard and Bear Island

Sampling of lakes at Svalbard and Bear Island was conducted in 1990-92 for calculation of critical loads and their exceedances for the area. The selection strategy was therefore to have an even geographical distribution of localities across the islands. Lakes with surface areas of more than 0.2 km^2 or lakes that had been sampled before were preferred (Lien *et al,* 1995). If lakes of this size were not available in the selected area, smaller lakes or suitable rivers or streams were chosen. A total of 163 localities were sampled, 106 lakes and 52 rivers at Svalbard and four lakes and one river on Bear Island. The sampling were conducted in.

The samples were analysed for: pH, conductivity, turbidity, alkalinity, SO_4, Cl, Ca, Mg, Na, K, NO_3 NH_4, total nitrogen (Tot-N), total phosphorus (Tot-P), total organic carbon (TOC), total monomeric Al and non-labile Al. Several of the samples showed very high turbidity values caused by high concentrations of silt from glaciers. This also caused contamination and resulted in large differences between sums of cations and anions. These problems were solved by filtering the samples followed by re-analyses of parameters sensitive to particulate matter.

No runoff data were available for Svalbard. Most of the precipitation on Svalbard is in the form of snow, which is easy to measure and is evenly distributed on the glaciers. The accumulation of snow was therefore used as the basis for drawing a precipitation map for Svalbard (see Lien *et al.* 1995 for details). The runoff for each lake was calculated from the estimated precipitation minus 15%

evaporation (sublimation) which is the same as the evaporation recorded for Finnmark, Northern Norway.

Åland

The nine lakes sampled in Åland in 1987 were part of the first national lake survey in Finland (see Kämäri *et al.* 1991). Northern Åland was one of the 125 target areas in Finland selected randomly by "Probability Proportional to Size" (PPS)-method, based on lake density on 1:50 000 topographic maps. Eight lakes with a minimum area of 0.01 km^2 were selected systematically from this map. One additional lake was chosen subjectively. Sampling methods, timing and analytical variables (excluding trace metals and total inorganic carbon) were essentially the same as in the Nordic Lake Survey 1995 (Henriksen *et al.* 1996).

Finland, Norway, Sweden and Denmark

For Finland, Norway and Sweden the lakes were selected using stratified random sampling with unequal sampling fractions from the national lake registers with the common requirements that:
- a minimum of 1% of the lakes within any county/region were included
- the proportion of lakes in size classes 0.04-0.1, 0.1-1, 1-10 and 10-100 km^2 shall be 1:1:4:8; all lakes >100 km^2 were included.

The final selection of lakes in the different counties/regions was made in slightly different ways, but with a common goal of achieving a larger proportion of lakes in areas with a high degree of acidification or critical load exceedance. Also in areas with more variable lake chemistry (as estimated from previous surveys) (Sweden) or few lakes (Finland) a larger proportion of lakes were sampled. The number of lakes to be sampled in the larger size classes was determined by multiplying the basic percentages by the factors 4 or 8 for these size classes on a county or region basis. (Henriksen *et al.* 1996, Henriksen *et al.* 1998).

For Denmark a selection of 19 lakes from the from the Danish Nationwide Monitoring Programme (Jensen *et al.* 1997) were included. These lakes were not based on a statistical selection, but the lakes are located all over the country. The samples were collected during or shortly after the autumn overturn following agreed procedures.

The variables analysed for the national lake surveys were: pH, conductivity, temperature, alkalinity, SO_4, Cl, F, Ca, Mg, Na, K, NO_3, NH_4, total nitrogen (Tot-N), total phosphorus (Tot-P), total organic carbon (TOC), total monomeric Al, non-labile Al, "trace" metals and SiO_2. Absorbance was analysed in Swedish lakes, total inorganic carbon (TIC), turbidity and phosphate-P in Finnish lakes. All analytical work was carried out by national laboratories with extensive quality assurance/quality control routines. In addition several intercalibrations were conducted (Henriksen *et al.* 1998). The recommended analytical methods and detection limits are described elsewhere (Henriksen *et al.* 1996).

Table 2. Total number of sampled lakes, percentage of total lake population (see **Table 1**), time of sampling and reference to previous national or Nordic reports.

	Number of sampled lakes	Number of lakes > 0.04	% sampled lakes	Time of sampling	References
Bear Island	4	>100	ca.4.0	1990-1992	Lien *et al.* 1995
Denmark	19	709	2.7	1996	Henriksen *et al.* 1997 and 1998, Skjelkvåle *et al.*1998 and 2001
Finland	873	29 515	3.0	1995	Mannio *et al.* 2000, Henriksen *et al.* 1997 and 1998, Skjelkvåle *et al.*1998 and 2001
Iceland	39	1 841	2.1	1995	Not published before
Norway	1006	38 845	2.6	1995	Skjelkvåle *et al.* 1996, Henriksen *et al.* 1997 and 1998, Skjelkvåle *et al.*1998 and 2001
Sweden	3075	60 288	5.1	1995	Wilander *et al.* 1998, Henriksen *et al.* 1997 and 1998, Skjelkvåle *et al.* 1998, 2001
Svalbard	163	>500	ca. 32.6	1990-1992	Lien *et al.* 1995
Åland	9	47	19.1	1987	Not published before
Sum	5188	132 345	3.9		

3. Factors influencing water chemistry

The chemical composition of surface waters not subjected to local pollution sources is mainly determined by contribution of ions through atmospheric deposition and from weathering and ion exchange processes in the catchment (**Figure 2**). The composition of the atmospheric deposition is largely influenced by salts from sea water and long-range transported air pollutants. In most of northern Europe contributions from soil dust and volcanic emissions are very small. In Iceland contribution from volcanic emissions can be a very important factor for the chemical composition of surface waters.

The chemical composition of precipitation is a function of distance from sea and anthropogenic pollution sources. A number of processes modify the composition of precipitation as it passes through a catchment. Such processes are biological (microbiological activity, uptake by growing plants, release of ions through decomposition etc.) and chemical (weathering, ion exchange, adsorption and desorption, redox processes, precipitation and dissolution). Biological processes mainly result in the re-circulation or removal of ions, while weathering gives a net contribution. The total sum of ions from deposition and weathering together with all the various processes occurring in a catchment determines the chemistry of the runoff water. Additional, but often similar, in-lake processes can further modify the ionic composition.
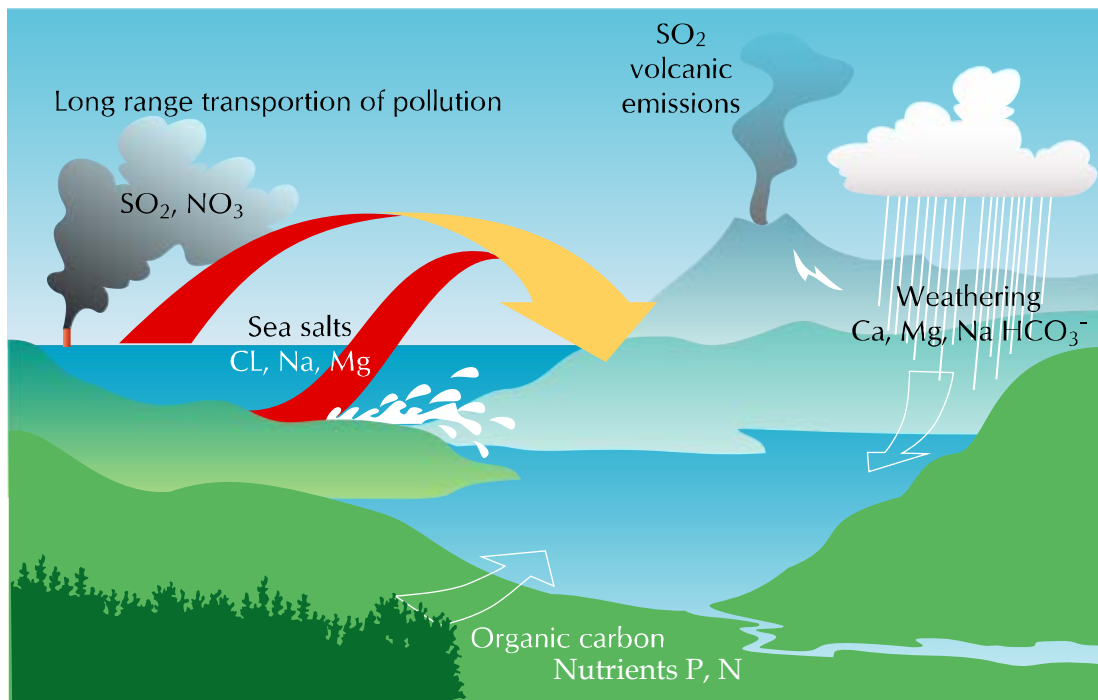

Figure 2. Schematic diagram showing the different processes influencing surface water chemistry.

3.1 Bedrock geology

The Nordic countries consist of a large variety in bedrock geology. The major geological provinces in the countries are formed with a time span from early Precambrian formations in the Fonnoscandian shield, to rocks formed through the last 400 million years at Svalbard, to recent formation of rocks at Iceland.

Iceland has been created by volcanic activity along the mid-Atlantic ridge during the last 20 million years. New volcanic rock is constantly being added and about one-tenth of Iceland is covered by basaltic lava deposits formed since the last ice age (Einarsson 1994).

Svalbard consist mainly of sedimentary rocks formed during Devonian to Tertiary (i.e. the last 400 million years), while the western and northern part consist of crystalline metamorphic rocks (the Hecla Hoeck formation) formed mainly during the Caledonian orogeny and as such it belongs to the Caledonian mountain range (Winsnes 1988). Bear Island consists of sedimentary rocks formed during Devonian to Tertiary (Winsnes 1988).

Norway, Sweden and Finland (including Åland) were formed as Precambrian and Caledonian geological provinces. The Precambrian in these countries is a part of the Fenno Scandian or Baltic shield consisting mainly of granites and gneisses. The Caledonian rocks form the mountain chain through Scotland, Norway and northern parts of Sweden, which also continues up to Svalbard. Areas with limestone are found in southern parts of Finland and Sweden.

Denmark is covered with thick glacial deposits from Quaternary in the northern part and Cretaceous and Tertiary deposits in the southeastern part.

The volcanic rocks in Iceland are predominantly mafic and with the large surface due to the vesicular appearance of the lava with glassy crusts and they weather readily. The sedimentary rocks at Svalbard and Bear Island comprises a large variability in mineralogy including limestone, dolomite, gypsum/anhydrite and shales containing phosphatic nodules, yielding waters with a large variety in ionic composition. The thick quaternary deposits in Denmark allow long contact time between percolating water and minerals yielding water with high ionic strength. The Precambrian rocks are dominated by gneiss and granitic gneiss giving low weathering rates, low content of base cations (Ca, Mg, Na and K), but high content of SiO_2 ("Acidic rocks"). The Caledonian province also includes rocks of more basic characters, such as gabbro, greenshists etc. with less SiO_2 ("basic rocks").

In general younger rocks, especially sedimentary rocks, and the newly formed Icelandic volcanic rocks, weather far more readily than old Precambrian rocks. Crystalline rocks are resistant to weathering, and lakes located in such formation have low ionic strength.

3.2 Soils

The soils in Iceland are largely formed by volcanic and glacial activity. Volcanic eruptions are frequent in Iceland, and volcanic ash deposits are widespread. In addition there are vast unstable sandy areas near glacial margins and along floodplains of glacial rivers. The volcanic and glacial deposits are subjected to intense eolian activity. Where vegetation stabilises eolian materials on the surface, they accumulate on the top of the soils. The surface is therefore gradually rising, commonly at rate of 0,1-1mm each year. Soils that form in materials rich in volcanic ashes are termed Andosols. They have unique properties, some of which are responsible for the erosion susceptibility. The soils have low cohesion but can absorb large quantities of water (>100% on dry weight basis) (Arnalds 1999).

The soils in Svalbard and Bear Island are thin and poorly developed with sparse vegetation, due to the arctic climate.

Most of the surficial deposits in Finland, including Åland, Sweden and Norway were deposited during the deglaciation period from 13 000 to 8 500 years ago. After the deglaciation, the Precambrian shield was bare or with only a thin or discontinuous cover of surficial deposits (mostly till). The glacial deposits derive from the underlying bedrock, and consequently consist of the same, mostly weathering resistant material – as the underlying bedrock. This is the dominant soil cover in large parts of Norway, Iceland and Svalbard, western Sweden and upland areas in southern and northern Finland. Thick deposits of till occur in Sweden, Finland and northern parts of Denmark. In general all alpine and arctic areas have thin soils. Thick soils allow longer contact time between percolating water and minerals and generally yield water with high ionic strength.

Soils in forested and wetland areas contain in general more organic material than in open areas. A high content of organic materials is also found in peatland areas in all countries. These soil types generate high inputs of organic acids to the lakes resulting in high TOC-levels and organic acidity, which lowers the pH of the lake.

Due to the isostatic uplift of Scandinavia after the last deglaciation, old marine deposits are found many places in lowland areas, and this is an important feature in most low level areas of Sweden and in the coastal areas of western Finland including Åland and southern Norway.

3.3 Vegetation

The vegetation types in the Nordic region range from nemoral, to boreo-nemoral, boreal and alpine zones (NMR 1984). The nemoral vegetation zone, which is dominated by deciduous forests, covers Denmark, the far southern and western parts of Sweden and the southern coast of Norway. About half of the total sampled area is forested. The non-forested parts are largely located in both uplands (mainly western areas of each country) and lowland areas in the north and along the coasts. Iceland is mostly sub-alpine without forests. Most of Svalbard is covered with snow and ice while the rest is arctic mountains and tundra with vegetation cover only in the lowland areas. There is no permanent ice on Bear Island, only arctic tundra. **Table 3** clearly illustrates the difference in vegetation types between the countries.

Table 3. Overview distribution of the main landscape types in the countries. (References: Finland: Aarne 1994, Norway: Låg 1981, Sweden: National Atlas for Sweden 1990, Denmark: Danmarks Statistik, 1994 and unpublished results (J.P. Jensen)).

	Mountains[1]	Forest[2]	Mires[3]	Ice and snow	Water	Cultivated land	Built up areas
	%	%	%	%	%	%	%
Denmark		10	3		2	79	6
Finland	<1	75	5		10	7	3
Iceland	85	1		11	2	1.4	0.07
Norway	48	36	7	1	5	3	1
Svalbard	40			60			
Bear Island	100						
Sweden	8	65	8		9	8	2
Åland	10	73	0.5	0	1.5	15	0.2

[1]This includes mountains and highlands with low vegetation cover and barren rocks and tundra.

[2] Some forest are on peatland. For Finland about 30% of the forest is on peatlands.

[3] Mires include peatland and bog

3.4 Climate – precipitation and runoff

The precipitation amount is very important for determining fluxes of ions; i.e. the amounts of ions that are transported from precipitation, through the catchment and lake and out of the lake. In general precipitation has low ionic strength. High precipitation amounts will dilute the runoff water, while in areas with very low precipitation and high evapo-transpiration, the effect will be increased concentrations.

There is a wide range of precipitation amounts in the area studied, and the precipitation patterns depend on distance from the sea and on topography.

A large part of precipitation in Iceland falls with winds between east and south. Accordingly, the highest precipitation amount is found in the southeastern parts, with estimated maximum annual values of more than 4000 mm on ice caps on glaciers. In southwest and west Iceland the yearly amounts are 1000 - 1600 mm in the lowlands at the coast, but only 700 - 1000 mm further inland. The northern and northeastern districts receive the lowest amounts of precipitation, 400 - 600 mm in the lower areas and less than 400 mm north of the glacier Vatnajökull. According to average values for several weather stations during 1965-1972, snow alone is only about 5-10% of the total precipitation in south Iceland during December through March. In North Iceland, in contrast, snow amounts to 50-70% during November through March (Anon 1996).

At Svalbard most of the precipitation falls as snow. According to Olav Liestøl (as cited in Lien *et al.* 1995) the range of precipitation is 200 - 1200 mm yr^{-1}. The majority of rainfall on Svalbard comes with polar eastern winds from the Barents Sea, and there is three times more rainfall on the southern coast of Svalbard as found in Longyearbyen and Ny-Ålesund which are located further north. Frequent low-pressure passages and the warm Atlantic Ocean water make the climate on Svalbard milder than in other northern areas at the same latitude. The annual average temperature in Longyearbyen is -4° C, but the climatic differences on the archipelago are greater. Svalbard has a permafrost layer that goes down to 450 metres. During the summer, only the upper layer of the soil defrosts, down to a maximum of one metre.

For Bear Island the precipitation is estimated to 370 mm yr^{-1} in (Lien *et al.* 1995).

In the Scandinavian countries there is a sharp gradient in precipitation amount from 5000 mm yr^{-1} close to the coast in western Norway (orographic precipitation) to 300 mm yr^{-1} in the driest areas in Central Norway. This orographic precipitation pattern is caused by the steep topography at the western coast. When the saturated air masses cross over the North Sea, they meet the steep mountains at the coast and are forced up to higher altitudes where the air is cooled and moisture in the air condenses. This precipitation pattern continues into Sweden, but there is increasing precipitation towards east and the Gulf of Bothnia. Within Sweden, there is a large gradient from the mountainous areas close to Norway (1500 mm yr^{-1}), through western part of Sweden (800-1000 mm yr^{-1}) to rather dry areas in the eastern parts (600 mm yr^{-1}). Precipitation in Finland exhibits smaller variations than Norway and Sweden. The precipitation in southern and central Finland is on average 600-800 mm yr^{-1}. In Denmark there is some variation in the precipitation, especially from west to east. In Jutland, precipitation is highest in the central part (around 900 mm yr^{-1}), and in general, this region has a higher precipitation amount than in the eastern part of Denmark. The lowest precipitation levels in Denmark are found along the western coast of Zealand (around 500 mm yr^{-1}).

The large variations in precipitation amounts in the study area are illustrated by the 50-percentile values for the runoff from the sampled lakes (**Table 4**).

Table 4. Runoff (mm yr^{-1}) percentiles for the sampled lakes.

Runoff, mm yr^{-1}

percentiles	2.5 %	10 %	25 %	**50 %**	75 %	90 %	97.5 %
Denmark	113	185	247	**284**	378	785	3760
Finland	239	242	280	**315**	356	387	403
Iceland	785	785	1005	**1570**	1623	2983	3202
Norway	315	444	705	**1159**	1701	2457	3150
Svalbard	173	298	339	**424**	531	681	848
Sweden	101	198	299	**300**	347	599	945
Åland	270	270	270	**270**	270	270	270

References:

Finland: Hyvärinen *et al.* 1995

Sweden: SMHI, Vattenföring i Sverige, Svenskt vattenarkiv

Norway: Norwegian Water and Energy Administration (NVE) (mean values for 1961-1990)

Denmark: unpubl. results (J.P.Jensen)

Åland: Hyvärinen *et al.* 1995

Iceland: The Hydrological Service, National Energy Authority, Iceland.

Svalbard: See: Olav Liestøl as cited in Lien *et al.* 1995.

3.5 Precipitation chemistry

The chemistry of the precipitation is largely determined by inputs of sea salt and long-range transported and local air pollutants.

Sea salt concentrations in precipitation are a function of distance from sea and precipitation amounts. In Norway, most of the sea salt aerosols are "washed out" of the air close to the coast in the areas with high precipitation. In areas located further away from the sea, the sea-salt concentration in precipitation is low, < 0.5 mg Cl L[-1], whereas in coastal areas of Norway it can be > 30 mg Cl L[-1].

Long-range transported air pollutants originate largely from emissions from industry, transport and agriculture in western and central Europe. The gradients in concentrations of S and N in precipitation decrease therefore from south to north in northern Europe, except around some large point sources located in the Kola Peninsula in Russia. Sulphur concentrations in precipitation range from about 1.3 mg S L^{-1} in southern Sweden to less than 0.4 mg S L^{-1} in the northern parts of Finland, Sweden and Norway, and most parts of central and western Norway (NMR 1993). The deposition pattern of S is somewhat different to this due to the large range in precipitation amounts over the countries. Both Iceland and Svalbard are little subjected to anthropogenic long-range S-deposition. The mean S-concentration at the long term measuring station at Ny-Ålesund (Svalbard) for the period 1990-1998 is 0.33 mg S L^{-1}. At Iceland the yearly average is 0.3 mg S L^{-1}.

Inorganic N-concentrations ($NH_4 + NO_3$) in deposition range from > 2 mg N L^{-1} in southern Sweden to < 0.1 mg N L^{-1} in the north (NMR 1993). In Ny-Ålesund the average inorganic N-concentration was 0.3 mg N L^{-1} for the period 1990-1998. In Iceland the yearly average is 0.12 mg N L^{-1}.

3.6 In-lake processes

Biological processes

Even though most elements are more or less essential for organisms, some are more important than others. *Bioactive elements* (nutrients) are those used by biota and in this context present in relatively low concentrations in water. Thus, their concentrations may vary seasonally, depending on biological processes both in the drainage area and in the lake. Some examples are presented in **Figure 3**, where the seasonal variation is low for both base cations (BC) and sulphate, whereas a pronounced variation can be seen for nitrate and silica. Changes in total N, total P and TOC are less evident. The cause of these changes can be found in phytoplankton production. All phytoplankton species take up nitrate and in addition diatoms use silica to build a skeleton. As a consequence, the concentrations of these elements in the water diminish during the vegetation (growing) period. Phosphorus is also taken up, but as long as the algae remain in the water the analysis of total-P will not distinguish between the dissolved forms and the portion taken up, and thus the seasonal variation is less pronounced.

Parts of the algae settle and transport the nutrients to the hypolimnion (bottom water) where the nutrients are released by mineralization processes leading to increasing concentrations during the summer stratification. With the autumn turnover these amounts of nutrients will be dispersed in the whole water column raising the concentrations.

The consequence of this seasonal variation is that one sample collected in the autumn may not adequately reflect a lakes characteristic concentration of nutrients. When a long time has passed between end of vegetation period and turnover the higher can the concentration of nitrate be. For the other compounds the seasonal variations in autumn are less drastic, and lake sampling time will only affect the results to a minor extent.
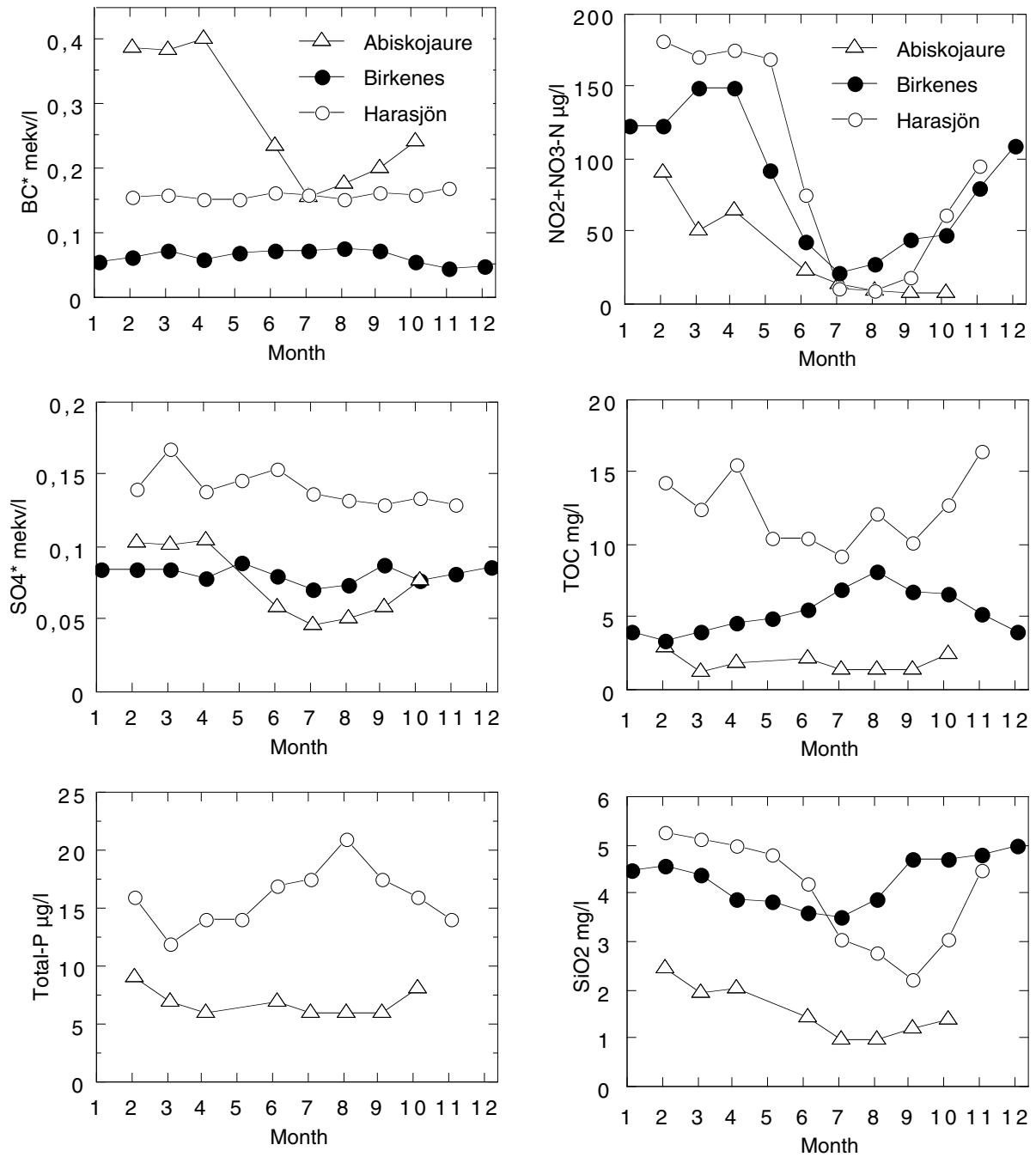
Figure 3. Seasonal variation in three waters for selected parameters. Lake Abiskojaure is situated in the Alpine region in Northern Sweden, Birkenes is a Norwegian stream located in the Boreal zone in the most heavily acidified area in southernmost Norway, and Lake Harasjön is located in the Nemoral zone in southern Sweden.

Physical processes

Physical conditions may affect the water quality in several ways. The relative positions of major inlets and the outlet influence the flow of water in the lake; parts of the lake may have a relatively long retention time while in other parts there is a fast exchange of water. When the retention time is high, effects of physical processes such as sedimentation and photochemical processes, become more pronounced. Thus, in general, lakes with a long retention time are more transparent than lakes with a short retention time. Biological processes, such as plankton production and denitrification, will lower nutrient concentrations in lakes with a longer retention time.

Lakes may be stratified due to temperature differences. During the summer, in relatively deep lakes the surficial water (epilimnion) has a higher temperature than deeper water (hypolimnion) and these two water volumes are separated from each other (**Figure 4**). During the summer stratification the hypolimnion receives nutrients and organic matter from the settling of dead algae which raises the concentrations of biotic elements. This stratification is turned over in the autumn due to lowering of surface water temperature and wind force. Then the total lake volume becomes mixed.

A thermally stratified lake may have more or less different water chemistry in the epilimnion and hypolimnion. Our intention for the Lake surveys was to sample the mixed lake when a surface sample will represent the complete water volume. Previous studies indicated that at a surface water temperature of 6° C the majority of lakes are mixed. Therefore the samples were sampled in the autumn.
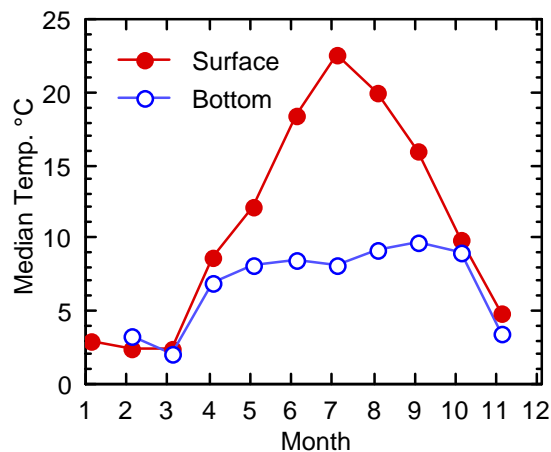

Figure 4. Seasonal temperature variation in two lakes. Lake Abiskojaure (to the left) in the alpine northern Sweden and Lake Sännen (to the right) in the southern Sweden.

4. Results and discussion

4.1 Chemistry of the lakes

Of the analysed components, the concentrations of the base cations Ca, Mg and K, and the anions HCO_3, SO_4 and F in lake water are heavily influenced by weathering and hydrology. NO_3, NH_4, tot-N, SiO_2 and TOC are bioactive elements and are largely controlled by biological processes in the catchments and lakes. The concentrations of Cl and Na are strongly influenced by sea salt deposition, but in some cases also the bedrock or surficial deposits contribute, when made up by old marine deposits.

Water chemistry is normally reported as concentrations. Here, the chemistry of the lakes is discussed with respect to both concentrations and fluxes. The concentration of the solutes in water is important for the biota. The flux is a measure of the total transport of an element and is an indirect measurement of the production or weathering of an element in a catchment. Calculation of fluxes needs information of both the concentrations of the compounds and the runoff.

4.1.1 Fluxes and weathering

Chemical weathering releases base cations from minerals to solution, to an exchange site, or to the biota. Chemical weathering comprises a major process by which acids are neutralised in the terrestrial environment. A good estimate of the present-day weathering rate is necessary to determine the long-term resistance of ecosystems to soil acidification in areas exposed to acid deposition. Weathering rates are usually determined by laboratory studies, mass balance studies and field studies. Weathering rates within a defined catchment can be estimated by monitoring the chemistry of wet and dry deposition and runoff and calculate the difference between the input and output, given the assumption that the catchment ecosystem is at steady-state. Environmental disturbance such as acid deposition, however, perturbs such steady-state conditions. In such cases, a significant fraction of base cations in surface waters can come from cation exchange processes in the catchment. Net release of base cations (output minus input) is termed "cation denudation rate" and is largely comprised of weathering plus cation exchange.

The cation denudation rate for a site can be calculated from yearly flow-weighted average chemistry and yearly average runoff. Since such values are not available for most lakes, rates here are mostly estimated on the basis of a single sample considered representative of yearly flow-weighted averages. A sample collected shortly after the fall circulation of a lake fulfils this purpose (Henriksen *et al.* 1992). Henriksen and Posch (2001) checked this assumption by comparing rates calculated from yearly flow-weighted average concentrations with rates calculated from a single fall value for sites for which long-term data series are available. Such data was available from the calibrated catchments in the Norwegian monitoring program for long-range transported air pollutants (SFT 2000). Results for seven catchments indicated clearly that the single fall value is representative for the annual average chemistry. Thus, this result indicate strongly that cation denudation rates calculated on this basis, can be suitable for comparing approximate rates, which in turn can be related to the basic geology in the catchments.

Precipitation amount is an important factor for determining weathering rates in a catchment system. In areas with the same type of bedrock geology and thus similar weathering rates, there are lower concentrations in the high precipitation areas than in low precipitation areas due to dilution. This is nicely illustrated in **Figure 5** where the 50-percentiles for the concentration and flux, respectively, for non-marine base cations (Ca+Mg*) are compared for the Iceland, Finland, Denmark, Norway, Svalbard and Sweden. Comparison between fluxes and concentrations of base cations are also illustrated on map in **Figure 6**.

Thus, cation denudation rates are more similar than are concentration in the studied area. The weathering rates are rather similar for Norway, Sweden and Finland, reflecting the homogeneous geological settings in these countries. The highest weathering rates are found in Iceland and Denmark.
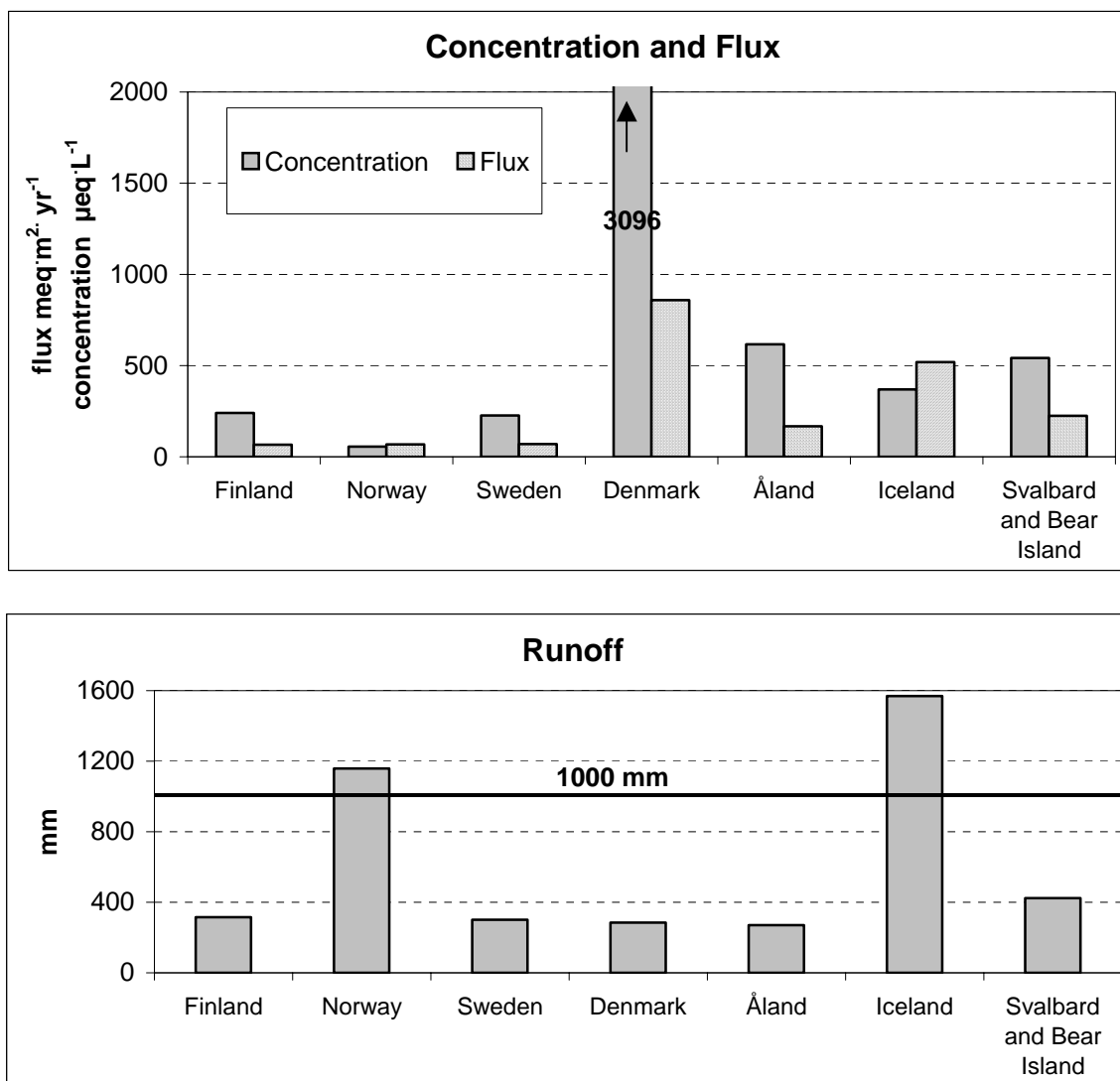

Figure 5. Comparing 50-percentiles for non-marine base cation concentrations and fluxes for the lake population in this study. Also shown are the 50-percentiles for runoff (mm yr^{-1}).

Base cations and alkalinity
Base cations (BC = Ca^{2+} + Mg^{2+} + Na^+ + K^+) and hydrogen carbonate (HCO_3^-) derive principally from weathering reactions and ion-exchange processes in the catchments. Bedrock and soils are thus the main source of these ions in runoff water, except in near coastal near areas where sea salt deposition contributes significantly to the concentrations of Mg^{2+} and Na^+. Soil mineralogy, soil depth and hydrological flow path are also important factors in determining base cation fluxes. Inorganic weathering processes release equal amounts of base cations and bicarbonate (alkalinity).

In order to estimate changes in surface water due to atmospheric deposition other than seawater, it is necessary to subtract the ions that originate from sea salt spray. It is assumed that all chloride in the water comes from sea salt spray, and that all sea salt components are transported and deposited in the same ratio as chloride as is found in seawater. Sea salt corrected values are marked with an asterisk (*). The lowest concentrations of non-marine base cations are found in southern and western Norway and in the mountainous areas of Sweden bordering Norway. Higher concentrations of non-marine base cations are found in southern Sweden, and in scattered areas in Finland and the northern parts of Norway and Sweden (**Figure 6**). Lakes in Denmark, Åland, Iceland and Svalbard have the highest concentrations of base cations and alkalinity (Appendix A). Although the concentrations of calcium are very high in Svalbard, the fluxes and thus the weathering rates are lower here than in Iceland.

Concentrations of alkalinity and non-marine base cations are closely related for most of the sampled lakes, except for lakes with high TOC concentrations (see below). Thus, alkalinity shows the same pattern as non-marine base cations, with the lowest alkalinity values in coastal and inland areas of southern Norway and in southwestern Sweden (**Figure 7**).

4.1.2 Acidity

Most oligotrophic lakes not influenced by human activities will have a pH above about 5.5. Such lakes are dominated by hydrogen carbonate ions and in coastal areas also sea salts. pH values below 5.5 in pristine lakes can be caused by organic anions (humic acids). Acid deposition can acidify lake water to pH < 5.5, and in such lakes strong acid anions (sulphate + nitrate) will contribute to an increasing portion of the total anion concentration. When pH falls below 5, the water is dominated by acid anions of anthropogenic origin, organic anions or a mixture of both.

pH

High pH lakes (pH > 7) are found scattered in regions in southern, eastern and central Sweden and in the mountains along the border of Norway and in Denmark (**Figure 7**). Lakes with especially high pH (> 8) are found in Iceland (10 lakes) and Svalbard (29 lakes). These lakes are associated with high inputs of base cations and hydrogen carbonate through weathering in the catchment. One lake in Iceland (Myvatn S) has a pH of 10.5. This is largely due to high biological activity of diatom algae at the time of sampling (Jonasson and Adalsteinsson 1979) resulting in uptake of carbon dioxide (CO_2) which in turn raises the pH-value.

The lowest pH values are found in southern and western Norway and in southwestern Sweden. There are also low pH lakes scattered elsewhere throughout Sweden and Finland in areas influenced by both acidic deposition and organic acids; low pH sites in northern areas of these countries are usually associated solely with organic acidity.

Non-marine sulphate

Sulphate (SO_4) in acid deposition is the major driving force leading to acidification of surface waters. Sulphate is normally a "mobile anion"; i.e. nearly all sulphate in deposition is transported through the catchment. As sulphate moves through the catchment, equivalent concentrations of cations are also transported. These cations are mainly Ca^{2+}), Mg^{2+}, H^+ and Al^{n+}.

Lakes with high concentrations of non-marine sulphate (SO_4^*) are found in parts of all countries (**Figure 8**). Iceland has the lowest 50-percentile value of 10 µeq L^{-1} followed by Norway with 50-percentile value of 26 µeq L^{-1} (Appendix A). Åland has the highest value of 177 µeq L^{-1} (excluding Denmark). This is only partly due to sulphur deposition, since it also reflects the geo-chemical influence of old marine deposits. In Sweden and Finland, the concentrations increase in a north-to-south direction. In Norway the gradient is west-to-east which reflects the deposition and precipitation

patterns. In Sweden, the gradient is due to diminishing precipitation and higher evapotranspiration leading to increasing concentration.

Some lakes in Denmark also have "negative" non-marine sulphate concentrations, largely due to inputs of chloride from fossil marine salts in the soil.

In Iceland the high sulphate lakes are found in the active geological zones while on Svalbard and Bear Island they are related to gysum/anhydrite in the soils and bedrock.

In Åland the high sulphate lakes are most probably related to old marine deposits of S containing clay soils and sediments. The whole of Åland lies below the shoreline of the post-glacial Litorina Sea (7000-7500 years ago). This influence of marine deposits increases the concentration of several other ions as well (Ca, Mg, F).

Fluoride
The source of fluoride in surface water is mainly weathering, although input through deposition from anthropogenic sources may contribute in polluted areas (Skjelkvåle *et al.* 1993).

Sweden has the highest median value of F at 93 µg L^{-1}. This is due to weathering of granites with presence of fluorspar and fluorapite (Aastrup *et al.* 1995) with a general high level of F in eastern parts of Sweden (**Figure 8**). The median for Norway is < 40 µg L^{-1}, the sensitivity of the method used in Norway is less than those for the other countries. The highest values are found in southeastern Finland and Åland due to areas with Rapakivi granite formations, which have an anomalously high content of fluoride (Lahermo *et al.* 1995).

4.1.3 Bioactive elements (nutrients)

Bioactive elements are those used by biota and normally present in relatively low concentrations in water.

Nitrate
Acid precipitation contains high concentrations of nitrate (NO_3) and ammonium (NH_4) as well as sulphate. Most deposited N is taken up by vegetation and in soils. Nitrate concentrations in runoff waters are therefore generally low in areas not impacted by human activities, such as agriculture and settlements. If the deposition of nitrogen exceeds the retention capacity of the catchment, then excess N will leach as nitrate and acidify the lake water in a similar as sulphate.

The highest nitrate concentrations are found in Denmark largely due to high agricultural activity. The high levels of nitrate in southern and western Norway, southern Sweden, southern Finland and Åland are related to long-range transported air pollutants. Low concentrations are found in the northern parts of the Scandinavia and in Iceland. The concentrations of nitrate vary between countries ranging from a median value of < 1 µg N L^{-1} in Iceland to as high as 515 µg N L^{-1} in Denmark (**Figure 9**).

The low values in Iceland are most likely due to very low N-deposition and that most of the incoming nitrate is used by plants, mainly on land. The Icelandic lakes were sampled in September, a biologically active period.

Ammonia
Ammonia in lakes originates mainly from agriculture activities and deposition; about half of the total-N- deposition is ammonia. Ammonia shows much of the same picture as nitrate, although the concentrations are much lower (**Figure 9**). Ammonia is both taken up by plants and oxidised to nitrate by bacteria. Thus the concentrations found in precipitation diminish quickly.

Total Nitrogen

Total Nitrogen (tot-N) (**Figure 10**) is the sum of nitrate, ammonia and organic nitrogen. The patterns of tot-N are remarkably similar to that of TOC. This is because in natural water most tot-N is bound as organic N and thus strong related to organic C. Deviations are found in agricultural areas, where nitrate dominates tot-N.

Phosphorus

The natural sources of phosphorus (P) are from weathering and precipitation. In areas not influenced by human activities, total P concentrations in runoff water are usually low (< 10 µg P L^{-1}). Discharge from different types of human activities, such as agriculture and settlements, increase total P concentrations in lakes.

Total P concentrations in Nordic lakes are shown in **Figure 10**. In Iceland and Svalbard many lakes have rather high concentrations of tot P, median values are 8 and 22 µg P L^{-1}, respectively. The higher tot-P concentrations in the Icelandic lakes are possibly due to inputs from volcanic bedrock in the southern areas (Gíslason *et al.* 1996). Also Icelandic lakes with higher TOC have higher total phosphorus than lakes with low TOC values located in non-volcanic bedrock. In Svalbard, most of the samples have very high turbidity. For many of the high-P lakes the concentrations are related to influence of clay from glaciers. For some lakes, dense population of waterfowl may contribute to high total P concentrations, and finally some areas of Svalbard have phosphorus nodules in the bedrock.

In Finnish lakes, the highest total P concentrations are found mostly in lowland (agricultural) areas of southern and western Finland. An important factor that may contribute to the high total P levels in scattered areas of Finland is the extensive forestry practices on peatlands. Originally one third of the land cover of Finland was peatland, whereas half of this has now been ditched and fertilised with K and P.

Norwegian lakes show the lowest P-concentrations due to low weathering rates combined with high precipitation. The highest concentrations in Sweden are located in densely populated agricultural areas and on the plains along the large lakes.

Organic carbon (TOC)

In areas with organic, peaty soils and bogs, runoff waters usually contain humic compounds which give the water a characteristic brown colour. The anionic contributions of these humic compounds can be inferred from concentrations of organic carbon (TOC). When TOC concentrations exceed 3-5 mg L^{-1}, the water will have a yellowish colour due to humic substances. With increasing TOC concentration, the colour changes from yellow to dark brown and the contribution of organic anions to acidity increases.

The pattern of TOC shows a clear increasing gradient from west-to-east in Fennoscandia (**Figure 11**), reflecting changes from mountainous non-forested areas with thin soils and high runoff in Norway to lowland areas with forest, thicker soils, lower runoff and more peatland in Finland and Åland. Similarly, there is also a slight increasing gradient from north-to-south in the same area. Svalbard and Iceland have, not unexpectedly, the lowest TOC concentrations, with median values as low as 0.5 and 1.0 mg C L^{-1}, respectively, reflecting the sparse vegetation and soil cover, especially in Svalbard. Lakes in Denmark have high TOC concentrations largely due to their high biological productivity.

Silica

Silica is released as siliceous acid during weathering of minerals in the soil. Thus, easily weathered minerals and a long retention time of water in the soil can lead to high concentrations in the surface water.

The highest values are found in Icelandic lakes, but also in Denmark concentrations are high (**Figure 11**). The volcanic soils in Iceland are easily weathered and also the relatively warm climate supports a high weathering rate as compared to the colder countries Norway, Finland and Sweden. Also some Danish lakes have high concentrations. Finland has intermediate concentrations. The reason for this is not clear, but may be due to formation of soluble aluminium-silicate-humic complexes.

Acidified lakes usually lie in catchments whose soils have low weathering. The release of silica will be low in such waters as well, while waters with a higher buffer capacity (and high pH) in general have higher silica concentrations.

Algae with a silica structure, mostly diatoms, use dissolved silica. Diatom blooms may occur in the early spring and late autumn at which periods the concentrations of dissolved silica will be low (**Figure 3**).

4.1.4 Sea salts

Chloride
Chloride (Cl) concentrations in lakes provide a measure of the influence of sea salt, because catchment sources of chloride are generally negligible.

The highest values of chloride are, as expected, found in lakes located in the coastal zone (Gorham 1961, Wright and Henriksen 1978). Higher values of chloride are found in Iceland, Svalbard, Åland and Denmark (**Figure 12**). The 50 percentile ranges for Åland at 180 μeq L^{-1}, Iceland at 166 μeq L^{-1} and Svalbard at 127 μeq L^{-1} are up to five times greater than the 50 percentile values for the other countries (except for Denmark). All lakes in Iceland, Svalbard, Bear Island and Åland are located relatively close to the sea, and thus strongly influenced by sea salts from precipitation.

High chloride concentrations in the Danish lakes are most probably due both to sources in the catchments such as post-glacial marine sediments and to input from sea salts.

Chloride concentrations in Norwegian lakes show a steep gradient from very high levels close to the sea, to extremely low values within 100-200 km from the coast. From southern Sweden through Finland there is a small decreasing gradient in chloride with high levels in most of southern Sweden and a decrease in Finland from the coastal area in west and south to low values in east and north.

Areas in southern Sweden located below the highest coastline after the last deglaciation are been influenced by fossil sea water deposits. Lakes in contact with marine deposits from this period can contain water with high concentrations of chloride and sulphate. This is also the case for lowland areas along the coast in southern Norway, Denmark and Western Finland. The altitude of the highest coastline after the last deglaciation varies from 0 to 250 m above the present sea level.

Industrial and domestic effluents and road salts can also lead to elevated chloride concentrations. However, no information is available to separate lakes with anthropogenic Cl-sources from those with natural sources.
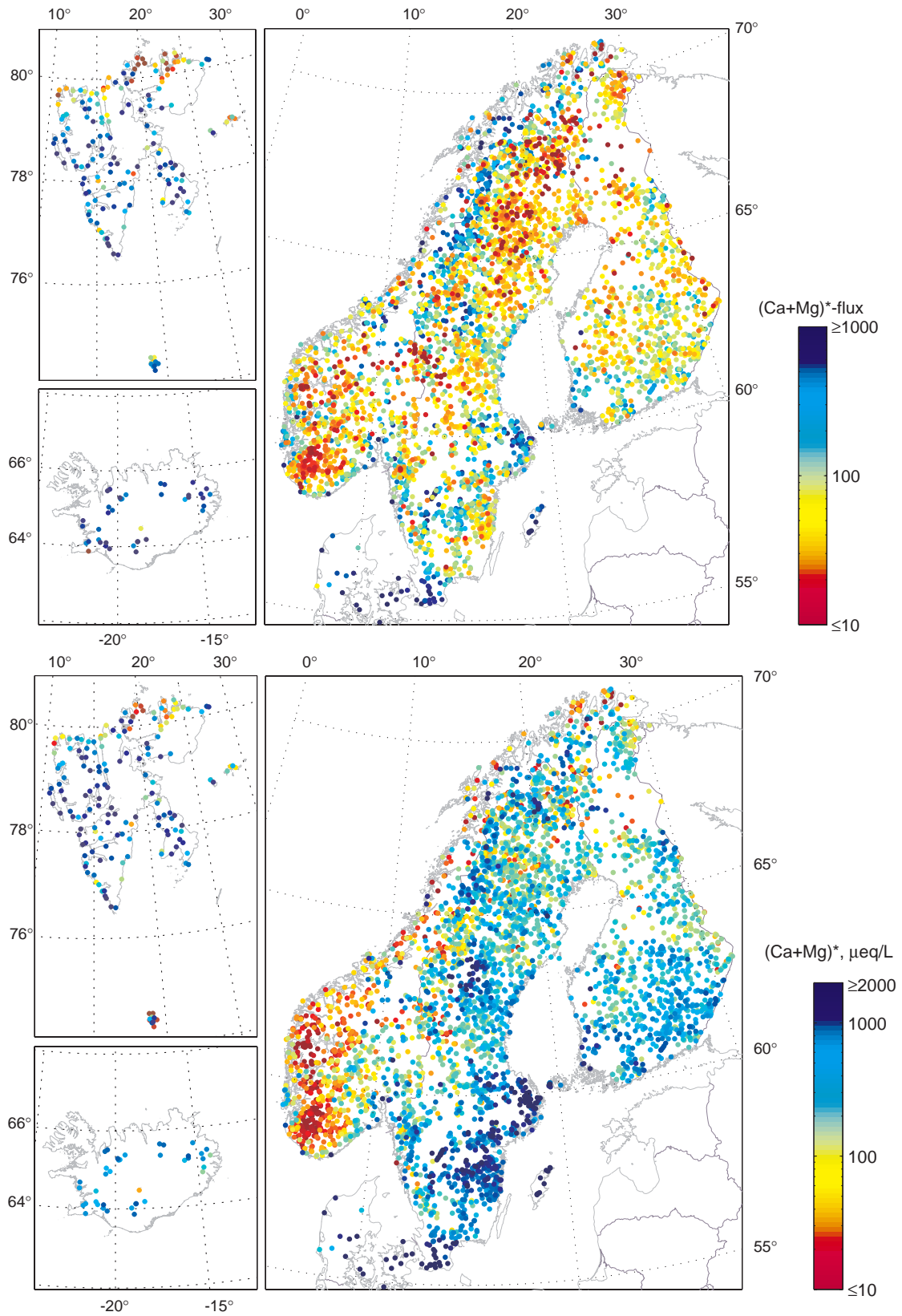
Figure 6. Map of fluxes (upper panel) and concentrations (lower panel) of non-marine calcium + magnesium (Ca+Mg)* in the Nordic lakes.
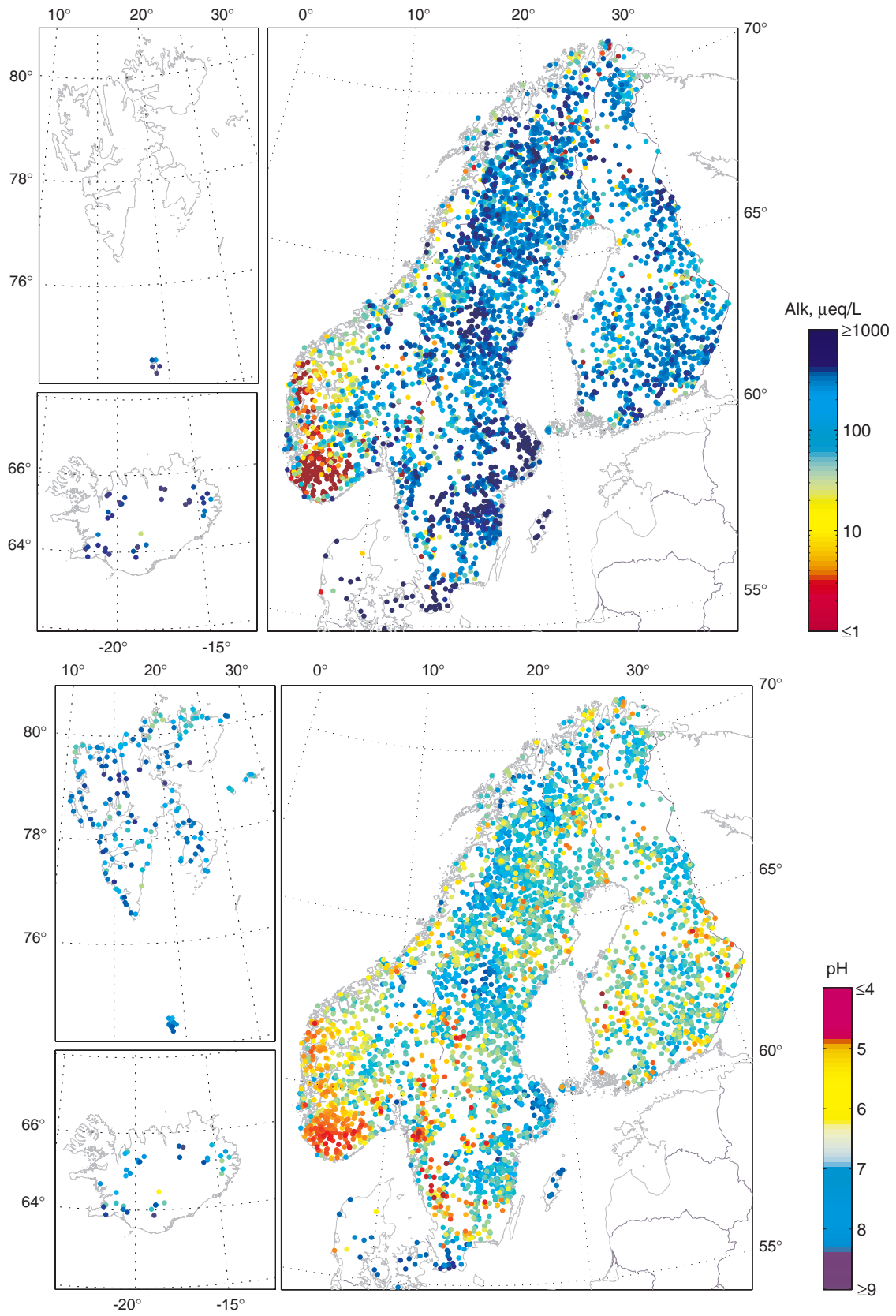
Figure 7. Map of alkalinity (upper panel) and pH (lower panel) in Nordic lakes.
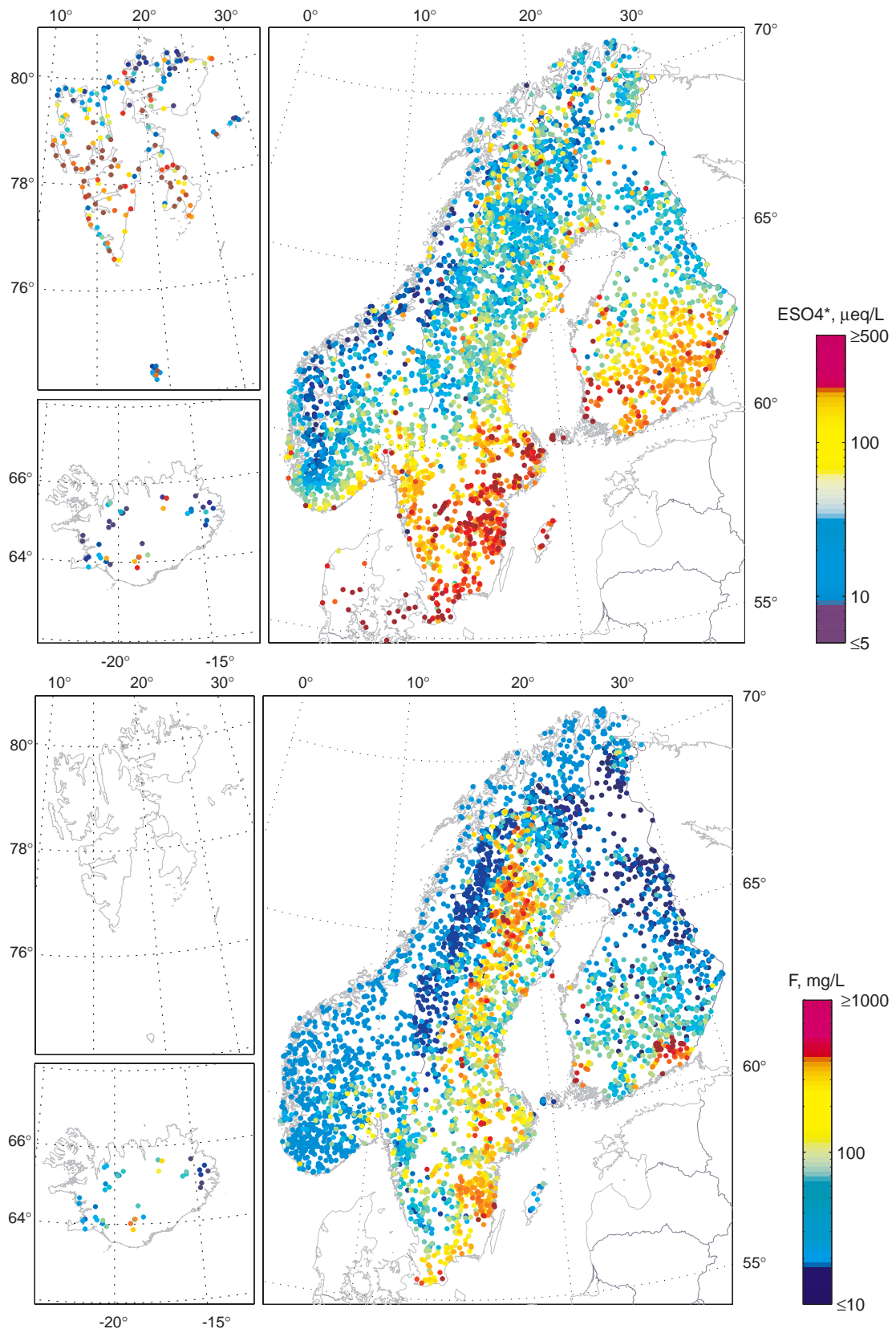
Figure 8. Map of concentrations of non-marine sulphate (SO$_4$$^{*)}$) and fluoride (F) in Nordic lakes.
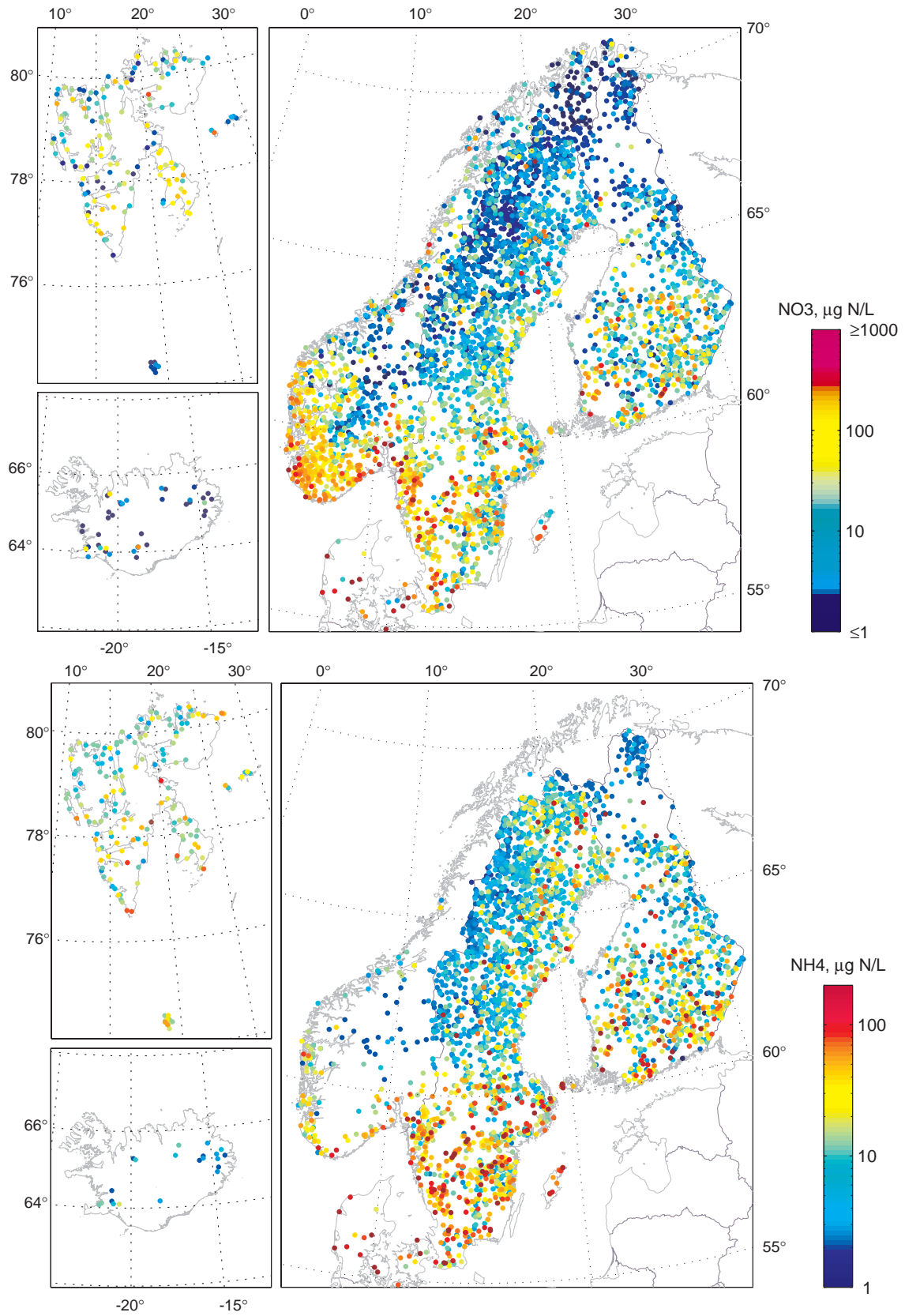
Figure 9. Map of conecntrations of nitrate (upper panel) and ammonia (lower panel) in Nordic lakes. For Norway only lakes that are assumed influnced by agricultur activity are analysed for ammonia .

Figure 10. Map of concentrations of tot-N (upper panel) and tot-P (lower panel).

Figure 11. Map of concentrations of SiO$_2$ (upper panel) and TOC (lower panel) in Nordic lakes.

Figure 12. Map of concentrations Cl in Nordic lakes.

4.2 Critical loads for sulphur acidity in the lakes
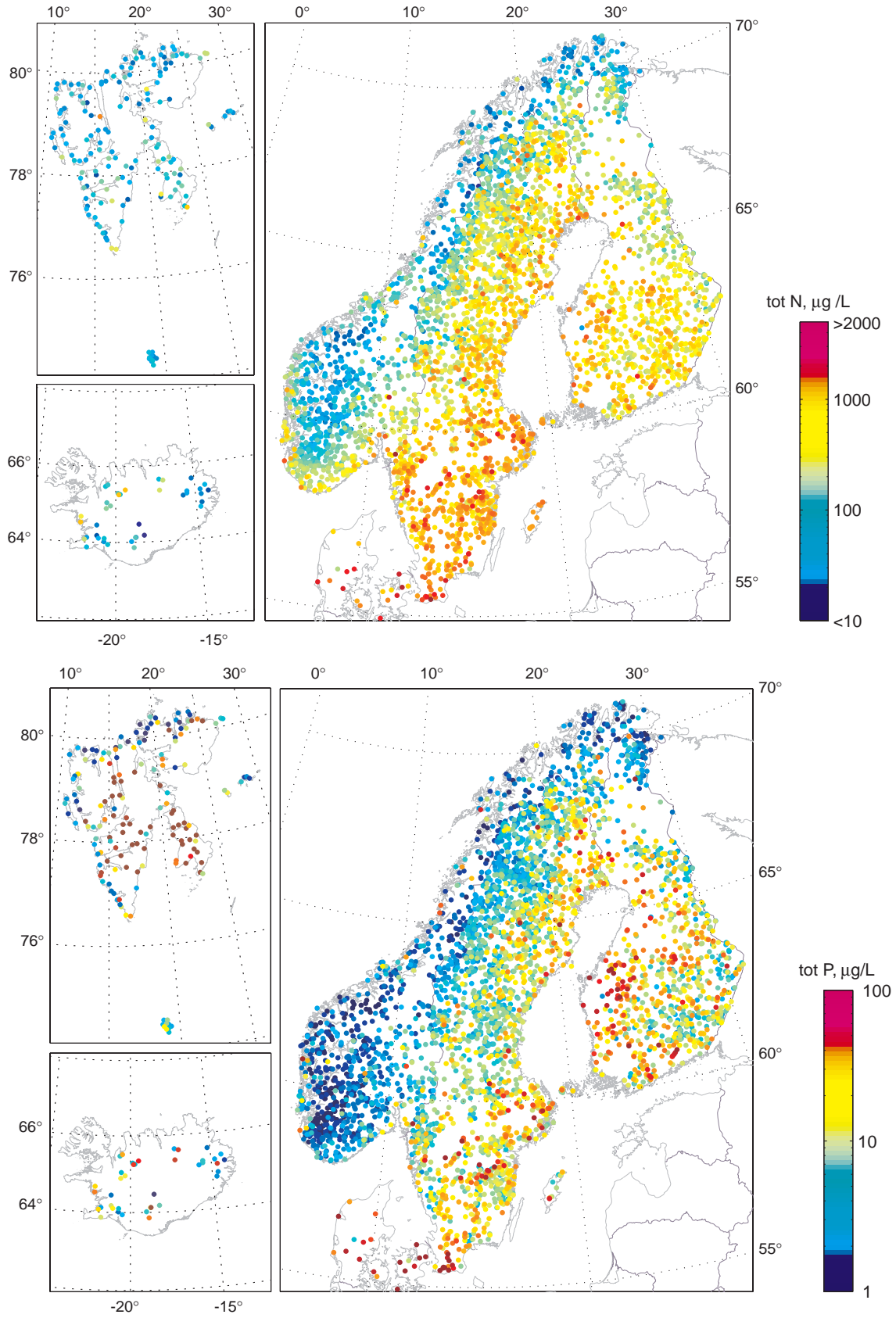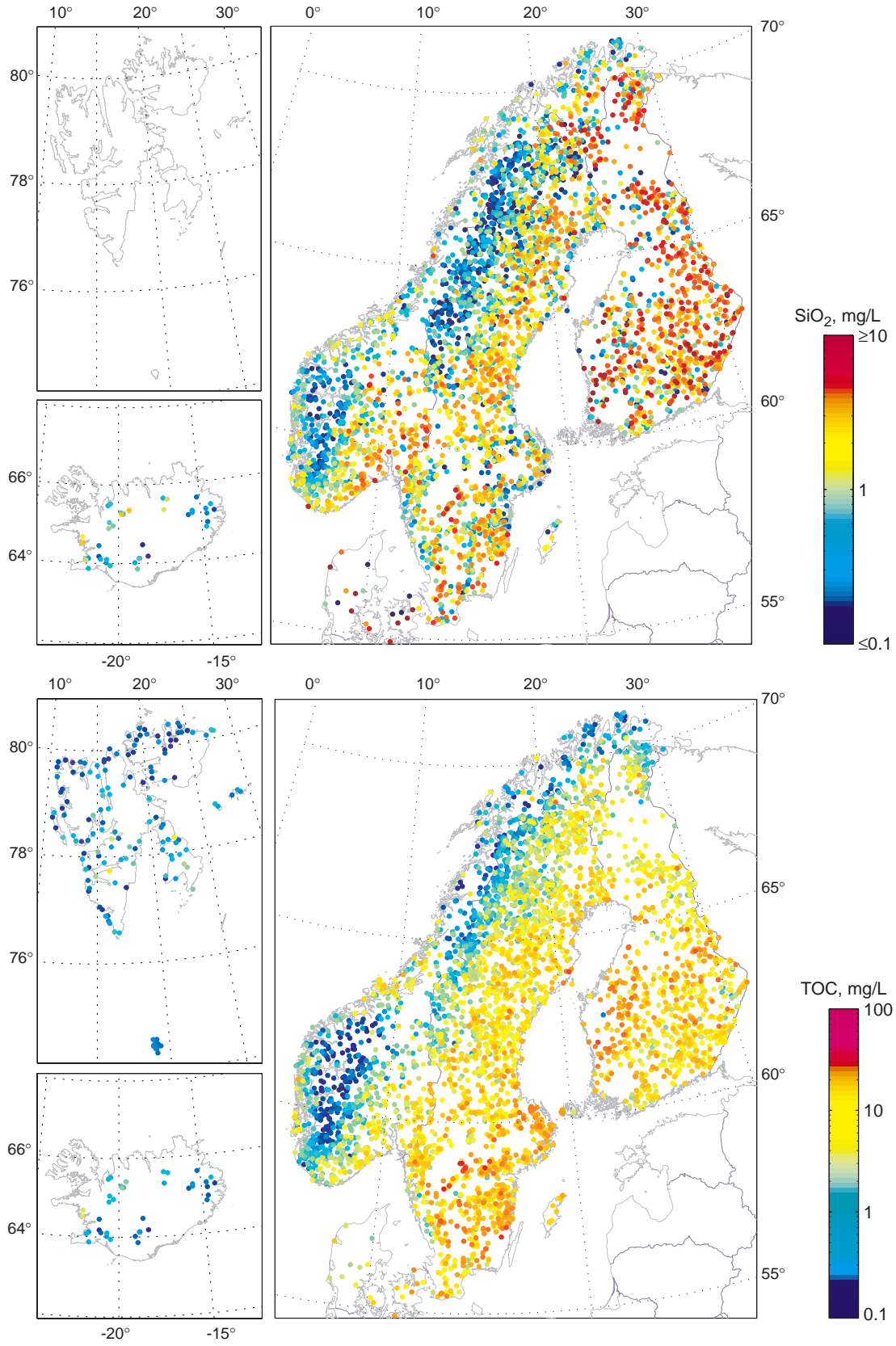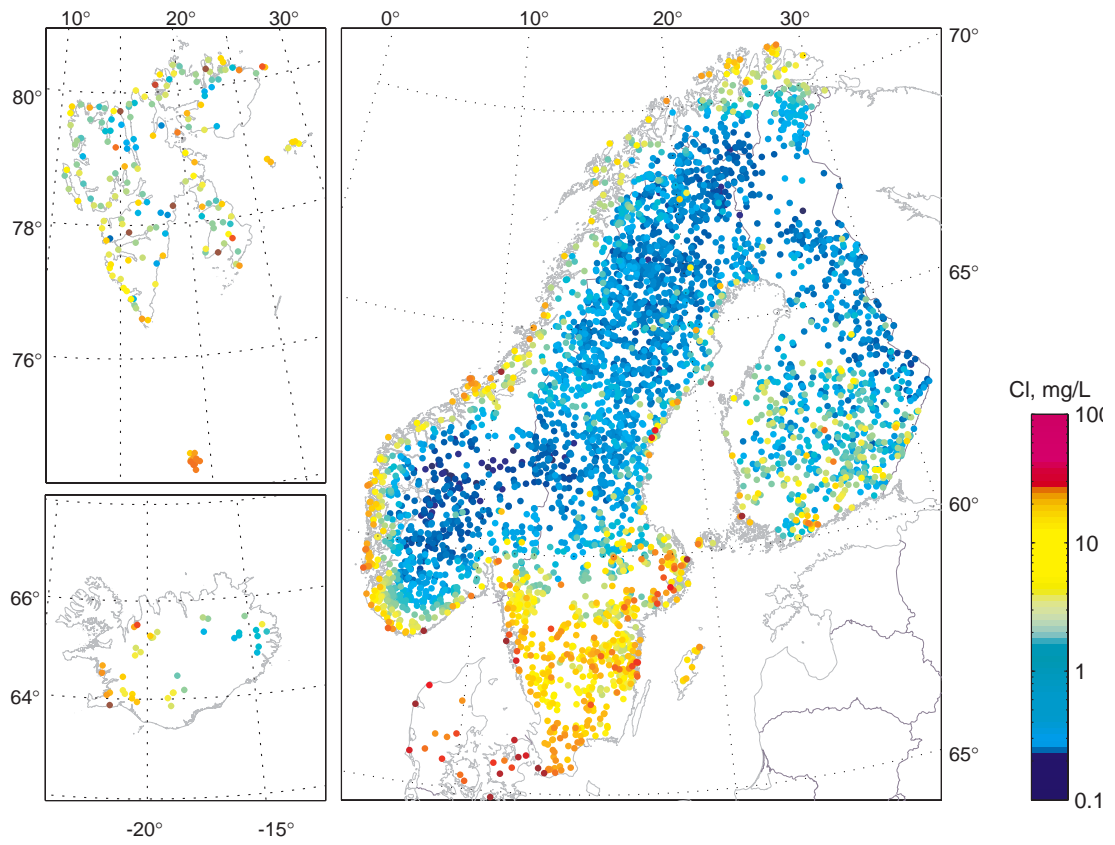
The influence of acidic deposition on lake runoff water is a function of the acidifying potential of sulphur and nitrogen deposition and the characteristics of the catchment. When the acidifying potential exceeds the ability of the catchment to produce alkalinity, the lake water will lose all its alkalinity and become acidic. Catchments with thin soils derived from bedrock with low weathering capacity such as gneiss and granitic gneiss normally have low acid neutralising capacity.

Critical loads (CL) have been widely accepted as a basis for most recent control strategies for regional air pollution. The critical load concept was used to prepare the two Protocols for reducing emissions of sulphur and nitrogen in Europe, the Oslo-Protocol in 1994 (UN/ECE 1994) and the Gothenburg Protocol in 1999 (UN/ECE 1999).

Two models - one empirical and one process-oriented – are widely used to calculate critical loads of acidifying deposition (both S and N) for surface waters. The Steady-State Water Chemistry (SSWC) model allows the calculation of critical loads of acidity and their present exceedances. The First-order Acidity Balance (FAB) model allows the simultaneous calculation of critical loads of acidifying N and S deposition and their exceedances (see Henriksen and Posch 2001). The SSWC-model includes both S and N acidity, in such a way that present N-leaching (N_{leach}) is considered in the calculation of critical load exceedance (present Ex(Ac)). An inherent assumption is that no anthropogenic sources of nitrate other than long-range transported nitrogen compounds are included in the N_{leach} term. At present such a separation is not possible for the lake survey data considered here, therefore only critical loads for sulphur acidity have been calculated.

Percentiles of the calculated CL are shown in **Table 5**. The 50-percentiles for all countries are plotted in **Figure 13**.

Because of the high critical loads and the low sulphur deposition in Iceland critical loads are not exceeded in any of the studied lakes, thus acidification of lakes is not a problem in Iceland*.*

The critical loads and critical load exceedances for Norway, Sweden, Finland, Denmark and Svalbard have been discussed elsewhere (Henriksen *et al.* 1998, Lien *et al.* 1995). Lakes in Finland, Norway, Sweden all have a 50 percentile for critical load around 50 meq m^{-2}yr^{-1} (**Table 5**). However, the frequency distributions are slightly different. Norway has both the highest proportion of low CL lakes and high CL lakes while in Finland nearly 50% of the lakes have CL at 50 ±10 meq m^{-2} yr^{-1}.

Denmark has very few lakes with low critical load values. Of the 19 analysed Danish lakes, there are only 2 that have CL < 50 meq m^{-2}yr^{-1}, in Åland also 2 lakes have a critical load less than 50 meq m^{-2} yr^{-1}. In Iceland only one lake has a critical load of 50; all others are higher than 180 meq m^{-2}yr^{-1}. In Svalbard, however, lakes are more sensitive, with 20 lakes < 50 meq m^{-2}yr^{-1}.

Small exceedances (1990 deposition) of critical loads were recorded in 5% of the ice-free area of Svalbard and Bear Island, and only in the northern parts (Lien *et al.* 1995). The S-deposition in Åland was about 34 meq m^{-2} yr^{-1} (0.55 g S m^{-2} yr^{-1}) in 1990, and has decreased to about 19 meq m^{-2} yr^{-1} (0.3 g S m^{-2} yr^{-1}) in 1997, indicating that none of the lakes was ever exceeded in Åland.

Table 5. Percentiles for critical loads (meq m^{-2} yr^{-1}) using the catchment dependent ANC$_{limit}$ (Henriksen and Posch 2001) and Norwegian background sulphate for all countries, except for Sweden (Wilander 1994).

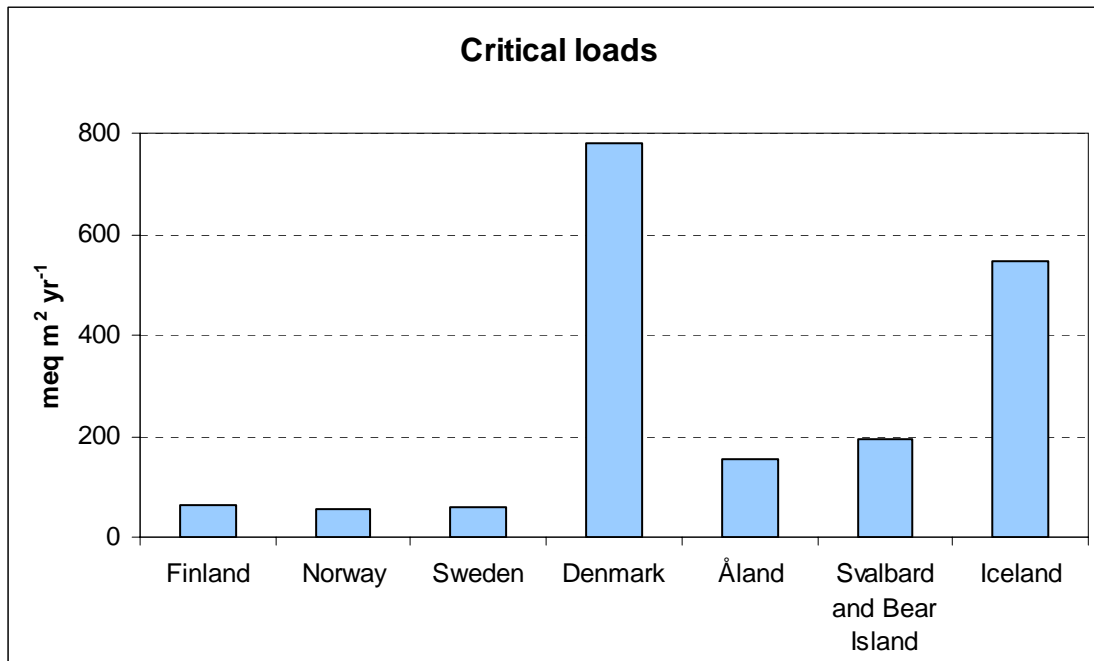| Percentile	2.5	10	25	50	75	90	97.5	n
Denmark	1	30	352	**780**	1167	1409	1625	19
Finland	15	32	46	**63**	86	117	192	873
Iceland	180	251	345	**546**	851	1100	1274	38
Norway	7	15	28	**56**	115	271	736	1010
Svalbard	8	26	73	**193**	440	661	1118	162
Sweden	9	21	39	**61**	107	215	552	3075
Åland	39	45	95	**153**	384	413	458	9

Figure 13. 50-percentiles for critical loads in the studied areas.

5. Concluding remarks

The common Nordic lake-chemistry database presented here provides a basis for evaluation of lake resources with respect to international pollution risks in the Nordic region. This work illustrates for the international community how a common effort can result in a joint presentation of the chemical properties of a very important ecosystem, freshwater lakes. Although lakes are more common in the Nordic countries than in most of the other parts of Europe, the lake water resources are of great importance today, and the importance will inevitably grow in the future. The need for extensive knowledge of the present status of the lake populations in all Europe will most likely increase, and the approach used in the Nordic countries could form the basis for further co-operative projects in Europe. The Nordic lake surveys will provide important baseline information for implementation of the EU Water Directive.

Regional lake surveys are necessary for accumulating knowledge of the past, present and future status of freshwater resources, thus giving a valuable basis for future decisions. Regional lake surveys provide important base-line information with respect to large-scale and long-term changes in lakes, such as acidification, climate change and effects of land-use practices. A regional lake survey serves as an important basis for sub-sampling of lakes for special topics, for example dedicated biological investigations. The lakes selected for the Nordic fish population survey (Rask *et al.* 2000) are based on the Nordic lake survey carried out in 1995 (Henriksen *et al.* 1998).

Sweden repeated their lake survey in 2000, five years after the first survey in 1995. They intend to repeat the survey every fifth year. Norway and Finland did not join Sweden in 2000. We strongly recommend that new extensive lake surveys should be carried out in 2005 in the Nordic countries, and this time also the Faroe Islands and Greenland should be included. Possible extension of the survey area into the arctic and Northern Boreal zone and further into Canada and the northern parts of Russia should also be considered.

The lake surveys discussed here have been important for the Nordic identity and co-operation, and further similar and extended surveys would certainly increase and improve the Nordic co-operation further. We do hope that the results shown here will lead to general international co-operation for extensively studying the quality of the freshwater resources in Europe and North America.

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Appendix A. Percentiles

Fluxes

Ca + Mg meq m^{-2} yr^{-1}

percentiles	2.5 %	10 %	25 %	50 %	75 %	90 %	97.5 %
Denmark	80	185	433	**859**	1301	1421	1585
Finland	16	33	46	**66**	91	137	762
Iceland	65	251	330	**519**	872	1178	2265
Norway	10	18	30	**55**	115	229	4061
Svalbard and Bear Island	8	27	74	**224**	504	786	2757
Sweden	10	26	43	**70**	132	263	4141
Åland	42	45	71	**123**	158	190	223

Concentrations

percentiles	2.5 %	10 %	25 %	50 %	75 %	90 %	97.5 %
(Ca + Mg)* µeq L^{-1}							
Denmark	230	271	1722	**3096**	4537	5448	6741
Finland	49	130	173	**240**	352	490	753
Iceland	129	215	275	**369**	563	670	771
Norway	5	14	33	**79**	193	367	846
Svalbard and Bear Island	20	75	198	**541**	1085	1601	2213
Sweden	30	71	138	**226**	392	701	1504
Åland	155	176	372	**617**	1407	1915	1992
Alkalinity µeq L^{-1}							
Denmark	5	25	1508	**2222**	2897	3716	3833
Finland	-6	22	53	**111**	181	278	521
Iceland	121	192	319	**441**	583	725	826
Norway	<0	<0	8	**36**	123	298	667
Svalbard and Bear Island	27	45	188	**492**	859	1137	1674
Sweden	-23	10	49	**119**	223	446	1081
Åland	11	34	219	473	1229	1342	1500
Cl µeq L^{-1}							
Denmark	549	607	764	**1086**	1732	2273	5861
Finland	8	11	16	**28**	50	93	213
Iceland	45	53	85	**166**	303	445	1182
Norway	6	10	18	**47**	118	243	459
Svalbard and Bear Island	31	45	85	**127**	246	441	2493
Sweden	8	12	17	**24**	62	217	401
Åland	128	131	149	**180**	304	431	585
pH							
Denmark	5.42	5.98	7.64	**7.87**	8.05	8.11	8.24
Finland	5.12	5.68	6.19	**6.58**	6.90	7.08	7.29
Iceland	5.36	6.56	6.8	**7.30**	7.80	8.20	8.35
Norway	4.72	5.07	5.67	**6.36**	6.92	7.30	7.66
Svalbard and Bear Island	6.42	6.68	7.00	**7.54**	7.97	8.26	8.70
Sweden	4.86	5.76	6.40	**6.75**	7.03	7.30	7.68
Åland	5.44	5.84	6.92	**7.36**	7.44	7.62	7.64
SO4* µeq L^{-1}							
Denmark	33	192	407	**614**	956	1604	2564
Finland	15	23	34	**57**	106	155	250
Iceland	0	0	1.3	**10**	34	140	293
Norway	6	10	15	**26**	45	80	142
Svalbard and Bear Island	4	10	22	**82**	305	751	1324
Sweden	12	18	26	**41**	85	162	317
Åland	87	93	134	**177**	236	538	794

percentiles	2.5 %	10 %	25 %	50 %	75 %	90 %	97.5 %
F µg L⁻¹							
Denmark	n.a	n.a	n.a	**n.a**	n.a	n.a	n.a
Finland	10	10	27	**61**	95	138	674
Iceland	<10	18	40	**60**	82	170	343
Norway	<40	<40	<40	**<40**	<40	<40	110
Svalbard and Bear Island	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sweden	23	23	42	**92**	182	293	492
Åland	182	188	210	**240**	310	376	424
NO3 µeq L⁻¹							
Denmark	0.7	1.5	7.8	**36.8**	126.3	153.7	351.6
Finland	<O.1	0.1	0.2	**0.8**	1.7	3.8	11.2
Iceland	<0.1	<0.1	<0.1	**<0.1**	0.3	0.9	1.5
Norway	<0.1	<0.1	<0.1	**0.7**	4.2	8.2	16.4
Svalbard and Bear Island	<0.1	<0.1	0.4	**1.9**	4.6	6.6	10.3
Sweden	0.1	0.1	0.3	**0.7**	1.8	4.4	11.5
Åland	2.0	2.3	2.6	**3.4**	4.1	8.7	9.1
Tot-N µg N L⁻¹							
Denmark	429	639	709	**1310**	2549	3076	3622
Finland	119	191	281	**401**	556	746	1000
Iceland	20	40	67	**125**	180	359	752
Norway	36	51	80	**138**	240	368	568
Svalbard and Bear Island	41	54	80	**100**	161	245	372
Sweden	118	179	270	**402**	644	953	1423
Åland	526	544	690	**800**	970	1020	1080
TOC mg C L⁻¹							
Denmark	3.0	4.0	4.8	7.4	11.0	17.2	19.0
Finland	1.7	3.6	5.4	7.6	11.6	15.7	22.9
Iceland	0.2	0.3	0.5	1.0	1.7	2.3	5.2
Norway	< 0.2	0.2	0.6	1.9	4.4	7.3	10.5
Svalbard and Bear Island	0.2	0.2	0.3	0.5	1.2	2.1	3.5
Sweden	0.7	1.8	3.4	6.1	9.3	13.0	19.7
Åland	6.3	8.7	9.9	10.1	16.0	16.7	16.7
Tot-P µg P L⁻¹							
Denmark	10	27	41	**75**	170	251	471
Finland	2	4	7	**13**	22	33	59
Iceland	2	3	5	**8**	22	60	74
Norway	< 1	< 1	1	**2**	5	8	19
Svalbard and Bear Island	2	2	6	**22**	155	445	2256
Sweden	3	4	6	**9**	14	21	37
Åland	10	10	10	**22**	22	28	28
SiO₂ mg L⁻¹							
Denmark	<1	<1	<1	**3**	10	16	17
Finland	0.2	0.5	1.4	**2.8**	4.6	6.4	9.3
Iceland	<0.1	0.4	2.0	**6.0**	9.9	13.7	23
Norway	<0.1	0.3	0.5	**0.9**	1.7	2.7	4.5
Svalbard and Bear Island							
Sweden	<0.1	0.1	0.4	**1.0**	2.0	2.9	4.0
Åland							