Convention on Long-range Transboundary Air Pollution

International Cooperative Programme on Assessment and Monitoring of Acidification of Rivers and Lakes

ICP-WATERS REPORT

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Critical loads and their exceedances for ICP-Waters sites

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Abstract

The International Co-operative Programme on Assessment and Monitoring of Acidification of Rivers and Lakes (ICP Waters) is designed to assess, on a regional basis, the degree and geographical extent of acidification of surface waters. We report here an assessment of critical loads and their exceedances of sulphur and nitrogen acidity for the 92 ICP-sites (72 in Europe and 20 in North America). At 46% of the European sites the critical loads of acidity are less than 50 meq/m^2/yr, and 68% of the sites have critical loads less than 100 meq/m^2/yr. The corresponding figures for the North American sites are 40 and 75%, respectively. Comparing the critical loads with the nitrogen and sulphur depositions in 1990, the current reduction plans (CRP) and maximum feasible reductions (MFR) scenarios in 2010, it was found that of the 72 European sites 51 were exceeded in 1990, 32 will still be exceeded in 2010 under the current reduction plans, and only two at maximum feasible reductions. Apparently, the sensitivity of surface waters to acidification in parts of Europe has not received proper attention.

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CONVENTION ON LONG-RANGE TRANSBOUNDARY AIR POLLUTION

INTERNATIONAL COOPERATIVE PROGRAMME ON ASSESSMENT AND MONITORING OF ACIDIFICATION OF RIVERS AND LAKES

Critical loads and their exceedances for ICP-Waters sites

Prepared by the Programme Centre
Norwegian Institute for Water Research
Oslo, March 1998

Preface

The "Nine Year Report" prepared by the International Cooperative Programme on Assessment and Monitoring of Acidification of Rivers and Lakes (ICP Waters) showed clearly that many sites included in the programme's database were suitable for detecting trends in changes in water chemistry as a result of reduced emissions of sulphur in Europe and North America during the last decades. The present report is an attempt to assess critical loads of sulphur and nitrogen acidity and their exceedances for sites included the ICP Waters programme. Since the programme was not particularly designed for this purpose, an important point was to check whether the required data were available, and if not, to point out which data should be collected to make such an analysis possible. A first draft report was presented to the Task Force meeting in Pitlochry (Scotland) in October 1997. This is the final report revised according to the recommendations given by the Task Force meeting.

Oslo, 05.03.98

Merete Johannessen
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Contents

Summary

The International Cooperative Programme on Assessment and Monitoring of Acidification of Rivers and Lakes (ICP Waters) is designed to assess, on a regional basis, the degree and geographical extent of acidification of surface waters. A new database was established when a long-term trend analysis was carried out in 1997. Here, we report on the computation of critical loads of acidity and their exceedances for the ICP-Waters sites. Of the 112 sites in the new database, 92 sites could be used; 72 located in Europe and 20 in North America. Critical loads and their exceedances were calculated for these sites using two models, the Steady-State Water Chemistry (SSWC) model and the First-order Acidity Balance (FAB) model.

At 46% of the European sites the critical load of acidity is less than 50 meq/m^2/yr, and 68% of the sites have critical loads less than 100 meq/m^2/yr. The corresponding figures for the North American sites are 40 and 75%, respectively. This indicates that many lakes and streams may be sensitive to acidification. The critical loads at the European ICP-Waters sites compared well with the 5-th percentiles of those in the contiguous 50×50 km^2 EMEP grid cells derived from the European critical load database maintained at the Coordination Center for Effects (CCE) under the Task Force on Mapping.

Comparing the critical loads with the nitrogen and sulphur depositions in 1990, and the current reduction plans (CRP) and maximum feasible reductions (MFR) scenarios in 2010, we find that of the 72 European sites 51 were exceeded in 1990, 32 will still be exceeded in 2010 under the current reduction plans, while implementation of maximum feasible reductions would reduce the number of exceeded sites to only two.

The results presented in this report indicate that many of the selected ICP-Waters sites are sensitive to acidification. This suggests that surface waters should generally be included in critical load assessments in Europe. The ICP-Waters database was not designed for calculating critical loads. Nevertheless, parts of the database contained suitable data for calculating critical loads, especially with the SSWC-model. However, for making critical load calculations with the FAB model additional data, especially characteristics of the terrestrial catchment (e.g. landuse), had to be drawn from other sources.

1. Introduction

The International Cooperative Programme on Assessment and Monitoring of Acidification of Rivers and Lakes (ICP Waters) was established in Oslo, Norway in 1986 and is designed to assess, on a regional basis, the degree and geographical extent of acidification of surface waters. The data collected should provide information on dose/response relationships under different conditions and correlate changes in acidic deposition with the physical, chemical and biological status of lakes and streams.

During the last ten years emission reduction measures in Europe and North America have resulted in a decrease in atmospheric sulphur deposition of up to 50%. Nitrogen deposition has stayed almost constant. To relate these developments to changes in surface water chemistry and biology, the ICP Waters data base was used to prepare a 9-year report in 1997 (Lückewille *et al.* 1997).

The 9-year report:

- Compiled a subset of selected and quality controlled water chemistry and site description data (> 120 sites) that can be used for statistical analyses.
- Calculated trends in surface water chemistry separately on data from the 1980s and 1990s for the single ICP Waters sites and for geographic regions (clustering based on similarities in water chemistry).
- Assessed the importance of nitrogen leaching at ICP Waters sites.
- Showed effects of acidification on aquatic fauna

The following criteria for establishing the new data base were applied:

- Sites where data reporting ended before or in 1993 have not been transferred to the new data base.
- For streams and lakes with more than one sampling site, only one was chosen..
- For lakes where data of several depths had been reported, only one was chosen (0.5 to 1.0 m below surface).
- Parameters important for statistical analyses were checked “manually” site by site to find outliers and to check the continuity of time series. Only corrected data were read into the new data base.
- For many sites ion balances could not be calculated because one or more parameters are missing. Since the models for analyzing, e.g., sulphate and nitrate concentrations in water are quite reliable, datasets including at least SO_4, NO_3, Cl, pH, Ca and Mg were read into the new data base.

The main conclusions from the report were: *"Trend analyses (1980's and 1990's) indicate that the reduction in sulphur deposition has lead to an improvement in water chemistry and particularly also to a recovery of the invertebrate fauna at many ICP Waters sites. Decreasing sulphate concentrations emphasize the importance of nitrate as the second important acidifying anion. Besides nitrogen deposition, the overall nitrogen status of ecosystems, changes in climate or climate extremes and hydrology can have strong influences on leaching of excess nitrate (and ammonium) from a watershed".*

The calculation of critical loads for various receptors (surface water, forest soils) is an approach which seeks to link emissions abatement strategies to the capacity of ecosystems to withstand and buffer acid deposition. Critical load calculations formed the basis for the negotiations resulting in the Second Sulphur Protocol that was signed in Oslo (Norway) in 1994. This report presents calculations of critical loads of acidity and their exceedances for sites included in the new ICP Waters database and having the minimum data required for such calculations. The sites used in this study are listed in Table 1 and their locations are displayed in Figure 1.

Table 1. ICP Waters sites for which critical loads are calculated.

Site code	Country, Site name	Site code	Country, Site name
D01	Germany, Black Forest, Duerreychbach	N10	Norway, Telemark, Storgama outflow
D02	Germany, Black Forest, Kleine Kinzig	NL01	The Netherlands, Achterste Goorven, Station E
D03	Germany, Colditzer Forest, Ettelsbach	NL02	The Netherlands, Gerritsflies
D04	Germany, Dahlener Heide, Heidelbach	NL03	The Netherlands, Kliplo
D05	Germany, East Bavaria, Grosse Ohe	P01	Poland, Dlugi Staw Gasienicovy
D10	Germany, Elbansteingebirge, Tauberbach	P02	Poland, Zielony Staw Gasienicovy
D12	Germany, Erzgebirge, Rote Pockau	S01	Sweden, Delaangeraan
D14	Germany, Erzegebirge, Wolfsbach	S03	Sweden, Alsteraan, Stroemsborg
D15	Germany, Fichtelgebirge, Eger	S04	Sweden, Anraasen, Hoersvatn
D16	Germany, Fichtelgebirge, Roeslau	S05	Sweden, Tvaeringen
D17	Germany, Fichtelgebirge, Zinnbach	S06	Sweden, Stensjoen
D18	Germany, Harz, Dicke Bramke	S08	Sweden, Brunnsjoen
D19	Germany, Harz, Grosse Bode	S09	Sweden, Fiolen
D20	Germany, Harz, Grosse Soese	S10	Sweden, Storasjoen
D21	Germany, Harz, Grosse Schacht	S11	Sweden, Fraecksjoen
D22	Germany, Hunsrueck, Graefenbach	SF01	Finland, Hirvilampi
D23	Germany, Hunsrueck, Traunbach	SF02	Finland, Vuorilampi
D24	Germany, Kaufunger Wald, Nieste	SF03	Finland, Maekilampi
D25	Germany, Odenwald, Schmerbach	SF05	Finland, Lapland, Suopalampi
D26	Germany, Rothaargebirge, Elberndorfer Bach	SF06	Finland, Lapland, Vasikkajaervi
D27	Germany, Rothaargebirge, Zinse	UK01	UK, Scotland, Loch Coire nan Arr
D28	Germany, Taunus, Rombach	UK04	UK, Scotland, Lochnager
DK01	Denmark, Sepstrup Sande, Skaerbaek, Station F	UK07	UK, Scotland, Round of Glenhead
DK02	Denmark, Sepstrup Sande, Skaerbaek, Station B	UK10	UK, England, Scoat Tarn
HU01	Hungary, Matra Mountains, Csorret	UK15	UK, Wales, Llyn Llagi
I01	Italy, Lake Paione Inferiore	UK21	UK, N.Ireland, Blue Loch
I02	Italy, Lake Mergozzo	C01	Canada, Ontario, Algoma Region, Batchawana Lake
I03	Italy, Lake Paione Superiore	C02	Canada, Ontario, Algoma Region, Wishart Lake
I04	Italy, River Cannobino	C03	Canada, Ontario, Algoma Region, Little Turkey Lake
I05	Italy, River Pellino	C04	Canada, Ontario, Algoma Region, Turkey Lake
I06	Italy, River Pelesimo	C08	Canada, Quebec, Laflamme Lake
IR01	Ireland, Glendalough, Lake Upper, Mid Lake	C10	Canada, Nova Scotia, Mount Tom Lake
IR02	Ireland, Lough Maumwee, Mid Lake	C11	Canada, Nova Scotia, Mountain Lake
IR03	Ireland, Lough Veagh, Mid Lake	C12	Canada, Nova Scotia, Little Red Lake
LA01	Latvia, Daugava, 3 km above Daugavpils	C13	Canada, Nova Scotia, Kejimkujik Lake
LA02	Latvia, Tulija, Zoseni	C14	Canada, Nova Scotia, Beaverskin Lake
LA03	Latvia, Zvirbuli stream, hydrosite	US05	USA, Maine, Little Long Pond
N01	Norway, Aust Agder, Birkenes	US06	USA, Maine, Tilden Pond
N02	Norway, Aust Agder, Tovdalselva, Boen Bruk	US08	USA, Michigan, Buckeye
N03	Norway, Buskerud, Langtjern outflow	US10	USA, Minnesota, Cruiser
N04	Norway, Finmark, Dalelva, Jarfjord	US11	USA, New York, Adirondack Mountain, Arbutus
N05	Norway, Oppland, Aurdoela, Aurdalsfjorden	US12	USA, New York, Adirondack Mountain, Constable
N06	Norway, Rogaland, Vikedalselva, Vindafjorden	US13	USA, New York, Adirondack Mountain, Dart Lake
N07	Norway, Sogn og Fjordane, Gaular, Eldalen	US15	USA, New York, Adirondack Mountain, Lake Rondaxe
N08	Norway, Sogn og Fjordane, Nausta, Naustdal	US16	USA, New York, Adirondack Mountain, Moss Lake
N09	Norway, Sogn og Fjordane, Trodoela	US17	USA, New York, Adirondack Mountain, Otter Lake

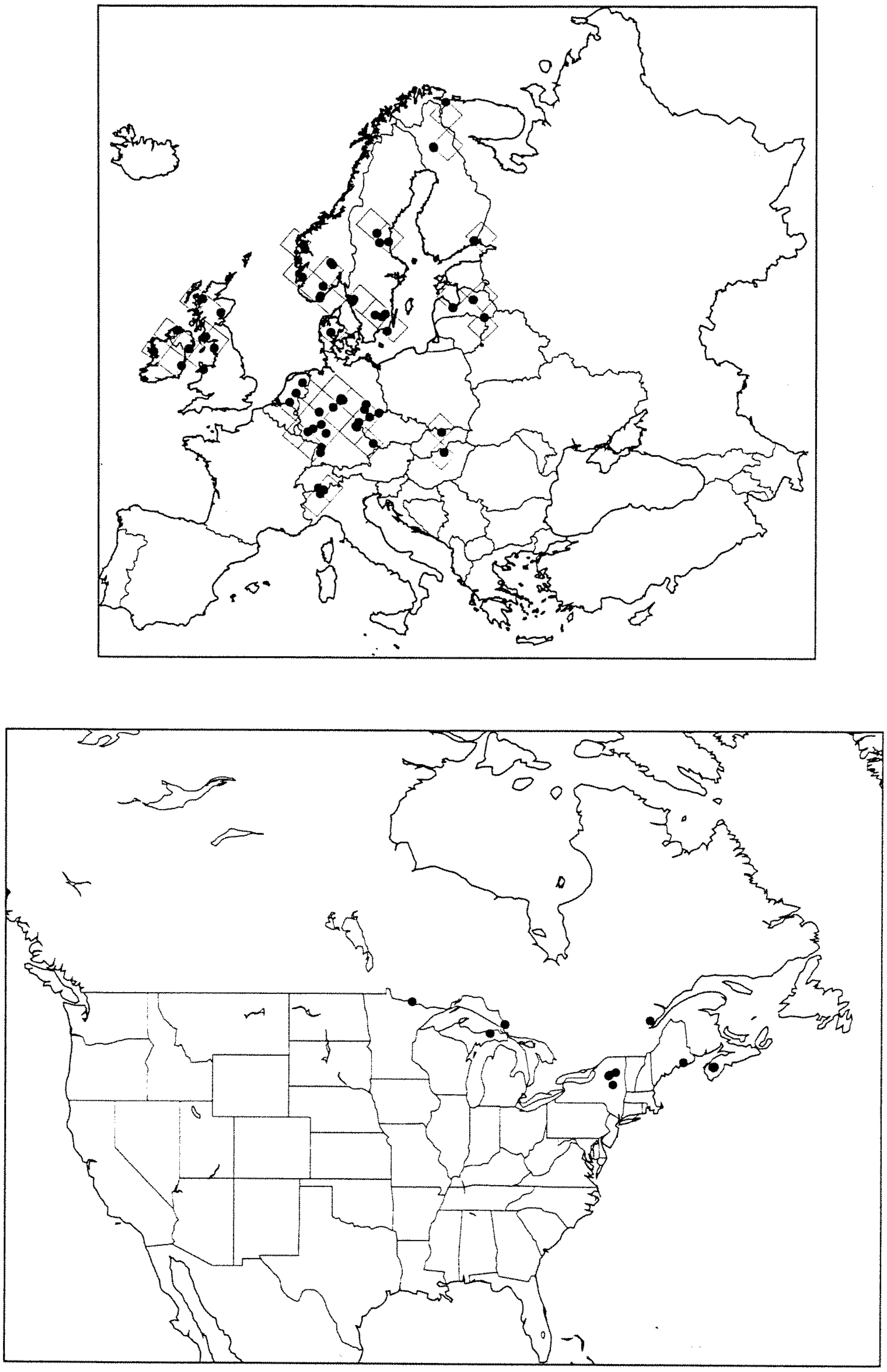

Figure 1. Location of the ICP-Waters sites in Europe and North America for which critical loads are calculated in this study. Also shown are the EMEP150 grid cells in Europe in which the sites are located and from which the deposition data have been used.

2. Critical loads and their exceedances

2.1 The critical load concept

The concept of critical loads has been widely accepted as a basis for designing control strategies to reduce regional air pollution. In order to gain more insight in the magnitude and spatial variation of critical loads, the UN/ECE Excecutive Body of the Convention on Long-range Transboundary Air Pollution (LRTAP) has set up a Task Force on Mapping Critical Levels/Loads under the Working Group on Effects. Critical loads data from individual countries are collected, mapped and reported by the Coordination Center for Effects (CCE), located at the National Institute of Public Health and the Environment (RIVM) in Bilthoven, the Netherlands. The results are reported biannually (see Posch *et al.* 1997a for the latest report).

The calculation of critical loads for various receptors (surface water, forest soils) is an approach which seeks to link emissions abatement strategies to the capacity of ecosystems to withstand and buffer the effects of acid deposition A critical load is defined as (Nilsson and Grennfelt 1988):

"A quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge".

Until 1994 the international work focused on the development of methodologies and the synthesis of national data to produce European maps of critical sulphur deposition used in the negotiations of the Second Sulphur Protocol, signed in Oslo in June 1994. In order to prepare the scientific support for the negotiations of a revised protocol on the reduction of nitrogen emissions, a new methodology was developed to take into account multiple effects (i.e. eutrophication and acidification) of multiple pollutants (sulphur and nitrogen). The critical loads of S and N are interrelated and therefore a single critical load for one pollutant cannot be defined without making assumptions about the other.

2.2 Calculating critical loads for surface waters

Two models – one empirical and one process-oriented – for calculating critical loads of acidifying deposition (both S and N) for surface waters are summarized: The (modified) 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. The FAB-model is based on the steady-state mass balance approach, widely used in many models for computing critical loads for forest soils (see UBA 1996, Posch *et al.* 1997a). Here only the model formulations are presented, and for a derivation of the models we refer to the cited literature.

2.2.1 The modified SSWC-model

The critical load of acidity is calculated as (see, e.g., Henriksen *et al.* 1990):

$$CL(A) = Q\,([BC^*]_0 - ANC_{limit}) \quad (1)$$

where Q is the runoff, $[BC^*]_0$ is the original base cation concentration, and ANC_{limit} is the chosen critical ANC threshold.; the star refers to sea salt corrected quantities. $[BC^*]_0$ is estimated from the present leaching of base cations and the long-term changes in the inputs of strong acid anions using the so-called F-factor (Henriksen 1984, Brakke *et al.* 1990):

$$[BC^*]_t - [BC^*]_0 = F\,([SO_4^*]_t + [NO_3]_t - [SO_4^*]_0 - [NO_3]_0) \quad (2)$$

where the subscripts 0 and t refer to the original (background) and present concentrations, respectively, $[SO_4^*]_0$ is estimated from a linear regression with $[BC^*]_t$ using data from Norwegian background lakes, whereas $[NO_3]_0=0$. The F-factor is calculated following Brakke *et al.* (1990) but modified to account for catchment with low runoff:

(3) $$F = \sin((\pi/2)Q[BC^*]_t/S) \quad \text{for} \quad Q[BC^*]_t < S$$

where S is the annual base cation flux above which F=1. The critical ANC-limit is calculated by a model suggested by Henriksen *et al.* (1995) and results in values between 0 and 50 μeq/l depending on the catchment characteristics.

The SSWC-model was modified to include both S and N acidity by considering the present (measured) N-leaching (N_{leach}) in the calculation of the present exceedance of the critical load (Kämäri *et al.* 1992):

(4) $$\text{Present Ex(Ac)} = S_{dep} + N_{leach} - CL(A)$$

where S_{dep} is the present deposition of sulphur. The N leaching term describes the balance between N deposition and the N processes in the catchment such as uptake, immobilization, denitrification and in-lake retention of nitrogen.

2.2.2 The FAB-model

When considering the effects of both sulphur and nitrogen simultaneously, one cannot expect to obtain unique critical loads of S and N, since a reduction in the deposition of sulphur might allow a higher deposition of acidifying nitrogen compounds without causing 'harmful effects'. From an acidity balance one can derive the following equation, describing the trade-off between sulphur and nitrogen critical loads (Posch *et al.* 1997b):

(5) $$a_N\, CL(N) + a_S\, CL(S) = b_1 N_{upt} + b_2 N_{imm} + BC_{le,crit}$$

where N_{upt} and N_{imm} are the net growth uptake (harvested N) and immobilization of N, respectively, and a_N, a_S, b_1 and b_2 are dimensionless constants depending on lake and catchment properties alone:

(6a) $$a_N = (1-f_{de}(1-r))(1-\rho_N)$$

(6b) $$a_S = 1-\rho_S$$

(6c) $$b_1 = f(1-f_{de})(1-\rho_N)$$

(6d) $$b_2 = (1-r)(1-f_{de})(1-\rho_N)$$

where f is the fraction of forest area within the catchment and r is the lake:catchment area ratio. In deriving eq.5 not only the uptake and immobilization of N have been taken into account, but also denitrification and the in-lake retention of N and S, all three as linear functions of the net input of N (respectively S) with proportionality coefficients f_{de}, ρ_N and ρ_S, leading to the coefficients above. The in-lake retention coefficient ρ_N is modeled by a kinetic equation (Kelly *et al.* 1987, Dillon and Molot 1990):

(7) $$\rho_N = s_N / (Q/r + s_N)$$

where s_N is the net mass transfer coefficient for N (m/yr). An analogous equation holds for ρ_S (Baker and Brezonik 1988). Finally, the critical base cation leaching from the catchment is computed from water quality data by the steady-state model introduced above (eq.1):

(8) $$BC_{le,crit} = Q([BC^*]_0 - [ANC]_{limit})$$

In addition to eq.5 the critical load of S is limited by the following constraint:

(9) $$CL(S) \leq CL_{max}(S) = BC_{le,crit} / a_S$$

Below a value of

(10) $$CL_{min}(N) = (b_1 N_{upt} + b_2 N_{imm}) / a_N$$

all N deposition is taken up, retained or immobilized in the catchment. On the other hand, the highest critical load of N (in the absence of S deposition) is given by

(11) $$CL_{max}(N) = CL_{min}(N) + BC_{le,crit} / a_N$$

Eq.5, together with these constraints, determines the so-called critical load function (Figure 2), separating the N- and S-deposition values which cause 'harmful effects' (exceedance) from those which do not (non-exceedance).

As mentioned above, unique critical loads for S and N cannot be specified; however, this may be an advantage, since it allows to determine (cost-)optimal deposition reductions. If the deposition of one of the compounds is fixed (prescribed), a unique critical load for the other can be computed from eq.5.

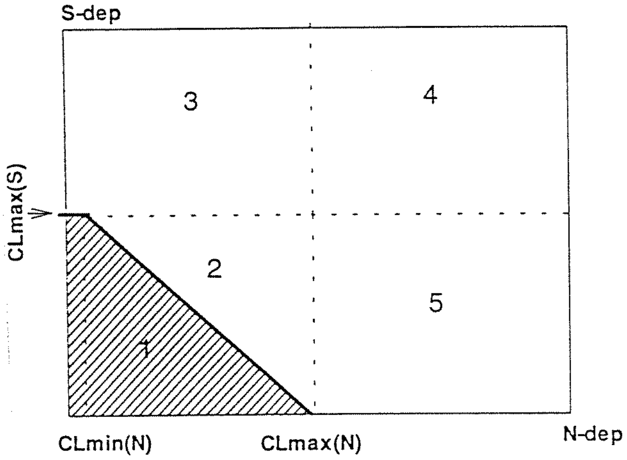

Figure 2. The critical load function as defined by the FAB-model. The shaded area (1) indicates those N and S deposition values not causing exceedance. The critical load function (thick line) is determined by the values of $CL_{max}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$. The location of the lake's N and S deposition in the diagram determines the reduction requirements: 1=no reductions required; 2=N or S reductions required (free choice); 3=mandatory S reductions; 4=mandatory S and N reductions; 5=mandatory N reductions.

3. Data

Table 2 shows the data required to calculate the critical load of acidity for the SSWC- and the FAB-model. As can be seen the data requirements for the FAB model are more extensive than those required for the SSWC-model.

Table 2. Input data requirements for the critical load models

SSWC-model: Data needed for the calculation of critical loads of acidity are:

Variable	Value
Base cations: Ca, Mg, Na, K	Yearly weighted average values
Anions: SO_4, NO_3, Cl	Yearly weighted average values
Runoff	Yearly mean runoff

FAB-model: Requires in addition to the data for the SSWC-model the following data:

Variable	Value
Lake area	Measured from maps
Catchment area	Measured from maps
Forest fraction of catchment	Measured from maps
N_{upt}: net N uptake in catchment	Depends on tree species and harvesting practice For non-productive forests $N_{upt} = 0$
N_{imm}: N immobilization	0.5-1 kg/ha/yr (UBA 1996)
f_{de}: denitrification fraction	estimated as $0.1+0.7f_{peat}$; f_{peat} ...peat fraction in catchment
s_N: mass transfer coefficient for N	2-8 m/yr (Dillon and Molot 1990) (=0 for streams)
s_S: mass transfer coefficient for S	0.2-0.8 m/yr (Baker and Brezonik 1988) (=0 for streams)

When the draft report was prepared, the new database contained runoff values only for about half of the sites. Thus, of the 112 sites, only 59 were used for calculations of critical loads of acidity in the draft report. After the Pitlochry meeting the Focal Centres responsible for the sites with missing data were contacted. The additional information provided by them allowed to calculate critical loads for a total of 92 sites (72 in Europe and 20 in North America; see Table 1).

To calculate the critical loads for the sites we decided to use the average data for the chemical components for the time period 1992 to last entry, normally 1994 or 1995. The period and number of observations for each value are given in Table A1 (Appendix), and the water chemistry for the sites are given in Table A2 (Appendix).

4. Results

4.1 SSWC-model: Critical loads and their exceedances

We have calculated the critical load of acidity for each of the sites given in Table 1 using the chemistry data given in Table A2 (Appendix). The results are given in Table 3 (second column). We have also calculated the critical load exceedances for 1990 sulphur deposition and the deposition according to the Current Reduction Plan (CRP) scenario for 2010 (mainly a result of the 1994 Sulphur Protocol). In addition, also the exceedances under the Maximum (Technically) Feasible Reduction (MFR) scenario for the year 2010 have been calculated. The emission data were taken from the Task Force of Integrated Assessment Modelling (TFIAM) under the LRTAP Convention and the depositions were calculated using transport matrices provided by the MSC-West of EMEP.

The critical load distribution of the European sites (Figure 3) shows that for 46% of them the critical load is less than 50 meq/m^2/yr, and 68% of the sites have critical loads less than 100 meq/m^2/yr. The corresponding figures for the North American sites are 40 and 75%, respectively. This indicates that many surface waters both in Europe and in North America may be sensitive to acidification. The least sensitive sites are found in Latvia and Germany. Figure 3 also shows the distribution of critical loads for 4650 lakes in Norway, Sweden, Finland and Russian Kola selected statistically to represent the population of lakes > 0.04 km^2 in the area (Henriksen et al. 1998). For 41% of the lakes the critical load is less than 50 meq/m^2/yr, and for 71% below 100 meq/m^2/yr. Although the three populations are not strictly comparable because they have been selected on the basis of different criteria, it is interesting that the distributions are rather similar, with the majority of the sites located in areas with low critical loads.

In Table 3 the sites are sorted according to decreasing exceedance due to the 1990 S-deposition. The highest exceedances are found in Germany, the Netherlands and in the Tatra Mountains in Poland. Especially German sites are highly exceeded despite a high critical load, because of very high acid load. For 61% of the sites the critical loads for sulphur were exceeded in 1990, while the Current Reduction Plans (CRP) will reduce the number of exceeded sites down to 14%, and the MFR-scenario will result in only 8% exceeded sites.

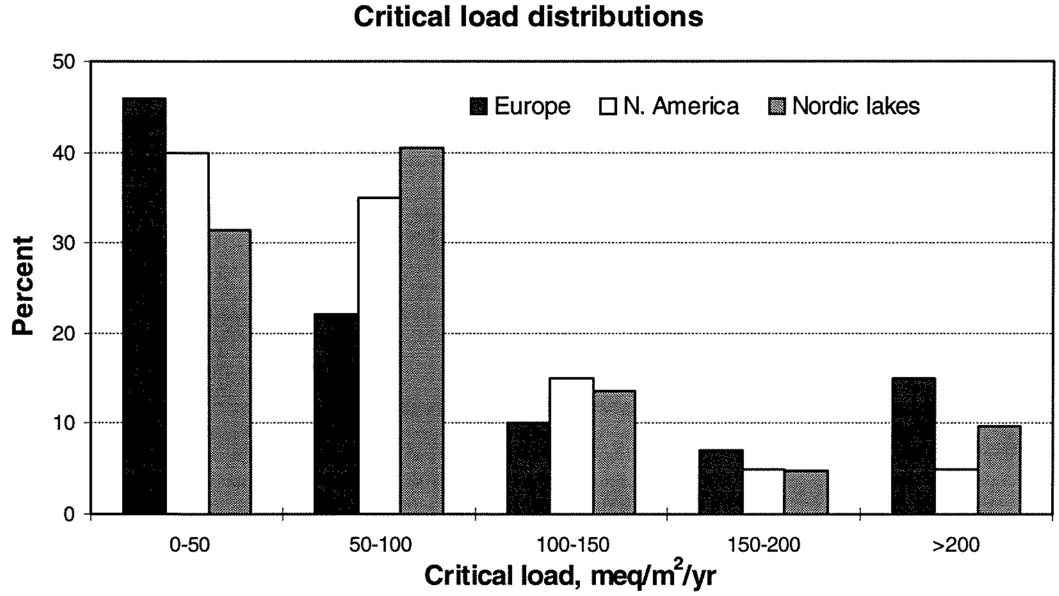

Figure 3. Critical load frequency distributions for European and North American ICP Waters sites compared with lake populations in Norway, Sweden, Finland and Russian Kola (Henriksen et al. 1998).

Table 3. Critical loads of acidity and their exceedances according to the SSWC model (in meq/m^2/yr) sorted according to 1990 decreasing exceedance. Positive values indicate exceedance, negative values non-exceedance. (CL(A) = critical load of acidity, CRP = Current Reduction Plans for 2010, MFR = Maximum Feasible Reductions for 2010).

European sites

		Sulphur deposition			Exceedance		
Site code	**CL(A)**	**1990**	**CRP**	**MFR**	**Ex-1990**	**Ex-CRP**	**Ex-MFR**
D04	29	571	142	50	**542**	113	21
D12	61	571	142	50	**510**	81	-11
D10	154	571	142	50	**417**	-13	-104
D03	259	571	142	50	**312**	-118	-209
D19	104	363	69	24	**259**	-35	-80
D20	144	363	69	24	**219**	-75	-120
NL01	30	177	72	21	**147**	42	-9
NL03	9	135	49	14	**126**	40	5
D24	13	138	45	14	**125**	32	1
NL02	12	135	49	14	**123**	37	2
D17	31	134	40	14	**103**	9	-17
D16	36	134	40	14	**98**	4	-22
P01	118	216	95	29	**98**	-23	-89
D21	268	363	69	24	**95**	-199	-244
D25	27	107	37	11	**80**	10	-16
D28	29	107	37	11	**78**	8	-18
D15	69	134	40	14	**65**	-29	-55
D22	64	129	48	14	**65**	-16	-50
I03	46	111	68	15	**65**	22	-31
P02	165	216	95	29	**51**	-70	-136
N04	35	83	78	13	**48**	43	-22
LA03	32	73	44	12	**41**	12	-20
I01	74	111	68	15	**37**	-6	-59
UK10	36	71	27	7	**35**	-9	-29
N10	27	60	26	9	**33**	-1	-18
S10	34	66	29	10	**32**	-5	-24
D23	76	105	50	13	**29**	-26	-63
UK07	43	71	27	7	**28**	-16	-36
N02	47	75	34	10	**28**	-13	-37
D01	58	85	38	10	**27**	-20	-48
N01	37	60	26	9	**23**	-11	-28
UK21	30	53	22	5	**23**	-8	-25
S04	34	55	25	9	**21**	-9	-25
UK15	65	79	31	7	**14**	-34	-58
SF01	38	51	36	9	**13**	-2	-29
S08	71	84	36	12	**13**	-35	-59
UK04	34	46	17	5	**12**	-17	-29
SF06	13	24	18	5	**11**	5	-8
S09	60	66	29	10	**6**	-31	-50
D18	127	133	40	13	**6**	-87	-114
SF03	46	51	36	9	**5**	-10	-37
SF02	47	51	36	9	**4**	-11	-38
N09	36	35	17	8	**-1**	-19	-28
N07	37	35	17	8	**-2**	-20	-29
N06	60	56	25	9	**-4**	-35	-51
SF05	29	24	18	5	**-5**	-11	-24
N03	39	33	15	6	**-6**	-24	-33
DK02	79	72	29	9	**-7**	-50	-70

Table 3 (continued).

		Sulphur deposition			Exceedance		
Site code	**CL(A)**	**1990**	**CRP**	**MFR**	**Ex-1990**	**Ex-CRP**	**Ex-MFR**
N05	45	33	15	6	**-12**	-30	-39
S06	38	26	15	5	**-12**	-23	-33
N08	48	35	17	8	**-13**	-31	-40
IR02	46	29	19	6	**-18**	-27	-40
S03	94	66	29	10	**-28**	-65	-84
UK01	71	37	18	7	**-34**	-53	-64
D14	170	134	40	14	**-36**	-130	-156
IR03	64	28	15	6	**-36**	-49	-58
D05	156	119	41	14	**-37**	-115	-142
S05	61	18	10	4	**-43**	-51	-57
S11	103	55	25	9	**-48**	-78	-94
DK01	135	72	29	9	**-63**	-106	-126
S01	92	26	15	5	**-66**	-77	-87
IR01	127	41	26	6	**-87**	-101	-121
D02	176	85	38	10	**-91**	-138	-166
D27	284	138	45	14	**-146**	-239	-270
D26	293	138	45	14	**-155**	-248	-279
I02	357	111	68	15	**-246**	-289	-342
I04	367	111	68	15	**-256**	-299	-352
I06	348	85	53	11	**-263**	-295	-337
I05	397	85	53	11	**-312**	-344	-386
LA01	624	83	47	13	**-541**	-577	-611
H01	785	175	106	43	**-610**	-679	-742
LA02	1223	64	41	11	**-1159**	-1182	-1212

North American sites

		Sulphur deposition			Exceedance		
Site code	**CL(A)**	**1990**	**CRP**	**MFR**	**Ex-1990**	**Ex-CRP**	**Ex-MFR**
C09	44	86	62	n.a.	**42**	18	
C07	46	86	62	n.a.	**40**	16	
C05	52	86	62	n.a.	**34**	10	
C06	54	86	62	n.a.	**32**	8	
US05	37	56		n.a.	**19**		
C10	27	43	34	n.a.	**16**	7	
C14	27	43	34	n.a.	**16**	7	
C11	29	43	34	n.a.	**14**	5	
C13	37	43	34	n.a.	**6**	-3	
US17	62	67		n.a.	**5**		
US13	64	67		n.a.	**3**		
C08	84	86	62	n.a.	**2**	-22	
US06	60	56		n.a.	**-4**		
C01	90	73	55	n.a.	**-17**	-35	
US15	84	67		n.a.	**-17**		
US16	110	67		n.a.	**-43**		
C02	124	73	55	n.a.	**-51**	-69	
US11	139	67		n.a.	**-72**		
C03	170	73	55	n.a.	**-97**	-115	
C04	188	73	55	n.a.	**-115**	-133	
US08	229	n.a.	n.a.	n.a.			
US10	175	n.a.	n.a.	n.a.			
US12	92	n.a.	n.a.	n.a.			

4.2 FAB-model: Critical load functions and their exceedances (European sites)

For the European sites (see Table 1 and Figure 1) critical loads have also been calculated using the FAB-model. Since this model requires additional input data (see Table 2), especially concerning the terrestrial catchment, the following assumptions have been made: (a) for the forest fraction in the catchment the values for coniferous and deciduous trees have been added (and assumed zero if no data are given in Table A3 in the Appendix); (b) the net nitrogen uptake, N_{upt}, has been extracted from the CCE's European critical load data base as the mean of all uptake values in the 50×50 km^2 EMEP grid cell in which the lake/stream is located (called the contiguous EMEP50 grid cell in the sequel); (c) for N immobilization, N_{imm}, a value of 1 kgN/ha/yr (=7.143 meq/m^2/yr) has been used for all sites (see UBA 1996); (d) the denitrification fraction f_{de} has been estimated from the fraction of bogs (peatlands) in the catchment area (assumed zero if no data are given in Table A3 in the Appendix) according to the formula $f_{de} = 0.1+0.7f_{peat}$, and (e) for the mass transfer coefficients we assumed s_N=5 m/yr and s_S=0.5 m/yr as mean values of data reported in the literature (see Posch et al. 1997b; s_N=s_S=0 for streams).

Table 4 compares the site specific critical loads for S and N calculated with the FAB-model and the 5-th and 95-th percentiles of the critical load distribution in the contiguous EMEP50 grid cell, extracted from the CCE database. Note that this database contains critical loads for a variety of ecosystems, mostly for lakes in the Nordic countries and forest soils in the rest (see Posch et al. 1997a). These percentiles are chosen to illustrate the range of critical loads within each grid cell. Figure 3 compares the site specific critical load values for sulphur with the 5-th and 95-th percentile values of the contiguous grids. The distributions of the critical loads are very similar for the ICP-site specific value and the 5-th percentile of the grid in which it is located, and about 70% of the sites have critical loads less than 100 meq/m^2/yr. Not surprisingly, the 95-th percentile values are generally significantly higher than the ICP-site values and the 5-th percentile values. There was no correlation between the critical loads for ICP-sites and the 5-th percentile grid values, but for the 30 ICP-sites with values below 100 meq/m^2/yr, as many as 27 of the corrtiguous 5-th percentile grid values were also less than 100 meq/m^2/yr. Most of the grid values are based on forest soils as ecosystem, except for the Nordic countries where the grid values are also based on lakes. This indicates that surface waters in many European countries could be as sensitive as forest soils.

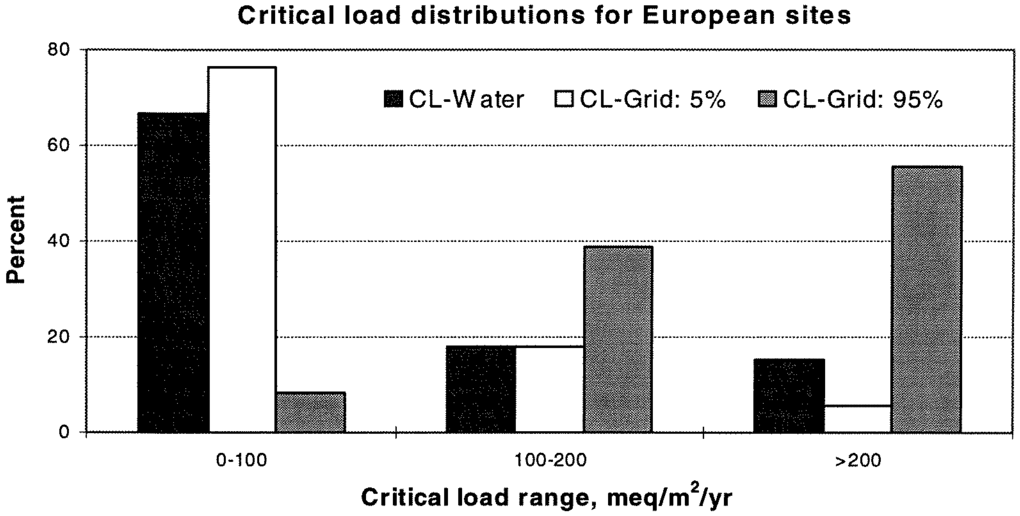

Figure 3. Comparison of the frequency distributions of the critical loads of sulphur computed with the FAB-model for the European ICP-Waters sites and the 5-th and the 95-th percentiles of the $CL_{max}(S)$ of the contiguous EMEP50 grid cells.

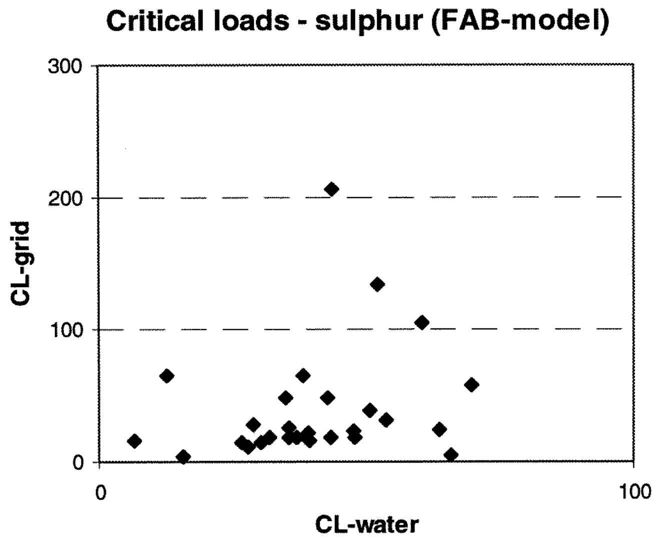

Figure 4. Comparing critical loads of sulphur less than 100 meq/m^2/yr for European ICP-Waters sites with CCE's 5-th percentile contiguous grid values of $CL_{max}(S)$.

Table 4. FAB critical load values for S and N for the European ICP Waters sites and the 5-th and 95-th percentiles of the critical loads in the contiguous EMEP50 grid cells extracted. from the CCE-data base (Units: meq/m^2/yr).

	EMEP50 grid cell		Site values		Contiguous EMEP50 grid cell CL-values			
Site	*I50*	*J50*	*$CL_{max}(S)$*	*$CL_{max}(N)$*	*$CL_{max}(S)$ 5%*	*$CL_{max}(S)$ 95%*	*$CL_{max}(N)$ 5 %*	*$CL_{max}(N)$ 95%*
D01	66	42	58	138	56	222	129	285
D02	66	41	175	262	17	129	85	204
D03	67	50	258	339	29	249	77	303
D04	67	51	29	79	23	247	69	293
D05	71	47	156	238	15	104	78	197
D10	69	51	154	288	38	170	90	340
D12	68	50	60	130	47	162	126	253
D14	68	48	170	316	30	135	92	211
D15	68	48	69	136	30	135	92	211
D16	68	48	36	99	30	135	92	211
D17	68	48	31	93	30	135	92	211
D18	63	49	127	214	66	231	141	323
D19	64	49	104	183	49	221	116	312
D20	64	49	144	228	49	221	116	312
D21	64	49	267	365	49	221	116	312
D22	63	43	64	132	38	283	88	374
D23	63	42	76	150	31	256	92	360
D24	63	48	13	88	69	250	150	334
D25	65	44	27	104	78	248	169	319
D26	62	46	292	421	81	215	157	322
D27	62	46	284	401	81	215	157	322
D28	64	45	29	97	119	368	176	435

Table 4, (continued)

	EMEP50 grid cell		Site values		Contiguous EMEP50 grid cell CL-values			
Site	*I50*	*J50*	$CL_{max}(S)$	$CL_{max}(N)$	$CL_{max}(S)$ 5%	$CL_{max}(S)$ 95%	$CL_{max}(N)$ 5 %	$CL_{max}(N)$ 95%
DK01	56	56	134	249	134	297	183	352
DK02	56	56	79	243	134	297	183	352
H01	80	54	812	1281	151	151	151	151
I01	70	37	75	100	107	158	118	1106
I02	70	37	380	707	107	158	118	1106
I03	70	37	46	67	107	158	118	1106
I04	71	37	367	605	159	264	229	1159
I05	71	36	396	510	191	191	258	1191
I06	71	36	348	451	191	191	258	1191
IR01	42	38	127	160	29	388	45	417
IR02	38	38	62	86	24	413	33	420
IR03	39	42	66	101	50	91	58	118
LA01	70	72	624	700	331	1000	398	2000
LA02	67	73	1223	1366	294	454	359	1545
LA03	66	70	32	43	320	440	390	1502
N01	51	59	38	58	15	101	23	126
N02	52	58	47	67	23	134	36	155
N03	50	63	41	86	22	226	32	252
N04	46	90	34	57	28	97	47	115
N05	49	63	45	66	18	1000	50	1477
N06	48	59	59	77	24	535	32	553
N07	45	62	37	50	18	288	26	318
N08	45	62	48	63	18	288	26	318
N09	45	62	35	53	18	288	26	318
N10	51	60	27	44	14	104	32	126
NL01	58	44	80	574	84	241	176	519
NL02	58	46	39	312	105	204	186	362
NL03	58	47	26	202	65	189	155	481
P01	78	56	118	151	151	437	341	832
P02	78	56	169	261	151	437	341	832
S01	53	71	113	133	16	132	58	319
S03	60	63	93	111	34	215	112	307
S04	55	61	34	71	11	293	67	332
S05	51	70	66	139	4	204	40	392
S06	53	70	46	160	8	141	59	370
S08	62	61	73	161	206	206	255	255
S09	59	62	75	409	31	182	111	309
S10	60	62	37	143	18	138	97	318
S11	55	61	109	192	11	293	67	332
SF01	62	79	40	70	48	94	85	184
SF02	62	79	53	130	48	94	85	184
SF03	62	79	59	210	48	94	85	184
SF05	49	85	33	82	3	120	15	177
SF06	49	85	17	56	3	120	15	177
UK01	39	48	70	87	58	93	79	119
UK04	42	48	36	67	25	165	46	179
UK07	43	44	44	67	39	194	60	222
UK10	45	43	36	53	65	338	78	366
UK15	45	40	65	84	59	293	74	320
UK21	42	41	31	48	14	102	44	111

In Figure 5 the critical load functions for all 72 European ICP Waters sites calculated with the FAB-model are displayed as thick lines in the (N_{dep},S_{dep})-plane together with the range of critical load functions of the contiguous EMEP50 grid cell indicated as grey shaded area delimited by their 5-th and 95-th percentiles (see also Table 4). For many sites the critical load function lies close to the 5-th percentile of the distribution of the critical load functions (see also Fiure 3). This indicates that the ICP-Waters sites are at the end of the range of critical loads in those grid cells. Thus , in order to account for sensitivity of all ecosystems in a grid cell, surface waters should be included in critical loads mapping where applicable. For the Nordic countries (N, S and SF), where the grid critical loads are dominated by lakes, the ICP-Waters sites (mostly streams in Norway and lakes in Sweden and Finland) fit well into the overall distribution within each grid, albeit at the lower end.

Also shown in Figure 5 are the nitrogen and sulphur deposition pairs for 1990, current reduction plans (CRP) and maximum feasible reductions (MFR) in 2010 (see Table 3). Note that these are not deposition values measured at the site, but average values from the contiguous EMEP150 grid cell. Of the 72 sites 51 were exceeded in 1990, 32 of those will still be exceeded in 2010 under the current reduction plans, whereas implementation of maximum feasible reductions would reduce the number of exceeded sites to only two.

Furthermore, for the lakes among the ICP-Waters sites the critical load function is also computed by neglecting inlake S- and N-retention and displayed a dashed line. Note that in this case the intersection with the S-axis (labelled with SSWC) represents the critical load calculated by the SSWC-model ($CL_{max}(S)$ = CL/Ac)). This also shows how the critical load for lakes depend on the assumption about inlake retention processes. As expected (s_N ten times s_S) the critical load for nitrogen is more affected by inlake retention processes.

4.3 North American sites

Data for 1990 sulphur and nitrogen deposition are available for all Canadian sites (Table 3). Deposition data for 1990 for the US-sites are available for Maine and the Adirondacks only (Table 3). Deposition data for CRP are available for Canada only. For North America we cannot compare the site critical loads with EMEP-grid percentiles, because they are not available. For nine Canadian sites the critical load is exceeded in 1990 (Table 3), while seven will still be exceeded at the 2010 CRP-deposition. The Algoma lakes appear not to be sensitive to acidification at present loading, while the Nova Scotia and Quebec lakes appear rather sensitive. The critical loads are slightly exceeded for three US-sites in 1990, one in Maine and two in the Adirondacks (Table 3).

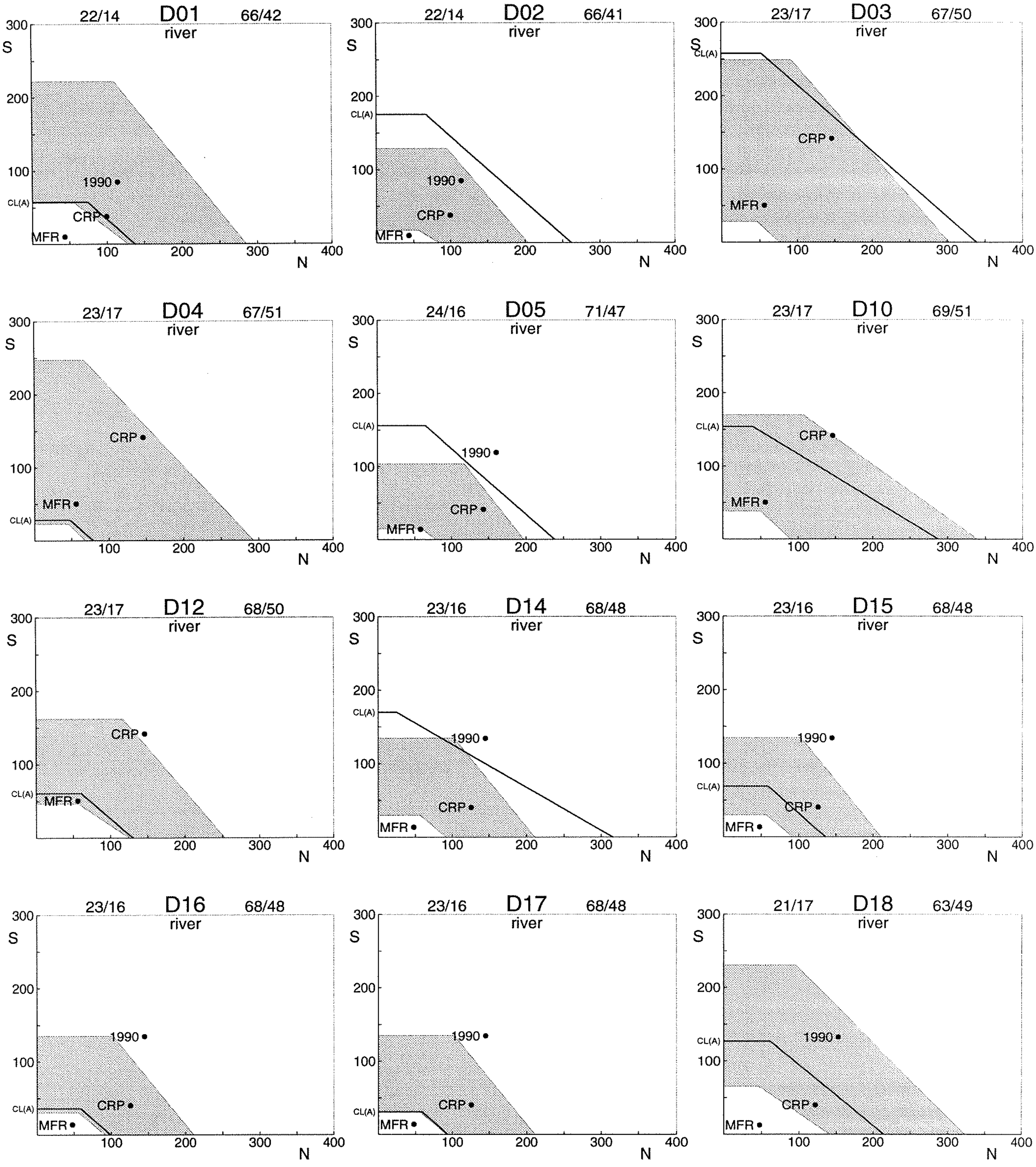

Figure 5. Critical load functions for the European ICP Waters sites (thick and dashed lines). Also shown are the range between the 5-th and 95-th percentiles of the critical load functions in the contiguous EMEP50 grid cell as grey shaded areas. Also depicted are the N and S depositions in 1990 and in 2010 according to the CRP and MFR scenarios (all only when in the displayed area). The critical load of acidity CL(A) computed with the SSWC-model is indicated on the S-axis. To the left and right of the site code the EMEP150 and EMEP50 grid cell indices are shown, respectively.

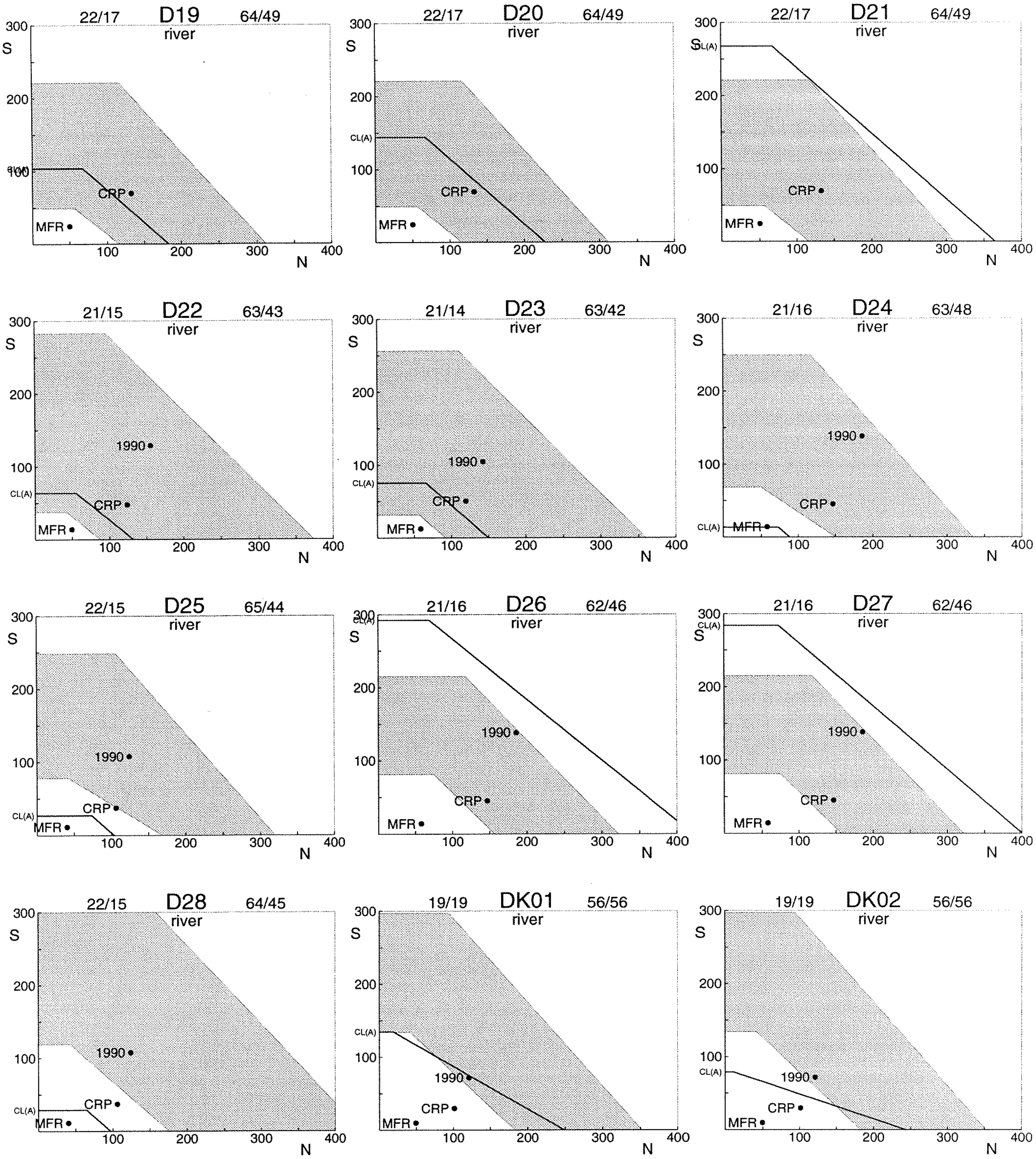

Figure 5 (continued).

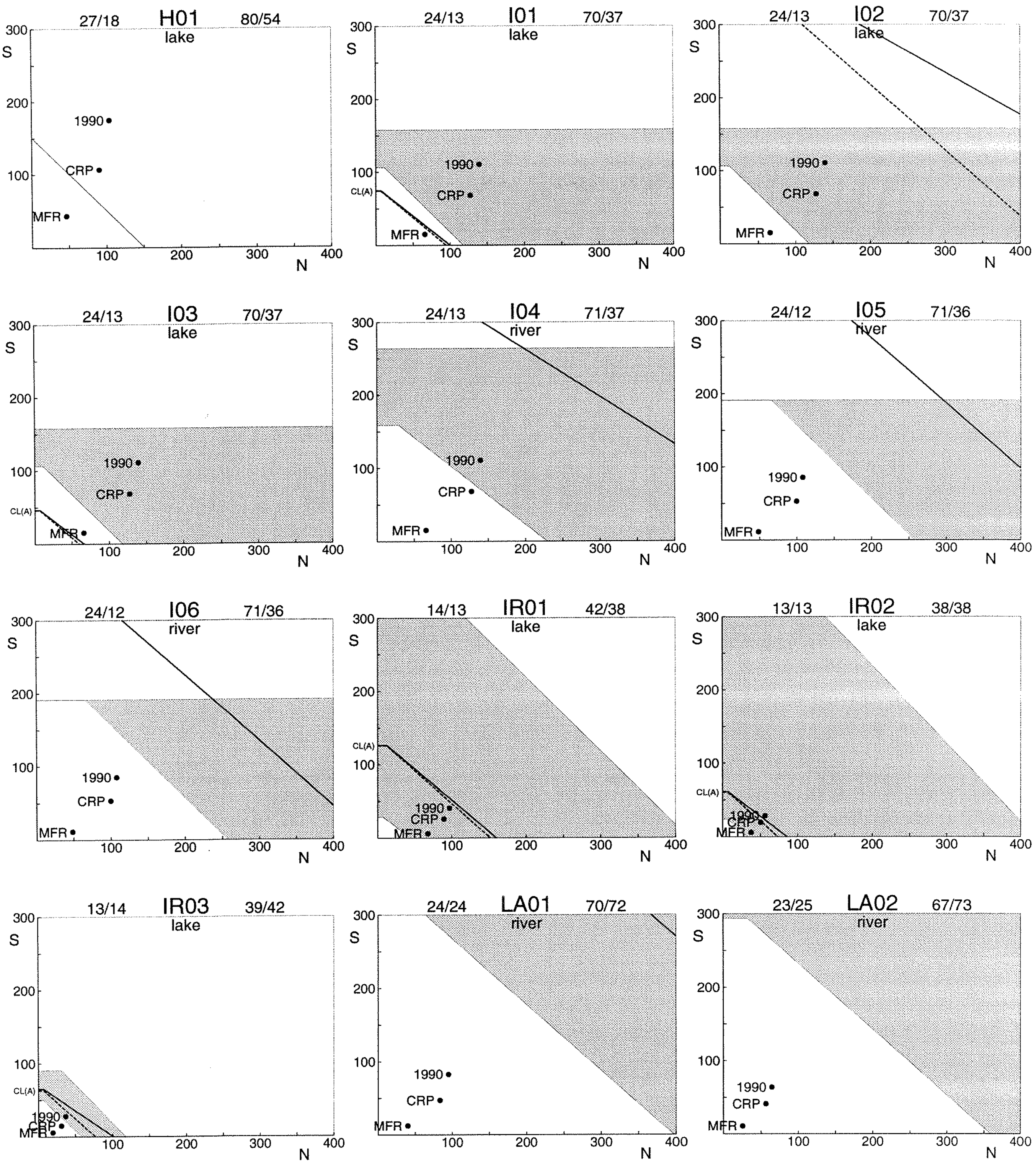

Figure 5 (continued).

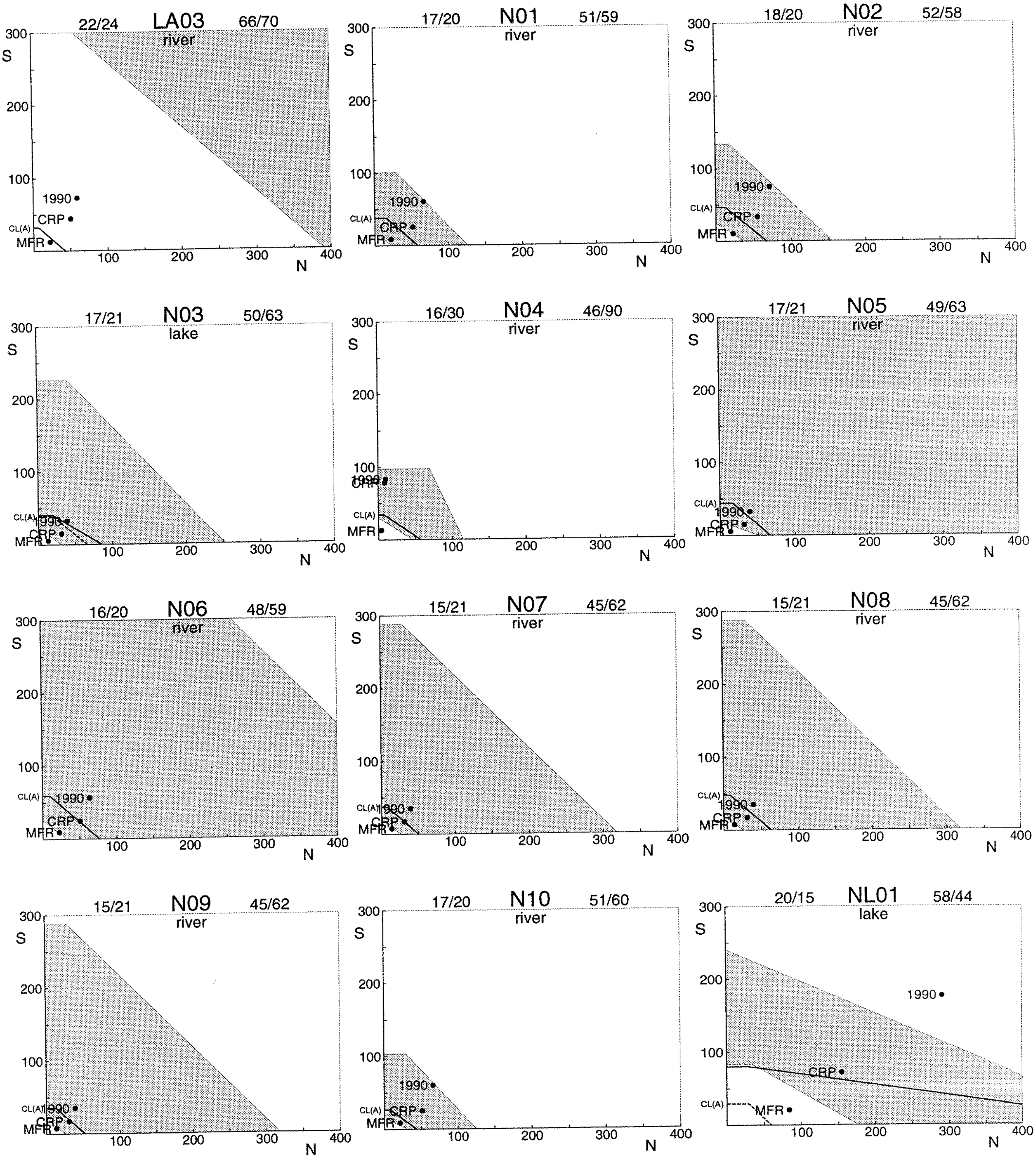

Figure 5 (continued).

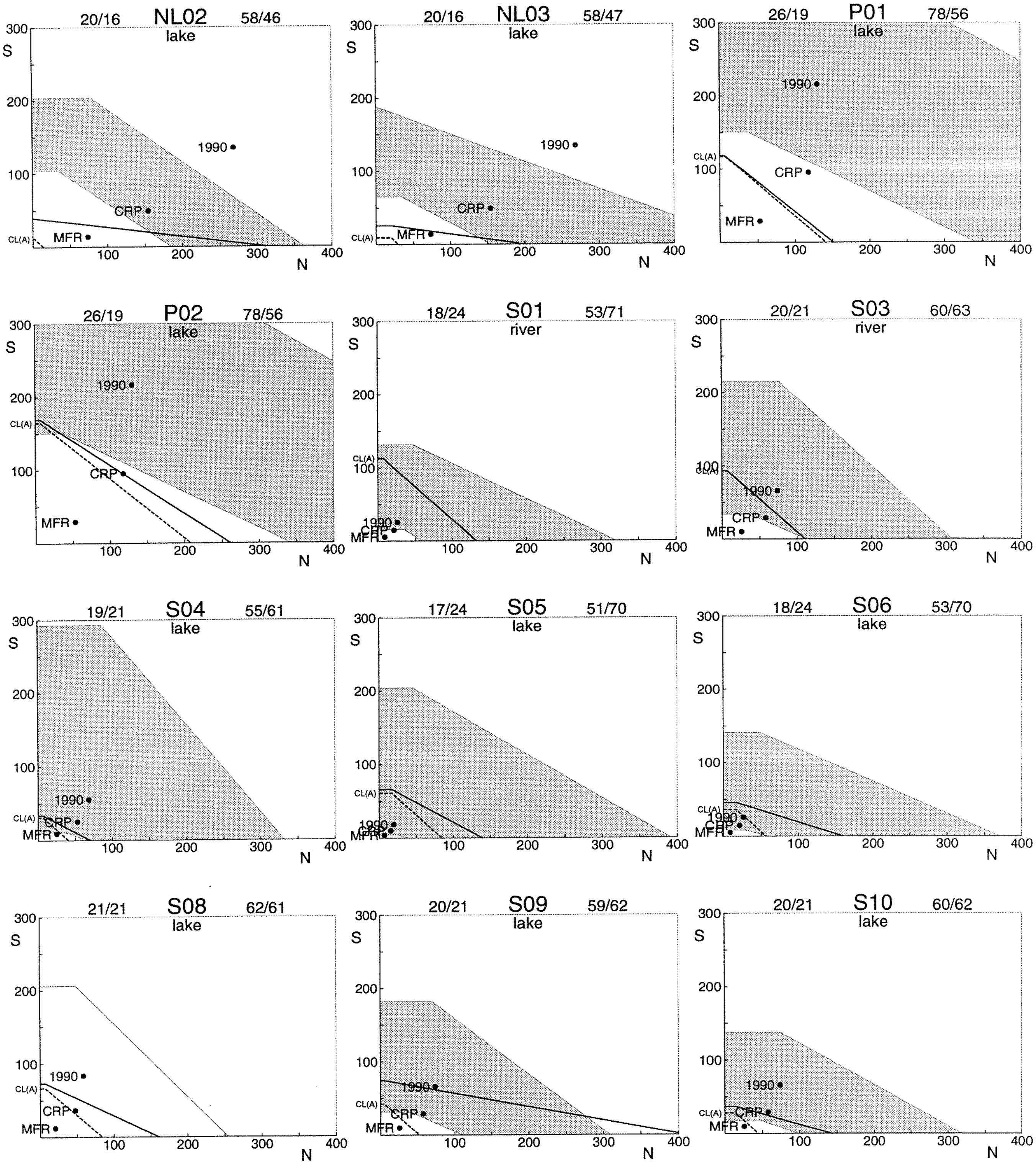

Figure 5 (continued).

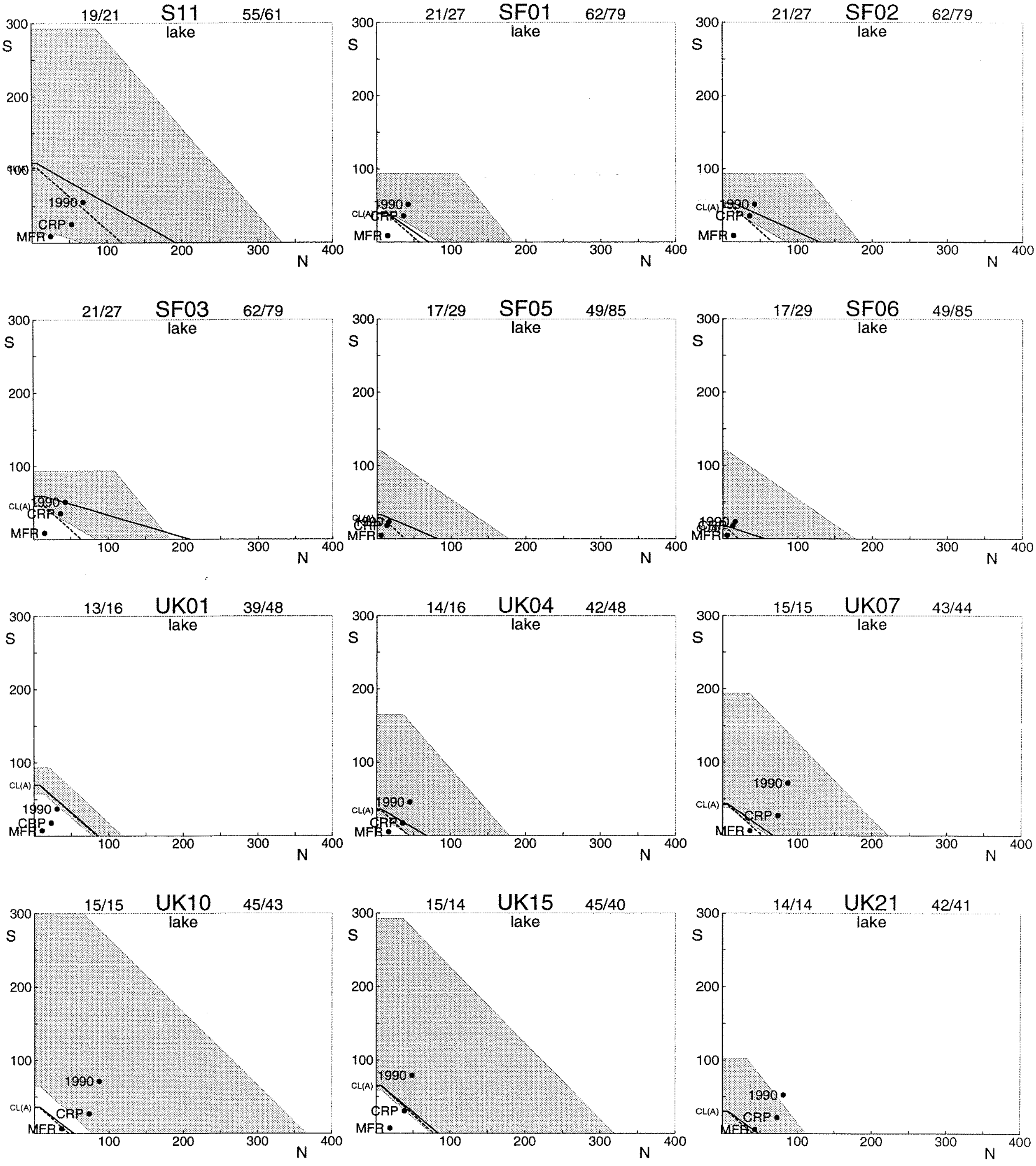

Figure 5 (finished).

5. Concluding remarks

The critical loads for the ICP-Waters sites compare in many instances well with the critical load data from the UN/ECE Mapping Programme for the grid cells in which the sites are located. Whereas in the Nordic countries surface waters are generally the most sensitive receptors (especially in Norway), forest soils have been considered the most important receptor in major parts of Europe, and for these areas mostly data for soils are used in the Mapping Programme. The results presented in this report indicate that many of the selected ICP-Waters sites (not only in the Nordic countries) are sensitive to acidification. This suggests that surface waters should generally be included in critical load assessments in Europe.

The ICP-Waters database was not designed for calculating critical loads. Nevertheless, parts of the database contained suitable data for calculating critical loads, especially with the SSWC-model. However, for making critical load calculations with the FAB model additional data, especially characteristics of the terrestrial catchment (e.g. landuse), had to be drawn from other sources. The authors believe that these data could also be of use in other analyses within the ICP-Waters, and thus an effort should be made by the participating countries to collect these rather easily available data.

As can be seen from the geographical distribution if the ICP-Waters sites most of them are located in the northern and western parts of Europe. For large areas such as France and the Mediterranean countries no sites suitable for critical loads calculations were available. Given the observed high sensitivity at the analyzed sites, it would of interest to investigate whether this sensitivity extends to those areas. However, this would require further commitments by the countries who have signed the LRTAP-Convention.

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7. Appendix A

Site data used in the critical load calculations

Table A1. Number of observations for the data used for the critical load calculations for the period 1992-96.

Site code	Period	N obs.
D01	92-94	27
D02	92-94	28
D03	92-95	26
D04	92-95	24
D05	92-94	22
D06	92-96	52
D07	92-96	53
D08	92-96	53
D09	92-95	9
D10	93-94	11
D11	93-95	31
D12	93-95	32
D14	93-95	32
D15	92-96	53
D16	92-96	74
D17	92-94	35
D18	92-94	28
D19	92-94	28
D20	92-94	28
D21	92-94	28
D22	92-95	34
D23	92-95	37
D24	92-95	45
D25	92-95	25
D26	92-95	77
D27	92-95	85
D28	92-95	44
DK01	92-95	34
DK02	92-95	34
HU01	92-95	252
I01	92-95	26
I02	92-95	4
I03	92-95	22
I04	92-95	72
I05	92-95	48
I06	92-95	48
IR01	92-95	5
IR02	92-94	3
IR03	92-95	4
LA01	92-95	18
LA02	92-96	31
LA03	92-96	15
N01	92-96	262
N02	92-96	63
N03	92-96	248
N04	92-96	254
N05	92-96	59
N06	92-96	67
N07	92-96	65
N08	92-96	91
N09	92-96	257
N10	92-96	254
NL01	92-94	12
NL02	92-94	28
NL03	93-94	8
P01	92-95	74
P02	92-95	73
S01	92-95	46
S03	92-95	29
S04	92-95	67
S05	92-95	25
S06	92-95	27
S08	92-95	31
S09	92-95	32
S10	92-95	30
S11	92-95	32
SF02	92-95	17
SF03	92-95	18
SF05	92-95	29
SF06	92-95	32
UK01	92-95	13
UK04	92-95	12
UK07	92-95	14
UK10	92-95	12
UK15	92-95	13
UK21	92-95	12
C01	92-94	215
C02	92-94	216
C03	92-94	213
C04	92-94	226
C08	92-94	140
C10	92-94	5
C11	92-94	9
C12	92-94	6
C13	92-94	9
C14	92-94	9
US05	92-94	5
US06	92-94	5
US08	92-94	8
US10	92-94	8
US12	92-94	36
US13	92-94	40
US15	92-94	36
US16	92-94	42
US17	92-94	35

Table A2. ICP-Waters - Water chemistry used in calculating critical loads (see also Table 1)

Site Code	Runoff *mm/yr*	pH	Ca *mg/l*	Mg *mg/l*	Na *mg/l*	K *mg/l*	Cl *mg/l*	SO_4 *mg/l*	NO_3N *µg/l*
D01	485	5.26	2.21	0.55	0.94	1.16	1.8	3.9	1239
D02	1019	6.81	3.43	0.96	1.81	1.02	3.4	3.6	807
D03	492	4.21	55.06	12.92	8.3	2.81	13.4	184.3	1690
D04	115	3.69	52.65	10.73	10.6	3.45	19.1	179.6	428
D05	956	6.25	2.12	0.67	2.02	0.59	1.1	3.3	812
D10	311	6.46	29.99	2.66	2.11	2.11	5.9	69.2	1803
D12	416	5.07	10.08	4.01	4.8	1.37	7.2	40.5	2010
D14	259	6.92	20.04	6.99	10.1	2.81	23.8	49.7	5534
D15	473	5.77	2.59	1.22	5		8.9	4.8	813
D16	946	4.95	2.67	0.67	1.2		2.1	12.5	581
D17	158	3.89	4.26	0.99	1.8		3.3	22.9	1234
D18	591	6.48	6.4	4.41	2.62	0.91	4.3	26.4	1789
D19	869	5.68	2.76	0.88	3.33	0.87	2.8	10.6	926
D20	1043	6.51	3.86	2.13	2.45	0.54	3.2	13.7	773
D21	1168	7	5.31	2.81	2.93	0.62	3.3	16.8	1163
D22	390	4.24	5.92	2.69	3.7	0.98	5.4	27.9	1394
D23	980	4.26	2.34	1.57	4.6	0.6	8.8	10	831
D24	20	4.61	9.51	3.16	4.71	1.31	7.8	30.1	920
D25	1183	4.2	3.24	2.13	1.85	1.67	5.9	16.9	1166
D26	1191	6.41	4.02	3.2	2.31	1	2.8	13.5	874
D27	1419	6.25	3.75	2.6	2.23	1	2.6	12.3	732
D28	105	4.85	4.79	1.95	7.32	0.62	13.1	16.6	2337
DK01	365	6.64	8	2.97	9.68	1.26	17	16.7	2695
DK02	365	5.51	4.55	2.01	8.54	1.1	15.1	12.3	1042
H01	205	6.72	49.65	21.07	9.08		28.2	42.6	2290
I01	1000	6.49	1.56	0.15	0.32	0.33	0.1	2.5	366
I02	1300	6.94	5.45	1.43	2.08	0.93	1.3	9.8	594
I03	1000	5.71	0.93	0.1	0.23	0.27	0.1	2	329
I04	1400	7.4	4.04	1.39	1.62	0.73	0.9	5.8	632
I05	1300	7.35	4.07	1.02	3.14	0.53	1.6	4.7	1397
I06	1300	7.28	3.38	0.74	3.4	0.57	1.8	3.6	1436
IR01	1655	6.13	1.48	0.63	4.46	0.6	6.3	3.7	201
IR02	1700	6.44	1.32	0.83	5.82	0.38	14.6	2.8	22
IR03	950	6.08	1.15	1.08	9.45	0.46	15.4	3	50
LA01	223	7.92	41.62	11.23	6.79	2.77	11.1	30	1161
LA02	321	8.04	56.37	13.22	3.31	1.87	6.3	30.7	734
LA03	279	3.98	2.2	0.7	1.38	0.89	4.3	7.2	14
N01	1100	4.67	1.08	0.35	3.35	0.13	5.5	5	106
N02	1111	5.27	1.04	0.31	2	0.28	3.3	3.2	165
N03	550	4.99	1.17	0.19	0.68	0.13	0.6	2.5	22
N04	281	6.18	1.67	0.96	3.95	0.29	6.3	5.4	21
N05	567	6.19	1.32	0.21	0.73	0.2	0.7	2.3	37
N06	2727	5.63	0.75	0.38	2.55	0.23	4.5	2.1	158
N07	2432	5.61	0.51	0.23	1.66	0.26	3	1.2	102
N08	2510	5.84	0.59	0.29	1.9	0.31	3.4	1.3	79
N09	2510	5.55	0.39	0.28	1.96	0.23	3.4	1.2	72
N10	900	4.75	0.64	0.12	0.91	0.08	1.3	2.7	103
NL01	265	4.48	3.07	1.35	6.68	2.24	13	19.4	77
NL02	188	4.53	1.44	0.68	4.54	1.13	8.3	8.4	126

Table A2 (continued)

Site Code	Runoff	pH	Ca	Mg	Na	K	Cl	SO_4	NO_3N
	mm/yr		*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*µg/l*
NL03	248	5.15	1.21	0.76	6.49	2.95	12.1	10.4	125
P01	1654	5.94	2.25	0.12	0.35	0.14	0.3	3.5	737
P02	1544	6.64	2.97	0.2	0.43	0.18	0.3	3.5	442
S01	315	6.91	3.71	1.22	2.83	0.78	2.7	5	122
S03	260	6.32	6.08	1.85	7.91	1.06	10.8	14.6	173
S04	570	4.48	1	1.09	8.01	0.54	12.9	8.5	142
S05	330	6.58	2.41	0.61	1.24	0.51	0.8	2.3	17
S06	315	6.33	1.44	0.39	1.21	0.28	0.8	2.3	17
S08	220	5.43	5.16	1.94	5.41	0.89	7.3	16.3	101
S09	315	6.43	3.75	1.32	4.43	1.36	7.6	11.1	56
S10	250	5.39	1.89	0.79	3.51	0.55	5	6.7	28
S11	500	6.29	4.5	1.59	8.5	0.75	13.9	10.6	74
SF01	330	5.2	1.84	0.51	1.42	0.35	1.4	8.5	41
SF02	330	5.55	2.14	0.59	1.65	0.35	1.4	8.3	27
SF03	330	5.9	2.71	0.4	0.96	0.44	1.2	7.1	39
SF05	330	6.05	0.8	0.26	0.97	0.19	0.3	1.1	27
SF06	330	5.76	0.42	0.15	0.49	0.18	0.3	2	13
UH04	835	5.36	0.56	0.41	2.28	0.29	3.5	2.7	245
UK01	2632	6.39	0.83	0.72	5.57	0.35	9.7	2	35
UK07	2001	4.89	0.64	0.51	3.8	0.26	6.4	3.4	84
UK10	1454	5.03	0.58	0.54	3.46	0.28	6	3	241
UK15	2192	5.22	0.91	0.49	3.45	0.23	5.9	2.8	125
UK21	934	4.67	0.74	0.65	5.46	0.47	9.1	4.5	341
C01	720	5.95	2.31	0.38	0.44	0.19	0.2	4.7	218
C02	770	6.59	3.39	0.41	0.51	0.18	0.2	5	367
C03	920	6.75	4.35	0.45	0.55	0.2	0.2	5.3	332
C04	870	6.85	5.23	0.47	0.58	0.22	0.2	5.2	310
C08	537	6.41	2.33	0.51	0.99	0.28	0.4	3.6	80
C10	850	4.8	0.25	0.33	2.34	0.25	3.3	1.7	16
C11	850	5.27	0.4	0.31	2.43	0.24	3.5	2.1	20
C12	850	4.5	0.41	0.41	2.4	0.2	3.7	1.6	10
C13	800	5.12	0.57	0.37	3.09	0.33	4.4	1.4	18
C14	850	5.42	0.33	0.34	2.54	0.23	3.7	1.7	19
US05	635	5.64	0.86	0.3	2.2	0.28	2.9	3.5	6
US06	635	6.31	1.2	0.4	2.24	0.3	2.5	2.7	6
US08	381	7.02	3.08	0.84	0.43	0.41	0.2	3.4	16
US10	127	6.86	1.96	0.71	0.68	0.56	0.3	2.7	7
US11	635	6.49	3.18	0.56	0.75	0.33	0.4	6.3	133
US12	762	4.98	1.75	0.31	0.54	0.33	0.3	6.3	301
US13	762	5.33	1.84	0.32	0.55	0.32	0.4	5.6	314
US15	762	6.1	2.25	0.42	0.72	0.35	0.4	5.5	295
US16	762	6.39	2.92	0.53	0.88	0.41	0.4	5.8	369
US17	508	5.27	1.5	0.36	0.59	0.21	0.4	5.8	186

Table A3. Catchment characteristics for ICP-sites used for calculating critical load.

Site code	Lake area R=river *km2*	Catch. area *km2*	Bare rock %	Conif. forest %	Culti-vated %	Desid. forest %	Grassland, bogs a.s. %	Lat *Degrees*	Lon *Degrees*
D01	R	6.5		100				48.750	8.450
D02	R	6.5		100				48.422	8.365
D03	R	3.07		45		55		51.118	12.763
D04	R	1.92		85		15		51.432	12.928
D05	R	19		70		30		48.936	13.414
D10	R	2.33		60			40	50.836	14.131
D11	R	6.5	2	95		2	1	50.416	12.534
D12	R	10	2	85			4	50.618	13.196
D14	R	2.8		25	20	10	45	50.321	12.139
D15	R	2		95		5		50.086	11.830
D16	R	2		95		5		50.046	11.901
D17	R	2		100				50.009	11.901
D18	R	0.32		90			10	51.861	10.431
D19	R	3.81		100				51.756	10.598
D20	R	4.84		100				51.772	10.429
D21	R	5.4		100				51.741	10.372
D22	R	5		40		50	10	49.929	7.621
D23	R	1.5		90				49.720	7.116
D24	R	1.6		50		50		51.303	9.619
D25	R	0.075		100				49.656	8.889
D26	R	4.5		50		40	10	50.991	8.202
D27	R	2		60		35	5	51.002	8.206
D28	R	0.6		50		50		50.208	8.438
DK01	R	5		30	20		45	56.077	9.448
DK02	R	2		10			80	56.083	9.423
H01	0.12	8.38	14.3	61		13	7.4	47.935	19.960
I01	0.014	1.14	90				8	46.171	8.191
I02	1.825	10.431				69	2.5	45.956	8.463
I03	0.014	0.55	93				5	46.177	8.191
I04	R	110.4	10	2	1	43	36	46.069	8.699
I05	R	17.5				83	0.8	45.802	8.389
I06	R	3.4	0.2			78	0.4	45.797	8.386
IR01	0.38	18.7	27	24		5	39	53.000	-6.353
IR02	0.27	4.3	11				79.5	53.480	-9.529
IR03	2.3	35	5			4.5	90	55.133	-7.700
LA01	R	64500						55.883	26.633
LA02	R	33.4			51			57.133	25.917
LA03	R	1.55						56.917	23.467
N01	R	0.41	2	80	0	10	1	58.384	8.250
N02	R	1888	35	46	1.4	5.1	6.4	58.250	8.133
N03	0.22	4.8	5	65	0	10	10	60.366	9.717
N04	R	3	10	5	0	0	30	69.683	30.383
N05	R	225.2	14.8	60	0	15.2	2.7	60.500	9.500
N06	R	119	64.7	18	0	5.4	1.7	59.533	5.967
N07	R	689	75.8	7.5	1	7.2	2.4	61.333	6.117
N08	R	274	71.5	8.3	4.9	9.5	2.4	61.567	5.883
N09	R	10	46	24	0	52	0	61.566	5.934
N10	R	0.6	59	5	0	6	22	59.017	8.533

Table A3 (continued)

Site code	Lake area R=river *km2*	Catch. area *km2*	Bare rock *%*	Conif. forest *%*	Culti-vated *%*	Desid. forest *%*	Grassland, bogs a.s. *%*	Lat *Degress*	Lon *Degrees*
NL01	0.024	0.022	2	75		20	5	51.566	5.214
NL02	0.055	0.063	10	5		5	70	52.161	5.818
NL03	0.006	0.007	30	65		25	40	52.835	6.439
P01	0.016	0.66	92	1.3			3.9	49.227	20.018
P02	0.038	0.47	72	6			13.9	49.229	20.000
S01	R	1992			4			61.639	17.090
S03	R	247.2						57.099	15.663
S04	0.19	2.21						58.021	12.032
S05	1.76	32.62	3	83				62.244	15.676
S06	0.569	3.65		68				61.644	15.908
S08	0.107	2.71					7	56.014	15.731
S09	1.64	5.46			19		7	57.092	14.533
S10	0.378	2.95		41				56.948	15.274
S11	0.27	4.26			1			58.149	12.184
SF01	0.08	4	40	50			3	60.683	27.917
SF02	0.03	0.37	30	60	2			60.733	27.917
SF03	0.12	0.62	1	70				60.733	27.883
SF05	0.39	4.2						67.065	26.101
SF06	0.25	1.58	1					67.116	26.088
UH04	0.1	0.92						56.759	-3.230
UK01	0.12	8.97		1				57.417	-5.651
UK07	0.12	0.95						55.094	-4.429
UK10	0.05	0.95						54.482	-3.298
UK15	0.06	1.57						53.015	-4.014
UK21	0.02	0.42						54.157	-5.968
C01	0.058	0.856	2	8.7		70.3		47.059	-84.399
C02	0.192	3.44	2	4.2		79.8		47.046	-84.403
C03	0.192	4.91	2	4.1		78.9		47.045	-84.410
C04	0.52	8.03	2	4		76		47.051	-84.413
C08	0.061	0.684		87.3		2.7	1	47.317	-71.117
C10	0.14	0.6	5	40		10		44.368	-65.300
C11	1.37	8	5	37.5		12.5		44.328	-65.264
C12	0.2	3.8	20	27		18	20	44.339	-65.395
C13	24.4	723		48		32		44.369	-65.221
C14	0.061	1		80		20		44.308	-65.333
US05	0.25	2.38				95		44.638	-68.078
US06	0.15	0.49				100		44.635	-68.072
US08	0.48	3.28				85		46.466	-85.739
US10	0.48	1.19				60		48.498	-92.805
US11	0.49	3.42		5		85		43.988	-74.242
US12	0.21	13.8		6		88	3	43.833	-74.796
US13	0.58	106		6		81		43.797	-74.857
US15	0.68	139.37				90	3	43.764	-74.906
US16	0.45	12.48		5		81	6	43.786	-74.850
US17	0.16	3.21						43.188	-74.500

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