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Application of the first-order Acidity Balance (FAB) model to Norwegian surface waters

NATURENS TÅLEGRENSER

Miljøverndepartementet
Fagrapport nr. 94

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REPORT

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Abstract

We have applied the First-order Acidity Balance (FAB) model and the Steady State Water Chemistry (SSWC) model to data from the Norwegian lake survey carried out in 1995, the Norwegian Critical Load database, the calibrated catchments and the rivers monitored through the national programme for long-range transported air pollutants and to seven lakes monitored through the REFISH-project. Today, with present N-leaching, 29% (11.000 lakes) of the lakes in Norway are exceeded, while 44% (16.700 lakes) will be exceeded at maximum N-leaching. In year 2010 the number of exceeded lakes will be reduced to 6.800 lakes (18%) at present N-leaching, while 13.000 lakes (35%) will be exceeded at maximum N-leaching. Most rivers and calibrated catchments will still be exceeded at present N leaching when the Second Sulphur Protocol has been implemented, but only N-reduction will then be required to reach non-exceedance. At present N-leaching, however, they will reach non-exceedance at the Second Sulphur Protocol scenario. The future acidification situations estimated by means of the two models clearly indicate that nitrogen will be the critical factor in the future. The crucial questions are whether the situation predicted by the FAB-model ever will occur for lakes and rivers and whether the present leaching will increase with present N-loading.

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Contents

Summary

The concept of critical loads has been widely accepted in Europe as a basis for negotiating control strategies for transboundary air pollution as evidenced by the signing of the Second Sulphur Protocol in Oslo in June 1994. 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. In order to prepare the scientific support for the negotiations of a revised protocol on the reduction of nitrogen, a new methodology was designed to take multiple effects (i.e. eutrophication and acidification) of multiple pollutants (sulphur and nitrogen) into account. Since the critical loads of S and N are interrelated, a single critical load for one pollutant cannot be defined without making assumptions about the other. For this purpose the so-called First-order Acidity Balance (FAB)-model was developed. We have applied the FAB-model to the data for the Norwegian lake survey carried out in 1995, the Norwegian Critical Load database, to the calibrated catchments and the rivers monitored through the national programme for long-range transported air pollutants and to seven lakes monitored through the REFISH-project. Today, with present N-leaching, 29% (11.000 lakes) of the lakes in Norway are exceeded, while 44% (16.700 lakes) are exceeded at maximum N-leaching. In year 2010 the number of exceeded lakes will be reduced to 6.800 lakes at present N-leaching, while 13.000 lakes will be exceeded at maximum N-leaching. The lake database gives a higher percent of exceeded lakes than the area exceeded. The two sets of figures cannot be compared directly since the lake database represent individual lakes of different sizes and different areal density, while the area database assume evenly regional distribution of lakes. The figures are, however, remarkably similar, indicating that the area approach represent a satisfactory estimate of the properties of the lakes in Norway. The area database gives an estimate of the properties within given areas and regions and can therefore be used for assessing liming needs on a regional basis. All monitored rivers in Southern Norway are exceeded at present N- and S-deposition and at maximum N-leaching. When the Second Sulphur Protocol has been implemented, all rivers except Aurdøla will still be exceeded. At present S-deposition and present N-leaching, however, Gjerstadelva and Aurdøla are not exceeded., and at the Second Sulphur Protocol scenario and at present N-leaching none of the rivers except Dirdalselva and Modalselva will be exceeded. Also all the calibrated catchments will reach non-exceedance in year 2010 with present N-leaching. The six lakes included in the REFISH-project will require only N-reduction when the new sulphur protocol is implemented- At present S-deposition and present N-leaching all lakes are exceeded, but only S-reduction will be required to reach non-exceedance. This implies that with current reduction plans and no further N-leaching, all lakes will reach non-exceedance. The future acidification situations estimated by means of the two models clearly indicate that nitrogen will be the critical factor in the future. The crucial questions are whether the situation predicted by the FAB-model ever will occur for lakes and rivers and whether the present leaching will increase with present N-loading.

1. Introduction

The concept of critical loads has been widely accepted in Europe as a basis for negotiating control strategies for transboundary air pollution. 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 (Posch *et al.* 1995, 1997a, UN/ECE 1996). The 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 critical load work focused on the development of methodologies and the synthesis of national data to produce maps of critical sulphur deposition. This work resulted in the Second Sulphur Protocol that was signed in Oslo in June 1994 (UN/ECE 1994). In order to prepare the scientific support for the negotiations of a revised protocol on the reduction of nitrogen, a new methodology was designed to take multiple effects (i.e. eutrophication and acidification) of multiple pollutants (sulphur and nitrogen) into account. 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. The work for surface waters will in large be based on the so-called First-order Acidity Balance (FAB)-model (Posch *et al.* 1997b).

We have applied the FAB-model to the data for the Norwegian lake survey carried out in 1995 as part of a co-ordinated Nordic lake survey (Henriksen *et al.* 1998, SFT 1996,) and the Norwegian Critical Load database (Henriksen *et al.* 1996b). We have further applied the FAB-model to the calibrated catchments and the rivers monitored through the programme for long-range transported air pollutants that was started in 1980 as a part of the "National Programme for Pollution Monitoring" administered by the Norwegian Pollution Control Authority (SFT). The FAB-model has also been applied to seven lakes monitored through the REFISH-project (Rosseland *et al.* 1990, Kroglund *et al.* 1992, Dalziel *et al.* 1995).

2. Materials and methods

2.1 Data

2.1.1 The regional lake survey 1995

In the autumn of 1995, regional lake surveys were conducted in the Northern European countries on the initiative of the environmental authorities in Sweden, Finland and Norway. These countries have previously carried out nation-wide lake surveys. The 1995 surveys were, however, co-ordinated with respect to lake selection, analytical methods, sampling techniques and sampling period. The project was expanded to include Denmark, Russian Kola, Russian Karelia, Scotland and Wales (Henriksen *et al.* 1997) The key objectives of this integrated survey were to:

- assess the status of the lakes with respect to general water quality;
- determine the occurrence and regional variations of acidification;
- establish a new up-to-date reference dataset to quantify the future effects of the Second Sulphur Protocol (UN/ECE 1994);
- provide data on effects of nitrogen deposition on lake water chemistry in connection with the development of critical loads for nitrogen;
- establish the regional eutrophication status of lakes;

- provide a database for the concentrations of heavy metals in lakes.

The basic information on the lake populations in Finland, Norway, Sweden, Denmark, Russian Kola, Russian Karelia and Scotland and Wales has been presented (Henriksen *et al.*, 1996a). Here, background information on the present lake surveys with selection criteria, sampling methods and other relevant information about the surveys were presented together with an overview of previous lake surveys carried out in the participating countries. A manual presenting the procedures applied in the selection of lakes as well as sampling procedures and the analytical programme including quality assurance and control was prepared (included in Henriksen *et al.*, 1996a).

The results from the integrated survey have been published (Henriksen *et al.* 1997, 1998). The countries included in the North European Lake survey cover a geographic area of ca. 1.300.000 km^2. This is about 13% of Europe's total area including the European part of Russia, and 28% of Europe not including Russia. The total number of lakes > 4 ha in the study area is ca. 155.000 and of these 5.690 lakes were sampled in this survey, corresponding to 3.7 % of the total lake giving a sampling density of one lake pr 244 km^2.

2.1.2 The Norwegian Critical Load database

The official critical load database for surface waters in Norway is based on assessing representative water chemistry for lakes and rivers in area grids. Area description of water quality was chosen because the extent of fish damage due to acidification historically has been assigned to area damage (Overrein *et al.* 1981).

Grid Size: Each 1º longitude by 0.5º latitude grid was divided into 16 sub-grids, each covering about 12 x 12 km in southern Norway, and with decreasing grid width at higher latitudes. The land area covered by each grid (2315 in number) has been calculated.

Data Sources: National regional lake surveys and monitoring programs.

Precipitation: A weighted average total deposition value for each NILU-grid (a 3 by 3 subdivision of an EMEP-grid) has been calculated from ambient air concentrations and wet deposition taking land use data (coverage of different receptors) into account (Tørseth and Pedersen 1994). Weighted means for the period 1988-1992 were used. The deposition values for each of the surface water grids (see above) was estimated from the NILU-grid database.

Water: The chemistry of surface water within a sub-grid was estimated by comparing available water chemistry data for lakes and rivers within each grid. The chemistry of the lake that was judged to be the most typical was chosen to represent the grid. If there were wide variations within a sub-grid, the most sensitive area was selected, if it amounted to more than 25% of the grid's area. Sensitivity was evaluated on the basis of water chemistry, topography and bedrock geology. Geology was determined from the geological map of Norway (1:1,000,000) prepared by the Norwegian Geological Survey (NGU). Mean annual runoff data is from runoff maps prepared by the Norwegian Water and Energy Works (NVE).

The database was revised in February 1995 and in October 1996.

2.1.3 Monitored rivers and calibrated catchments

The monitoring programme for long-range transported air pollutants was started in 1980 as a part of the "National Programme for Pollution Monitoring". The programme is based on the knowledge and experience gained from the research programme "Acid Precipitation - Effects on Forest and Fish" (the SNSF-project, 1972-1980) (Overrein *et al.*, 1981). The Norwegian Ministry of Environment has given the overall responsibility for co-ordination and performance of the programme to the Norwegian Pollution Control Authority (SFT). SFT is funding the monitoring of atmospheric inputs and water and soil chemistry, while the Directorate for Nature Management (DN) is funding the biological monitoring activities.

The programme is carried out by several Norwegian research institutes. The Norwegian Institute for Air Research (NILU) has the responsibility for atmospheric input measurements (air and precipitation quality). The Norwegian Institute for Water Research (NIVA) is responsible for the water chemistry sub-programme (rivers, lakes, groundwater, calibrated catchments and intensive studies), while the Norwegian Institute for Nature Research (NINA) is investigating the fish populations. The Norwegian Forest Research Institute (NISK) is monitoring soil chemistry in calibrated catchments (in addition to their responsibility for parts of the Norwegian Monitoring Programme for Forest Damage). The University of Bergen (UiB) is responsible for investigations of aquatic invertebrates.

The water chemistry sub-programme includes monitoring of six calibrated catchments (weekly sampling), 16 rivers (monthly sampling, weekly during snowmelt) and yearly sampling of 200 lakes all over the country.

2.1.4 REFISH lakes

The REFISH project (Dalziel *et al*. 1995).) collected samples from a selection of lakes from two areas in southern Norway. We have applied the FAB-model to six of those lakes based on average chemistry data for the period 1989-1995.

2.1.5 Deposition data

Present deposition: Data for present deposition of sulphur and nitrogen compound were taken from Tørseth and Pedersen (1994) derived in this way: A weighted average total deposition value for each NILU-grid (a 3 by 3 subdivision of an EMEP-grid) has been calculated from ambient air concentrations and wet deposition taking land use data (coverage of different receptors) into account. Weighted means for the period 1988-1992 were used.

Deposition 2010: Estimated deposition in NILU-grids according to the Second Sulphur Protocol.

The deposition values for each of the lakes. the area grids, the rivers and calibrated were estimated from the two NILU-grid databases.

3. Critical loads

In order to gain more insight in the magnitude and spatial variation of critical loads, the UN/ECE Executive 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 Co-ordination Centre 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).

3.1 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 summarised: 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 UN/ECE 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.

3.1.1 The modified SSWC-model

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

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

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):

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

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 catchments with high and 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 formula used for Norway is:

(4) $ANC_{limit} = 0.25{*}Q{*}[BC0]\,/(1+0.25{*}Q)$

where Q is runoff in m/yr.

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):

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

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, immobilisation, denitrification and in-lake retention of nitrogen.

3.1.2 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):

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

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

(7a) $a_N = (1-f_{de}(1-r))(1-\rho_N)$

(7b) $a_S = 1-\rho_S$

(7c) $b_1 = f(1-f_{de})(1-\rho_N)$

(7d) $b_2 = (1-r)(1-f_{de})(1-\rho_N)$

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 immobilisation 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 modelled by a kinetic equation (Kelly *et al.* 1987, Dillon and Molot 1990):

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

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):

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

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

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

Below a value of

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

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

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

Eq.6, together with these constraints, determines the so-called critical load function (Figure 1), 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.

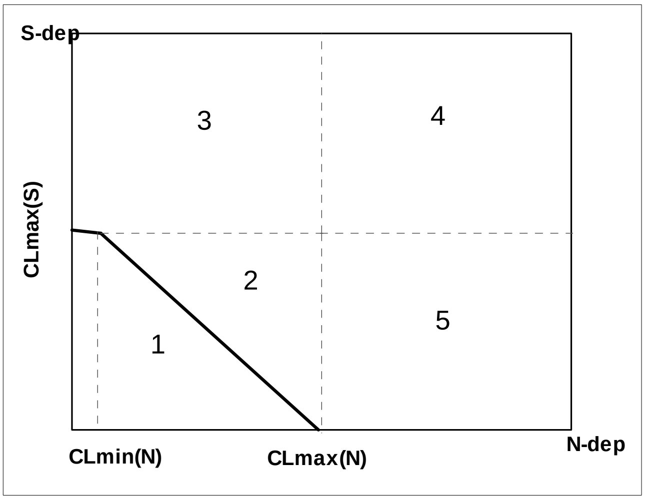

Figure 1. The critical load function. Each lake has its own diagram. The critical load function (thick line) is given by the calculated values for $CL_{max(S)}$, $CL_{min(N)}$ and $CL_{max(N)}$. The area below the thick line (1) indicates N and S deposition values not causing exceedance. The location of the lake's N and S deposition in the diagram gives the reduction requirements for the lake to give non-exceedance: 1. no reductions required, 2. N or S reduction, 3. mandatory S-reduction, 4. mandatory S and N reduction, 5. mandatory N-reduction.

The FAB-model gives us the reduction requirements to reach non-exceedance for a given deposition scenario and can as mentioned be used to achieve optimal reduction conditions. In order to estimate the total potential critical load exceedance (Pot-Ex) both from N and S deposition the following equation can be used.

(13) $\text{Pot Ex} = -CLAc + S_{dep} + (N_{dep} - CL_{min(N)})$

3.2 Input data

3.2.1 SSWC-model:

Data necessary for the calculation of critical loads of acidity for lakes are:

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

3.2.2 The 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 in catchment	Measured from maps
Soil fraction in catchment	Measured from maps
N_u: nitrogen uptake in catchment	Dependent on tree species and harvesting practice
	For non-productive forests and non-forested areas $N_u = 0$
N_{imm}: N immobilisation	0.5-1 kg/ha/yr (UBA 1996)
f_{de}: denitrification fraction	$=0,1+0,7\bullet f_{peat}$
S_N: mass transfer coefficient for N	2-8 m/yr (Dillon and Molot 1990)
S_S: mass transfer coefficient for S	0,2-0,8 m/yr (Baker and Brezonik 1988)
r. lake/catchment ratio	0-1

For the calculations presented in this report we have used 0,5 kg/ha/yr for N_{imm}, 5 for S_N and 0,5 for S_S.

4. Results and discussion

4.1 Lake survey and critical load database

The official critical load database for surface waters in Norway is based on assessing representative water chemistry for lakes and rivers in small grids. Area description of water quality was chosen because the extent of fish damage due to acidification historically has been assigned to area damage. In order to check the validity of this database that was first compiled in 1990 and updated regularly, we have calculated the exceedance for S and N deposition using both databases and critical load models. Exceedances were calculated for two deposition scenarios: 1) the average deposition of S and N for the years 1988-1992 (expressed as 1990) (Tørseth and Pedersen 1994) and for the S deposition scenario given by the Second Sulphur Protocol and with "present" N-deposition (Table 1).

All calculations based on the lake survey data are deweighted values. The lakes were selected by stratified sampling in order to give a throughout coverage of different regions and lake sizes. Because this sampling strategy favoured acidified regions and large lakes, the lakes from over-represented strata were deweighted in order to estimate unbiased descriptive statistics for the lake population (Henriksen *et al.* 1997, 1998).

Table 1. The SSWC- and FAB-models applied to the regional lake database and to the area critical load database for two deposition scenarios for sulphur. Numbers refer to percent exceeded.

Scenario	Database	Model	
		FAB	*SSWC*
1990	Lakes	44	29
	Area	37	25
2010	Lakes	35	18
	Area	25	11

Today, with present N-leaching, 29% of the lakes (11.000 lakes) are exceeded, while 44% are exceeded at maximum N-leaching (16.700 lakes). In year 2010 the number of exceeded lakes will be reduced to 18% (6.800 lakes) at present N-leaching, while 35% (13.000) lakes will be exceeded at maximum N-leaching.

The lake database gives a higher percent of exceeded lakes than the area exceeded. The two sets of figures cannot be compared directly since the lake database represent individual lakes of different sizes and different area density, while the area database assume evenly regional distribution of lakes. The figures are, however rather similar, indicating that the area approach represent a satisfactory estimate of the acidification status of the lakes in Norway. The area database is useful to estimate the total excess acid in our country, which can be done on a regional basis. The lake database gives us the properties of our lake population, but not where all lakes are located geographically. The area database, however, give an estimate of the properties within given areas and regions and can therefore be used for assessing liming needs on a regional basis (see Henriksen *et al.* 1996b).

4.1.1 Reduction requirements for Norwegian lakes

The main purpose of the FAB-model is to assess how much N and S deposition has to be reduced in order to achieve non-exceedance. As pointed out above there is no specific values for S and N deposition that will give non-exceedance, but a combination of ways. It is, however, possible to identify where in the critical load function diagram (Figure 1) each lake will be located, that is, the reduction requirement for each lake can be estimated. (Table 2).

Table 2 illustrate that it is important to deweight all results. Without deweighting the number of lakes where the critical loads of S and N deposition is exceeded is overestimated (54% before deweighting and 44% after).

Table 2. Reduction requirements (percent) for S- and N-deposition for the Norwegian lake population using the FAB-model. Both non-weighted and deweighted values are given for the lake survey.

Database		Lakes				Area	
		Non-weighted		*Deweighted*			
Reduction requirements	Case	1990	2010	1990	2010	1990	2010
No reductions required	1	45,8	56,9	*55,6*	*65,3*	*63,3*	*71,9*
N- or S-reduction	2	18,2	10	*13,8*	*8,2*	*13,2*	*8,0*
S-reduction only	3	3,4	0,6	*5,2*	*1,1*	*3,8*	*0,4*
Both S- and N-reductions	4	28,2	14,9	*22,2*	*12,2*	*16,8*	*5,8*
N-reductions only	5	4,4	17,6	*3,1*	*13,2*	*2,9*	*13,9*
Exceeded		***54,2***	***43,1***	***44,4***	***34,7***	***36,7***	***28,1***

Today, 50% of the *exceeded* lakes require both N and S reductions (Case 4, Table 3), and for 31% of the lakes we can chose between S and N reduction (Case 2). Only 12% of the lakes will reach non-exceedance with S-reduction only (Case 3). This indicate the strong potential threat of N-deposition to the critical load exceedance of Norwegian lakes. After the Second Sulphur Protocol has been implemented, only 3% of the lakes will reach non-exceedance with further reductions of S-deposition (Case 3), for 24% we can chose between S- and N-deposition reduction. This imply that for about one fourth of our exceeded lakes we can today reach non-exceedance by S-reduction only, while for the remaining three fourth of our lakes reductions in N-deposition are required to reach non-exceedance. This shows the great importance of knowing whether the nitrogen leaching will increase in the future with the present high N-deposition.

Table 3. Reduction requirements for the lakes that are exceeded according to the FAB-model.

Reduction requirements	**Case**	**Percent of exceeded lakes**	
		1990	*2010*
N or S-red.	2	31.2	23.6
S only	3	11.7	3.2
Both S and N	4	50.1	35.2
N only	5	7.0	38.0
Total		100	100

4.1.2 Regional distribution of the exceeded lakes

There are large regional differences in the amount of acidic deposition and thus also in critical load exceedance. We have estimated the total exceedance for S- and N-deposition for two deposition scenarios for the 19 counties in Norway (Figures 4 and 5). For the southernmost and south-western counties (9-12) especially Vest-Agder (10) and Rogaland (11). The two methods show rather similar numbers of exceeded lakes (Figure 4). This is largely because most of the lakes in these counties are exceeded even with present N-leaching. The largest differences between the two estimates are for the counties in eastern Norway (1-8). In these counties we find most of the productive forests in Norway, and thus the lowest levels of N-leaching. The scenario for the Second Sulphur Protocol leads to virtually non-exceedance in those counties using the SSWC-model, while the FAB-model predicts still high exceedances for the eastern counties because the potential N-leaching is high in these areas. This illustrates the severe potential impact of the N-deposition on lakes in large parts of Norway.

Table 4. Reduction requirements (percent) for lakes at different N-deposition scenarios with the Second Sulphur Protocol deposition using the FAB-model.

		N-dep. reduction, percent				
Reduction requirements	**Case**	**0**	**30**	**50**	**70**	**70+50%S-red.(2010)**
No reductions required	*1*	*65.3*	70.9	77.0	83.4	88.0
N- or S-reduction	*2*	*8.2*	9.5	8.3	6.2	5.3
S-reduction only	*3*	*1.1*	0.8	1.0	4.5	0.3
Both S- and N-reductions	*4*	*12.2*	12.0	11.3	5.8	3.4
N-reductions only	*5*	*13.2*	6.8	2.4	0.1	3.0
Ecxeeded		***34.7***	***29.1***	***23***	***16.6***	***12***

Large N-reductions are required even after the Second Sulphur Protocol has been implemented (Table 4). If present N-deposition is reduced by 70 percent, still almost 17 percent of the lakes will be exceeded. If we, at this scenario, reduce the sulphur deposition of the sulphur protocol by 50 percent, still 12 percent of the lakes will remain exceeded. To have full protection in Norway the S- and N-deposition have to be reduced by more than 90 percent each. Even at 90 percent reduction of both pollutants, still about 2 percent of the lakes will be exceeded. These lakes are small high mountain lakes located in high deposition areas in the counties West Agder, Rogaland and Hordaland.

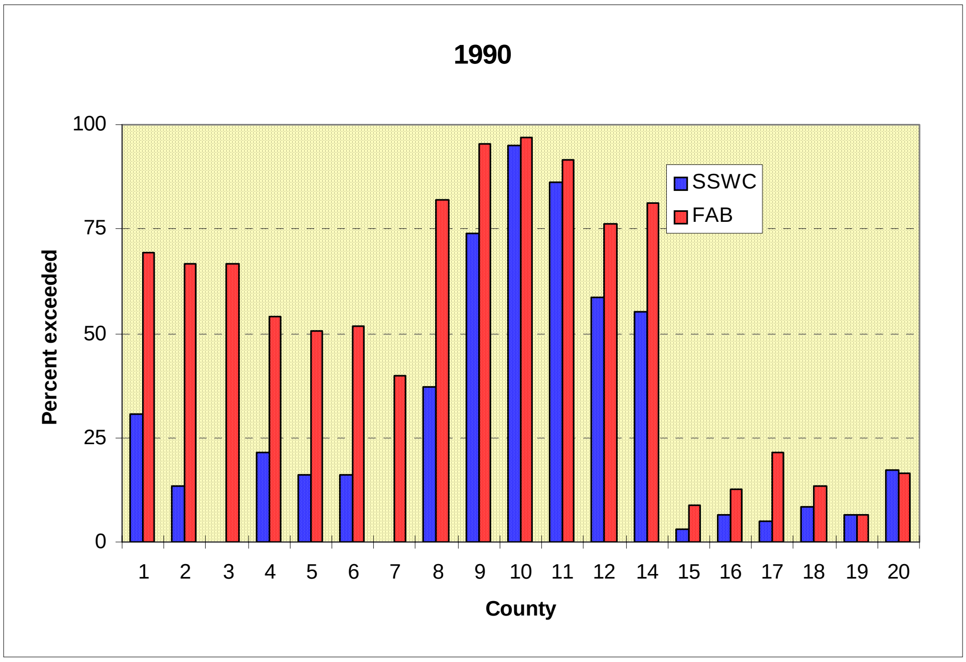

Figure 4. Estimated critical load exceedance (LAKES) for counties using two models at present N- and S-deposition (1990).

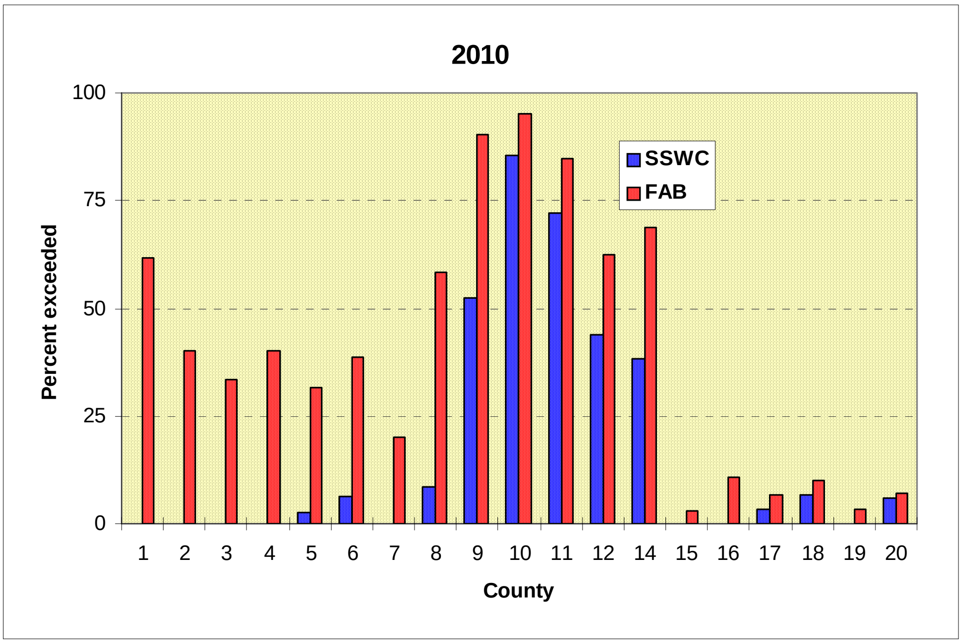

Figure .5 Estimated critical load exceedance (LAKES) for counties using two models at present N-deposition and S-deposition when the Second Sulphur Protocol has been implemented (2010).

4.2 Monitored rivers and catchments

The FAB-model was also applied to data for the 15 monitored rivers and the calibrated catchments in Norway (Skjelkvåle and Henriksen 1995). Background data for land use in the catchments above the sampling point are given in Tables 5 and 6. Runoff values are from NVE-maps. Chemistry data are from yearly averages for the period 1989 to 1995.

Table 5. Catchment characteristics for the monitored rivers.

			Catchment characteristics					
River no.	**Name**	**Runoff**	**Catchment area,**	**Lakes**	**Forest**	**Peat**	**Open**	**Agri-culture**
		l m^{-2} sec^{-1}	*km^2*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
3	Gjerstadelva	30,4	419	0,8	65,4	3,6	28,2	2,1
5	Nidelva	30,1	3985	1,0	71,8	3,3	13,4	1,2
7	Tovdalselva	35,2	1888	6,4	51,1	6,4	34,7	1,4
11	Mandalselva	48,4	1775	6,5	36,2	2,1	53,5	1,8
13	Lygna	52,8	661	0,9	36,8	5,8	52,8	3,6
19	Bjerkreimselva	77,1	693	1,6	8,6	1,1	83,1	5,5
23	Dirdalselva	80	158	0,1	7,1	0,1	89,4	3,4
26	Årdalselva	80	551	3,6	2,5	0	93,1	0,7
32	Vikedalselva	86,6	119	3,4	23,5	1,7	64,7	6,7
34	Nausta	79,7	274	2,6	18,6	2,4	71,5	4,9
45	Ekso	82,8	410	1,2	8,1	0,4	89,3	0,9
46	Modalselva	94,9	384	2,2	5,6	0,3	91,4	0,5
57	Gaula	77,2	689	4	14,7	2,4	75,8	3,2
77	Øyensåa	40	253	3,7	57,2	13,4	25,8	0
90	Aurdøla	18	225	6,7	75,8	2,7	14,8	0

Table 6. Characteristics for the monitored catchments.

		Catchment characteristics						
Catchment	**Runoff**	**Lake area**	**Catchment area**	**Lakes**	**Forest**	**Peat**	**Open**	**Agri-culture**
	$l\ m^{-2}\ sec^{-1}$	*km^2*	*km^2*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Birkenes	34,9	0	0,41	0	90	7	3	0
Dalelv	14,6	0	3,2	15	5	15	65	0
Kårvatn	60,2	0	25	4	18	2	76	0
Langtjern	17,5	0,23	4,8	5	5	16	74	0
Storgama	32,4	0,06	0,6	8	11	22	59	0
Svarttjern	107	0,06	0,42	0	40	2	58	0

We have calculated the reduction requirements for the sampling point for the rivers and the catchments with the FAB-model and prepared their critical load function diagrams (Figures 7 and 8). The chemistry data used are given in Table A1 (Appendix). Figure 6 illustrates how the legends in the diagrams are constructed. The distance from the point representing present N-leaching (a) to the point representing present N- and S-deposition (b) indicate the future potential leaching of N. Point (c) indicate the S-deposition when the Second Sulphur Protocol has been implemented, with potential N-leaching. Point (d) indicate the situation when the protocol has been implemented and with present N-leaching.

Figure 7 indicate that all monitored rivers in Southern Norway are exceeded at present N- and S-deposition (point b). With present N-leaching, however, Gjerstadelva, Øyensåa and Aurdøla are not exceeded (point a). When the Second Sulphur Protocol has been implemented (point c), all rivers except Aurdøla and Øyensåa will still be exceeded. The situation when the protocol has been implemented and with present N-leaching (point d) results in non-exceedance in all rivers except Dirdalselva and Modalselva. Also all the calibrated catchments will reach non-exceedance when the Second Sulphur Protocol has been implemented. The individual locations of the rivers and the calibrated catchments in the critical load function diagram at the four scenarios are summarised in Table 7

Table 7. FAB-cases at different deposition scenarios for monitored rivers and calibrated catchments (see figure 6 for definition of cases).

	Potential N-leaching		Present N-leaching	
	S- and N-deposition 1990	**S- deposition 2010 N-dep. 1990**	**S- and N-deposition 1990**	**S-deposition 2010 N-dep. 1990**
Rivers				
Gjerstadelva	2	2	1	1
Nidelva	4	5	3	1
Tovdalselva	4	5	3	1
Mandalselva	4	5	3	1
Lygna (before liming)	4	5	3	1
Bjerkreimselva	5	5	2	1
Dirdalselva	4	5	3	2
Årdalselva	4	5	3	1
Vikedalselva	5	5	2	1
Nausta	4	5	3	1
Ekso	2	2	2	1
Modalselva	4	5	3	2
Gaula	4	5	3	1
Øyensåa	1	1	1	1
Aurdøla	2	2	1	1
Calibrated catchments				
Langtjern	2	2	1	1
Birkenes	4	5	3	1
Storgama	4	5	3	1
Kårvatn	1	1	1	1
Dalelva	1	1	1	1
Svarttjern	4	5	3	1

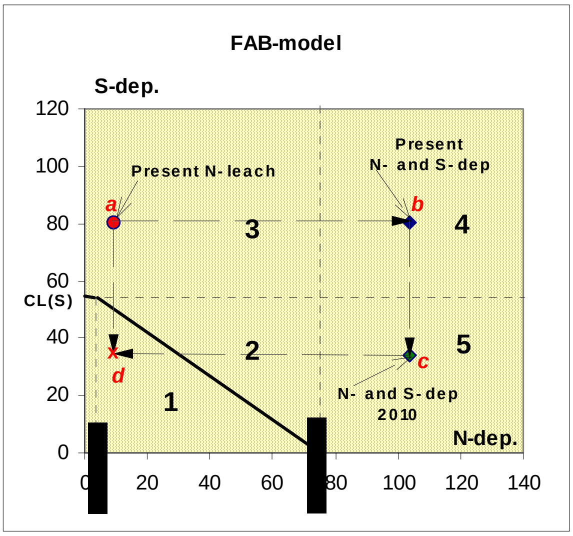

Figure 6. The critical load (CL) function of a lake or stream (thick line) is determined by the values of CL(S), CL (N)min and CL (N)max. The area below the thick line (1) indicates N and S deposition values not causing exceedance. The location of the lake's N and S deposition in the diagram determines 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. Each monitored site has its own diagram. Present N- and S-depositions (b), the predicted S-deposition in 2010 (Second Sulphur Protocol) and present N-depositions (c) and present N-leaching (d) are given in the diagram. Unit: meq/m^2/yr.

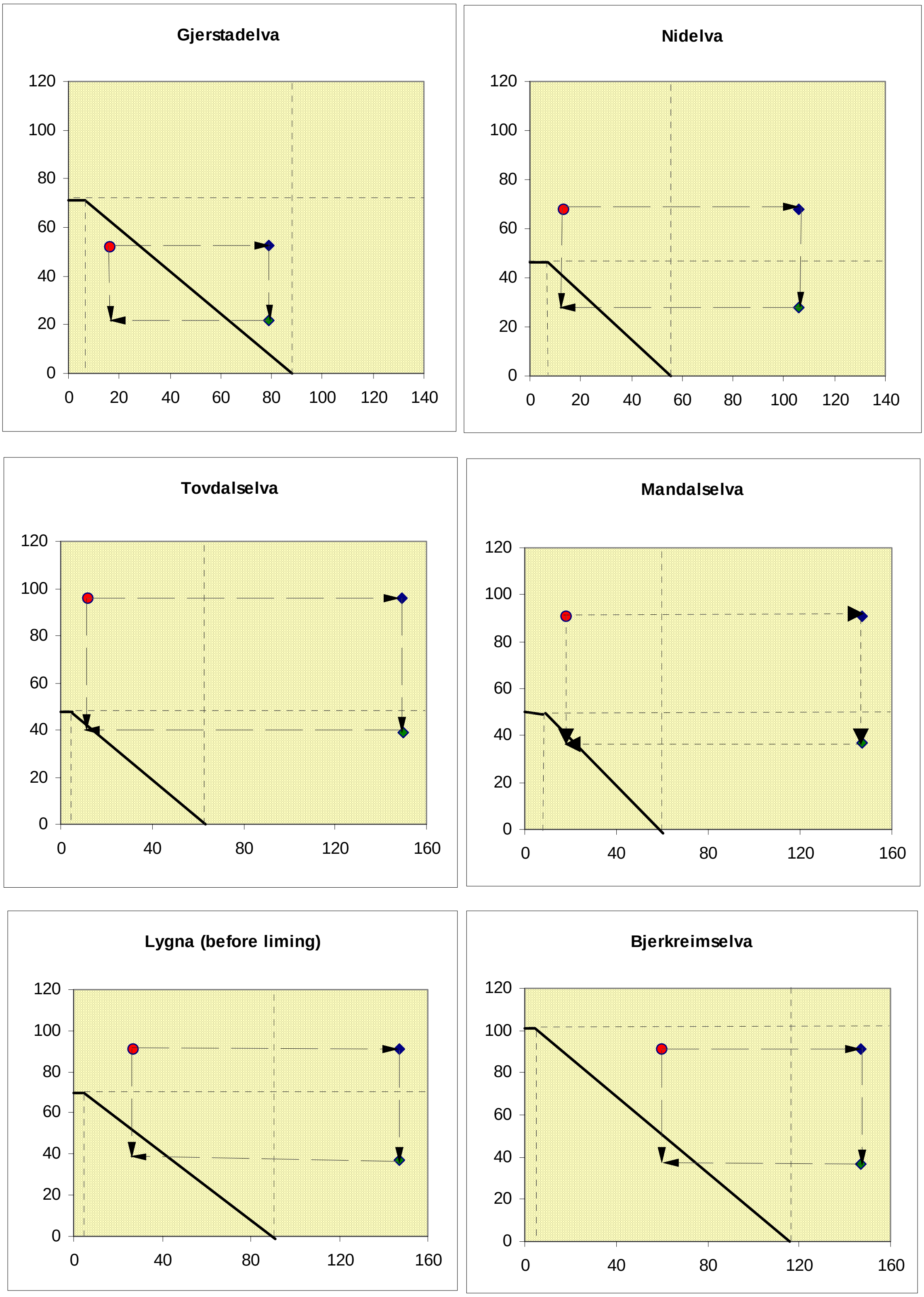

Figure 7. Critical load functions for the monitored rivers. See Figure 6 for explanation of legends.

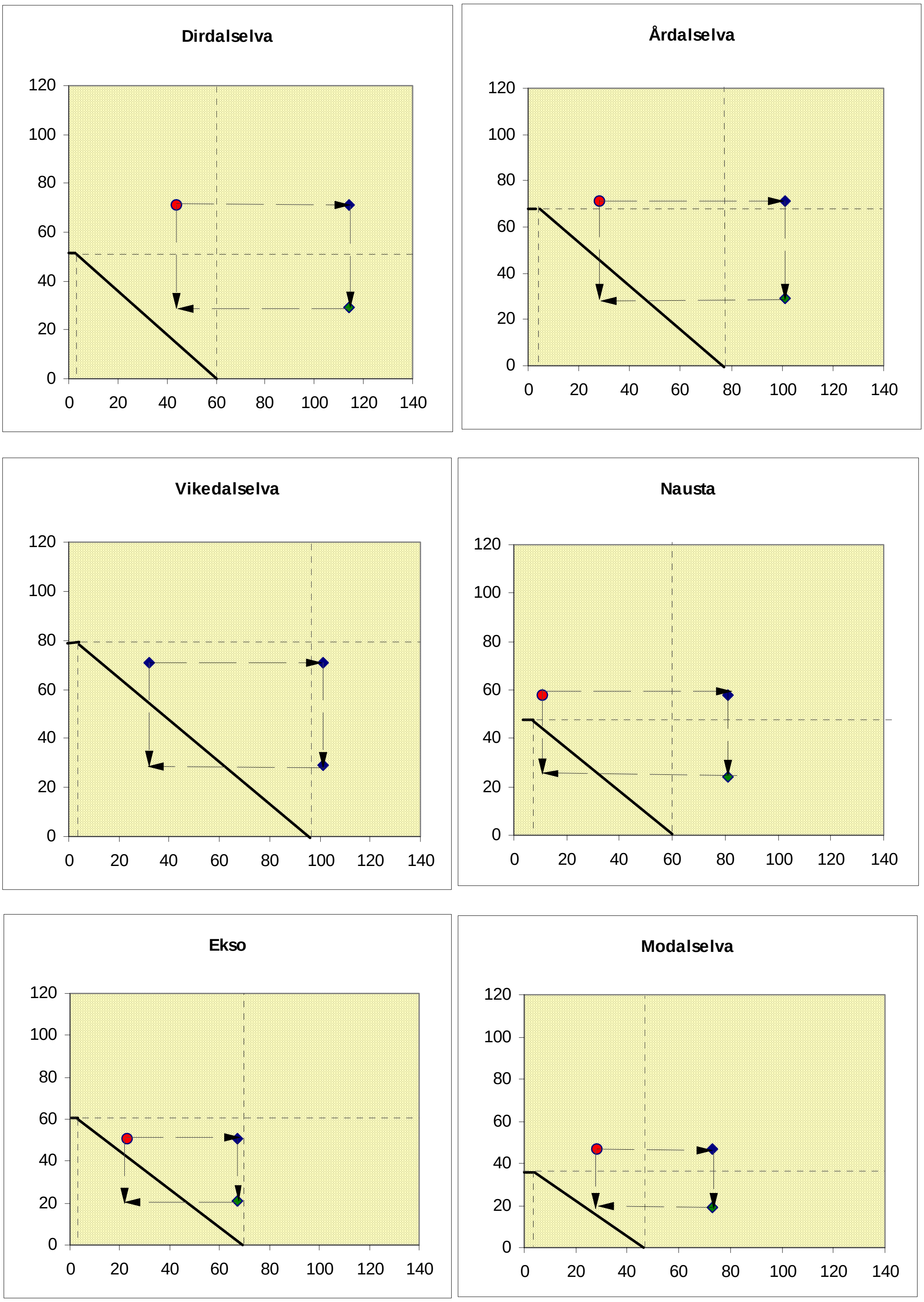

Figure 7. Continued.

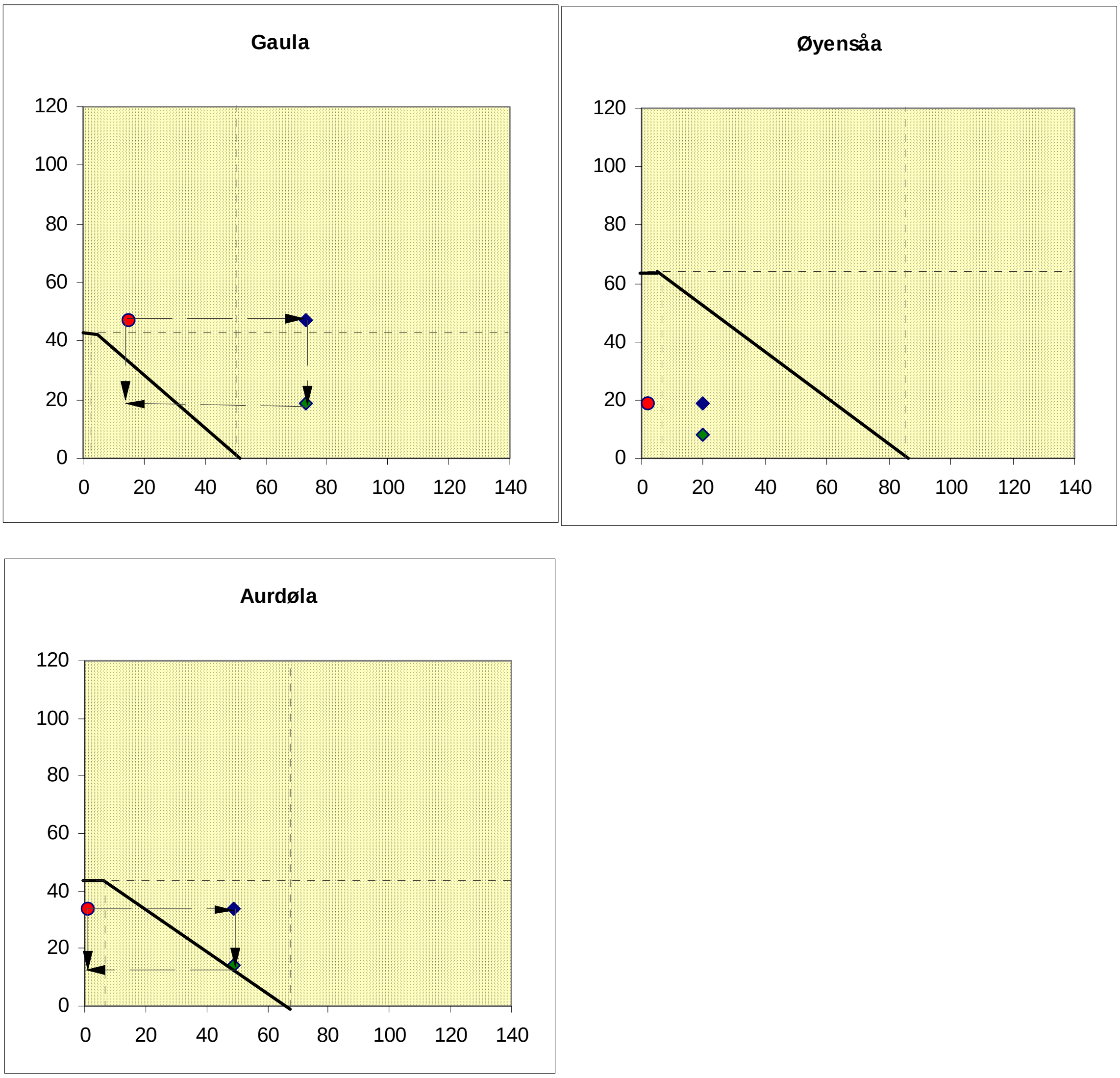

Figure 7. Continued.

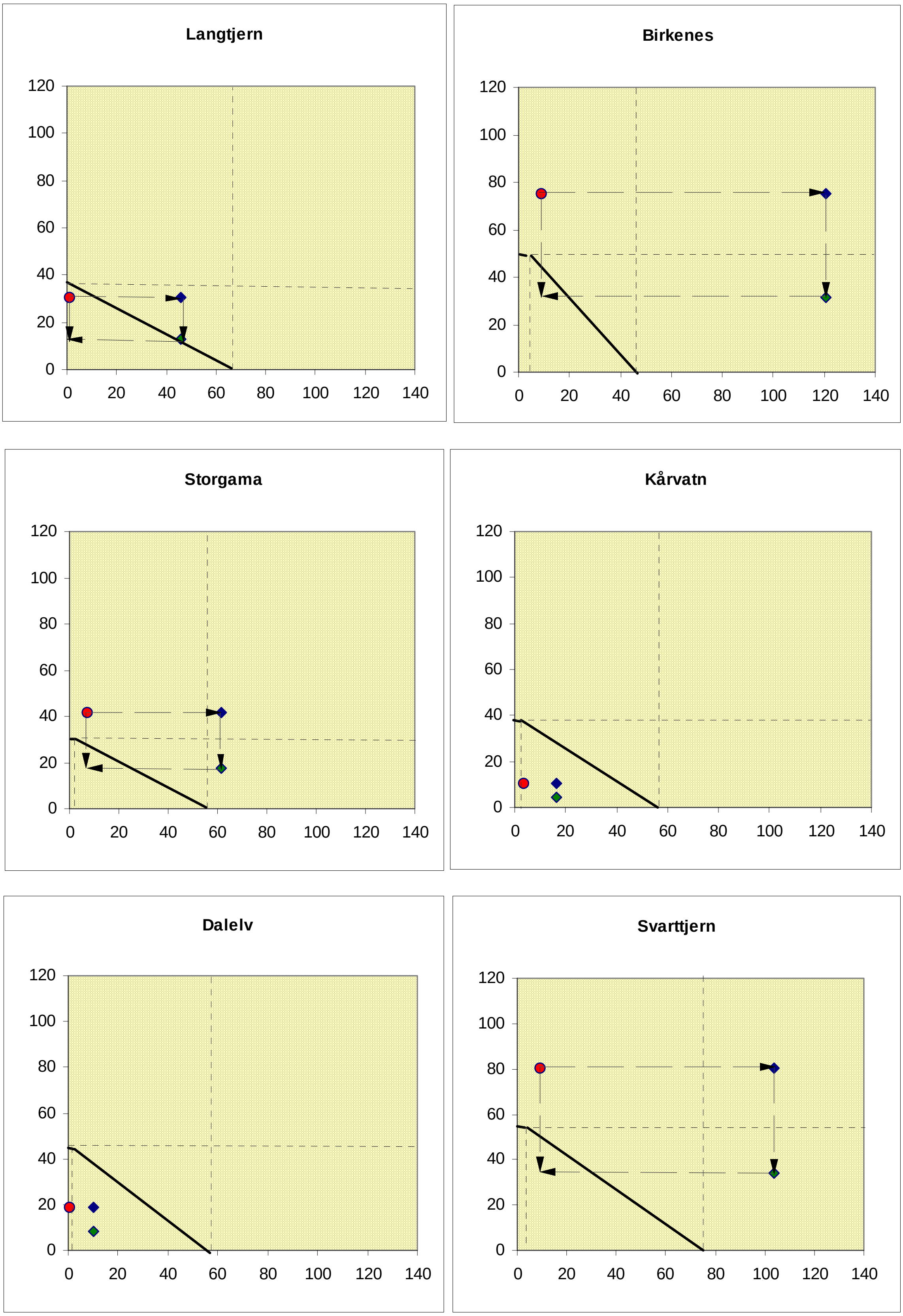

Figure 8. Critical load functions for the monitored catchments. See Figure 6 for explanation of legends.

4.3 REFISH lakes

Six of the lakes studied during the project period of the REFISH-project (Restoring Endangered Fish in Stressed Habitats) (Rosseland *et al.* 1990, Kroglund *et al.* 1992, Dalziel *et al.* 1995) have also been analysed.

The critical load functions for the REFISH lakes have also been calculated (Figure 9).

Table 8. Catchment characteristics for the monitored catchments.

				Catchment characteristics				
Lake	**Runoff**	**Lake area**	**Catchment area**	**Lakes**	**Forest**	**Peat**	**Open**	**Agri-culture**
	l m^{-2} sec^{-1}	*km^2*	*km^2*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
2.Homsvatn	57	0,38	1,6	20	2	0	78	0
3. Trollselvvatn	57	0,28	3,55	8	0	0	92	0
4. Sandvatn	57	0,26	2,58	11	0	0	89	0
5. Skjekelivatn	57	0,39	3,15	13	1	0	86	0
12. Repstadvatn	40	0,21	2,66	8	92	0	0	0
14. Mørklivatn	40	0,20	18,65	1	90	9	0	0

The six lakes included in the REFISH-project are all located in case 4 today and will require only N-reduction (case 5) when the new sulphur protocol is implemented- At present N-leaching all lakes are exceeded, but would, except for Mørklivatn, require only S-reduction to reach non-exceedance. This implies that with current reduction plans and no further N-leaching, all but one lake will reach non-exceedance. At potential N-leaching, however, large N-reductions are required to reach non-exceedance in 2010 (see Figure 9).

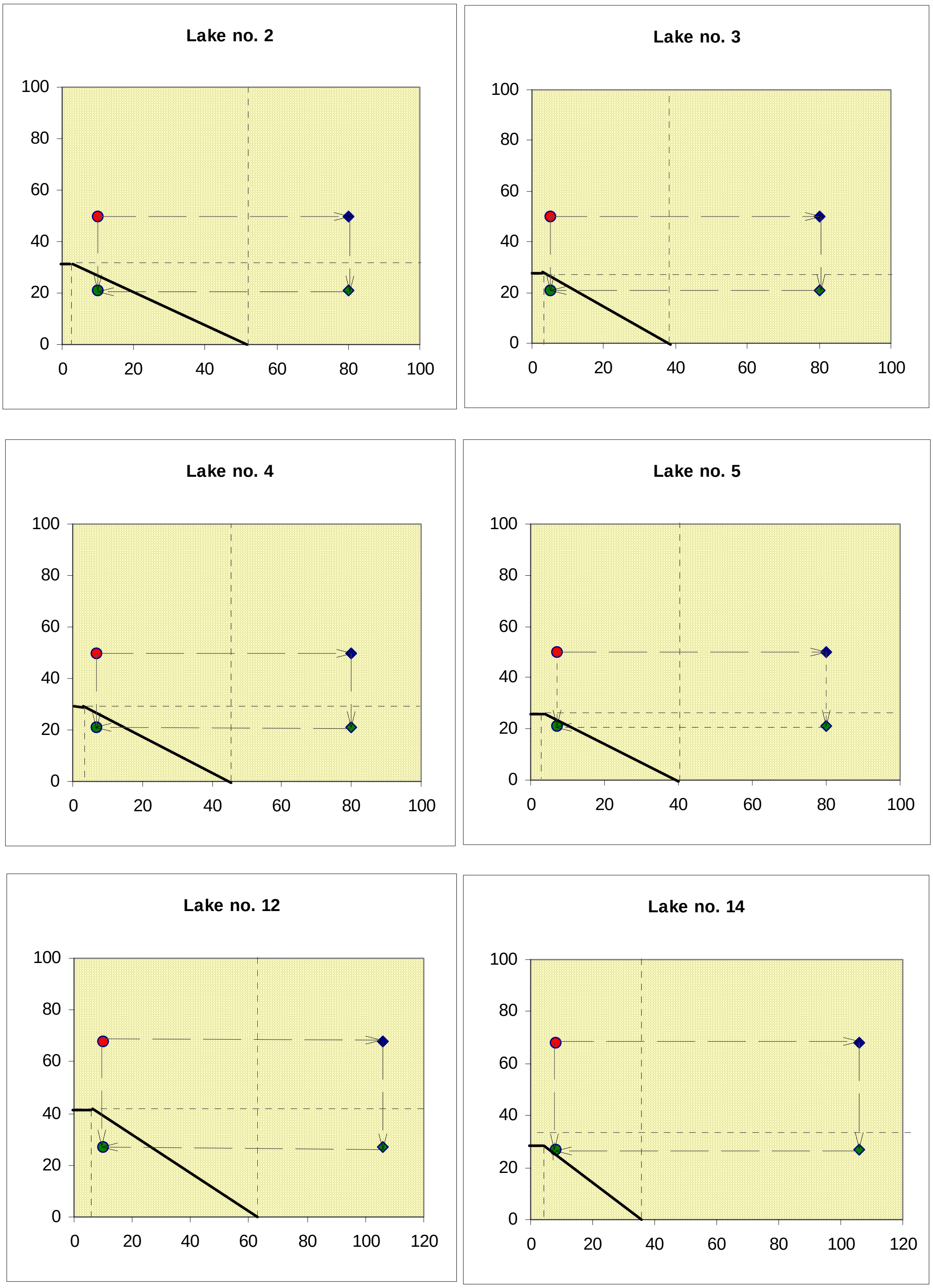

Figure 9. Critical load functions for REFISH lakes. See Figure 6 for explanation of legends.

5. Conclusions

The FAB-model predicts that most rivers and calibrated catchments, at present N-deposition, will require further N-reduction when or if the Second Sulphur Protocol has been implemented. If no further N-leaching occurs, the internationally agreed S-reductions will, if implemented, restore conditions for fish in many lakes and rivers in Norway. It should, however, be pointed out that the water samples for the rivers studied in this report have been taken close to the outlet. These locations do not necessarily reflect the conditions in the smaller lakes and streams further up in the catchment. Here, of course, many areas could still be exceeded at present N-leaching and the future predicted S-deposition. This is reflected in the predictions based on the SSWC-model which indicate that 18% of our lakes will still be exceeded. These lakes are mostly located in south-western and western Norway.

The future acidification situation estimated by means of the two models clearly indicate that nitrogen will be the critical factor in the future. Crucial questions are whether the situation predicted by the FAB-model ever will occur for lakes and rivers and whether the present leaching will increase with present N-loading. Lakes located in forested areas do not show any significant N-leaching today, even at rather high N-deposition, while for lakes located in non-forested areas N-leaching up to 40-50% of the N-deposition has been recorded. These lakes are largely found in areas with high precipitation amounts and with thin soil covers in south-western and western Norway. This indicate that soil type and vegetation cover is important for conditions leading to N-leaching.

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7. Appendix

Table A1. Average water chemistry for the monitored rivers and calibrated catchments for the period 1990-1996.

	pH	Ca	Mg	Na	K	Cl	SO_4	NO_3	TOC	R-Al	NL-Al	L-Al	TOTN	ANC
River		*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*µgN/l*	*mgC/l*	*µg/l*	*µg/l*	*µg/l*	*µgN/l*	*µeq/l*
3. Gjerstadelva	5,65	2	0,47	1,93	0,43	3,2	4,8	254	4,19	109	71	38	464	25
5. Nidelva	5,23	1,09	0,28	1,16	0,26	1,8	3,5	186	2,54	126	39	87	320	-2
7. Tovdalsleva	5,06	1,13	0,29	1,64	0,28	2,7	3,6	153	3,3	150	62	88	370	-3
11. Mandalselva	4,95	0,98	0,23	1,47	0,18	2,6	2,7	161	3,33	142	61	81	321	-5
13. Lygna	5,21	1,28	0,38	2,59	0,31	4,4	3,5	226	3,07	127	51	76	395	3
19. Bjerkreimselva	5,68	1,29	0,73	4,61	0,32	8	3,1	344	1,28	85	29	56	451	18
23. Dirdalselva	5,3	0,73	0,34	2,29	0,19	4,1	2,2	244	1,03	55	18	37	327	-10
26. Årdalselva	5,9	0,85	0,34	2,35	0,22	4,1	2	154	1,16	30	20	10	221	10
32. Vikedalselva	5,49	1,01	0,4	2,42	0,23	4,4	2,5	165	1,13	45	19	26	257	7
34. Nausta	5,66	0,44	0,26	1,68	0,25	2,8	1,4	59	1,42	31	21	10	140	11
45. Ekso	5,85	0,71	0,26	1,59	0,27	2,8	1,6	124	1,33	41	27	14	202	12
46. Modalselva	5,43	0,41	0,19	1,32	0,2	2,3	1,3	129	0,78	46	16	30	203	-3
57. Gaula	5,65	0,5	0,2	1,26	0,25	2,2	1,4	84	1,33	40	24	16	189	5
77. Øyensåa	6,08	1,14	0,7	5,01	0,29	8,7	2	27	4,57	50	42	8	163	51
90. Aurdøla	6,13	1,25	0,2	0,66	0,18	0,6	2,4	36	3,28	59	44	15	197	43

	pH	Ca	Mg	Na	K	Cl	SO_4	NO_3	TOC	R-Al	NL-Al	L-Al	TOTN	ANC
Calibrated catchment		*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*µgN/l*	*mgC/l*	*µg/l*	*µg/l*	*µg/l*	*µgN/l*	*µeq/l*
Birkenes	4,67	1,09	0,35	3,28	0,16	5,5	5	115	5,83	442	139	303	360	-38
Dalelv	6,13	1,66	0,97	3,9	0,31	6,3	5,5	19	3,11	44	39	5	154	47
Kårvatn	6,26	0,6	0,19	1,29	0,14	2,1	0,9	24	0,91	18	16	2	64	26
Langtjern	4,95	1,15	0,19	0,67	0,13	0,6	2,7	22	9,62	192	138	54	293	31
Storgama	4,7	0,63	0,13	0,91	0,08	1,3	2,8	102	4,62	154	70	84	357	-19
Svarttjern	5,15	0,23	0,25	2,08	0,16	3	1,6	39	3,22	114	82	32	165	6

Table A2. Average water chemistry for REFISH lakes for the period 1989-1995.

Lake	pH	Ca	Mg	Na	K	Cl	SO_4	NO_3	TOC	R-Al	NL-Al	L-Al	TOTN
		mg/l	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*mg/l*	*µgN/l*	*mgC/l*	*µg/l*	*µg/l*	*µg/l*	*µgN/l*
2.Homsvatn	4,79	0,56	0,27	2,06	0,17	3,6	2,5	249	1,93	119	23	95	377
3. Trollselvvatn	4,55	0,37	0,27	2,17	0,13	3,9	2,3	123	4,62	113	59	54	357
4. Sandvatn	4,70	0,51	0,29	2,20	0,16	3,8	2,4	167	3,72	114	51	64	366
5. Skjekelivatn	4,68	0,49	0,28	2,14	0,17	3,8	2,3	170	3,58	109	47	63	380
12. Repstadvatn	4,78	1,01	0,46	2,66	0,29	5,0	4,4	176	2,48	203	35	169	363
14. Mørklivatn	4,57	0,67	0,37	2,45	0,20	4,3	3,9	148	4,23	224	61	163	364

Naturens Tålegrenser - Oversikt over utgitte rapporter

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Henvendelser vedrørende rapportene rettes til utførende institusjon