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Development and application of the FAB model to calculate critical loads of S and N for lakes in the Killarney Provincial Park (Ontario, Canada)



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<p>Abstract</p> <p>In Sudbury, Canada, large reductions in sulfur emissions have resulted in reduced critical load exceedances and partial recovery of many lakes in the Killarney Provincial Park. The First-order Acidity Balance (FAB) model to calculate critical loads (CLs) for surface water includes the potential acidifying part of nitrogen, and takes into account the retention of nitrogen in both the terrestrial and aquatic part of the catchment. We have applied the FAB model to Killarney-lakes, and critical load functions for 43 lakes in the Park have been calculated. The model has been modified to include in-lake retention of nitrogen in upstream lakes in the calculation of CLs. This resulted in increased aquatic retention of nitrogen, giving higher CLs and thus making lakes in chains less sensitive to nitrogen deposition. Including upstream lakes in a simple manner increased the estimate of in-lake N retention by 47% on average and the lake-system method increased this estimate by 73% on average. Critical loads for nitrogen vary substantially within the Park, from 49 to 2472 meq m⁻² yr⁻¹. On the average N retained in the lake/sediment system (N_{lake}) was 57% of N deposited according to the modified model.</p>
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Killarney Park Restoration Program

**Development and Application of the FAB model
to calculate critical loads of S and N for lakes
in Killarney Provincial Park (Ontario, Canada)**

Preface

As part of a restoration program for Killarney Provincial Park south of Sudbury in Canada, NIVA has been working with critical load modelling since 1997. The first report focused on exceedance of critical load for strong acids by sulfur and was worked out as part of the newly established Northern Lakes Recovery Study (NLRS).

Based on the first report and as a result of discussions with the NLRS-group, NIVA suggested to include nitrogen in the calculations and to use the FAB-model. The purpose was to quantify the contribution of both sulfur and nitrogen deposition to the critical load exceedances for lakes in the Park.

Some of the problems we faced when using the FAB-model could not have been solved without the cooperation of Maximilian Posch (RIVM, Netherlands), who was invited and accepted to participate in this work. The report is based on calculations with an improved version of the FAB-model.

The FAB-model requires data for tree cover, bog areas and other catchment characteristics. Such data were not available and Christine Brereton was engaged to digitize the Park map and calculate the required areas. Through her work more exact data on catchment areas were made available.

We wish to thank Dr. Michael D. Moran of the Meteorological Service of Canada, Toronto, Ontario for providing deposition data and estimates for nitrogen.

The work has been financed by the Ontario Ministry of Environment and the Ontario Ministry of Natural Resources. Our contact there has been Dr. John Gunn.

Grimstad, May 30, 2000

Atle Hindar

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Summary

In Sudbury large reductions in sulfur emissions have resulted in reduced critical load exceedances and partial recovery of many lakes in Killarney Provincial Park. To achieve a more complete chemical recovery of the park even larger reductions are necessary (Hindar and Henriksen 1998).

To assess the importance of nitrogen for critical load exceedance calculations the First-order Acidity Balance (FAB) model has been applied on a selection of 43 lakes in the park. Critical load functions for these lakes have been calculated. The FAB-model takes into account the retention of nitrogen in both the terrestrial and aquatic part of the catchment, and requires detailed knowledge of each lake catchment. Critical loads, especially those for nitrogen, vary substantially within the Park, from 49 to 2472 meq m⁻² yr⁻¹. This reflects the variations in geology, water chemistry, land cover, and lake size in relation to the size of the catchment. On the average N retained in the lake/sediment system (N_{lake}) was 57% of N deposited. The variation in N_{lake} is almost entirely explained by r , the lake:catchment ratio.

Because of the complex lake systems a modified version of the FAB-model was developed for systems of lakes, i.e. sets of lakes draining into each other. The derivation of the improved model is given in this report. The results show that the number of upstream lakes have marked influence on the in-lake retention in the end lake, especially for nitrogen. The big-lake method (including upstream lakes in a simple manner) increases the N_{lake} estimate by 47% on average and that the lake-system method increases the N_{lake} estimate by 73% on average. Taking into account upstream lakes makes the end lake less sensitive to acid deposition, and thus giving a higher critical load.

The sensitivity of the FAB-model output to immobilization of nitrogen in the terrestrial catchment soils has been investigated as a first step of a more thorough sensitivity/uncertainty analysis.



Photo by Ed Snucins

1. Introduction

Calculations of critical load (CL) and their exceedances have been the basis for negotiations of emission reductions in Europe and Northern America. The Second Sulphur Protocol, signed in Oslo in 1994, was based on critical loads for soils for most of Europe, and on critical loads for surface waters for Scandinavia. The reason is that surface waters are the most sensitive ecosystems in Scandinavia. The latest protocol, which was signed in Gothenburg, Sweden, 1 December 1999, is also based on CLs and aims at limiting the emissions of sulfur, nitrogen and volatile organic compounds.

In Sudbury large reductions in sulfur emissions (about 90% since 1960) have resulted in reduced CL exceedances, as calculated with the Steady State Water Chemistry (SSWC) model, and partial recovery of many lakes in the Killarney Provincial Park. To achieve a more complete chemical recovery even larger reductions are necessary (Hindar and Henriksen 1998).

The First-order Acidity Balance (FAB) model may be used to assess the importance of nitrogen for CLs for acidity and present and future exceedances. This model has also been used for the CL calculations for surface water in the 1999 Protocol.

The FAB-model takes into account the retention of nitrogen in both the terrestrial and aquatic part of the catchment, and requires more detailed knowledge of each catchment than the SSWC-model. A new derivation of the model is given in Appendix B of this report, and results for those catchments for which sufficient data were available are presented in the main text. For the first time a modified version of the FAB-model is applied to systems of lakes, i.e. sets of lakes draining into each other, and results show that the explicit consideration of such dependencies has a marked influence on the in-lake retention, especially of nitrogen. Finally, the sensitivity of the FAB-model output to immobilization of nitrogen in the terrestrial catchment soils has been investigated as a first step towards a more thorough sensitivity/uncertainty analysis.

2. Material and Methods

2.1 Killarney Park Area

Killarney Provincial Park (46°3'N, 81°21'W) is situated approximately 60 km south-west of Sudbury, Ontario. This 48,500 ha wilderness area includes much of the La Cloche Mountains located close to Georgian Bay in the north-eastern part of Lake Huron.

The over 500 lakes and ponds in the park are widely different in size, elevation, catchment characteristics and water chemistry, and they have therefore reacted differently to acid deposition (Snucins and Gunn 1998). Most of the park is underlain by ridges of quartzite, a material that is very weathering resistant. In these areas many of the lakes are acidified resulting in water quality levels below threshold limits for many fish species.

The park area is now part of a national ecological monitoring and assessment network (EMAN), and will continue to be the site for long-term monitoring of the impacts of a variety of environmental stressors.

The Sudbury area has a long-lasting winter. The combination of a large fraction of the precipitation falling as snow and low annual runoff have impacts on flushing patterns and retention times of the

lakes in the area. Mean annual runoff for the Sudbury area is 0.4 m yr⁻¹ and 0.35 m yr⁻¹ for Killarney (Government of Ontario 1984).

2.2 Deposition

An overview of sulfur deposition in the area has been given by Hindar and Henriksen (1998). N-deposition data were made available for this report by Dr. Michael Moran, see **Table 1**. Nitrogen deposition data are from the following sources: Environment Canada (1997), RMCC (1990), Sukloff (1988) and Acidifying Emissions Task Group (1997).

Table 1. Deposition scenarios for the Killarney area. The data are from sources cited in the reference list and have been summarized by Dr. Michael Moran of the Atmospheric Environment Service, Ontario. The S-deposition for 1981 is based on a declining trend in lake-sulphate (Lakes-trend) as suggested by Hindar and Henriksen (1998).

Scenario	Year	S-wet	S-tot.	S-tot.	
		kg SO ₄ ha ⁻¹ yr ⁻¹	kg SO ₄ ha ⁻¹ yr ⁻¹	meq m ⁻² yr ⁻¹	
Lakes-trend	1981			69.0	
BASE	1989	21	26.3	54.7	
CCONLY*	1994	19.8	24.8	51.6	
CCUSA1**	1997	18.1	22.6	47.1	
CCUSA2**	2010	16.7	20.9	43.5	
25FCAP	2010 (-25%)	14.4	18.0	37.5	
5CCUS2	2010 (-50%)	11	13.8	28.6	
75FCAP	2010 (-75%)	7.4	9.3	19.3	
		NO ₃ -wet	NO ₃ -tot	NH ₄ -wet***	NH ₄ -tot.
		kg NO ₃ ha ⁻¹ yr ⁻¹	kg NO ₃ ha ⁻¹ yr ⁻¹	kg NH ₄ ha ⁻¹ yr ⁻¹	kg NH ₄ ha ⁻¹ yr ⁻¹
	1980-83	17	34	4	5.3
	1986-90	19	38	4	5.3
	1990-93	18	36		
	2007****	13.4	26.8		

BASE 1989
 CCONLY* Canadian controls only
 CCUSA1** First phase of the US SO₂ emissions reductions
 CCUSA2** Second phase of the US SO₂ emissions reductions
 25FCAP 2010 emissions reduced by 25 % (2030)
 5CCUS2 2010 emissions reduced by 50 % (2030)
 75FCAP 2010 emissions reduced by 75 % (2030)

*Referring to the 1985 Eastern Canada Acid Rain Control Program

**Referring to the 1990 U.S. CAAA (Clean Air Act Amendments)

*** In the periods 1982-87 and in 1986 wet NH₄ deposition was 4 kg NH₄ ha⁻¹yr⁻¹ according to RMCC (1990) and Sukloff (1988).

According to Mike Moran, based on mass budget analyses over eastern North America of simulations of ADOM, an Eulerian acid deposition model, the dry deposition of total oxidized nitrogen (NO₂+HNO₃+PAN) was found to contribute about 50% of the total deposition of oxidized nitrogen whereas the dry deposition of reduced nitrogen provided about 25% of the total deposition of reduced nitrogen.

**** The emission scenario for the year 2007 corresponds to reductions of NO_x emissions of roughly one-third from 1990 levels.

2.3 Water sampling

A synoptic survey of 151 lakes in the Killarney Provincial Park was carried out during the period January 23 to February 13, 1996 (Snucins and Gunn 1998). Water chemistry data together with a mean runoff value of 0.35 m yr⁻¹ (Government of Ontario 1984) were used to calculate the critical load for each lake (Hindar and Henriksen 1998). The Killarney Park area is probably too small to have large

variability in run-off. However, the run-off may vary considerably from year to year. No data exists, however, from the area to document patterns and between-year differences.

2.4 Catchment characteristics

All morphometric data of the lakes and their watersheds are from the Cooperative Freshwater Ecology Unit at the Laurentian University in Sudbury (Snucins and Gunn 1998). To obtain area-specific data for catchment properties, a digitized map was produced based on the area types given in **Table 2**.

Table 2. Area types and characteristics used for digitization of the Killarney Provincial Park map.

Area type	Characteristics
Cat.	catchment number
Lake	catchment name
Cat. Area	the total area within each catchment. These values were extracted from the Killarney Watershed map of the Coop Unit.
Lake Area	the surface area of the major water body within each catchment
Productive Forest	this includes all forest types
Treed Muskeg	has a tree cover of at least 10% crown closure. It includes peatlands, swamps, and bogs supporting limited tree growth due to excessive moisture
Open Muskeg	has a tree cover of less than 10% crown closure. It too includes peatlands, swamps, and bogs supporting limited tree growth due to excessive moisture
Brush + Alder	includes brush and alder stands that are not significant for timber harvesting
Exposed Rock	all exposed rock
Water	all the waterbodies found within each catchment.
Streams	all streams found within each catchment
Campground + Road	the combined total of the George Lake campground and road
Total	the sum of all the classification types (Productive Forest, Treed Muskeg, Open Muskeg, Brush + Alder, Exposed Rock, Water, Streams, and Campground + Road)

The classification covers (Productive Forest, Treed Muskeg, Open Muskeg, Brush & Alder, Exposed Rock, Water, Streams, and Campground & Road) were calculated using ARCInfo, whereas Cat. Area and Lake Area were calculated with MapInfo. This classification system was then used in the critical load calculations with the FAB-model.

For the application of the FAB model to non-headwater lakes (see below) it is necessary to know their upstream lakes. For each of the 151 lakes **Table 3** indicates which lakes drain directly into the end lake and which lakes are further upstream these lakes.

2.5 Critical load models

Two steady-state models - one empirical and one more process-oriented - for calculating critical loads (CLs) of acidifying deposition (both S and N) for surface waters are in current use. The Steady-State Water Chemistry (SSWC) model allows the calculation of CLs of acidity (S+N) and their *present* exceedance. The First-order Acidity Balance (FAB) model allows the simultaneous calculation of CLs 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 CLs for forest soils (see UBA 1996). While the derivation of the SSWC model can be found in the quoted literature, the derivation of the modified and extended FAB-model is presented in Appendix B.

Table 3. ID-numbers of the sampled Killarney lakes, of lakes directly draining into them (2nd column), and of lakes further upstream (3rd column). A star indicates that the critical load of acidity, CL(A), was calculated for that lake with the SSWC model (Hindar and Henriksen 1998). The FAB model is applied to the 43 lakes marked in bold. This table is a modified and corrected version of the table in Snucins and Gunn (1998).

ID-no.	Lakes directly draining into ID-numbered lake	Lakes further upstream
1	27	13,78,86
2*	47	102
3*		
4*	26,74	30,31,37,44,73
5*		
6*	4,19,25	26,30,31,37,44,55,73,74,104,105,106,107,108,110
7		
8		
9		
10*		
11*		
12*		
13		
14*	146	
15*	90	12,40
16*	67	98,133,134,135,136
17*		
18*		
19*	55	104,105,106,107
20	85	109
21*		
22		
23		
24*		
25*	108,110	
26	30	73
27	86	13,78
28	24	
29*	39	33,57
30	73	
31		
32*	51,53,82,101	2,45,47,52,59,68,70,75,81,84,102,111,112,113,114,117,119,120,121,122,123,124
33*		
34*	29,64,79	24,28,33,36,39,42,56,57,63,77,92,93,94,99,100,131,132
35*	3,21,32,58,140	2,45,47,51,52,53,59,68,70,75,81,82,84,101,102,111,112,113,114,117,119,120,121,122,123,124,141,142,149
36	77	42,99,100
37		
38*		
39*	33,57	
40		
41	8	
42	99	100
43*	5,100	
44*	31	
45*		
46*		
47*	102	
48*	34	24,28,29,33,36,39,42,56,57,63,64,77,79,92,93,94,99,100,131,132
49*	46	
50*	15,20,54,60,80,97	4,6,8,12,19,25,26,30,31,37,40,41,44,55,73,74,85,90,104,105,106,107,108,109,110

Table 3 (continued).

51*	45,52	
52		
53*	59,68,75,84,112,113,117,120,122,123,124	2,47,70,81,102,111,114,119,121
54		
55	104	105,106,107
56		
57		
58*		
59*		
60	6	4,19,25,26,30,31,37,44,55,73,74,104,105,106,107,108,110
61*	46	
62*	144	1,13,27,78,86
63	28	24
64*		
65*	69,143	89
66*	16,48	24,28,29,33,34,36,39,42,56,57,63,64,67,77,79,92,93,94,98,99,100,131,132,133,134,135,136
67	98,134	133,135,136
68*	70,81	2,47,102
69*	89	
70		
71*	115,126,127	116
72		
73		
74	37,44	31
75*		
76	118	
77	42	99,100
78		
79*	36,56,63,93,131,132	24,28,42,77,92,94,99,100
80*		
81	2	47,102
82		
83		
84*		
85	109	
86	13,78	
87		
88		
89		
90	12,40	
91		
92		
93	92,94	
94		
95	11,71,83,103,125,128,129,130,138,139,150,151	76,115,116,118, 126,127,137
96		
97	41	8
98		
99	100	
100*		
101*		
102*		
103*		
104	105,106	107
105		
106*	107	
107		
108		
109		
110		
111*		
112*	111	
113*	114	
114*		

Table 3 (continued).

115	116	
116		
117*		
118		
119		
120*	119	
121*		
122*		
123*		
124*	121	
125*		
126		
127		
128*		
129		
130		
131*		
132*		
133		
134*	133,135	136
135	136	
136		
137		
138*	137	
139		
140*	141,149	142
141	142	
142		
143		
144	1	13,27,78,86
145*		
146		
147*		
148		
149		
150*	76	118
151		

The modified SSWC model

In the Steady-State Water Chemistry (SSWC) model the critical load (CL) of acidity is calculated as (see, e.g., Henriksen *et al.* 1990):

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

where Q is the runoff, $[BC^*]_0$ is the original base cation concentration, and $[ANC]_{limit}$ is the chosen critical ANC concentration above which the risk of harmful effects on the indicator organism (fish) is considered negligible; 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):

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

where the subscripts 0 and t refer to the original (background) and present concentrations, resp. $[SO_4^*]_0$ is estimated from a linear regression with $[BC^*]_t$ using data from Norwegian background lakes, whereas $[NO_3]_0$ is set to zero. The F-factor is calculated following Brakke *et al.* (1990), but with the modification accounting for both high and low runoff (Hindar and Henriksen 1998):

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

where $S=400 \text{ meq m}^{-2} \text{ yr}^{-1}$ is the annual base cation flux above which $F=1$. The critical ANC-limit is calculated by a model suggested by Henriksen and Posch (2000) and results in values between 0 and 50 meq/m^3 depending on the catchment characteristics. The formula used here (and in Norway) is:

$$(4) \quad [\text{ANC}]_{\text{limit}} = \min\{Q[\text{BC}^*]_0/(Q+4), 50\}$$

The runoff Q is given in m/yr . The original SSWC-model has been 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):

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

where S_{dep} is the 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.

The modified FAB model

The SSWC model is solely based on water chemistry data and incorporates the influence of the terrestrial catchment in an empirical way (e.g. via the F -factor). The FAB-model takes into account the sources and sinks of N in the terrestrial catchment as well as the retention of S and N in the lake in a simple fashion. This is comparable to the widely used SMB critical load model for (forest) soils (Sverdrup and de Vries 1994, UBA 1996). A first version of the FAB model has been presented in Kämäri *et al.* (1992), and the first "definitive version" is reported in Henriksen *et al.* (1993). Short descriptions for the "Mapping community" can be found in Downing *et al.* (1993) and Posch (1995). The 1993 report by Henriksen *et al.* appeared in the peer-reviewed literature as Posch *et al.* (1997). In Appendix B of this report we present a new derivation of the FAB model, considering more land use types and correcting for an inconsistency pointed out by C.Curtis (1998, pers. comm.). In addition, the generalization of the FAB model for taking into account upstream lakes is provided.

The FAB model is made "compatible" with the SSWC model by inserting eq.1 for the base cation and ANC runoff ($L_{\text{crit}} = \text{CL}(A)$; see Appendix B). Every pair of N - and S -deposition, ($N_{\text{dep}}, S_{\text{dep}}$), satisfying the following equation, is called a critical load:

$$(6) \quad a_S S_{\text{dep}} + a_N N_{\text{dep}} = L_N + \text{CL}(A)$$

where

$$(7) \quad a_S = 1 - \rho_S, \quad a_N = (1 - \rho_N) b_N, \quad L_N = (1 - \rho_N) M_N$$

and M_N and the dimensionless coefficients b_N depend on the magnitude of N_{dep} :

N_{dep}	b_N	M_N
$N_{\text{dep}} \leq N_i$:	$1 - f - g$	0
$N_i < N_{\text{dep}} \leq N_i + N_u$:	$1 - f - g f_{\text{de}}$	$(1 - f_{\text{de}}) g N_i$
$N_{\text{dep}} > N_i + N_u$:	$1 - (f + g) f_{\text{de}}$	$(1 - f_{\text{de}})[(f + g)N_i + f N_u]$

In the above equations, N_i and N_u are the immobilization of N and the net growth uptake (harvested N), respectively. f_{de} is the fraction of N denitrified in the soils. f and g are the fraction of forests and grass/heathland in the catchment, respectively, and ρ_N and ρ_S are the in-lake retention coefficients for N and S , respectively. The in-lake retention coefficient ρ_N is modeled by a kinetic equation (Kelly *et al.* 1987, Dillon and Molot 1990):

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

where s_N is the net mass transfer coefficient for N (m/yr) and r is the lake:catchment ratio. An analogous equation holds for ρ_S with mass transfer coefficient s_S (Baker and Brezonik 1988).

Since sinks of N cannot compensate the deposition of S, the maximum critical load of S is given by

$$(9) \quad CL_{\max}(S) = CL(A)/a_S$$

and the maximum critical load of N is given by setting $S_{\text{dep}}=0$ in eq.6 (see Appendix).

Eq.6, together with these constraints, determines the so-called critical load function, separating the N- and S-deposition values which cause "harmful effects" (exceedance) from those which do not (non-exceedance). An example of a critical load function is shown in **Figure 1** (see also Appendix B). As explained in Appendix B, a unique exceedance, i.e. unique reduction requirements for N and S, cannot be derived. Thus, in accordance with present practice in the protocol negotiations under the LRTAP Convention, we *define* the exceedance as $Ex = \Delta N + \Delta S$, where ΔN and ΔS are the horizontal and vertical components of the shortest distance of the point $(N_{\text{dep}}, S_{\text{dep}})$ to the critical load function (Posch *et al.* 1999; see **Figure 1**; note that this exceedance is different from the excess leaching defined in Appendix B).

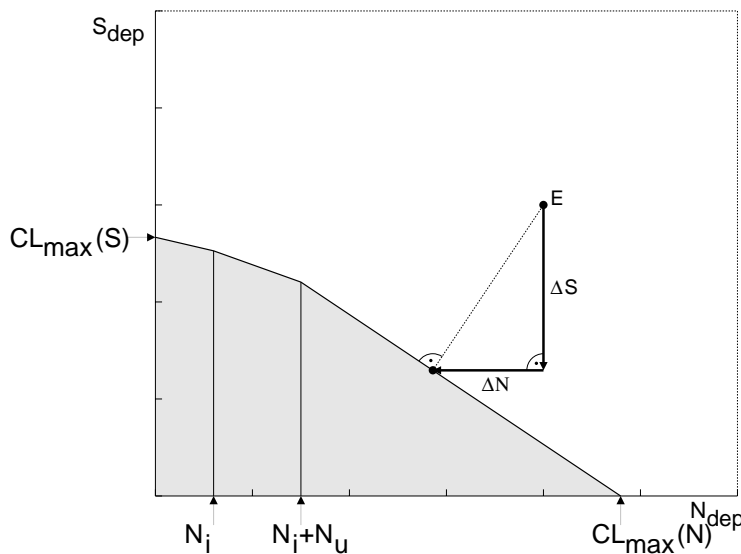


Figure 1. Example of a critical load function defined by the FAB model. The piece-wise linear function defines all pairs of $(N_{\text{dep}}, S_{\text{dep}})$ for which eq.6 is fulfilled. Also shown is an example of the exceedance defined in the text.

3. Results and Discussion

Input data for the calculations of critical loads are from the 1996 lake survey (Snucins and Gunn 1998), see Appendix A. The water chemistry data from winter 1996 are considered as representative for the lakes and catchments, and are treated as volume-weighted values in the model.

Total S deposition are from different sources, and has been estimated to have decreased from 69 meq m⁻² yr⁻¹ in 1981 to 47 meq m⁻² yr⁻¹ in 1997 (see **Table 1**). A deposition scenario for 2010 predicts a decrease to 43 meq m⁻² yr⁻¹, and three other scenarios relate to this decrease. They represent an additional 25, 50 or 75 % emission reduction, respectively.

Critical load of acidity, CL(A), has been calculated for the whole park area with the **SSWC model** (Hindar and Henriksen 1998). The critical loads for sulfur were estimated to have been exceeded in 57 % of the Killarney park area in 1981, whereas 38 % of the area was exceeded in 1997. Depending on which of the 2010-scenarios will be implemented, the critical load will be exceeded in 0 to 31 % of the park area according to Hindar and Henriksen (1998).

A target load for total S deposition of 30 meq m⁻² yr⁻¹ (corresponding to 14.4 kg SO₄ ha⁻¹ yr⁻¹) corresponds to a 2010-scenario according to the Clean Air Act Amendments with an additional 50 % emission reduction. This emission level will protect the park area almost completely from exceedances of the CLs (Hindar and Henriksen 1998). A target load of 40 meq m⁻² yr⁻¹ will result in almost complete elimination of CL exceedances above 15 meq m⁻² yr⁻¹. This load corresponds to a combination of the expected 2010 and the 2010 + 25 % - scenario.

To calculate CLs of sulfur and nitrogen acidity with the **FAB model**, additional input data and parameters are required. The required data have been generated.

The catchment and lake sizes as well as the fraction of forests and open land within the terrestrial catchments have been derived from maps of the Park (see section 2.4. and Appendix A). In all calculations we assume that the net growth uptake of nitrogen is zero (N_u=0), i.e. we assume that no N is exported from the catchments by harvesting. For the long-term immobilization of N in the soils we assume a value of 1 kgN ha⁻¹ yr⁻¹ (=7.143 meq m⁻² yr⁻¹) for all catchments, a value recommended for critical load calculations in Europe (UBA 1996). Note that present immobilization (retention) in soils might be considerably higher due to elevated inputs, but the value of 1 kgN represents the long-term sustainable input of N due to the build-up of soils. The denitrification fraction is estimated for every catchment as $f_{de}=0.1+0.7f_{peat}$, where f_{peat} is the fraction of peatland in catchment (UBA 1996). Finally, for the net mass transfer coefficients of N and S, which determine the fraction of N and S retained in the lake/sediment system, we selected $s_N=5$ m yr⁻¹, the mean of the range 2-8 m yr⁻¹ (Dillon and Molot 1990), and $s_S=0.5$ m yr⁻¹, the mean of the range 0.2-0.8 m yr⁻¹ (Baker and Brezonik 1988), using the same values for all catchments in the Park.

The SSWC model depends on water chemistry data, which represent a mixture of all contributions, including upstream catchments. The FAB model has originally been developed for headwater catchments only (Posch *et al.* 1997), but it had to be modified to solve some of the problems we faced in this work. A generalization to systems of lakes was therefore derived (see Appendix B). In order to apply this generalized model to a system of lakes, the topographical and land cover parameters (but not the water chemistry) for all upstream catchments must be known.

Hindar and Henriksen (1998) calculated CLs on basis of water chemistry data from 73 of the 151 sampled lakes and applied this to 84 catchments. These 84 catchments covered the whole park area.

Catchment characteristics for all upstream catchments were only available for 43 of the 73 sampled catchments (lakes). Out of these 43 lakes, 35 are headwater lakes, 6 have a single headwater lake upstream and 2 lakes have two sampled upstream lakes. The results with the FAB-model are presented as CL functions for each of the 43 catchments in **Figure 2**. The solid line represents the critical load function as it was calculated with the FAB-model, whereas the dashed lines are based on calculations without in-lake N retention processes. D1 in the figure is present deposition of N and S (D1) and D2 the 5CCUS2 deposition scenario for 2010 with an additional 50% reduction in S deposition (see **Table 1**). Depending on whether D1 or D2 lies above or below a CL function shows whether (and how much) CLs are (or will be) exceeded or not.

Whenever the sulphur deposition component of D1 and/or D2 is smaller than $CL(A)$, critical loads of acidity are not exceeded according to the SSWC model. But N deposition can lead to an exceedance also in those cases, since net acidifying N and S deposition compete for the same base cations. This shows the importance of considering N and the processes involving it when deriving critical loads for acidity and calculating their exceedance.

The quantities defining the critical load functions shown in **Figure 2**; $CL(A)$, $CL_{\max}(S)$ and $CL_{\max}(N)$, are summarized in **Table 4**. As can be seen, critical loads, especially those for nitrogen, vary substantially within the Park, reflecting the variations in geology, water chemistry, land cover, and lake size in relation to the size of the catchment (“r” in **Table 4**).

Also listed in **Table 4** is the amount of N retained in the terrestrial catchment (N_{terr}) and the lake(s) (N_{lake}), expressed as percentage of the total N-deposition in 1993. It appears that, in general, much of the N deposited (57%) is retained in the lake/sediment system and a smaller fraction in the terrestrial part. The variation in N_{lake} is almost entirely explained by r, the lake:catchment ratio, according to the model.

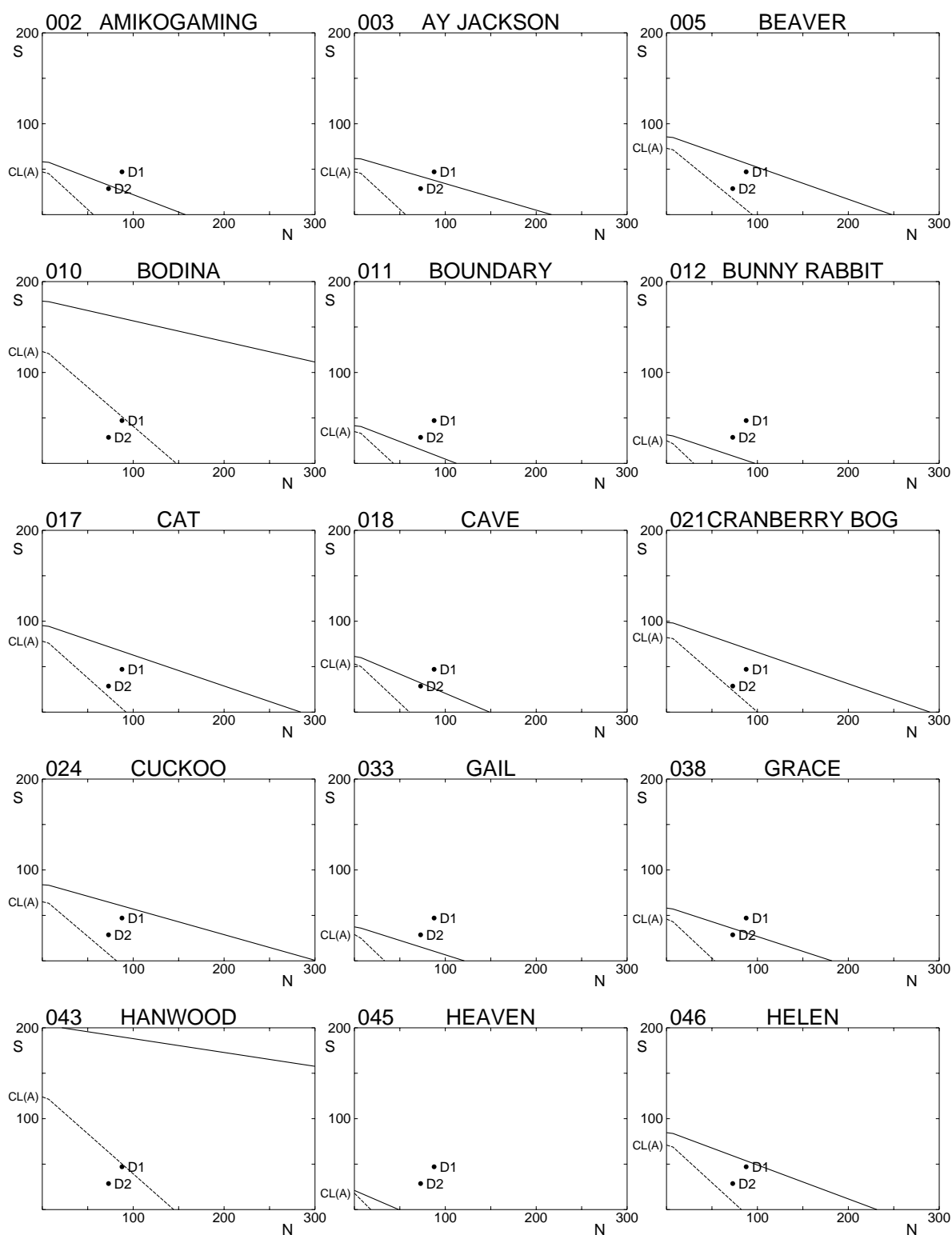


Figure 2: Critical load functions for the 43 catchments with sufficient input data, as determined with the FAB model (solid line). The dashed line indicates the critical load function when neglecting in-lake retention processes; in this case the maximum critical load of S is given by CL(A) from the SSWC model. Also indicated are the present deposition of N and S (D1) and the 5CCUS2 deposition scenario for 2010 (D2; see **Table 1**).

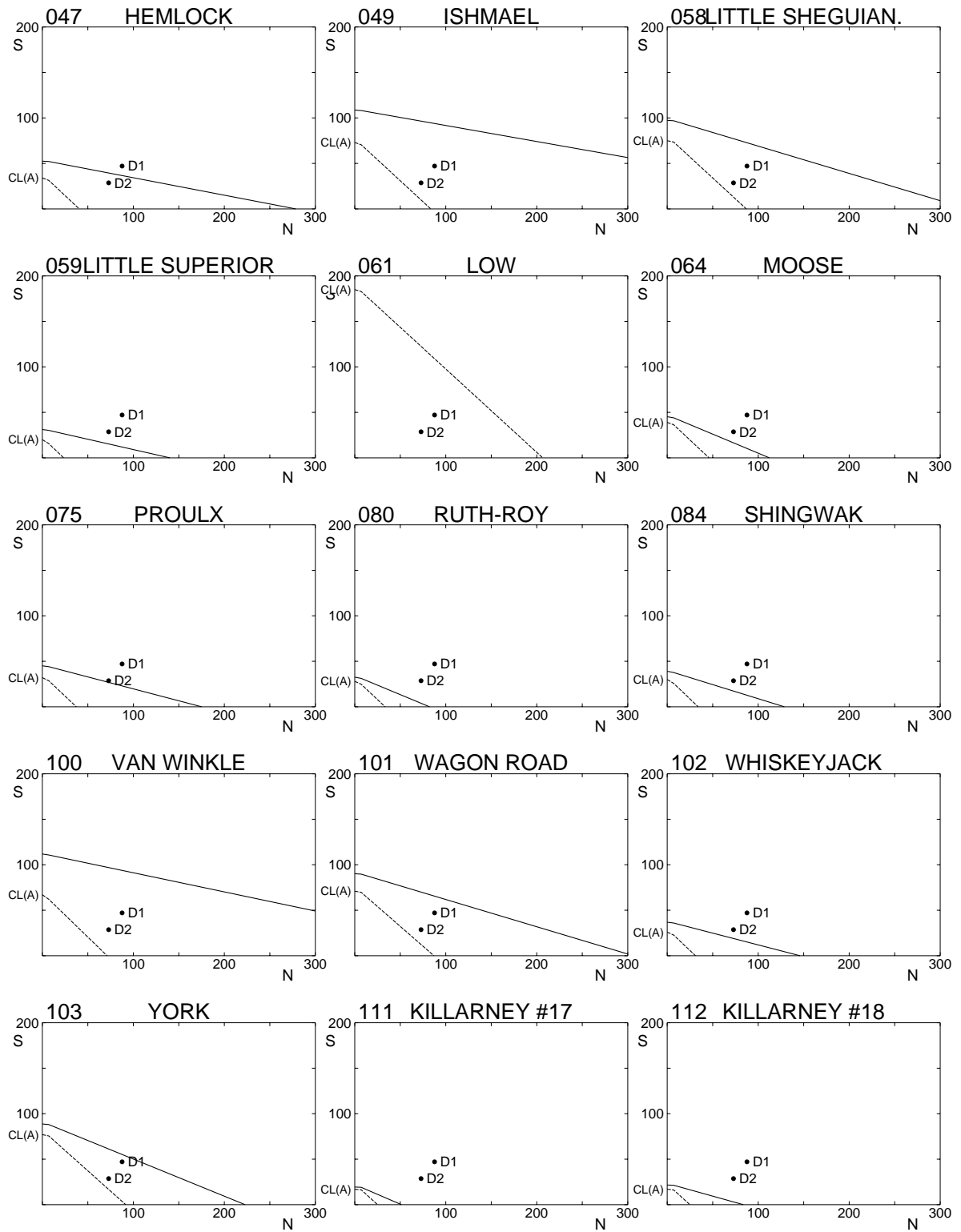


Figure 2 (continued).

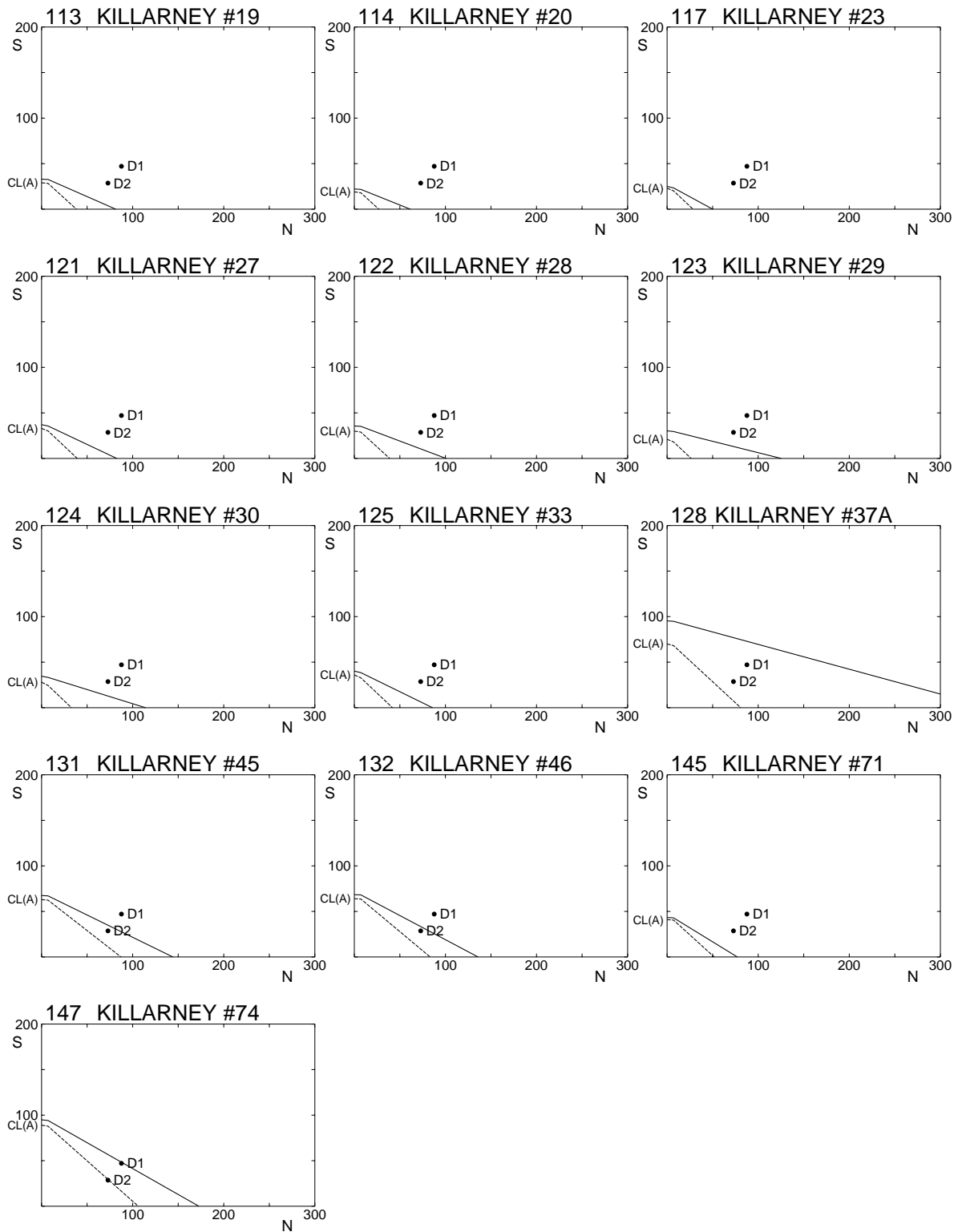


Figure 2 (continued).

Table 4. Critical load of acidity, $CL(A)$, computed with the SSWC model (Hindar and Henriksen 1998), the maximum critical load of sulfur, $CL_{max}(S)$, and nitrogen, $CL_{max}(N)$, computed with the FAB model (using the lake system approach; see Appendix A), and the N retained in the terrestrial part (N_{terr}) and the lake(s) (N_{lake}) (expressed as % of the 1993 total N deposition). The second column is the lake:catchment area ratio r .

Lake no.	r	$CL(A)$	$CL_{max}(S)$	$CL_{max}(N)$	N_{terr}	N_{lake}
		meq m ⁻² yr ⁻¹			%	%
2	0.132	47	58.2	157.4	13.4	54.0
3	0.220	47	61.8	216.9	13.5	65.6
5	0.120	73	85.6	247.9	23.0	48.7
10	0.316	123	178.5	791.7	18.4	66.8
11	0.128	35	41.4	112.2	13.0	56.2
12	0.179	25	31.4	97.3	9.2	65.2
17	0.154	78	95.2	284.3	15.5	58.1
18	0.109	53	61.3	148.7	10.5	54.5
21	0.141	82	98.5	289.8	18.9	54.2
24	0.202	65	83.7	302.2	20.1	59.3
33	0.203	29	37.4	120.9	7.4	68.8
38	0.184	46	58.1	182.0	10.5	64.8
43	0.233	124	202.6	1335.6	15.9	61.8
45	0.120	18	21.1	48.8	0.1	63.0
46	0.135	71	84.6	231.4	13.4	56.9
47	0.252	34	52.5	278.5	10.9	69.0
49	0.160	73	108.6	620.0	12.4	60.3
58	0.209	75	97.4	330.1	13.7	64.6
59	0.393	20	31.2	140.2	6.8	79.1
61	0.153	185	305.0	2472.4	13.3	58.5
64	0.112	39	45.2	112.3	11.0	54.7
75	0.285	32	45.0	175.1	9.1	73.0
80	0.115	28	32.6	82.2	9.5	56.3
84	0.211	30	39.0	128.7	7.4	69.6
100	0.468	67	111.8	533.5	5.3	82.4
101	0.189	71	90.1	306.3	18.3	59.6
102	0.293	26	36.9	145.9	9.3	73.2
103	0.107	77	88.7	222.8	16.2	50.6
111	0.098	17	19.4	51.3	15.6	49.3
112	0.114	17	21.6	83.6	15.4	52.2
113	0.090	29	33.0	81.5	15.7	47.3
114	0.116	19	22.2	61.4	15.0	53.1
117	0.062	23	25.0	50.0	10.3	42.0
121	0.086	33	37.1	82.6	10.4	49.5
122	0.132	30	35.7	100.7	14.8	55.7
123	0.310	21	30.3	125.3	10.3	73.2
124	0.094	28	34.6	114.1	8.6	52.4
125	0.081	36	40.2	85.9	9.6	48.4
128	0.254	70	95.4	355.1	12.9	68.2
131	0.049	63	67.4	144.2	27.7	29.9
132	0.048	64	68.4	135.8	22.8	31.4
145	0.039	41	43.3	77.1	16.0	30.2
147	0.046	89	94.9	172.7	17.2	33.0

In Appendix B two methods are derived for computing the CLs for a **system of lakes**: the "big-lake approach", which treats all lakes in the system as a single lake situated in the combined catchment, and the "lake-system approach", which treats each subcatchment separately. In addition, one can ignore all upstream lakes in the CL calculation and treat the whole catchment as draining directly into the lake. We call this the "one-lake" approach in the sequel.

Computing the CL functions with either one of the three approaches yields, of course, identical results for all 35 headwater lakes. For the other 8 lakes the values of $CL_{\max}(S)$ and $CL_{\max}(N)$ are listed in **Table 5** for all three approaches.

Table 5. $CL_{\max}(S)$ and $CL_{\max}(N)$ computed for the 8 lakes with sampled upstream catchments using three approaches: (i) ignoring upstream lakes ("one-lake" approach); (ii) using the "big-lake" approach" and (iii) using the "lake-system" approach (see Appendix B). Also given is $CL(A)$, the critical load of acidity, computed with the SSWC model (Hindar and Henriksen 1998).

Lake no.	Upstream lake (s) no.	One-lake			Big-lake		Lake-system	
		$CL(A)$	$CL_{\max}(S)$	$CL_{\max}(N)$	$CL_{\max}(S)$	$CL_{\max}(N)$	$CL_{\max}(S)$	$CL_{\max}(N)$
<----- meq m ⁻² yr ⁻¹ ----->								
2	47,102	47	51.9	109.7	55.8	152.4	58.2	157.4
43	5,100	124	137.0	288.1	165.2	608.8	202.6	1335.6
47	102	34	36.5	67.4	46.2	171.1	52.5	278.5
49	46	73	79.7	155.9	89.7	264.2	108.6	620.0
61	46	185	194.0	303.8	225.4	646.9	305.0	2472.4
112	111	17	18.5	41.6	19.8	55.3	21.6	83.6
113	114	29	32.4	75.5	32.7	79.1	33.0	81.5
124	121	28	29.7	50.5	31.8	72.5	34.6	114.1

It is obvious from the way the two approaches are designed that the CLs in the "big-lake approach" are always smaller than the corresponding values computed with the "lake-system approach". This is due to the fact that the latter allows the S and N draining from an upstream catchment to be retained again in all downstream lakes. The results in **Table 4** show that the differences, especially in $CL_{\max}(N)$, can be substantial. This depends on several factors, such as the lake/catchment ratio and land cover (fraction of forests) in the terrestrial catchment.

In **Table 6** the influence of the three calculation methods for lake systems on the amount of nitrogen retained in the lake/sediments is summarized. It is worth noting that the big-lake method (including upstream lakes in a simple manner) increases the N_{lake} estimate by 47% on average and that the lake-system method increases the N_{lake} estimate by 73% on average. From this we can tentatively conclude that it is more important to include upstream lakes at all (even in a simple manner) than to put too much emphasis on refining that inclusion (especially if it requires additional data). **Table 6** also shows that the relative amounts of N retained in the lake are, in general, substantial. Investigation and quantification of the processes leading to that retention deserves further attention.

Table 6. The fraction of N (as % of deposition) retained in the terrestrial catchment, N_{terr} , and retained in the lake, N_{lake} , of the 8 lakes with sampled upstream catchments using three approaches: (i) ignoring upstream lakes ("one-lake" approach); (ii) using the "big-lake" approach" and (iii) using the "lake-system" approach (see Appendix B). The total N deposited in 1993 ($41.3 \text{ meq/m}^2/\text{yr}$) has been used as basis. Note that $100 - N_{terr} - N_{lake}$ is the percentage of N_{dep} leaving the catchment at the outflow according to the calculations with FAB.

Lake no.	one-lake		big-lake	lake-system
	N_{terr} %	N_{lake} %	N_{lake} %	N_{lake} %
2	13.4	44.3	56.5	57.6
43	14.7	43.7	64.9	75.3
47	10.9	37.8	69.7	77.4
49	12.3	42.0	60.9	76.3
61	13.2	28.3	59.4	79.6
112	15.4	40.0	52.5	64.2
113	15.7	45.4	47.3	48.5
124	8.6	34.3	52.5	67.1
Average		39.5	58.0	68.3

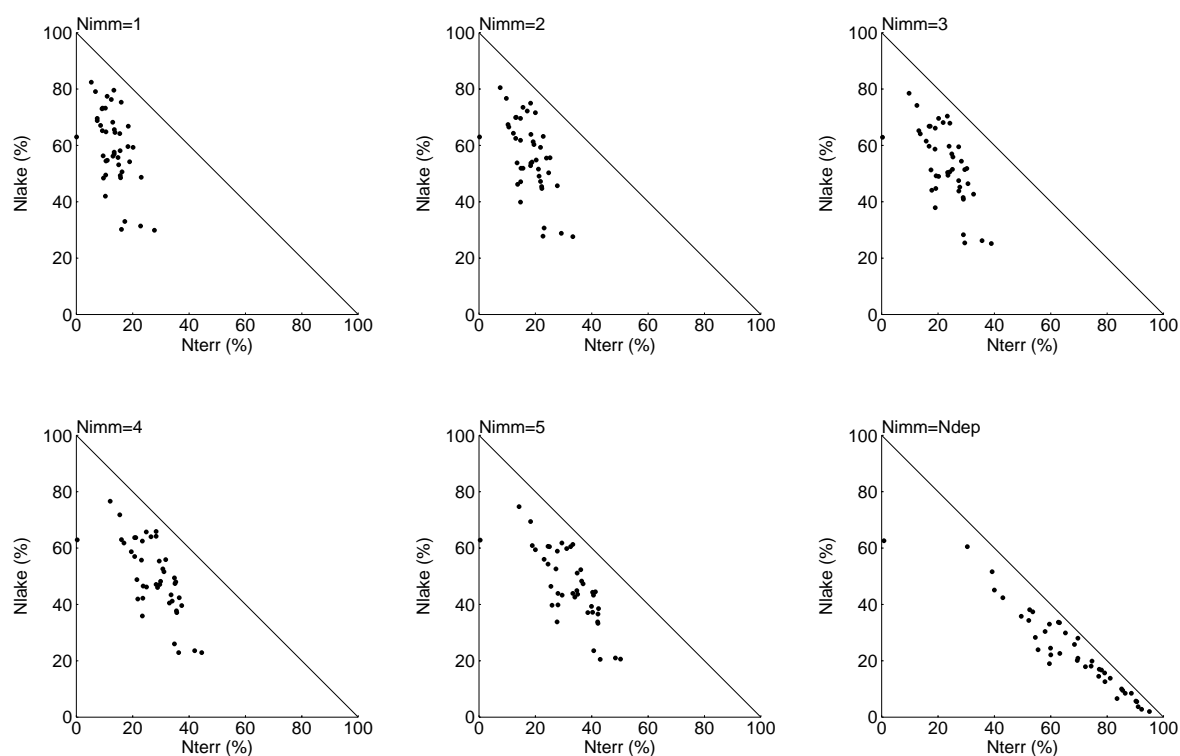


Figure 3. "Fate" of nitrogen in the 43 catchments, for which FAB model calculations have been carried out, as a function of the immobilization rate ($N_{imm}=1 \text{ kgN ha}^{-1}\text{yr}^{-1}$ to $N_{imm}=N_{dep}$ in steps of $1 \text{ kgN ha}^{-1}\text{yr}^{-1}$). Every catchment is represented by a dot in the graphs. The amount of N retained in the terrestrial catchment, N_{terr} , can be read from the horizontal axis and the amount retained in the lake(s), N_{lake} , from the vertical axis. N_{terr} and N_{lake} are expressed as percentage of the 1993 N-deposition, N_{dep} . The percentage of N leaving the catchment at the outlet is given by the distance from the diagonal line.

Another way of visualizing the relative size of the N-pools (soil and lake/sediment) and fluxes (outflow from the catchment) is shown in **Figure 3**. The upper left graph in **Figure 3** represents the situation for the default value of $N_i = N_{imm} = 1 \text{ kgN ha}^{-1}\text{yr}^{-1}$. To study the influence of this parameter on the N pools and fluxes, we ran the FAB model also for $N_{imm} = 2, 3, 4$ and $5 \text{ kgN ha}^{-1}\text{yr}^{-1}$. Also shown is a situation with $N_{imm} = N_{dep}$ (which corresponds to about $6 \text{ kgN ha}^{-1}\text{yr}^{-1}$). The fraction retained in the catchment soils increases with increasing N_{imm} (which is obvious), but this increase is fairly modest for $N_{imm} = 2$ and 3 kgN . Only when N_{imm} approaches N_{dep} will most of the incoming N be retained in the catchment soils. Even for $N_{imm} = N_{dep}$ not all N ends up in the soils, since (a) some N is directly deposited onto the lake surfaces, and (b) N deposited on bare rocks is also entering the lakes undiminished.

This type of graph can also be used to investigate the influence of other parameters on the fate of N for a large number of lakes, thus aiding the assessment of model sensitivities.

4. Concluding remarks

This work has focused on how nitrogen may affect critical load (CL) calculations. Known sinks of nitrogen in both catchment and lakes are recognized, but a large fraction of deposited nitrogen is probably stored temporarily. This is shown by use of the First-order Acidity Balance (FAB) model. In-lake retention of nitrogen may be substantial and quantification of the processes leading to that retention deserves further attention. Good input-output budgets for S and N from lakes with different retention times (lake:catchment ratios) would be helpful. Default values in the model for immobilization and denitrification are based on figures from Europe and could be corrected based on data from Killarney.

CL calculations for surface water are traditionally based on data from headwater lakes. This work has also included lakes in chains, and in doing so a new module of the FAB-model has been developed and is presented in this report. Lakes in chains are favored by in-lake retention of a larger fraction of deposited N than headwater lakes, which increases their CLs. As long as lakes in chains are common on shield bedrock conditions, this difference in tolerance should be recognized.

Previous work with CL calculations in Killarney (Hindar and Henriksen 1998) has shown that large reductions in sulphur emissions have resulted in substantial reductions in CL exceedances. Further reductions are, however, needed to protect the most sensitive lakes. The results presented here show how nitrogen deposition influences critical loads and how reduction in nitrogen deposition also may lead to improvements in the acidification situation of Killarney lakes. Exceedance may be reduced by S reduction, N reduction or both, depending on the CL function of the particular lake.

Both the SSWC and the FAB model are static models in the sense that we may calculate end point exceedances of the CLs for lakes and catchments. This is helpful when negotiating on emission reductions, but may be less satisfactory if we want to know the temporal aspects of water chemistry improvements. Relatively long time delays of chemical recovery have been found for Norwegian catchments by use of the MAGIC (Model of Acidification of Groundwater in Catchments) model (Wright and Henriksen 1999). This may be due to release of adsorbed S, cation exchange in soils and sediments, oxidation-reduction processes and hydrological delays.

Increased focus on chemical and biological time delays points out dynamic modelling as potentially valuable for further investigation of Killarney lakes.

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Appendix A. Catchment characteristics and lake data

The catchments are characterized as follows, see also **Table 2**:

Cat.	catchment number
Lake	catchment name
Cat. Area	the total area within each catchment. These values were extracted from the Killarney Watershed map of the Coop Unit.
Lake Area	the surface area of the major water body within each catchment
Productive Forest	this includes all forest types
Treed Muskeg	has a tree cover of at least 10% crown closure. It includes peatlands, swamps, and bogs supporting limited tree growth due to excessive moisture
Open Muskeg	has a tree cover of less than 10% crown closure. It too includes peatlands, swamps, and bogs supporting limited tree growth due to excessive moisture
Brush + Alder	includes brush and alder stands that are not significant for timber harvesting
Exposed Rock	all exposed rock
Water	all the waterbodies found within each catchment.
Streams	all streams found within each catchment
Campground + Road	the combined total of the George Lake campground and road
Total	the sum of all the classification types (Productive Forest, Treed Muskeg, Open Muskeg, Brush + Alder, Exposed Rock, Water, Streams, and Campground + Road)

The lake data are mainly from the winter 1996 survey. All lakes from the survey are included. Lake numbers have also been used for the catchment numbering.

Size of area types as a result of digitization of the Killarney Watershed map. See methods for characterization of the area categories.

		Cat. Area	Lake Area	Productive Forest	Treed Muskeg	Open Muskeg	Brush & Alder	Exposed Rock	Water	Streams	Campground & Road	Total
Cat.	Lake	km ²	km ²	Area (km ²)								
2	AMIKOGAMING	2,116	0,179	1,609	0,000	0,027	0,000	0,271	0,202	0,005	0,000	2,114
3	AY JACKSON	0,295	0,065	0,230	0,000	0,000	0,000	0,000	0,065	0,000	0,000	0,296
4	BALSAM	26,130	2,791	19,135	0,674	0,658	0,000	0,000	5,630	0,077	0,000	26,174
5	BEAVER	2,634	0,162	1,556	0,066	0,384	0,000	0,287	0,317	0,028	0,000	2,639
6	BELL	26,430	3,579	19,602	0,552	0,942	0,020	0,968	4,220	0,120	0,000	26,425
10	BODINA	1,119	0,353	0,655	0,113	0,000	0,000	0,000	0,353	0,000	0,000	1,121
11	BOUNDARY	8,739	0,944	6,213	0,000	0,079	0,014	1,303	1,117	0,026	0,000	8,754
12	BUNNY RABBIT	0,965	0,127	0,502	0,000	0,004	0,000	0,289	0,172	0,000	0,000	0,967
14	CANIS	8,050	0,274	6,196	0,000	0,890	0,490	0,040	0,384	0,066	0,000	8,064
15	CARLYLE	9,775	1,685	6,852	0,017	0,330	0,000	0,489	2,025	0,029	0,000	9,741
16	CARMICHAEL	12,380	2,605	8,850	0,000	0,032	0,000	0,866	2,707	0,012	0,000	12,468
17	CAT	2,626	0,464	1,594	0,036	0,135	0,054	0,394	0,405	0,013	0,000	2,630
18	CAVE	1,140	0,124	0,680	0,000	0,004	0,000	0,333	0,125	0,000	0,000	1,142
19	CHAIN	4,954	0,109	3,710	0,165	0,290	0,000	0,212	0,563	0,023	0,000	4,963
21	CRANBERRY BOG	1,107	0,185	0,868	0,000	0,071	0,000	0,009	0,156	0,005	0,000	1,109
24	CUCKOO	1,231	0,248	0,815	0,133	0,000	0,000	0,033	0,248	0,000	0,000	1,229
25	DAVID	19,150	4,242	10,148	0,596	0,663	0,000	2,845	4,910	0,021	0,000	19,183
29	FISH	12,620	1,163	8,372	0,166	0,449	0,011	1,685	1,819	0,043	0,000	12,544
32	FREELAND	4,283	0,481	3,386	0,000	0,053	0,060	0,225	0,548	0,019	0,000	4,300
33	GAIL	1,033	0,209	0,444	0,000	0,000	0,000	0,382	0,209	0,000	0,000	1,035
34	GEM	4,134	0,307	2,528	0,000	0,092	0,000	1,140	0,351	0,018	0,000	4,130
35	GEORGE	8,414	1,887	3,834	0,000	0,074	0,000	2,315	1,928	0,042	0,233	8,426
38	GRACE	2,632	0,480	1,498	0,025	0,000	0,008	0,621	0,484	0,000	0,000	2,637
39	GREAT MOUNTAIN	9,733	2,055	6,048	0,255	0,198	0,017	0,856	2,357	0,019	0,000	9,750
43	HANWOOD	1,440	0,326	0,864	0,000	0,007	0,000	0,192	0,378	0,001	0,000	1,443
44	HARRY	7,478	1,378	5,415	0,219	0,177	0,000	0,022	1,623	0,015	0,000	7,471
45	HEAVEN	0,141	0,017	0,001	0,000	0,000	0,000	0,124	0,017	0,000	0,000	0,142

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		Cat. Area	Lake Area	Productive Forest	Treed Muskeg	Open Muskeg	Brush & Alder	Exposed Rock	Water	Streams	Campground & Road	Total
Cat.	Lake	km ²	km ²	Area (km ²)								
46	HELEN	8,834	0,852	5,807	0,056	0,186	0,063	1,513	1,188	0,036	0,000	8,850
47	HEMLOCK	0,203	0,033	0,168	0,000	0,000	0,000	0,000	0,033	0,002	0,000	0,203
48	HOWRY	6,428	1,185	3,941	0,003	0,000	0,000	1,305	1,166	0,001	0,000	6,416
49	ISHMAEL	3,592	0,732	1,949	0,000	0,025	0,000	0,822	0,798	0,005	0,000	3,598
50	JOHNNIE	34,550	3,471	24,843	0,630	0,483	0,067	2,651	5,564	0,134	0,000	34,372
51	KAKAKISE	6,980	1,190	3,923	0,000	0,032	0,000	1,709	1,269	0,012	0,000	6,946
53	KILLARNEY	17,600	3,359	10,696	0,013	0,015	0,000	3,300	3,516	0,044	0,000	17,583
58	LITTLE SHEGUIAN.	0,216	0,045	0,171	0,000	0,000	0,000	0,000	0,045	0,000	0,000	0,216
59	LITTLE SUPERIOR	0,354	0,139	0,139	0,000	0,000	0,000	0,077	0,139	0,000	0,000	0,355
61	LOW	1,170	0,338	0,828	0,000	0,000	0,000	0,005	0,339	0,001	0,000	1,173
62	LUMSDEN	7,777	0,238	4,249	0,000	0,018	0,013	2,618	0,791	0,036	0,000	7,725
64	MOOSE	1,572	0,166	0,993	0,000	0,000	0,000	0,406	0,175	0,000	0,000	1,575
65	MURIEL	3,998	0,317	2,822	0,000	0,010	0,000	0,721	0,442	0,010	0,000	4,006
66	MURRAY	9,455	0,930	7,020	0,000	0,091	0,008	1,359	0,870	0,010	0,000	9,358
68	NORWAY	7,709	0,634	4,645	0,000	0,000	0,019	1,966	1,067	0,008	0,000	7,704
69	OSA	8,663	2,936	3,171	0,003	0,014	0,000	2,412	3,049	0,017	0,000	8,666
71	PATTEN	4,116	0,119	2,720	0,004	0,050	0,010	1,018	0,256	0,013	0,000	4,071
75	PROULX	0,420	0,120	0,220	0,000	0,000	0,000	0,080	0,120	0,000	0,000	0,420
79	ROUND OTTER	22,930	0,204	16,292	0,770	0,974	0,048	0,809	3,596	0,119	0,000	22,609
80	RUTH-ROY	4,967	0,545	2,707	0,000	0,010	0,014	1,686	0,573	0,003	0,000	4,992
84	SHINGWAK	0,250	0,053	0,097	0,000	0,003	0,000	0,097	0,053	0,000	0,000	0,250
100	VAN WINKLE	1,070	0,859	0,325	0,000	0,000	0,000	0,245	0,501	0,000	0,000	1,072
101	WAGON ROAD	0,274	0,055	0,205	0,000	0,018	0,000	0,000	0,052	0,000	0,000	0,274
102	WHISKEYJACK	0,438	0,128	0,235	0,000	0,000	0,000	0,076	0,128	0,000	0,000	0,439
103	YORK	3,993	0,391	2,979	0,022	0,153	0,000	0,405	0,426	0,010	0,000	3,994
106	KILLARNEY #05	1,817	0,035	0,917	0,425	0,000	0,000	0,411	0,059	0,008	0,000	1,820
111	KILLARNEY #17	0,294	0,029	0,266	0,000	0,000	0,000	0,000	0,029	0,000	0,000	0,295
112	KILLARNEY #18	0,267	0,015	0,230	0,000	0,000	0,000	0,000	0,035	0,003	0,000	0,268
113	KILLARNEY #19	1,003	0,086	0,906	0,000	0,000	0,000	0,004	0,088	0,007	0,000	1,005
114	KILLARNEY #20	0,074	0,009	0,064	0,000	0,000	0,000	0,001	0,009	0,000	0,000	0,074
117	KILLARNEY #23	0,307	0,019	0,182	0,000	0,000	0,000	0,106	0,019	0,000	0,000	0,307
120	KILLARNEY #26	0,462	0,016	0,222	0,000	0,000	0,000	0,213	0,028	0,000	0,000	0,462

		Cat. Area	Lake Area	Productive Forest	Treed Muskeg	Open Muskeg	Brush & Alder	Exposed Rock	Water	Streams	Campground & Road	Total
Cat.	Lake	km ²	km ²	Area (km ²)								
121	KILLARNEY #27	0,364	0,031	0,218	0,000	0,000	0,000	0,115	0,031	0,000	0,000	0,364
122	KILLARNEY #28	0,190	0,025	0,163	0,000	0,000	0,000	0,004	0,025	0,000	0,000	0,191
123	KILLARNEY #29	0,077	0,024	0,046	0,000	0,000	0,000	0,007	0,024	0,000	0,000	0,078
124	KILLARNEY #30	0,237	0,025	0,079	0,000	0,000	0,000	0,133	0,025	0,000	0,000	0,237
125	KILLARNEY #33	1,149	0,093	0,637	0,000	0,000	0,000	0,420	0,093	0,000	0,000	1,151
128	KILLARNEY #37A	0,963	0,176	0,715	0,000	0,000	0,000	0,000	0,244	0,005	0,000	0,964
131	KILLARNEY #45	0,897	0,044	0,642	0,000	0,174	0,000	0,036	0,044	0,001	0,000	0,898
132	KILLARNEY #46	0,517	0,025	0,440	0,000	0,051	0,000	0,001	0,025	0,001	0,000	0,518
134	KILLARNEY #51	2,269	0,097	1,983	0,000	0,000	0,000	0,104	0,184	0,001	0,000	2,272
138	KILLARNEY #55	1,031	0,067	0,493	0,000	0,000	0,000	0,385	0,148	0,007	0,000	1,033
140	KILLARNEY #64	1,440	0,036	0,703	0,000	0,000	0,000	0,600	0,126	0,013	0,000	1,443
145	KILLARNEY #71	0,969	0,037	0,893	0,000	0,000	0,000	0,037	0,038	0,002	0,000	0,970
147	KILLARNEY #74	2,579	0,118	2,026	0,032	0,094	0,000	0,307	0,120	0,005	0,000	2,583
150	KILLARNEY #80	2,351	0,051	1,078	0,000	0,000	0,000	0,950	0,317	0,010	0,000	2,354
200	GREAT BOG	19,240	0,600	14,774	0,194	2,298	0,107	0,663	1,039	0,139	0,000	19,214
201	KIRK CREEK	16,910	0,429	13,779	0,177	0,683	0,028	1,679	0,430	0,128	0,000	16,903
202	Three N.South.	22,230	1,213	15,294	0,120	0,335	0,098	3,210	3,132	0,084	0,000	22,272
203	Three N.Middle	24,470	8,256	17,832	0,086	0,734	0,015	0,167	5,586	0,096	0,000	24,516
204	Three N. North	17,220	0,304	11,731	0,142	0,111	0,000	3,916	1,229	0,118	0,000	17,247
205	LEADING MARK	13,880	1,317	9,796	0,000	0,168	0,003	2,563	1,317	0,054	0,000	13,900
206	ARTIST LAKE	3,750	0,433	2,392	0,000	0,131	0,000	0,780	0,433	0,022	0,000	3,757
207	COLLINS	41,560	0,765	33,502	0,386	1,752	1,124	3,568	0,765	0,424	0,586	41,522
208	BAYE FINE	5,755	0,580	3,405	0,021	0,001	0,000	1,723	0,580	0,021	0,000	5,751
209	KIRK	7,561	0,315	6,346	0,100	0,419	0,035	0,312	0,315	0,033	0,000	7,558
210		3,121	0,126	2,706	0,189	0,009	0,000	0,084	0,126	0,012	0,000	3,126

Lake data from the 1996 survey (from Snucins and Gunn 1998).

No.	Lake	Date	pH	ALK-E µeq/L	DOC mg C/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO4 mg/L	NO3-N µg N/L	Tot. Al µg Al/L
1	ACID	30.01.1996	5,00	-5,4	1,6	1,10	0,44	0,44	0,23	0,0	6,5	75	205
2	AMIKOGAMING	23.01.1996	5,12	4,0	2,5	1,85	0,64	0,72	0,36	0,4	9,5	70	250
3	AY JACKSON	01.02.1996	5,82	24,6	2,7	1,70	0,70	0,74	0,37	0,4	7,5	55	42
4	BALSAM	23.01.1996	6,09	80,6	6,0	2,90	0,88	0,92	0,57	0,6	7,5	85	50
5	BEAVER	02.02.1996	5,98	108,7	8,0	2,65	0,80	0,84	0,44	0,4	4,5	125	11
6	BELL	23.01.1996	5,93	32,6	4,9	2,25	0,78	0,84	0,46	0,4	8,0	80	80
7	BETTY	27.08.1996	7,04	287,0	8,5	7,30	1,06	0,90	0,76	0,4	8,0	15	20
8	BILLY	27.08.1996	4,68	-5,6	5,0	1,55	0,64	0,72	0,24	0,0	8,0	10	210
9	BIZHIW	01.02.1996	4,52	-28,0	0,8	0,70	0,24	0,32	0,17	0,4	7,0	135	434
10	BODINA	02.02.1996	6,59	227,8	10,5	4,50	1,68	1,44	0,61	0,6	8,5	85	41
11	BOUNDARY	02.02.1996	5,21	2,0	2,3	1,35	0,50	0,52	0,35	0,4	6,5	85	128
12	BUNNY RABBIT	23.01.1996	4,77	-12,2	0,8	1,10	0,36	0,40	0,20	0,4	7,5	140	370
13	BURKE	02.02.1996	5,09	-3,4	1,8	1,40	0,48	0,52	0,26	0,4	7,5	85	185
14	CANIS	02.02.1996	6,39	437,8	16,5	7,60	3,32	1,92	1,05	1,2	10,0	150	113
15	CARLYLE	01.02.1996	5,85	22,9	3,7	1,90	0,72	0,88	0,34	0,4	7,5	50	74
16	CARMICHAEL	02.02.1996	4,63	-22,0	0,3	1,55	0,46	0,52	0,23	0,4	10,5	195	493
17	CAT	02.02.1996	6,38	131,2	4,1	2,70	1,08	0,92	0,48	0,4	6,0	165	0
18	CAVE	01.02.1996	5,60	36,6	4,2	1,95	0,88	0,70	0,44	0,4	8,5	50	129
19	CHAIN	23.01.1996	4,65	-16,2	5,7	1,30	0,44	0,56	0,37	0,4	7,5	60	260
20	CLEAR SILVER	23.01.1996	4,93	-6,4	1,8	1,10	0,38	0,48	0,27	0,4	7,0	45	230
21	CRANBERRY BOG	01.02.1996	6,15	190,2	7,7	2,45	1,08	1,00	0,64	0,4	4,0	40	88
22	CRATER EAST	02.02.1996	5,85	69,0	3,0	2,60	0,96	0,82	0,40	1,2	9,0	35	104
23	CRATER WEST	09.02.1996	5,42	32,5	6,2	0,65	0,20	0,48	0,67	0,4	3,0	55	108
24	CUCKOO	27.08.1996	6,65	88,0	4,2	2,40	0,68	0,76	0,38	0,0	6,0	10	0
25	DAVID	02.02.1996	5,00	-9,8	1,6	1,40	0,44	0,56	0,26	0,8	7,5	65	115
26	DEACON	23.01.1996	5,91	51,2	6,3	3,15	0,88	0,94	0,54	0,6	9,5	125	80

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No.	Lake	Date	pH	ALK-E µeq/L	DOC mg C/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO4 mg/L	NO3-N µg N/L	Tot. Al µg Al/L
27	DELAMORANDIERE	09.02.1996	4,98	-1,2	2,9	1,50	0,52	0,60	0,31	0,4	8,0	145	308
28	EAST HOWRY	27.08.1996	7,13	228,6	5,7	5,25	0,96	0,86	0,63	0,4	7,5	0	20
29	FISH	12.02.1996	5,94	38,1	3,8	2,00	0,70	0,80	0,39	0,4	7,5	95	54
30	FOX	23.01.1996	6,21	76,2	6,3	3,65	0,98	1,06	0,61	0,6	9,5	70	60
31	FRANK	23.01.1996	6,25	125,2	6,6	2,55	1,00	1,64	0,52	1,8	5,0	100	40
32	FREELAND	02.02.1996	5,52	11,6	1,1	2,00	0,68	0,72	0,34	0,4	9,0	125	169
33	GAIL	24.01.1996	4,63	0,0	0,6	1,25	0,36	0,48	0,18	0,4	7,0	80	380
34	GEM	02.02.1996	6,10	77,2	4,8	2,85	0,80	0,84	0,48	0,6	8,0	135	83
35	GEORGE	30.01.1996	5,79	20,2	1,7	1,95	0,72	0,76	0,38	0,4	8,5	90	94
36	GOOSE	24.01.1996	6,21	145,6	6,5	3,65	0,96	0,88	0,54	0,4	7,0	155	90
37	GOSCHEN	27.08.1996	6,23	76,4	8,0	2,55	0,90	1,02	0,48	0,4	7,0	15	60
38	GRACE	02.02.1996	5,11	-2,8	1,5	2,05	0,54	0,54	0,23	0,4	7,5	55	58
39	GREAT MOUNTAIN	24.01.1996	5,35	5,4	2,2	1,60	0,58	0,68	0,31	0,4	8,0	35	80
40	GREEN	23.01.1996	5,33	27,8	8,1	2,30	0,80	0,92	0,39	0,6	8,0	160	140
41	GREY	27.08.1996	4,90	-1,8	3,4	1,55	0,64	0,76	0,37	0,4	8,5	55	200
42	GROW	24.01.1996	6,57	169,4	4,1	4,05	0,76	0,76	0,36	0,4	6,5	115	20
43	HANWOOD	02.02.1996	6,38	149,8	4,8	3,20	0,92	0,86	0,42	0,4	5,5	110	0
44	HARRY	23.01.1996	6,35	78,6	5,1	2,30	0,80	0,80	0,47	0,4	6,5	70	20
45	HEAVEN	23.01.1996	4,77	-11,6	4,0	0,70	0,28	0,32	0,22	0,4	5,0	80	340
46	HELEN	30.01.1996	6,29	90,2	3,7	2,65	1,00	0,86	0,45	0,4	7,5	110	64
47	HEMLOCK	23.01.1996	4,74	-12,2	1,2	1,65	0,52	0,56	0,34	0,4	11,0	160	500
48	HOWRY	02.02.1996	6,31	85,9	4,5	2,85	0,84	0,88	0,46	0,4	7,5	105	36
49	ISHMAEL	30.01.1996	6,51	100,2	3,5	2,75	1,04	0,88	0,42	0,4	8,0	80	18
50	JOHNNIE	23.01.1996	5,60	12,9	3,4	1,90	0,64	0,72	0,37	0,4	7,5	95	120
51	KAKAKISE	30.01.1996	6,29	53,4	2,7	2,30	0,86	0,84	0,40	0,6	8,0	55	23
52	KIDNEY	01.02.1996	5,32	18,9	3,5	2,00	0,70	0,64	0,32	0,4	8,0	135	314
53	KILLARNEY	30.01.1996	5,08	-1,8	1,0	1,60	0,56	0,66	0,32	0,4	9,0	135	238

No.	Lake	Date	pH	ALK-E µeq/L	DOC mg C/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO4 mg/L	NO3-N µg N/L	Tot. Al µg Al/L
54	LAKE OF THE WOODS	27.08.1996	4,89	-1,6	3,3	1,45	0,64	0,68	0,30	0,0	8,0	0	120
55	LITTLE BELL	23.01.1996	4,58	-24,2	7,4	1,30	0,44	0,58	0,38	0,6	7,0	100	270
56	LITTLE MINK	24.01.1996	6,69	245,6	3,6	4,80	1,08	1,04	0,62	0,4	6,0	95	0
57	LITTLE MOUNTAIN	24.01.1996	5,07	-0,8	0,8	1,65	0,48	0,60	0,28	0,4	9,0	55	190
58	LITTLE SHEGUIANDAH	01.02.1996	6,12	105,9	4,7	2,40	1,16	1,10	0,75	0,4	7,5	100	78
59	LITTLE SUPERIOR	23.01.1996	4,32	-50,4	0,2	1,10	0,34	0,36	0,22	0,4	11,5	160	730
60	LOG BOOM	23.01.1996	5,48	24,4	2,4	1,65	0,56	0,64	0,34	0,4	7,5	75	110
61	LOW	30.01.1996	7,24	418,6	3,0	8,40	2,12	1,44	0,62	1,6	10,5	40	0
62	LUMSDEN	30.01.1996	5,19	-0,2	1,5	1,15	0,44	0,44	0,22	0,4	6,5	80	175
63	MINK	24.01.1996	6,30	223,4	7,4	5,50	1,18	1,00	0,77	0,8	8,0	225	50
64	MOOSE	02.02.1996	5,14	-1,2	1,5	1,55	0,56	0,60	0,27	0,4	8,0	40	156
65	MURIEL	01.02.1996	5,15	-3,2	1,2	2,30	0,68	0,68	0,29	0,4	10,0	155	151
66	MURRAY	02.02.1996	6,21	80,1	4,3	2,80	0,80	0,88	0,46	0,4	7,5	90	36
67	NELLIE	02.02.1996	4,58	-24,0	0,2	1,65	0,48	0,56	0,25	0,4	11,5	205	513
68	NORWAY	23.01.1996	5,14	3,0	1,7	1,75	0,60	0,64	0,31	0,4	8,5	115	260
69	OSA	30.01.1996	4,84	-14,6	0,3	2,05	0,62	0,64	0,29	0,4	10,0	240	194
70	PARTRIDGE	23.01.1996	5,68	13,8	1,8	2,40	0,72	0,72	0,32	0,4	10,0	30	70
71	PATTEN	02.02.1996	5,05	5,1	3,5	1,65	0,68	0,86	0,55	0,4	9,0	80	297
72	PEARL	01.02.1996	5,31	6,7	1,1	2,05	0,78	0,60	0,38	0,4	10,5	60	183
73	PETER	12.02.1996	6,50	87,4	3,3	3,85	1,00	0,98	0,56	0,4	11,0	65	5
74	PIKE	23.01.1996	5,59	106,8	7,6	2,85	0,88	0,88	0,67	0,8	6,0	95	70
75	PROULX	23.01.1996	4,50	-24,2	0,3	1,70	0,52	0,54	0,25	0,4	12,5	180	640
76	QUARTZITE	02.02.1996	4,80	-13,2	0,0	1,30	0,38	0,46	0,22	0,0	8,0	150	308
77	ROCKY	24.01.1996	6,59	187,8	4,9	4,70	0,94	0,92	0,42	0,4	6,0	105	30
78	ROQUE	02.02.1996	5,01	-0,2	3,4	1,45	0,52	0,60	0,33	0,4	8,0	75	358
79	ROUND OTTER	24.01.1996	6,20	161,0	7,6	4,40	1,10	1,02	0,65	0,6	8,5	195	80
80	RUTH-ROY	23.01.1996	4,85	-11,8	0,5	1,20	0,40	0,50	0,20	0,4	8,0	80	340

No.	Lake	Date	pH	ALK-E µeq/L	DOC mg C/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO4 mg/L	NO3-N µg N/L	Tot. Al µg Al/L
81	SANDY	23.01.1996	5,15	-5,0	2,0	1,75	0,60	0,68	0,32	0,4	8,5	105	250
82	SEALEY'S	01.02.1996	6,06	188,5	10,7	2,75	1,24	1,44	0,69	1,2	5,0	20	139
83	SHIGAUG	02.02.1996	4,83	-12,0	0,9	1,20	0,32	0,52	0,31	0,4	7,0	35	198
84	SHINGWAK	23.01.1996	4,71	-12,2	0,3	1,40	0,40	0,44	0,23	0,4	8,5	150	340
85	SILVER	23.01.1996	4,98	-0,4	2,3	1,25	0,36	0,46	0,29	0,4	7,0	115	380
86	SOLOMON	02.02.1996	5,56	31,0	3,8	1,55	0,52	0,60	0,57	0,8	7,5	45	284
87	SPARK	02.02.1996	4,46	-34,0	0,5	0,85	0,30	0,36	0,16	0,4	9,0	145	600
88	SUGARBUSH	02.02.1996	4,77	-12,2	2,2	1,20	0,54	0,48	0,26	0,4	9,5	45	445
89	TEARDROP	09.02.1996	6,51	55,0	1,1	1,85	0,90	0,58	0,34	0,4	7,5	25	0
90	TERRY	30.01.1996	5,37	16,1	5,5	1,85	0,68	0,82	0,44	0,4	7,5	70	215
91	THE THREE LAKES	09.02.1996	5,08	7,5	5,4	1,35	0,52	0,48	0,31	0,4	6,0	55	193
92	THREE NARROWS	30.01.1996	5,85	23,1	3,2	1,95	0,84	0,84	0,39	0,4	8,5	95	73
93	TOPAZ	01.02.1996	4,61	-22,0	0,3	1,40	0,44	0,48	0,31	0,4	9,5	110	435
94	THE TRI LAKES (NORTH)	27.08.1996	6,66	162,2	7,3	3,75	1,02	0,90	0,38	0,4	6,5	10	20
95	THE TRI LAKES (SOUTHEAST)	27.08.1996	6,51	158,2	7,0	3,65	1,00	0,88	0,36	0,4	6,0	0	20
96	THE TRI LAKES (SOUTHWEST)	27.08.1996	6,30	80,2	8,3	2,35	0,70	0,82	0,44	0,4	5,0	0	40
97	TURBID	27.08.1996	4,96	2,2	3,2	1,50	0,60	0,76	0,29	0,0	8,0	0	150
98	TURTLEBACK	02.02.1996	5,08	-0,4	2,1	1,70	0,52	0,74	0,31	0,4	8,5	45	136
99	VAN	02.02.1996	6,16	132,8	4,4	4,00	0,76	0,76	0,36	0,4	7,0	265	0
100	VAN WINKLE	02.02.1996	6,56	85,7	3,0	2,95	0,72	0,74	0,34	0,4	7,5	40	0
101	WAGON ROAD	30.01.1996	6,00	156,8	8,5	2,15	1,00	1,08	0,68	0,6	5,0	15	138
102	WHISKEYJACK	23.01.1996	4,61	-22,2	0,4	1,35	0,44	0,46	0,23	0,4	11,5	160	560
103	YORK	02.02.1996	6,08	73,9	6,2	2,85	1,24	1,08	0,46	0,6	9,0	90	63
104	KILLARNEY #03	12.02.1996	4,56	-24,0	6,2	1,20	0,42	0,60	0,45	0,4	7,5	80	350
105	KILLARNEY #04	12.02.1996	4,73	-11,6	4,8	1,80	0,62	0,74	0,35	0,4	10,0	60	394
106	KILLARNEY #05	12.02.1996	4,36	-40,0	11,9	0,90	0,28	0,40	0,46	0,6	4,5	40	139
107	KILLARNEY #06	12.02.1996	4,52	-24,0	10,5	1,00	0,30	0,40	0,44	0,6	4,5	20	156

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No.	Lake	Date	pH	ALK-E µeq/L	DOC mg C/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO4 mg/L	NO3-N µg N/L	Tot. Al µg Al/L
108	KILLARNEY #07	12.02.1996	4,97	7,7	9,8	0,90	0,36	0,44	0,34	0,6	3,5	35	127
109	KILLARNEY #09	12.02.1996	4,90	1,2	5,8	0,85	0,36	0,44	0,46	0,8	6,5	40	556
110	KILLARNEY #12	12.02.1996	4,92	-3,4	3,3	1,05	0,38	0,48	0,29	0,4	6,0	25	234
111	KILLARNEY #17	09.02.1996	4,62	-15,0	4,5	0,65	0,28	0,44	0,36	0,4	7,5	75	754
112	KILLARNEY #18	09.02.1996	5,35	42,3	5,3	0,80	0,30	0,44	0,51	0,8	7,0	50	559
113	KILLARNEY #19	09.02.1996	4,82	-6,4	2,7	1,20	0,40	0,52	0,37	0,4	7,5	105	402
114	KILLARNEY #20	09.02.1996	4,85	3,7	4,5	0,90	0,24	0,48	0,42	0,6	7,0	15	548
115	KILLARNEY #21	09.02.1996	4,97	0,5	2,1	1,65	0,52	0,64	0,40	0,4	8,5	140	328
116	KILLARNEY #22	09.02.1996	4,93	-4,4	1,5	1,25	0,44	0,50	0,28	0,4	7,5	75	288
117	KILLARNEY #23	09.02.1996	4,94	5,6	3,9	1,00	0,28	0,52	0,43	0,6	6,5	105	572
118	KILLARNEY #24	09.02.1996	4,84	-6,2	0,9	0,75	0,26	0,38	0,20	0,4	6,5	80	407
119	KILLARNEY #25	09.02.1996	4,81	4,8	6,1	0,60	0,20	0,44	0,46	0,6	5,5	15	494
120	KILLARNEY #26	09.02.1996	4,70	-14,0	2,7	0,55	0,20	0,44	0,28	0,4	5,5	25	461
121	KILLARNEY #27	09.02.1996	5,11	1,6	1,6	1,20	0,36	0,52	0,27	0,0	6,5	95	216
122	KILLARNEY #28	09.02.1996	4,90	-5,8	1,8	1,10	0,30	0,50	0,29	0,0	6,5	70	243
123	KILLARNEY #29	09.02.1996	4,34	-48,0	0,2	0,90	0,20	0,32	0,20	0,0	7,5	85	214
124	KILLARNEY #30	09.02.1996	4,76	-13,2	2,1	1,15	0,36	0,52	0,26	0,4	7,0	245	351
125	KILLARNEY #33	12.02.1996	5,08	-1,6	1,5	1,60	0,46	0,60	0,28	0,4	8,5	90	212
126	KILLARNEY #35	09.02.1996	4,85	-7,0	1,4	0,75	0,30	0,40	0,22	0,4	7,5	45	541
127	KILLARNEY #36	09.02.1996	5,92	90,3	7,1	2,65	1,30	1,04	0,50	0,4	11,0	75	120
128	KILLARNEY #37A	09.02.1996	6,16	73,9	4,6	2,50	1,08	0,98	0,39	0,4	8,5	90	36
129	KILLARNEY #38	09.02.1996	4,94	2,7	5,1	1,60	0,60	0,72	0,35	0,4	8,5	60	477
130	KILLARNEY #40	13.02.1996	5,04	-2,2	1,9	1,45	0,44	0,52	0,26	0,2	8,0	40	223
131	KILLARNEY #45	13.02.1996	4,92	15,5	17,4	2,45	0,84	0,94	0,39	0,8	7,0	60	171
132	KILLARNEY #46	13.02.1996	5,50	49,0	11,7	2,55	0,76	0,72	0,41	0,4	6,0	150	135
133	KILLARNEY #50	12.02.1996	4,59	-20,0	4,6	0,95	0,40	0,48	0,32	0,4	9,0	50	757
134	KILLARNEY #51	12.02.1996	4,67	-18,4	2,4	1,20	0,40	0,46	0,26	0,4	8,5	60	529

No.	Lake	Date	pH	ALK-E µeq/L	DOC mg C/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO4 mg/L	NO3-N µg N/L	Tot. Al µg Al/L
135	KILLARNEY #52	12.02.1996	4,66	-20,0	1,3	0,75	0,20	0,36	0,13	0,0	7,0	50	574
136	KILLARNEY #53	12.02.1996	4,81	-5,2	2,4	0,70	0,20	0,36	0,30	0,4	6,0	45	467
137	KILLARNEY #54	12.02.1996	4,71	-16,4	0,5	1,25	0,32	0,40	0,16	0,0	8,0	145	452
138	KILLARNEY #55	12.02.1996	4,93	-7,6	1,1	1,15	0,32	0,40	0,18	0,0	6,0	70	234
139	KILLARNEY #59	12.02.1996	6,40	113,0	6,3	2,95	1,64	1,20	0,68	0,4	9,5	135	29
140	KILLARNEY #64	09.02.1996	5,28	16,6	3,4	1,45	0,58	0,84	0,38	0,4	7,0	165	246
141	KILLARNEY #65	09.02.1996	5,51	31,6	2,6	1,00	0,40	0,40	0,22	0,4	5,0	70	163
142	KILLARNEY #66	09.02.1996	5,26	9,3	2,8	0,90	0,36	0,36	0,19	0,4	5,0	50	129
143	KILLARNEY #68	09.02.1996	5,41	3,7	1,5	1,55	0,52	0,52	0,23	0,4	7,5	15	128
144	KILLARNEY #69	09.02.1996	5,04	-1,0	2,2	1,35	0,48	0,52	0,27	0,4	7,0	115	244
145	KILLARNEY #71	09.02.1996	5,12	15,6	5,2	1,65	0,68	0,54	0,35	0,6	8,0	30	328
146	KILLARNEY #73	12.02.1996	6,26	379,0	17,8	8,45	2,66	1,68	1,05	0,8	10,5	245	98
147	KILLARNEY #74	12.02.1996	6,05	120,2	10,7	3,15	1,32	1,08	0,45	0,8	6,5	180	112
148	KILLARNEY #76	12.02.1996	7,03	866,6	10,1	14,20	3,84	1,40	0,82	0,4	7,5	225	0
149	KILLARNEY #79	09.02.1996	5,09	41,8	12,5	0,80	0,20	0,44	0,37	0,8	4,5	15	357
150	KILLARNEY #80	09.02.1996	5,05	4,6	2,1	1,70	0,48	0,68	0,40	0,4	8,0	150	271
151	KILLARNEY #82	13.02.1996	5,05	10,0	2,7	1,15	0,48	0,60	0,37	0,4	9,0	110	526

Appendix B. The FAB-Model for Acidity Critical Loads of S and N for Lakes

Here we derive the so-called First-order Acidity Balance model (FAB model) for calculating critical loads of sulfur (S) and nitrogen (N) for a lake taking into account sources and sinks within the lake and its terrestrial catchment. The lake and its catchment are assumed small enough to be properly characterized by average soil and lake water properties. With A we denote the total catchment area (lake+terrestrial catchment), A_l is the lake area, A_f the forested area and A_g the area covered with grass/heathland; we have $A_l + A_f + A_g \leq A$, and a non-zero difference represents a land area on which no transformations of the deposited ions take place ("bare rocks").

Starting point for the derivation of the FAB model is the charge balance ("acidity balance") in the lake water running off the catchment:

$$S_{runoff} + N_{runoff} = BC_{runoff} - ANC_{runoff} \quad (1)$$

where BC stand for the sum of (non-marine) base cations and ANC is the acid neutralization capacity. In the above equation we assume that the quantities are total amounts per time, e.g. eq/yr. In order to derive critical loads we have to link the ions in the lake water to their depositions, taking into account also their sources and sinks in the terrestrial catchment and in the lake.

For $X=S,N$ (and BC) the mass balance in the lake is given by:

$$X_{runoff} = X_{in} - X_{ret}, \quad X = S, N, BC \quad (2)$$

where X_{in} is the total amount of ion X entering the lake and X_{ret} the amount of X retained in the lake. The in-lake retention of S and N is assumed to be proportional to the input of the respective ion into the lake:

$$X_{ret} = \rho_X X_{in}, \quad X = S, N \quad (3)$$

where $0 \leq \rho_X \leq 1$ is a dimensionless retention factor. Thus the mass balances for the lake become:

$$X_{runoff} = (1 - \rho_X) X_{in}, \quad X = S, N \quad (4)$$

The total amount of sulfur entering the lake is given by:

$$S_{in} = A S_{dep} \quad (5)$$

where S_{dep} is the total deposition of S per unit area. Immobilization, reduction and uptake of sulfate in the terrestrial catchment are assumed negligible, and sulfate ad/desorption is not considered since we model steady-state processes only. Eq.5 states that all sulfur deposited onto the catchment enters the lake, and no sources or sinks are considered in the terrestrial catchment.

In the case of nitrogen we assume that immobilization and denitrification occur both in forest and grass/heathland soils, whereas net uptake occurs in forests only (equalling the annual average amount of N removed by harvesting); the deposition onto the remaining area (lake+"bare rocks") enters the lake unchanged. Thus the amount of N entering the lake is:

$$N_{in} = (A - A_f - A_g) N_{dep} + A_f (N_{dep} - N_i - N_u - N_{de})_+ + A_g (N_{dep} - N_i - N_{de})_+ \quad (6)$$

where N_{dep} is the total N deposition, N_i is the long-term net immobilization of N (including fixation), N_{de} is N lost by denitrification, and N_u the net growth uptake of N, all per unit area. The symbol $(x)_+$ or x_+ is a short-hand notation for $\max\{x,0\}$, i.e. $x_+=x$ for $x>0$ and $x_+=0$ for $x\leq 0$. The effects of nutrient cycling are ignored and the leaching of ammonium is considered negligible, implying its complete uptake and/or nitrification in the terrestrial catchment.

While immobilization and net growth uptake are assumed independent of the N-deposition, denitrification is modeled as fraction of the available N:

$$N_{de} = \begin{cases} f_{de} (N_{dep} - N_i - N_u)_+ & \text{on } A_f \\ f_{de} (N_{dep} - N_i)_+ & \text{on } A_g \end{cases} \quad (7)$$

where $0 \leq f_{de} \leq 1$ is the (soil-dependent) denitrification fraction. The above equation is based on the assumption that denitrification is a slower process than immobilization and growth uptake. Inserting eq.7 into eq.6 one obtains:

$$N_{in} = (A - A_f - A_g) N_{dep} + A_f (I - f_{de}) (N_{dep} - N_i - N_u)_+ + A_g (I - f_{de}) (N_{dep} - N_i)_+ \quad (8)$$

If sufficient data for quantifying the sources and sinks of base cations in the catchment, such as deposition, weathering and uptake, are available, the runoff of base cations, BC_{runoff} , could be described in the same way as S and N. This would be in analogy to the so-called SMB critical load model for (forest) soils. Alternatively, water quality data can be used to quantify the runoff of base cations and ANC, as is done in the SSWC model.

To arrive at an equation for critical loads, i.e. depositions of S and N which should not be exceeded, a link has to be established between a chemical variable and effects on aquatic biota. The most commonly used criterium is the so-called ANC-limit, i.e. a minimum concentration of ANC derived to avoid "harmful effects" on fish: $ANC_{runoff,crit} = AQ[ANC]_{limit}$.

Defining $L_{crit} = (BC_{runoff} - ANC_{runoff,crit})/A$, inserting eqs.5 and 8 into eq.4 and eq.1 and dividing by A yields the following equation to be fulfilled by critical depositions (loads) of S and N:

$$(I - \rho_S) S_{dep} + (I - \rho_N) \left\{ (I - f - g) N_{dep} + f (I - f_{de}) (N_{dep} - N_i - N_u)_+ + g (I - f_{de}) (N_{dep} - N_i)_+ \right\} = L_{crit} \quad (9)$$

where we have defined:

$$f = A_f / A, \quad g = A_g / A \quad \text{—} \quad I - f - g \geq r \quad \text{with} \quad r = A_1 / A \quad (10)$$

Eq.9 defines a function in the (N_{dep}, S_{dep}) -plane, the so-called **critical load function**, and in the following we will look at this function in more detail.

The general form of the critical load function is:

$$a_S S_{dep} + a_N N_{dep} = L_N + L_{crit} \quad (11)$$

with

$$a_S = 1 - \rho_S, \quad a_N = (1 - \rho_N) b_N, \quad L_N = (1 - \rho_N) M_N \quad (12)$$

The quantity M_N and the dimensionless coefficient b_N depend on N_{dep} :

(1) $N_{dep} \leq N_i$: In this case $(N_{dep} - N_i)_+ = 0$ and $(N_{dep} - N_i - N_u)_+ = 0$, which means that all N falling onto forests and grassland is immobilized and only the N-deposition falling directly onto the lake and "bare rocks" contributes to the leaching of N:

$$b_N = b_1 = 1 - f - g \quad M_N = M_1 = 0 \quad (13)$$

(2) $N_i < N_{dep} \leq N_i + N_u$: In this case $(N_{dep} - N_i)_+ = N_{dep} - N_i$, but $(N_{dep} - N_i - N_u)_+ = 0$, meaning that all N-deposition falling onto forests is immobilized or taken up, but N falling onto the other areas is (partially) leached:

$$b_N = b_2 = 1 - f - g f_{de} \quad M_N = M_2 = (1 - f_{de}) g N_i \quad (14)$$

(3) $N_{dep} > N_i + N_u$: Some N-deposition is leached from all areas:

$$b_N = b_3 = 1 - (f + g) f_{de} \quad M_N = M_3 = (1 - f_{de}) [(f + g) N_i + f N_u] \quad (15)$$

The maximum critical load of sulfur is obtained by setting $N_{dep} = 0$ in eq.9:

$$CL_{max}(S) = L_{crit} / a_S \quad (16)$$

Setting $S_{dep} = 0$ and considering the 3 different cases for N_{dep} , gives the following expression for the maximum critical load for nitrogen:

$$CL_{max}(N) = \min \left\{ \left(L_{crit} / (1 - \rho_N) + M_i \right) / b_i, i = 1, 2, 3 \right\} \quad (17)$$

For arbitrary N_{dep} and S_{dep} we can compute the excess leaching as:

$$Ex_{le}(N_{dep}, S_{dep}) = a_S S_{dep} + a_N N_{dep} - L_N - L_{crit} \quad (18)$$

where a_N and L_N have to be chosen depending on the range in which N_{dep} lies (see above).

If $Ex_{le}(N_{dep}, S_{dep}) = 0$, N and S deposition fulfil eq.11 and are critical loads, lying on the critical load function (thick line in Fig.A). If $Ex_{le}(N_{dep}, S_{dep}) > 0$, we say critical loads are exceeded, and isolines of positive excess leaching are shown in Fig.A as thin lines parallel to the critical load function. The grey-shaded area indicates all pairs of (N_{dep}, S_{dep}) for which $Ex_{le} < 0$, i.e. for which there is no exceedance. It is important to note that a (positive) Ex_{le} is *not* the amount of S and N to be reduced to reach non-exceedance; in fact, there is no such unique amount of N and S. This is illustrated in Fig.A: Let point E denote the current deposition of N and S. Reducing N_{dep} substantially, one reaches the point Z1 and therefore non-exceedance without reducing S; on the other hand one can attain non-exceedance also by only reducing S_{dep} (by a smaller amount) until reaching Z3; finally, by a reduction in both N_{dep} and S_{dep} one can reach non-exceedance as well (e.g. point Z2). In practice external factors, such as costs of emission reduction measures, will determine which path will be followed to reach non-exceedance.

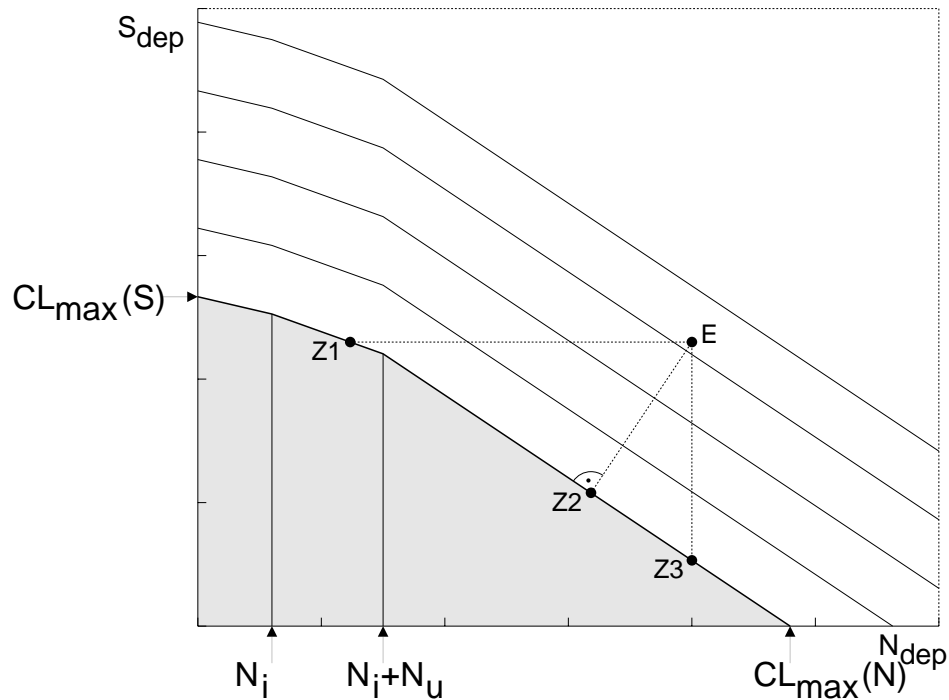


Figure A: Piece-wise linear critical load function for S and acidifying N as defined by catchment properties (thick line). The grey-shaded area below the critical load function defines deposition pairs (N_{dep}, S_{dep}) for which there is no exceedance. The thin lines parallel to the critical load function are isolines of excess acidity leaching. The points E and Z1-Z3 are explained in the text.

Systems of lakes:

The above derivation of the FAB-model is for (small) headwater lakes only. Critical loads will be mostly calculated for such lakes, since lakes with (many) upstream lakes tend to have larger catchments, and many (implicit) assumptions of the FAB-model, e.g. uniform depositions, will be violated. Nevertheless, in some areas systems of lakes can be found on a small scale, and therefore we consider in the following the FAB-model for a system of lakes.

When computing the critical load of acidity with the SSWC-method (which uses annual average lake water chemistry) for a lake receiving runoff from upstream lakes, one implicitly computes *the critical load for that lake and all its upstream lakes together*, since water samples taken from (the outlet of) the lowest lake is a mixture of the water of that lake and all its upstream lakes. Consequently, when applying the FAB-model to such a lake, one has to be aware that one computes the critical load for the whole system of lakes and thus must take into account the catchment and lake characteristics of all lakes in the system. In what follows we describe two methods for computing the critical load of a system of lakes: A simple one and a less simple one, both requiring the same input data.

Method 1: All lakes in the system are treated as a single lake ("big lake approach")

In this case the formulae derived above are valid; however, care has to be taken to properly add and average quantities. For example, the fraction of forest land is given by (see eq.10):

$$f = \sum_{n=1}^N A_{f,n} / \sum_{n=1}^N A_n \quad (19)$$

where N is the number of lakes in the system and A_n and $A_{f,n}$ are the total and forested area of catchment n , resp. Similarly for other quantities, such as the retention factors ρ_N and ρ_S (eq.3).

The shortcoming of this approach is that S and N in the water entering the topmost (=headwater) lake experiences the same retention as water entering the lowest lake in the system. This might be a gross simplification, since the currently used retention model depends on the turnover time of a lake, and thus S and N from water of the top lake will experience retention in all lakes of the chain consecutively, which have varying retention times. This is taken into account in the second method.

Method 2: Structure of the lake system is taken into account ("lake system approach"):

In this case the terms in the FAB-model have to be re-formulated. Here we present the result for two and three lakes. Assuming "Lake 1" flows into "Lake 2", eq.9 reads (before dividing by the area!):

$$(1 - \rho_{S,2}) (A_2 S_{dep,2} + (1 - \rho_{S,1}) A_1 S_{dep,1}) + N\text{-terms} = (A_2 + A_1) L_{crit} \quad (20)$$

with "N-terms" denoting all quantities involving nitrogen. Eq.20 tells that sulfur deposited onto "Catchment 1" enters "Lake 1", is partly retained there, then flows into "Lake 2" and is again subject to retention in that water body.

To be able to compute critical loads, the depositions have to be the same onto all (sub-)catchments (or at least have a time-independent constant ratio!); and in the following we will assume that $S_{dep,1} = S_{dep,2} = S_{dep}$. For the quantity $a_S = a_S^{(2)}$ we obtain then (see eq.20):

$$a_S^{(2)} = (1 - \rho_{S,2}) (A_2 + a_S^{(1)} A_1) / (A_2 + A_1) \quad (21)$$

with $a_S^{(1)} = 1 - \rho_{S,1}$. For three lakes forming a linear chain, i.e. "Lake 1" flows into "Lake 2" which, in turn, flows into "Lake 3", we obtain for $a_S = a_S^{(3)}$:

$$a_S^{(3)} = (1 - \rho_{S,3}) (A_3 + a_S^{(2)} (A_1 + A_2)) / (A_1 + A_2 + A_3) \quad (22)$$

whereas, if both "Lake 1" and "Lake 2" flow directly into "Lake 3", we get:

$$a_S^{(3)} = (1 - \rho_{S,3}) (A_3 + a_S^{(2,1)} A_1 + a_S^{(2,2)} A_2) / (A_1 + A_2 + A_3) \quad (23)$$

where $a_S^{(2,i)} = 1 - \rho_{S,i}$ ($i=1,2$). The last three equations indicate how to calculate a_S -coefficient *recursively* for any system of arbitrarily parallel and serially aligned lakes. The S -coefficient for the n -th level lake in the system, $a_S^{(n)}$, is given by

$$a_S^{(n)} = (1 - \rho_{S,n}) \left(A_n + \sum_{k=1}^{K_n} a_S^{(n-1,k)} S_{n-1,k} \right) / \left(A_n + \sum_{k=1}^{K_n} S_{n-1,k} \right), \quad K_0 = 0 \quad (24)$$

where K_n is the number of lakes directly flowing into lake n , and $S_{n-1,k}$ is the total catchment area, i.e. the area including all its upstream catchments, of the k -th lake of level $n-1$. For a linear chain of lakes with "Lake 1" flowing into "Lake 2", ... and "Lake $n-1$ " flowing into "Lake n ", the recursion simplifies to

$$a_S^{(n)} = (I - \rho_{S,n}) (A_n + a_S^{(n-1)} S_{n-1}) / S_n \quad \text{with} \quad S_0 = 0, S_n = S_{n-1} + A_n \quad (25)$$

Assuming N_{dep} , N_i and N_u are uniform for all subcatchments of a lake system, the recurrence relations for $a_N^{(n)}$ and $L_N^{(n)}$ can be derived in an analogous manner:

$$a_N^{(n,\cdot)} = (I - \rho_{N,n}) \left(b_N^{(n,\cdot)} A_n + \sum_{k=1}^{K_n} a_N^{(n-1,k)} S_{n-1,k} \right) / \left(A_n + \sum_{k=1}^{K_n} S_{n-1,k} \right), \quad K_0 = 0 \quad (26)$$

$$L_N^{(n,\cdot)} = (I - \rho_{N,n}) \left(M_N^{(n,\cdot)} A_n + \sum_{k=1}^{K_n} L_N^{(n-1,k)} S_{n-1,k} \right) / \left(A_n + \sum_{k=1}^{K_n} S_{n-1,k} \right), \quad K_0 = 0 \quad (27)$$

with $b_N^{(n)}$ and $M_N^{(n)}$ defined according to eq.12.