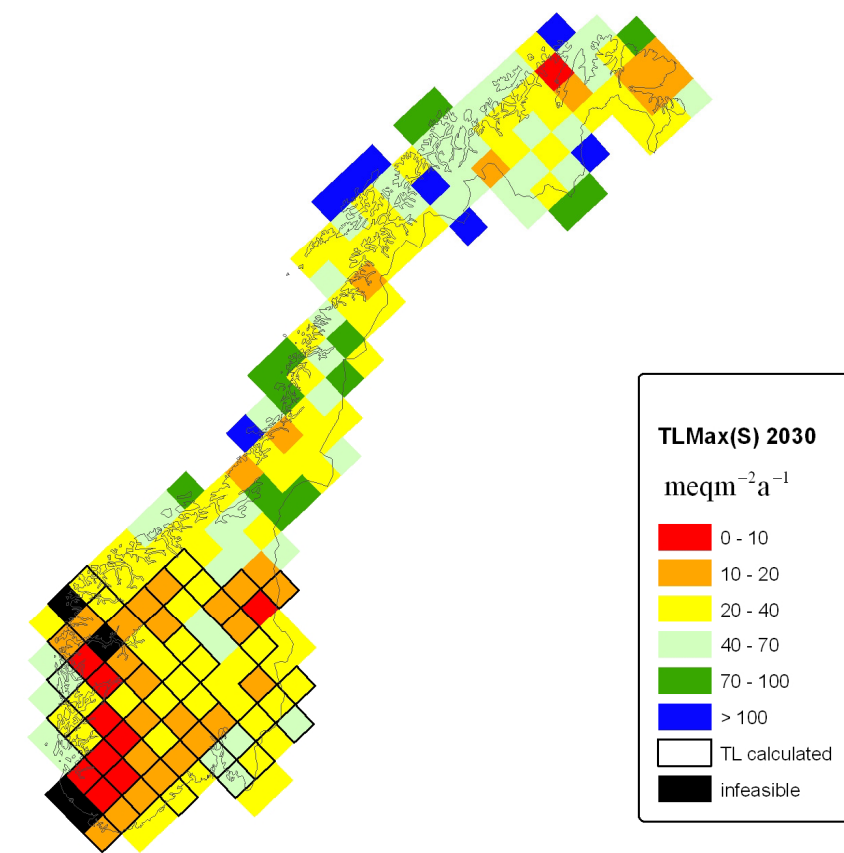




REPORT SNO 5099-2005

NATURENS  
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Fagrapport Nr.121

# Target loads for acidification of Norwegian surface waters



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Title Target loads for acidification of Norwegian surface waters	Serial No. 5099-2005	Date November 2005
	Report No. Sub-No. O-25125	Pages Price 33
Author(s) Thorjørn Larssen, Tore Høgåsen, Richard F. Wright	Topic group Acid rain	Distribution
	Geographical area Norway	Printed NIVA

Client(s) The Norwegian Pollution Control Authority (SFT)	Client ref. Contract 6005053
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**Abstract**

Target load is a logical extension of the critical load concept and incorporates the time delays in the chemical recovery from acidification. Calculations based on data from the Norwegian monitoring lakes and the dynamic acidification model MAGIC show that the increased ANC in Norwegian surface waters observed since 1990 can be expected to continue to increase to 2010 if the planned emission reductions of the Gothenburg protocol and other legislation are implemented. With no further reductions after 2010 the ANC will still increase slightly, but very slowly due to slow build up of base cations in the soils. A scenario assuming deposition reduction to background levels of sulphur and nitrogen show that there remains potential for additional increases in ANC if deposition is reduced beyond the Gothenburg protocol. Target loads are considerably lower than critical loads for southern Norway, showing that deposition reductions below the critical load are needed if the goal is to restore conditions suitable for sustainable fish populations within a few decades.

4 keywords, Norwegian	4 keywords, English
1. Sur nedbør	1. Acid rain
2. Tålegrenser	2. Critical loads
3. Balastningsmål	3. Target loads
4. Dynamisk modellering	4. Dynamic modelling



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Naturens tålegrenser

Fagrapport nr. 121

**Target loads for acidification of  
Norwegian surface waters**



## Preface

NIVA is the Norwegian National Focal Centre in the UNECE International Cooperative Programme on Modelling and Mapping of Critical Loads & Levels and Air Pollution Effects, Risks and Trends (ICP M&M) and participates with data and methodology regarding critical loads and dynamic modelling.

In November 2004 the Coordination Center for Effects (CCE) of the ICP M&M issued a call for data for target load functions (TLF) for soils and surface waters. In response to this call, the National Focal Centre at the Norwegian Institute for Water Research (NIVA) calculated target load functions for surface waters in Norway. The TLF data were submitted in March 2005 to the CCE.

Thanks to Max Posch at CCE, Filip Moldan at IVL and Chris Evans at CEH for help and fruitful discussions during the calculations and work with the report.

The work was conducted under contract from the Norwegian Pollution Control Authority (SFT). Contact at SFT has been Tor Johannessen.

Oslo, November 2005

*Thorjørn Larssen*

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## Summary

The concept of critical loads has been well established as a scientific basis in developing emission reduction plans of sulphur and nitrogen emissions in Europe. As the deposition of sulphur and nitrogen in Europe has decreased, it has been approaching the critical loads. It has been increasingly evident that a dynamic modelling approach as supplement to the static, steady state critical loads approach would be useful. As a response to this, a concept dynamic model approach compatible with and supplementary to the critical loads, called target loads, has been developed.

Within the framework of the United Nations Economic Commission for Europe (UNECE) Convention of Long-Range Transboundary Air Pollution (LRTAP) a call for data on targets loads was issued in November 2004. Norway submitted data in response to the call. The Norwegian data are summarized and presented in this report.

Data was submitted for surface waters in Norway south of 62.5°N for 131 lakes from the national monitoring programme. The calculations were done using the MAGIC model. Results are presented as scenarios for development in the acid neutralizing capacity (ANC) and as target loads for three different years (2030, 2050, 2100).

The results show that the increased ANC in Norwegian surface waters observed since 1990 can be expected to continue to increase to 2010 if the planned emission reductions of the Gothenburg protocol and other legislation are implemented. With no further reductions after 2010 the ANC will still increase slightly, but only very slowly due to slow build up of base cations in the soils. A scenario assuming deposition reduction to background levels of sulphur and nitrogen show that there remains potential for additional increases in ANC if deposition is reduced beyond the Gothenburg protocol.

Target loads are considerably lower than critical loads for southern Norway, showing that deposition reductions below the critical load are needed if the goal is to restore conditions suitable for sustainable fish populations within a few decades.

# 1. Introduction

The link between the emission of sulphur and nitrogen compounds to the atmosphere and the acidification of soils and surface waters is now well established and understood. These links form the basis for calculation of critical loads for surface waters and soils. Critical loads contributed to the scientific basis for the 1994 Oslo Protocol and the 1999 Gothenburg Protocol to the United Nations Economic Commission for Europe (UNECE) Convention of Long-Range Transboundary Air Pollution (CLRTAP) (internet web site [www.unece.org/env/lrtap](http://www.unece.org/env/lrtap)).

Ongoing work within the Convention now includes revision of these protocols. It has become increasingly clear that the static model approach used in estimating critical loads may be insufficient to determine the reduction in level of acid deposition necessary to allow recovery of acidified ecosystems within acceptable time. Deposition may have to be reduced to a target load below the critical load.

In November 2004 the Coordination Centre for Effects (CCE) of the International Cooperative Programme for Modelling and Mapping (ICP M&M) issued a call for data for target load functions (TLF) for soils and surface waters. In response to this call, the National Focal Centre at the Norwegian Institute for Water Research (NIVA) calculated target load functions for surface waters in the region of Norway south of Trondheim (south of 62.5°N latitude). The work was conducted under contract from the Norwegian Pollution Control Authority (SFT). The TLF data were submitted in March 2005 to the CCE. Sweden and the UK also submitted TLF data for surface waters. All three countries used the same dynamic model (MAGIC) and largely the same procedures to calculate TLFs. Here we describe the data used, the calculation procedures and the results obtained for Norway. The results for TLF for both waters and soils for all of Europe are reported by CCE (Posch, Slootweg et al. 2005).

## 2. Methods

### 2.1 Target loads

Outputs from dynamic models can be summarised and presented as a logical extension to the critical loads approach already used in the Integrated Assessment Modelling (IAM) process. For example, in the same way in which the critical loads of S and N are represented as a function for input to the Integrated Assessment Models (Figure 1), the deposition required to achieve a given chemistry within a specified time can be calculated from the dynamic models and expressed as a target load function (TLF) (Figure 1) (Jenkins, Cosby et al. 2003). At every combination of S and N deposition on the target load function, a target ANC will be reached in the specified target year. The major difference between the TLF and the critical load function (CLF) is the concept of time to reach the target chemistry; whereas the target load specifies that achievement be obtained by a specific year (the target year), the critical load refers to achievement given infinite time (Figure 2). The shapes of the CLF and TLF are similar; the 'shelf' at low N deposition represents the long-term capability of the system to utilise N. For systems in which the critical load is exceeded and damage has occurred, the TLF will always be lower than the CLF. For a target chemistry to be reached in the very long term (infinite timescale) the TLF and CLF are the same.

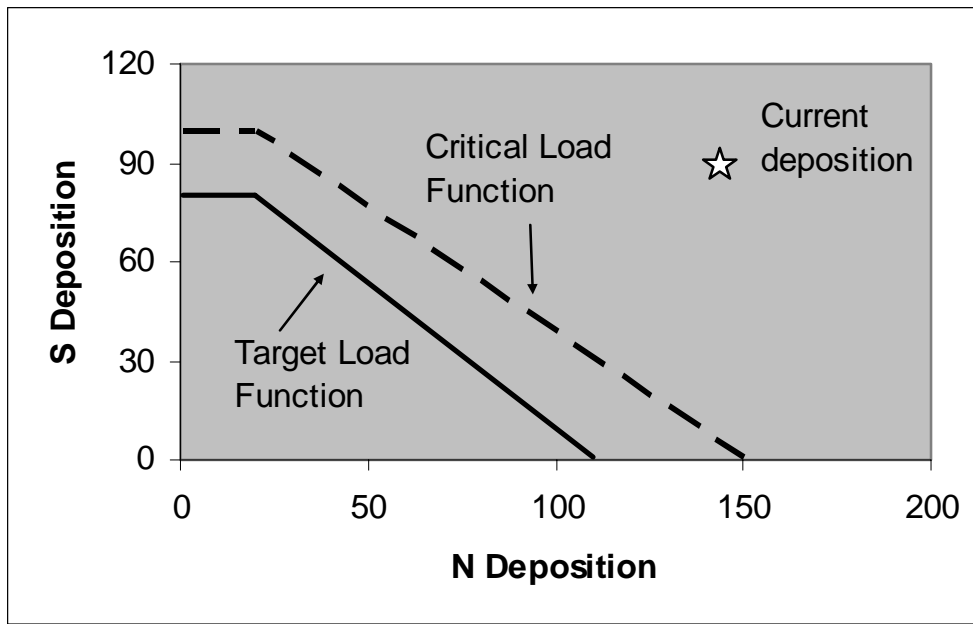


Figure 1. The critical load function (upper) as constructed and used by the Integrated Assessment Models for calculation of optimal deposition reduction scenarios. Emission reductions must be achieved at some future time to achieve the target chemistry at some (unknown) point in the future. The target load function is essentially the same but the timing of emission reductions must be specified to achieve the specified chemistry in a given year. Figure from (Jenkins, Cosby et al. 2003).

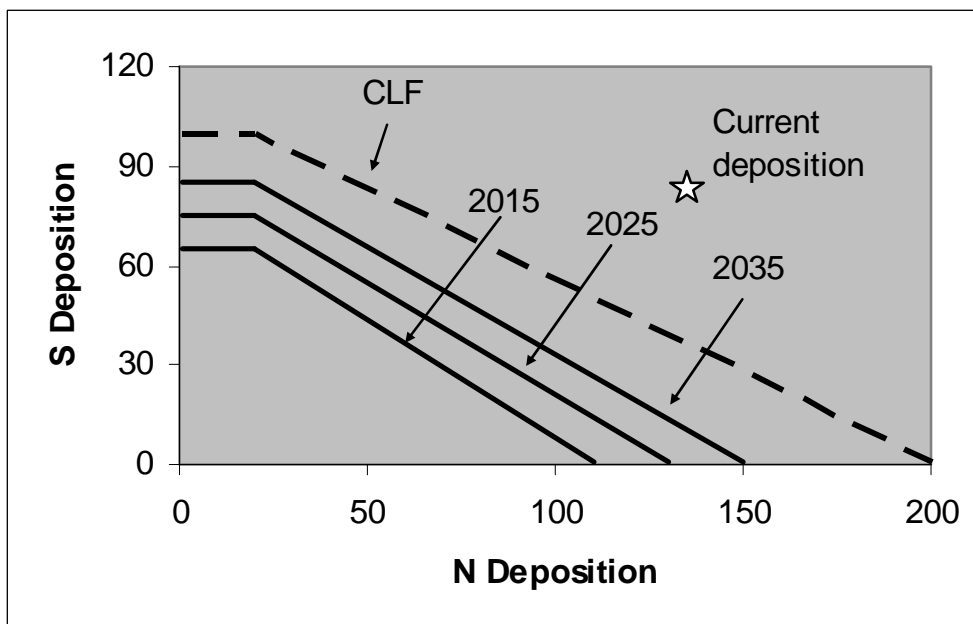


Figure 2. The effect of different target years on the target load function for a given target chemistry at an individual site. Here, for example, if the target is to achieve recovery of the ecosystem by the year 2015, a greater reduction in deposition is required, whereas if the target is later, for example the year 2035, a lesser reduction in deposition will be sufficient. Given infinite time the TLF will converge to the CLF. Figure from (Jenkins, Cosby et al. 2003).

At an acidified site the reduction in deposition required to reach a specified target within 15 years will be greater than that required to reach the same target over a longer timescale (Figure 2). Because costs increase with greater reduction of N and S, there is an increased cost associated with selecting a more immediate ecosystem recovery. The slopes of the TLFs under different target years will vary from site to site as a function of the buffering capacity of the soils (weathering rate, soil exchangeable base cations), the deposition (historical and current), and the predicted level of future deposition.

The specification of the TLF from a dynamic model requires one further specification, namely the years of implementation of emission reductions. The start (protocol year) and end (implementation) years of the required reductions must be specified, because any delay in emission reductions and the time period over which they are implemented will affect the position of the TLF.

In terms of achieving an optimal solution to emission reduction, therefore, the policy maker needs to make key decisions regarding: (i) the year in which the target chemistry is required (target year); (ii) the year in which emission reductions will start to be implemented (protocol year); and (iii) the year in which the emission reduction must be completed (implementation year). The regional TLF constructed for use by the IAM will incorporate the results of these three specifications. There is also the possibility to 'optimise' these three assumptions/decisions prior to application of the IAM.

## 2.2 The 2004 call for CLF and TLF data

The call for data issued in November 2004 by the CCE contained a number of specifications designed to obtain consistent and harmonised CLF and TLF for all countries in Europe. The CCE specified the three key years for which the TLFs were to be calculated: (i) the protocol year, (ii) the implementation year, and (iii) the target year. These were defined as follows:

The *protocol year* for dynamic modelling is the year up to which the deposition path is assumed to be known and cannot be changed. This can be the present year or a year in the (near) future, for which emission reductions are already agreed.

For this call the protocol year was 2010, and the deposition of S and N in 2010 was assumed to be that obtained following implementation of the Gothenburg Protocol, the EU NEC Directive and other (national) legislation. This is termed the current legislation scenario (CLE). The CCE provided S and N deposition data for years from 1860 to 2010 for each grid square in the EMEP 50x50 km grid for Europe.

The *implementation year* for dynamic modelling is the year in which all reduction measures to reach the final deposition (the target load) are assumed to be implemented. Sometimes the prefix 'DM' for 'dynamic modelling' is added to avoid confusion with the term 'implementation year' as used by integrated assessment modellers. For this call the DM-implementation year was specified to 2020, and deposition is assumed to change linearly between the protocol year and the implementation year (Figure 3).

The *target year* for dynamic modelling is the year in which the chemical criterion (e.g., the lake water ANC) is met (for the first time). Again, 'DM' is prefixed to emphasise the use of the term in dynamic modelling. For this call there were three target years specified: 2030, 2050, and 2100.

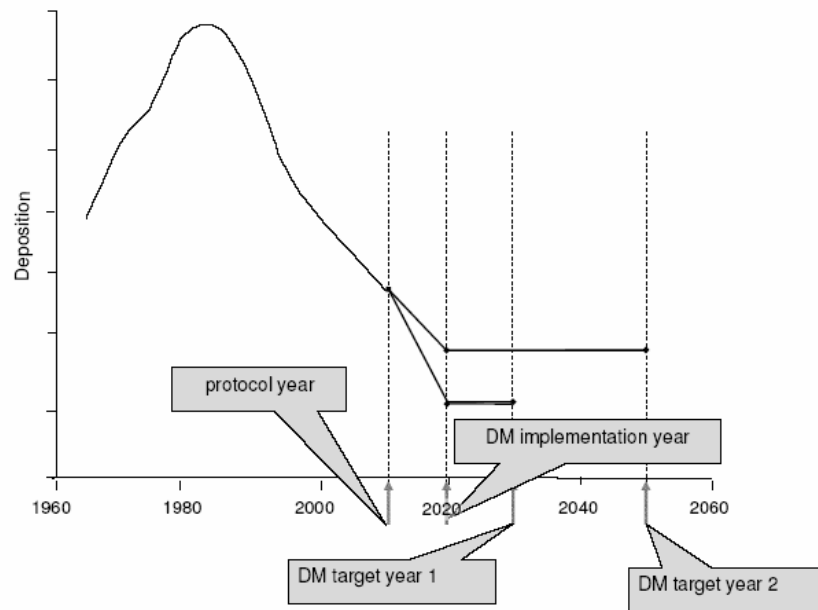


Figure 3. Illustration of a deposition path (for example, S) and the terminology used in target load calculations (from the CCE 2004 call document). (i) The year up to which the deposition is fixed (protocol year); (ii) the year in which the emission reductions leading to a target load are implemented (DM implementation year); and (iii) the years in which the chemical criterion is to be achieved (DM target years).

There were a number of other considerations regarding the relationship between CLF and TLF included in the call. First, the TLF should always be equal to or less than the CLF. Second, the chemical criterion reached in the target year should be maintained thereafter; that is, the ecosystem should not deteriorate later in the future. An example of this situation could be caused by increased nitrogen saturation in the future. If at present the ecosystem retains a large fraction of nitrogen deposition, the target load for N may be quite large. But this target load for N will cause reacidification of the system if in the future a decreasing fraction of N deposition is retained. Third, if the critical load is at present not exceeded and the chemical criterion not violated, the site is safe and no TLF is necessary. And fourth, there are some cases for which TLF need not be calculated; these are specified in the decision tree shown in Figure 4.

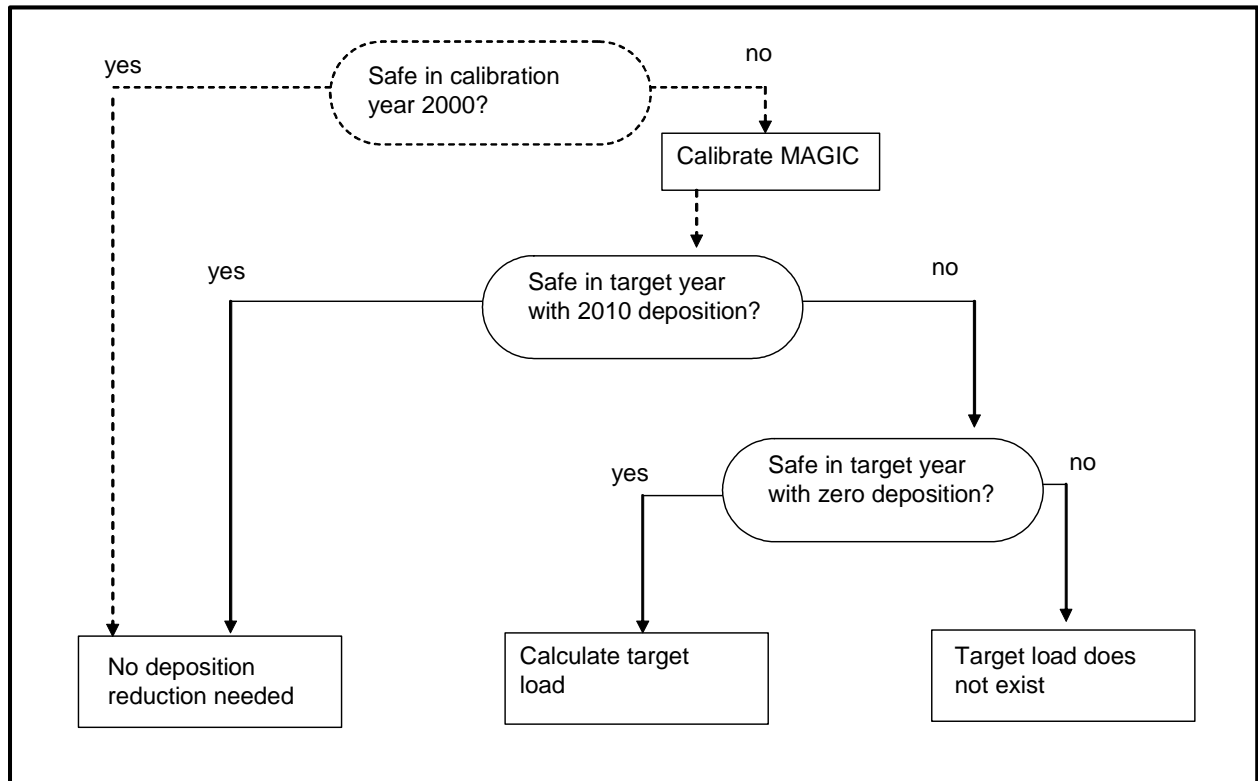


Figure 4. Decision tree for determining whether a target load has to be calculated. “Safe” means that the critical load is not exceeded and the criterion is not violated (adapted from the CCE 2004 call document).

## 2.3 The MAGIC Model

The dynamic model MAGIC was used to calculate the target load functions for Norwegian surface waters. MAGIC (Model of Acidification of Groundwater In Catchments) is a lumped-parameter model of intermediate complexity, developed to predict the long-term effects of acidic deposition on soils and surface water chemistry (Cosby, Hornberger et al. 1985; Cosby, Wright et al. 1985; Cosby, Ferrier et al. 2001). The model simulates soil solution chemistry and surface water chemistry to predict the annual average concentrations of the major ions in lakes and streams. MAGIC represents the catchment with aggregated, uniform soil compartments (one or two) and a surface water compartment that can be either a lake or a stream. MAGIC consists of (1) a section in which the concentrations of major ions are assumed to be governed by simultaneous reactions involving sulphate adsorption, cation exchange, dissolution-precipitation-speciation of aluminium and dissolution-speciation of inorganic and organic carbon, and (2) a mass balance section in which the flux of major ions to and from the soil is assumed to be controlled by atmospheric inputs, chemical weathering inputs, net uptake in biomass and losses to runoff. At the heart of MAGIC is the size of the pool of exchangeable base cations in the soil. As the fluxes to and from this pool change over time owing to changes in atmospheric deposition, the chemical equilibria between soil and soil solution shift to give changes in surface water chemistry. The degree and rate of change in surface water acidity thus depend both of flux factors and the inherent characteristics of the affected soils.

The soil layers can be arranged vertically or horizontally to represent important vertical or horizontal flowpaths through the soils. If a lake is simulated, seasonal stratification of the lake can be implemented. Time steps are monthly or yearly. Time series inputs to the model include annual or

monthly estimates of (1) deposition of ions from the atmosphere (wet plus dry deposition; (2) discharge volumes and flow routing within the catchment; (3) biological production, removal and transformation of ions; (4) internal sources and sinks of ions from weathering or precipitation reactions; and (5) climate data. Constant parameters in the model include physical and chemical characteristics of the soils and surface waters, and thermodynamic constants. The model is calibrated using observed values of surface water and soil chemistry for a specific period.

MAGIC has been modified and extended several times from the original version of 1984. In particular, organic acids have been added to the model (version 5; (Cosby, Wright et al. 1995)) and most recently nitrogen processes have been added (version 7; (Cosby, Ferrier et al. 2001)).

The MAGIC model has been extensively applied and tested over a 17 year period at many sites and in many regions around the world (Cosby, Ferrier et al. 2001). Overall, the model has proven to be robust, reliable and useful in a variety of scientific and environmental management activities (Cosby, Wright et al. 1995; Ferrier, Wright et al. 1995; Jenkins, Wright et al. 1998; Wright, Beier et al. 1998). Recently MAGIC was used to assess the recovery of European surface waters given the CLE (Gothenburg protocol and other agreed legislation) deposition scenario (Wright, Larssen et al. 2005).

## 2.4 List of required data

The data required to run MAGIC must be spatially and temporally averaged (or 'lumped') to represent the whole catchment area (divided into one or several soils and waters compartments) and the time step of the model (annual or monthly). If physical and chemical data are available at only one point in the catchment or from one point in time, it must be assumed that this is representative of the whole catchment at that time step. Any uncertainty in these data and in the representativeness is incorporated into the model and the prediction must be interpreted accordingly. The minimum data requirement is given below:

Hydrological parameters:

- Annual runoff (m/yr)
- Annual precipitation volume (m/yr)

Soil parameters:

- Soil depth (m)
- Porosity (%)
- Bulk density ( $\text{kg/m}^3$ )
- CEC (meq/kg)
- $\text{SO}_4$  maximum adsorption capacity (meq/kg)
- $\text{SO}_4$  half-saturation coefficient ( $\text{meq/m}^3$ )
- Dissociation constant for aluminium hydroxide solid phase,  $K_{\text{Al}}$  ( $\log_{10}$ )
- Temperature (annual average) ( $^{\circ}\text{C}$ )
- $\text{pCO}_2$  (%)
- Organic acids ( $\text{mmol C/m}^3$ )
- Dissociation constants for organic acids (pK)
- Nitrification (% of input)

Surface water parameters:

- Retention time (Yr)
- Relative area (%)
- Temperature (annual average) ( $^{\circ}\text{C}$ )
- Dissociation constant for aluminium hydroxide solid phase,  $K_{\text{Al}}$  ( $\log_{10}$ )



- $p\text{CO}_2$  (%)
- Organic acids ( $\text{mmol C/m}^3$ )
- Dissociation constants for organic acids (pK)
- Nitrification (% of input)

Surface water/soil chemistry in calibration year (i.e. 2001):

- Concentration of major ions (Ca, Mg, Na, K,  $\text{NH}_4$ ,  $\text{SO}_4$ , Cl,  $\text{NO}_3$ ) ( $\text{meq/m}^3$ )
- Soil exchangeable base cations (Ca, Mg, Na, K) ( $\text{meq/kg}$ )

Deposition parameters in calibration year (i.e. 2001):

- Concentration of major ions (Ca, Mg, Na, K,  $\text{NH}_4$ ,  $\text{SO}_4$ , Cl,  $\text{NO}_3$ )
- Time sequence of change in:
  - deposition concentration
  - dry deposition factors for each ion (= total deposition/wet deposition)

The historical sequences of changing deposition of sulphur and nitrogen were derived from estimates made by EMEP (Schöpp, Posch et al. 2003). These historical ‘trajectories’ at the scale of the EMEP grid are usually modified at a site or regional scale to incorporate more detailed measurements or estimates, particularly in more recent years. Updated deposition histories for the EMEP 50x50 km grid were provided by the CCE (available on the website [www.mnp.nl/cce](http://www.mnp.nl/cce)).

## 2.5 Model Calibration

MAGIC was calibrated in the usual manner in a series of steps. First, the concentration of chloride (Cl) in surface water was matched (simulated equal observed for the calibration year) under the assumption that the only source is atmospheric deposition and that there is no retention in the catchment or lake. Second, the concentration of sulphate ( $\text{SO}_4$ ) in surface water was matched under the assumption that atmospheric deposition and weathering are the sole sources of  $\text{SO}_4$  and that adsorption in the soil is at steady-state. Third, the concentration of nitrate ( $\text{NO}_3$ ) in surface water was matched under the assumptions that all ammonium deposition was nitrified to nitrate ( $\text{NO}_3$ ) and that the catchment and lake retain a fixed percent of incoming N deposition. This percentage retention is assumed to be constant throughout the model simulation. Fourth, the concentrations of the four major base cations in surface water and on the soil solid phase (expressed as a percentage of cation exchange capacity) were matched by adjusting the cation exchange selectivity coefficients and the base cation weathering rates. Finally, surface water pH, Al and organic anion concentrations were matched by adjusting the aluminium solubility coefficient and total organic acid concentration in surface water.

For  $\text{SO}_4$ , if surface water data is available for only one point in time the adsorption parameters (maximum adsorption capacity =  $E_{\text{mx}}$  and half-saturation constant = C) are required and must be estimated from soils data. For regions with geologically ‘young’ soils,  $\text{SO}_4$  adsorption is generally small. For the applications with long time-series the C and  $E_{\text{mx}}$  can be calibrated to match the observed trend in surface water  $\text{SO}_4$  given an observed trend in  $\text{SO}_4$  deposition.

The base cation calibration follows an iterative process whereby the base cation selectivity coefficients are set, values are chosen for base cation weathering, the model is run from some background, pre-acidification condition, the simulated values of base cations in soil and surface waters are compared with observed. This process is repeated, adjusting the selectivities and weathering rates until the observed target concentrations are achieved. If time-series data are available further adjustment may be undertaken to match trends. This part of the calibration procedure can be undertaken automatically using an appropriate numerical optimisation procedure.

### 3. Data

We calculated target load functions for surface waters according to the specifications in the call. The calculations are based on a population of 131 lakes in southern Norway. These are lakes included in the national monitoring program for which we have sufficient data to calculate target load functions with the dynamic model MAGIC. Due to resource limitations we confined our work to lakes south of 62.5° N latitude. Target loads were not calculated for lakes having measured ANC values in 1995-1997 (average) higher than  $ANC_{limit}$ . The variable  $ANC_{limit}$  was calculated in accordance with the Mapping Manual, except that  $BC^*_0$  was taken from the calibrated initial concentrations from the MAGIC model calibration. 83 of the lakes had ANC below  $ANC_{limit}$  and TLFs were calculated for these lakes. Ranges of model inputs and parameters and comments on their sources and justifications are listed in Table 1.

Table 1. Ranges of model inputs and parameters and comments on their sources and justifications. Parameter codes are given in the Mapping Manual.

Var	Unit	Min	Max	Assumptions, data sources and justifications
EcoArea	%	100%	100%	We consider 100% of the land area to contain catchments for lakes and rivers. We have not calculated the area of the EMEP grid cells, which should be given here (minus the part of the cell covering ocean).
CLmaxS	eq ha <sup>-1</sup> a <sup>-1</sup>	5.36	73.24	Calculated with FAB model (according to Mapping Manual, except $BC^*_0$ taken from MAGIC calibrations (1860))
CLminN	eq ha <sup>-1</sup> a <sup>-1</sup>	3.20	42.32	
CLmaxN	eq ha <sup>-1</sup> a <sup>-1</sup>	11.78	118.42	
CLnutN				Not applicable
crittype		6	6	ANC is used as criterion for all lakes
critvalue	µeq L <sup>-1</sup>	1.27	18.15	Variable $ANC_{limit}$
SoilYear		1995	1995	Same year (1995) used for all soil analyses
ExCa	%	2.17	40.41	Taken from nearest relevant soil sampling locations or as a combination of nearest forested and non-forested soil sampling location. Data from forested catchments from the National Forest Inventory; data from non-forested catchments from various research and monitoring projects.
ExMg	%	0.69	24.47	
ExNa	%	0.75	6.75	
ExK	%	0.26	7.43	
thick	m	0.03	0.89	
BulkDens	kg m <sup>-3</sup>	192.30	906.98	
CEC	meq kg <sup>-1</sup>	12.31	242.52	
Cpool	g m <sup>-2</sup>	2080	85371	
Npool	g m <sup>-2</sup>	99	4914	
Porosity	%	50	50	
Nimacc	eq ha <sup>-1</sup> a <sup>-1</sup>	34	34	Default values for FAB model from Mapping Manual
UptCa	meq m <sup>-2</sup> a <sup>-1</sup>	0.00	29.74	Based National Forest Inventory.
UptMg	meq m <sup>-2</sup> a <sup>-1</sup>	0.00	5.61	
UptK	meq m <sup>-2</sup> a <sup>-1</sup>	0.00	6.44	
UptNa	meq m <sup>-2</sup> a <sup>-1</sup>	0.00	1.06	
UptSO4	meq m <sup>-2</sup> a <sup>-1</sup>	0.00	0.00	
UptNH4	meq m <sup>-2</sup> a <sup>-1</sup>	0.00	0.00	
HlfSat	µeq L <sup>-1</sup>	100	100	Assumption. Constant value used for all sites.
Emx	meq kg <sup>-1</sup>	1.00	1.00	Assumption. Constant value used for all sites.
Nitrif	%	100	100	Assumption based on the fact that ammonium concentrations are

Denitrf	%	0.00	0.00	very low.
CNRange		11.00	11.00	Constant range based on empirical data from (Gundersen, Callesen et al. 1998)
CNUpper		10	73.4	Calibrated
DepYear		1995	1995	
Cldep	eq ha <sup>-1</sup> a <sup>-1</sup>	66.78	5366	Deposition flux of chloride, set equal to catchment output flux
Cadep	eq ha <sup>-1</sup> a <sup>-1</sup>	2.47	198.6	Calculated from [Cl <sup>-</sup> ] using standard sea salt ratios and assuming no non-sea salt deposition
Mgdep	eq ha <sup>-1</sup> a <sup>-1</sup>	13.09	1039.8	
Nadep	eq ha <sup>-1</sup> a <sup>-1</sup>	57.30	4363	
Kdep	eq ha <sup>-1</sup> a <sup>-1</sup>	1.20	96.60	
NH4dep	eq ha <sup>-1</sup> a <sup>-1</sup>	74.04	811.0	Calculated from observed ratios in deposition to SO <sub>4</sub> . SO <sub>4</sub> deposition was calculated from runoff flux assuming geological contribution and background deposition as described in mapping manual.
NO3dep	eq ha <sup>-1</sup> a <sup>-1</sup>	74.77	695.5	
LakeYear		1995	1995	Lake chemistry taken from the National Lake Monitoring Program (SFT 2004). Average for 1995-1997 was used.
Calake	μmol L <sup>-1</sup>	2.99	39.25	
Mglake	μmol L <sup>-1</sup>	1.78	37.43	
Nalake	μmol L <sup>-1</sup>	7.39	247.94	
Klake	μmol L <sup>-1</sup>	1.02	16.37	
NH4lake	μmol L <sup>-1</sup>	0.00	0.00	
SO4lake	μmol L <sup>-1</sup>	4.51	68.36	
Cllake	μmol L <sup>-1</sup>	8.46	302.75	
NO3lake	μmol L <sup>-1</sup>	1.38	34.76	
DOC	μmol L <sup>-1</sup>	0.73	31.96	Organic acid fraction of DOC assuming tri-protic acid and charge density of 10.2 μeq/mg C (From (Hruska, Kohler et al. 2003))
RelArea	%	0.41	36.36	Data for each catchment taken from maps
RelForArea				
RetTime	yr	0.50	0.50	Assumption. Constant value used for all sites.
Qs	m	0.41	4.49	Runoff taken from digital 30-year normal runoff database.
expAlllake		3.00	3.00	Assumption. Constant value used for all sites.
pCO2	%	0.05	0.05	Assumption. Constant value used for all sites.
Nitriflake	%	100	100	Assumption. Constant value used for all sites.
Cased	m a <sup>-1</sup>	0.00	0.00	Assumption. Constant value used for all sites.
Mgsed	m a <sup>-1</sup>	0.00	0.00	
Nased	m a <sup>-1</sup>	0.00	0.00	
Ksed	m a <sup>-1</sup>	0.00	0.00	
SO4sed	m a <sup>-1</sup>	0.00	0.00	
Clsed	m a <sup>-1</sup>	0.00	0.00	
NH4sed	m a <sup>-1</sup>	5.00	5.00	Assumption, based on generalization described in Mapping Manual
NO3sed	m a <sup>-1</sup>	5.00	5.00	
UptNH4lake	%	0.00	0.00	Assumption. Constant value used for all sites.
UptNO3lake	%	0.00	0.00	Assumption. Constant value used for all sites.
Sdep2010	eq ha <sup>-1</sup> a <sup>-1</sup>	80.43	621.5	Calculated from estimate of total input in 1995 and Current Legislation forecast scenarios taken from (Schöpp, Posch et al. 2003).
NOxdep2010	eq ha <sup>-1</sup> a <sup>-1</sup>	49.35	459.0	
NH3dep2010	eq ha <sup>-1</sup> a <sup>-1</sup>	71.08	778.6	

## 4. Results

Results from dynamic modelling and target load function calculation can be summarized in various ways. Box and whisker plots show the aggregated results for several scenarios (Figure 5), so called “snail trails” show the development over time for a single scenario (Figure 6), as do maps with coloured dots for each of the lakes included in the analysis (Figure 7 and Figure 8). The map presentation can be modified to show the results aggregated to EMEP grid cells (Figure 10). ANC is a suitable parameter, since ANC is the parameter used to link water chemistry to biological response through the  $ANC_{limit}$ . In order to illustrate target loads on maps and other aggregated presentations, we use the  $TL_{max}(S)$  values (this is the value for sulphur deposition where the N deposition is 0, parallel to  $CL_{max}(S)$  for critical loads). The complete target load functions (the relationship between S and N deposition) and the critical load functions are shown for all lakes in the Appendix.

### 4.1 Scenario analyses

Results for the two forecast scenarios (the Gothenburg protocol and a scenario with only background deposition) are shown in the box and whisker plot (Figure 5). These plots and the “snail trails” (Figure 6) show how the distribution of ANC in the lakes shifts to higher values in 2010 (compared to the base year 1990) given implementation of the Gothenburg protocol. Only small increases in ANC values are predicted further into the future under the assumption that there are no further emission reductions than the Gothenburg protocol. For the scenario with background deposition only, there is a considerable increase in the ANC compared to the Gothenburg protocol scenario from 2010 to 2030. This scenario shows the maximum possible increase in the ANC and would in the very long run bring the ANC back to the pre-acidification level. The background deposition scenario also indicates that there is only a small increase in the ANC from 2030 and onwards. The small changes after 2030 show that the Norwegian lakes respond fast to changes in deposition and that the build-up of exchangeable base cations in the soil from weathering is very slow.

On the maps (Figure 7) we show modelled ANC for each of the lakes in 2000, 2030, 2050 and 2100 under the Gothenburg protocol scenario and the background deposition scenario. The ANC values are split into three colour-coded classes:

- Red: ANC below  $0 \mu\text{eq L}^{-1}$ ; very low probability for a healthy self-reproducing brown trout population.
- Yellow: ANC between 0 and  $20 \mu\text{eq L}^{-1}$ ; moderate probability for a healthy self-reproducing brown trout population; extremely sensitive unacidified lakes may naturally fall into this category.
- Blue: ANC above  $20 \mu\text{eq L}^{-1}$ ; high probability for a healthy self-reproducing brown trout population.

The map for ANC in 2000 shows ANC values below  $0 \mu\text{eq L}^{-1}$  for very many of the lakes<sup>1</sup>. A considerable increase in ANC is predicted to 2030 with implementation of the Gothenburg protocol. About half of the lakes have shifted to one category better from 2000 to 2030, but still nearly half of the lakes have ANC below  $0 \mu\text{eq L}^{-1}$ . From 2030 to 2050 and 2100 there are only small improvements, and only a few lakes shift to one category better.

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<sup>1</sup> It is important to remember here that to be included in the dataset modelled, the criterion ANC in 1990 below the  $ANC_{limit}$  had to be met. Hence the selection of lakes is purposely skewed towards acid lakes. The results should therefore be viewed as representative for acid-sensitive lakes and not the entire population of lakes in southern Norway.

For the background deposition scenario most lakes shift to a better category from 2000 to 2030 and only two of the lakes remain in the lowest category (red) in 2030. These two lakes shift to the intermediate category (yellow) further into the future. This means that with the background deposition scenario in the long run no lakes remain with ANC below  $0 \mu\text{eq L}^{-1}$ , although several decades are necessary for recovery.

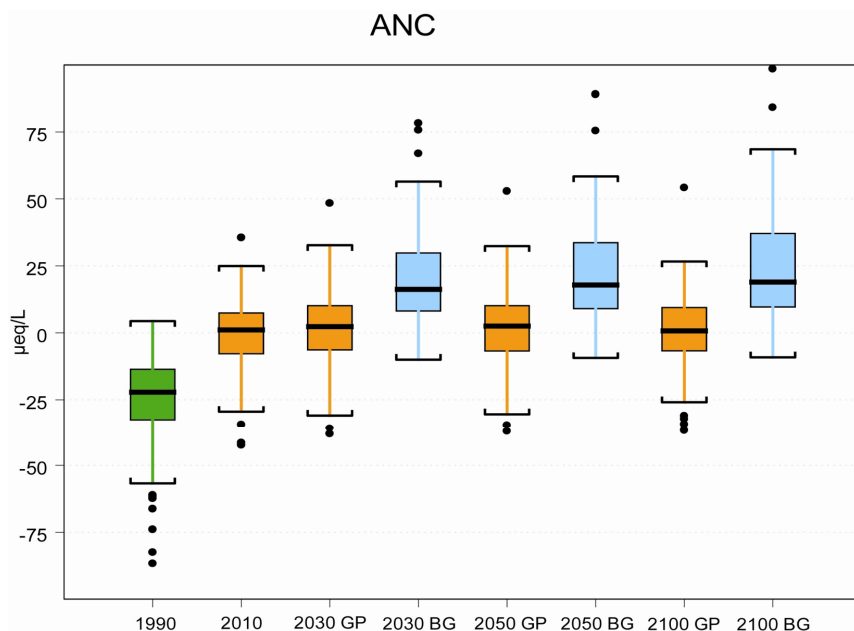


Figure 5. Box and whisker plots of distribution of ANC for the two different scenarios in different years. The green box shows the distribution of ANC in the lakes in 1990; the orange boxes the modelled distribution of ANC in the lakes under the Gothenburg protocol scenario for 2010 and 2030. The blue boxes show the distribution for modelled ANC for the scenario with only background deposition. The heavy line shows the median, the box shows the quartiles, the whiskers the 95% interval and the dots outliers.

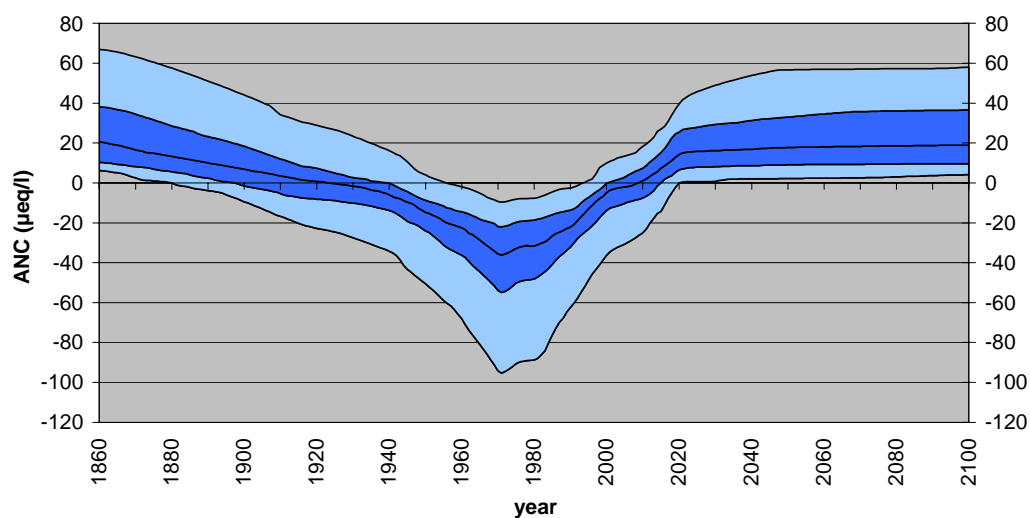


Figure 6. Distribution of ANC modelled in lakes from 1860 to 2100 given implementation of the Gothenburg protocol. Lines (from top down) are 95<sup>th</sup>, 75<sup>th</sup>, median, 25<sup>th</sup> and 5<sup>th</sup> percentiles; dark blue band encompasses 50% of lakes; the whole coloured band 90% of lakes.

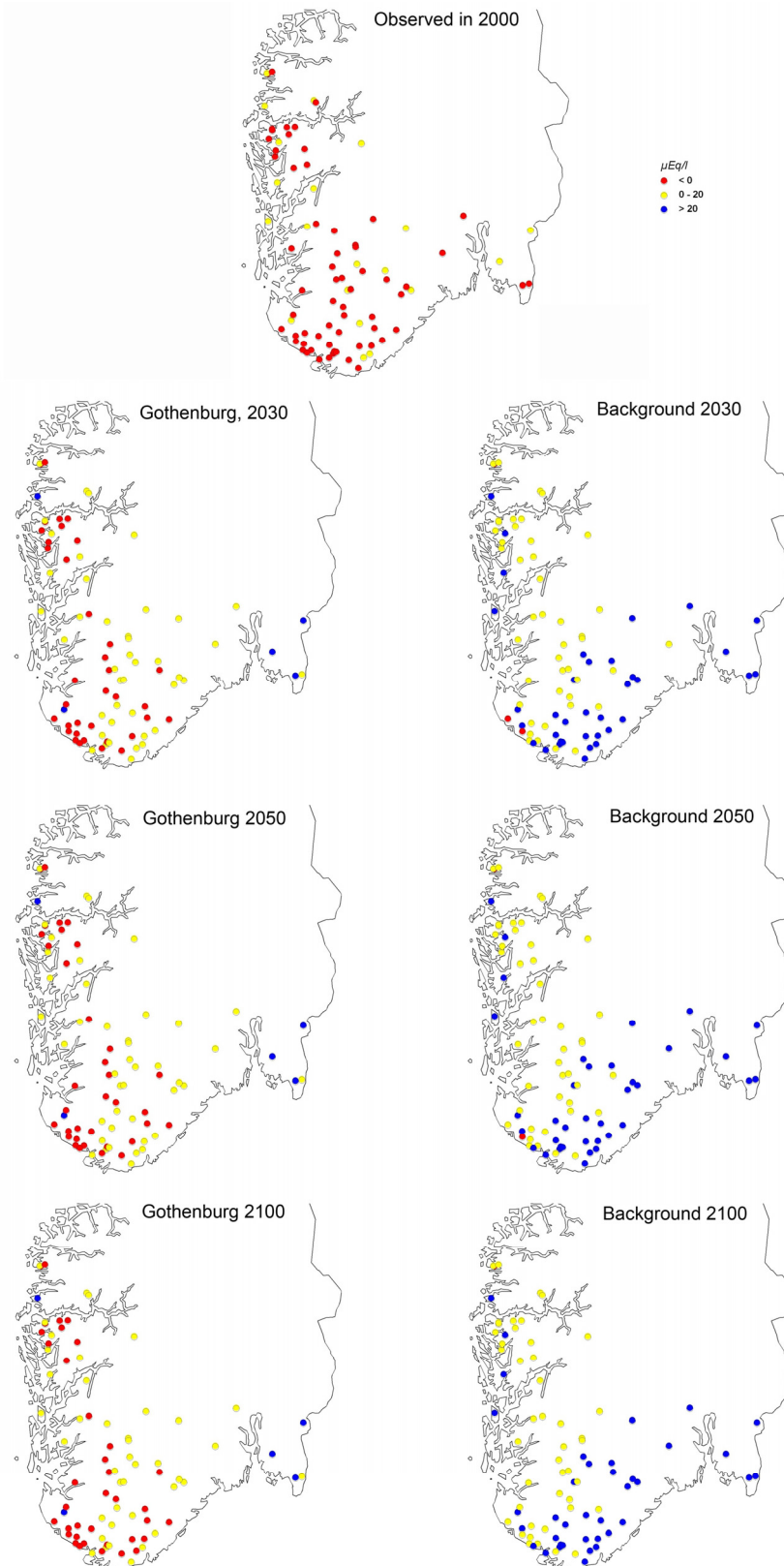


Figure 7. Observed ANC values in year 2000 in the lakes for which TLFs were calculated (upper panel) and modelled ANC values in 2000, 2030, 2050 and 2100 for two future deposition scenarios. Left-hand column: the Gothenburg protocol; right-hand column: the background scenario. Only lakes not safe with the 2010 deposition are included (see decision tree in Figure 4).

## 4.2 Target load functions

Target loads were calculated for three target years (2030, 2050 and 2100); the results for each lake are summarized as  $TL_{\max}(S)$  in maps in Figure 8. Target load functions for each individual lake are shown in the appendix.

The map of the target loads reflects the geographical pattern of the critical loads, but with lower values. The differences between the target loads for various target years are shown in Figure 9. There is an increase in  $TL_{\max}(S)$  from 2030 to 2050 and further to 2100 (almost all points are above the 1:1 lines in Figure 9). This implies that larger reductions in deposition are necessary to reach the target load deposition for 2030 than for instance for 2050, and also that larger reductions in deposition are needed to reach the target load than the critical load.

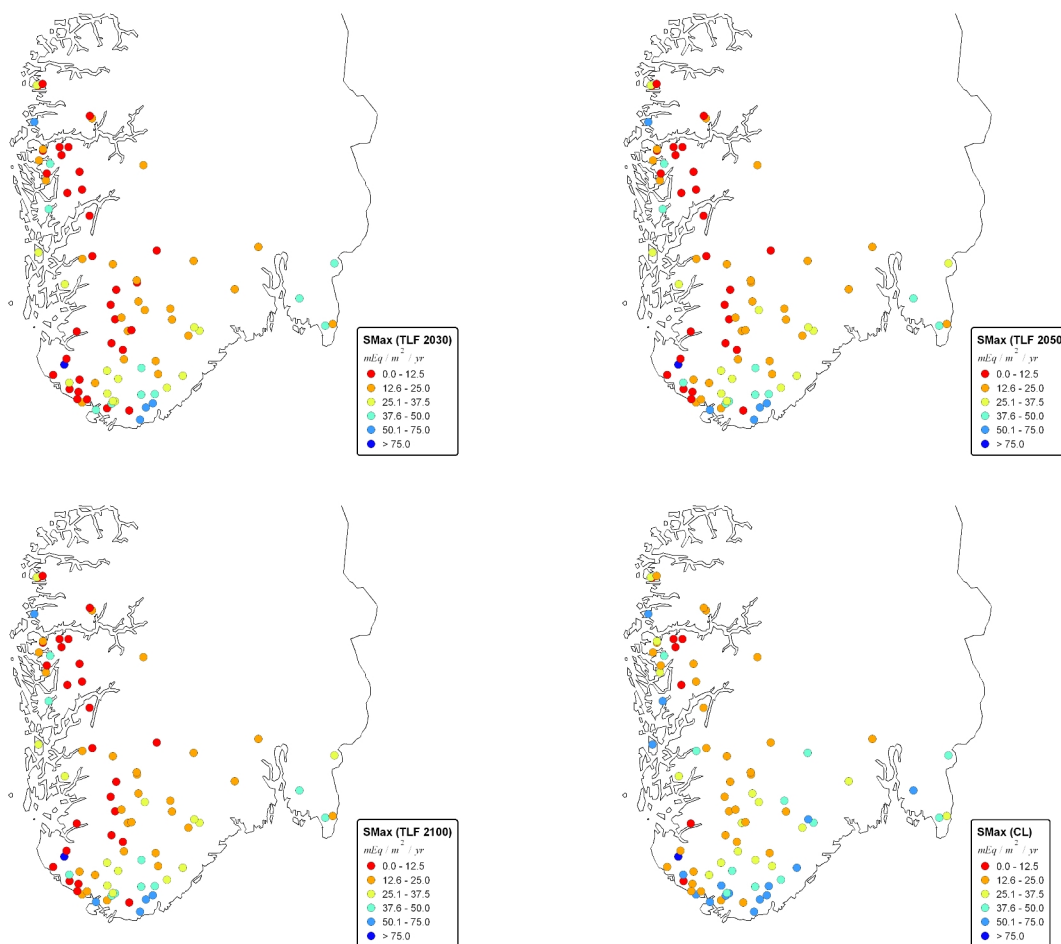


Figure 8.  $TL_{\max}(S)$  for the target load functions in 2030, 2050, 2100 and the critical loads ( $CL_{\max}(S)$ ) for each of the lakes included in the calculations. Only lakes not safe with the 2010 deposition are included (see decision tree in Figure 4).

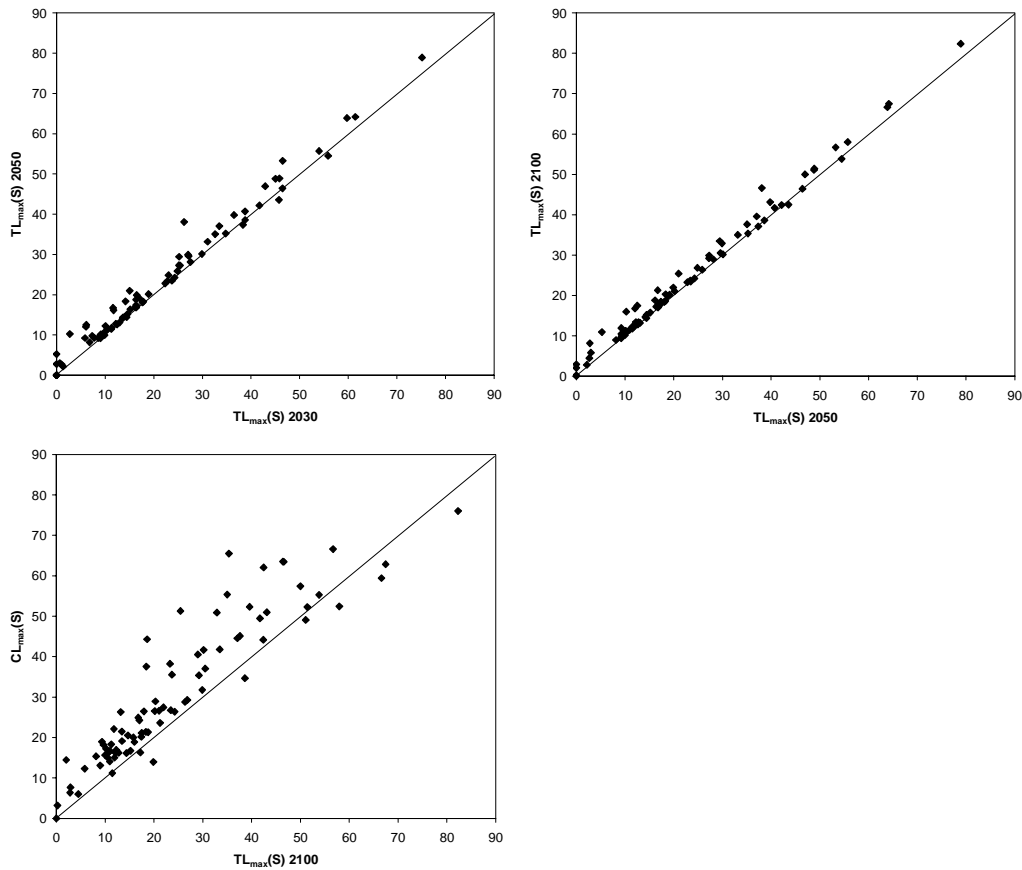


Figure 9. Relationships between  $TL_{max}(S)$  for different years and between  $TL_{max}(S)$  and  $CL_{max}(S)$ .

For reporting at European scale and for use in the integrated assessment model RAINS, data from each country are aggregated to EMEP grid cells. Most EMEP grid cells in the acid sensitive areas in southern Norway are now covered with at least one target load function (for critical loads there are approximately 16 critical load values per EMEP grid cell). Figure 9 shows the target loads data on a map as they may be used on European scale. The EMEP grid cells where target loads are calculated are marked with black squares. For grid cells where no target loads are calculated, the critical loads will be used instead. When aggregating results to EMEP grid cells, a certain percentile of the data must be used for illustration on the map (e.g. the 5<sup>th</sup> percentile).

There are important differences between the maps of target loads and critical loads, with considerably lower value for the target loads (Figure 10). For four of the grid cells fall into the category “infeasible”, which means that 5% or more of lakes within this grid cell will not recover within the target year even with only background deposition. Although the four grid cells remain “infeasible” for all the target load years, the number of red grid cells gets smaller for the later target load years, showing that when more time is permitted for recovery, a larger deposition can be tolerated.



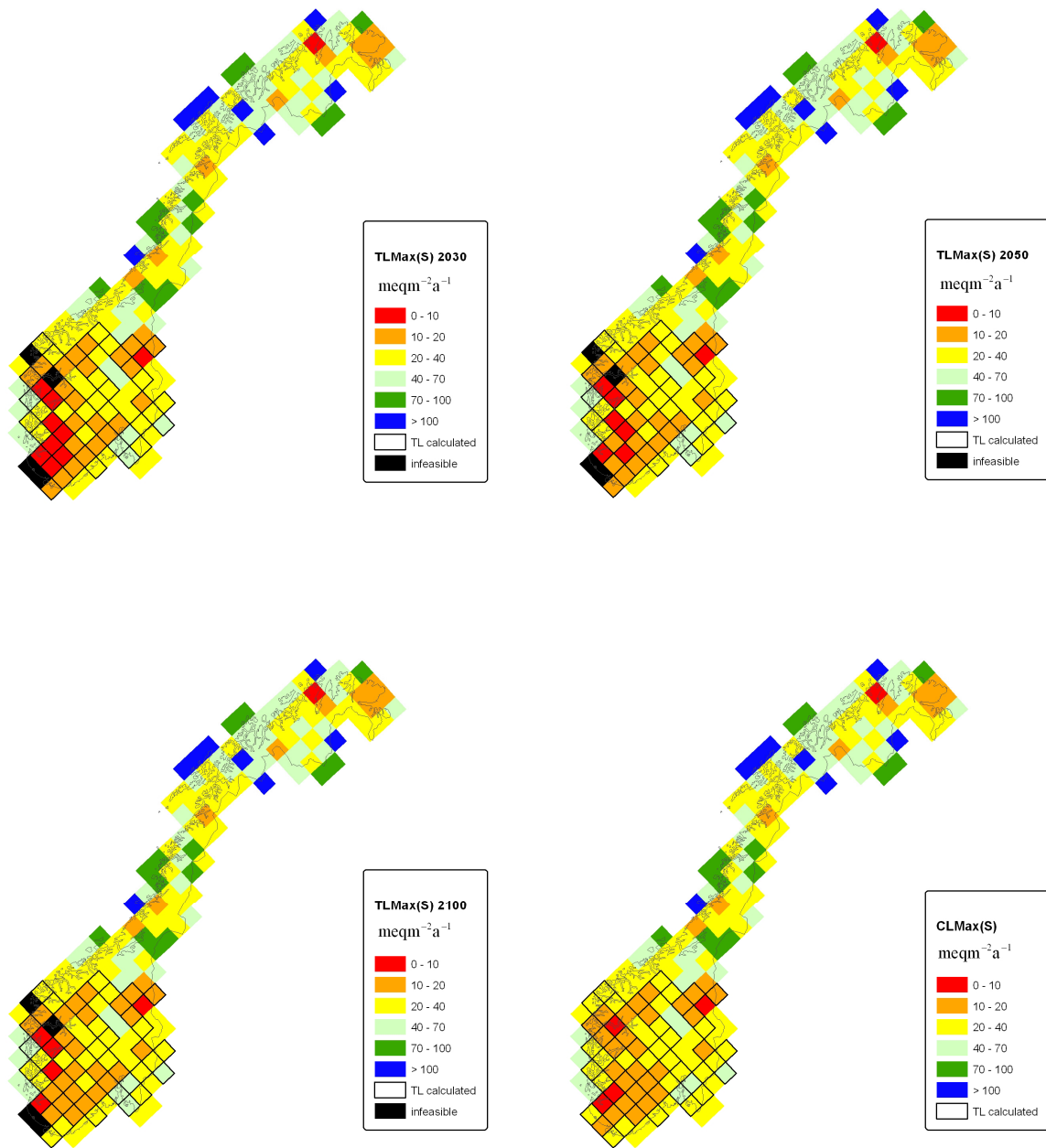


Figure 10. Maps showing the 5<sup>th</sup> percentile of the target loads (TL<sub>max</sub>(S)) or critical loads (CL<sub>max</sub>(S)) for different years on the EMEP grid cell scale. This is the resolution that will be used in a European assessment. Target loads are calculated for grid squares marked with black borders. For the other cells CLs are shown.

## 5. Conclusions

Target load is a logical extension of the critical load concept and incorporates the time delays in the chemical recovery from acidification. Calculations based on data from the Norwegian monitoring lakes and the dynamic acidification model MAGIC show that the increased ANC in Norwegian surface waters observed since 1990 can be expected to continue to increase to 2010 if the planned emission reductions of the Gothenburg protocol and other legislation are implemented. With no further reductions after 2010 the ANC will increase little and only very slowly due to slow build up of base cations in the soils. A scenario assuming deposition reduction to background levels of sulphur and nitrogen show that there remains potential for additional increases in ANC if deposition is reduced beyond the Gothenburg protocol.

Target loads are considerably lower than critical loads for southern Norway, showing that deposition reductions below the critical load are needed if the goal is to restore conditions suitable for sustainable fish populations within a few decades.

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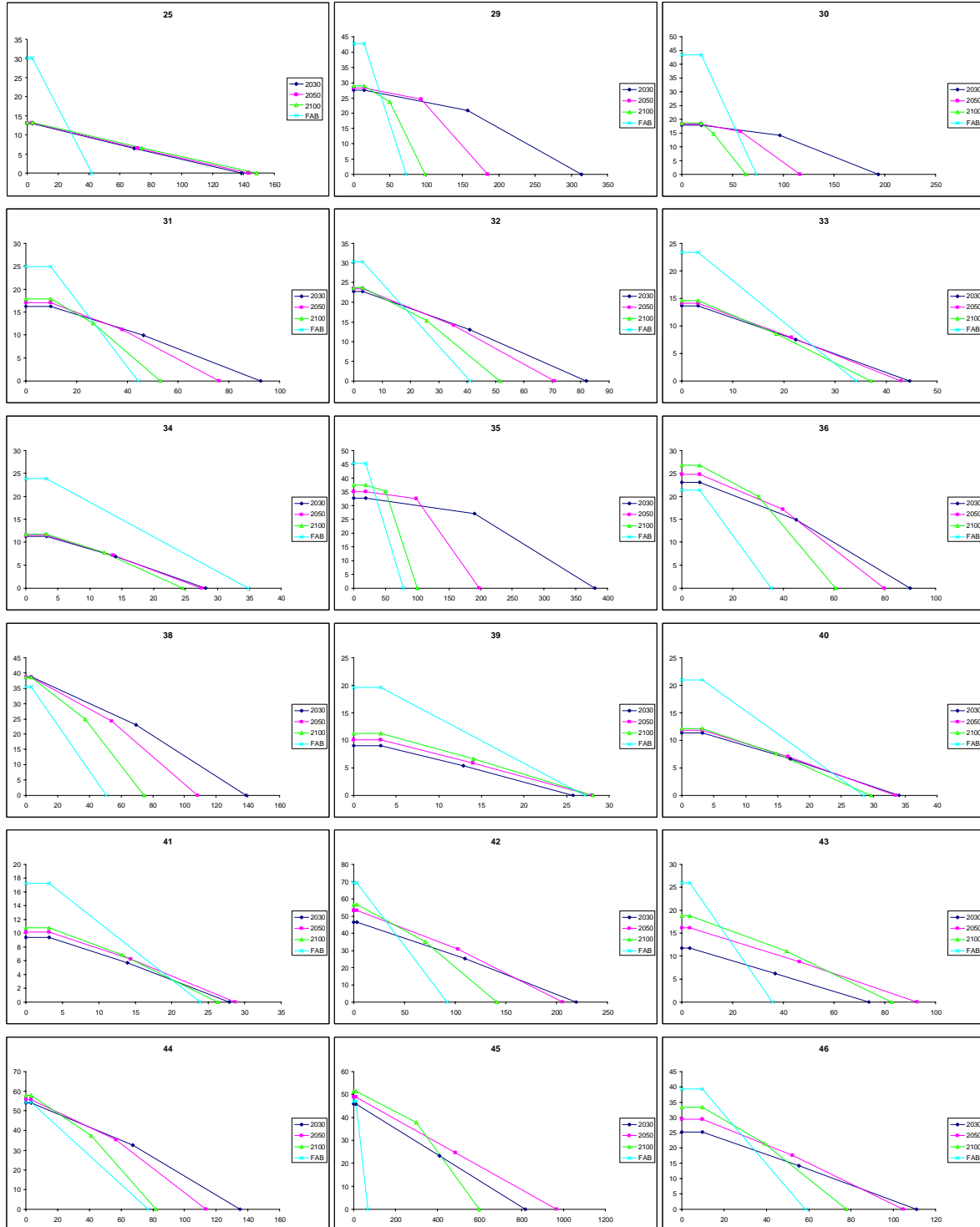
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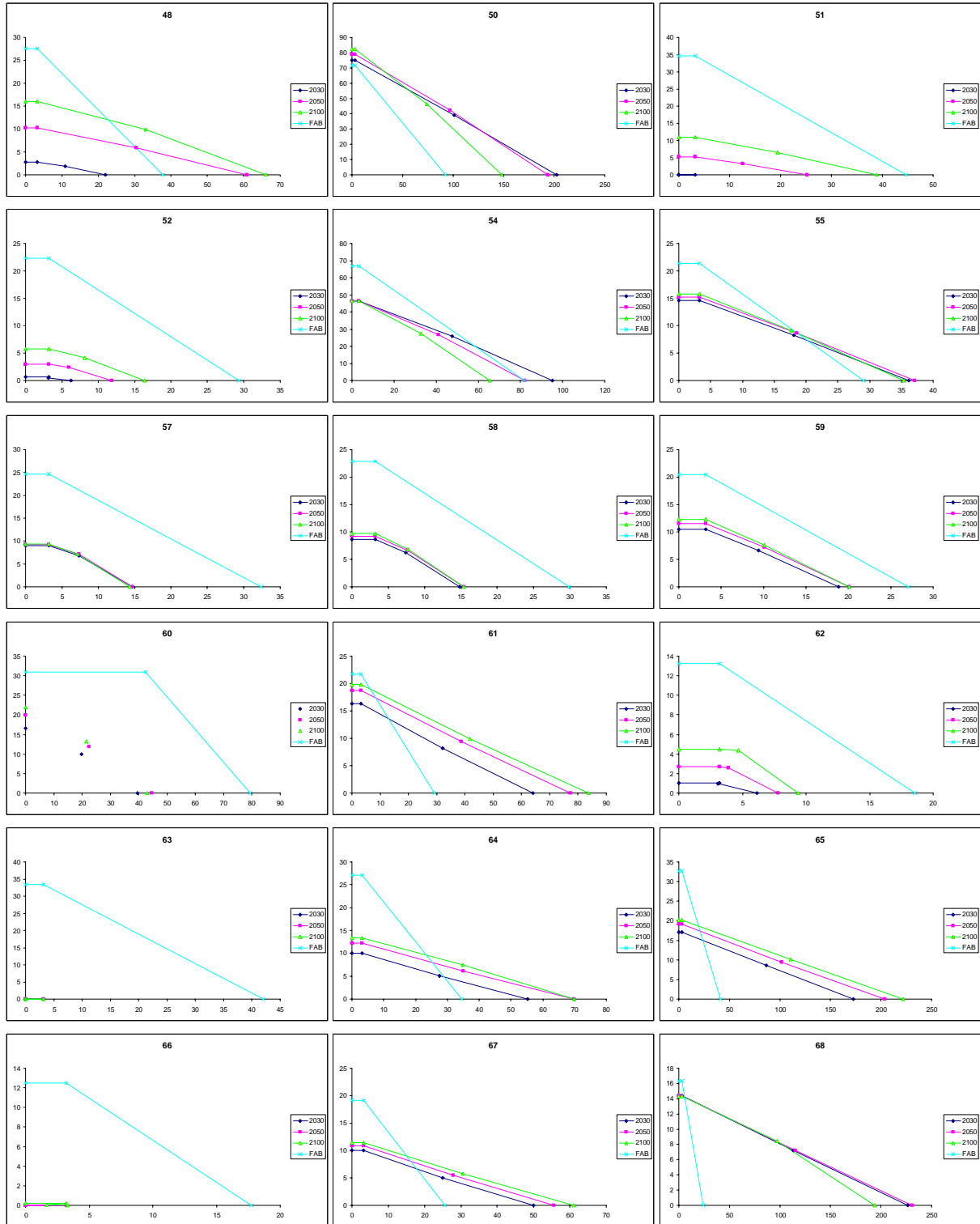
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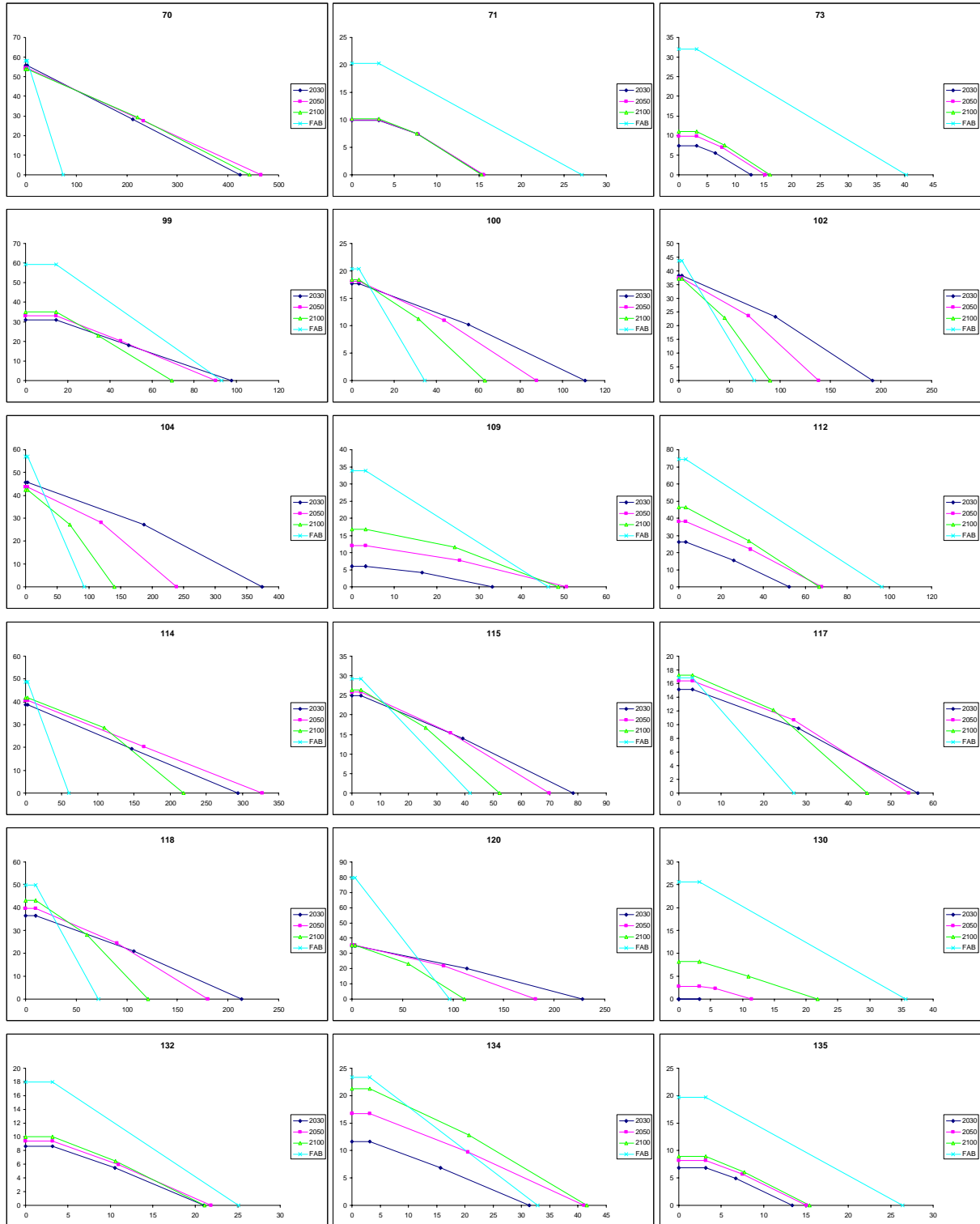
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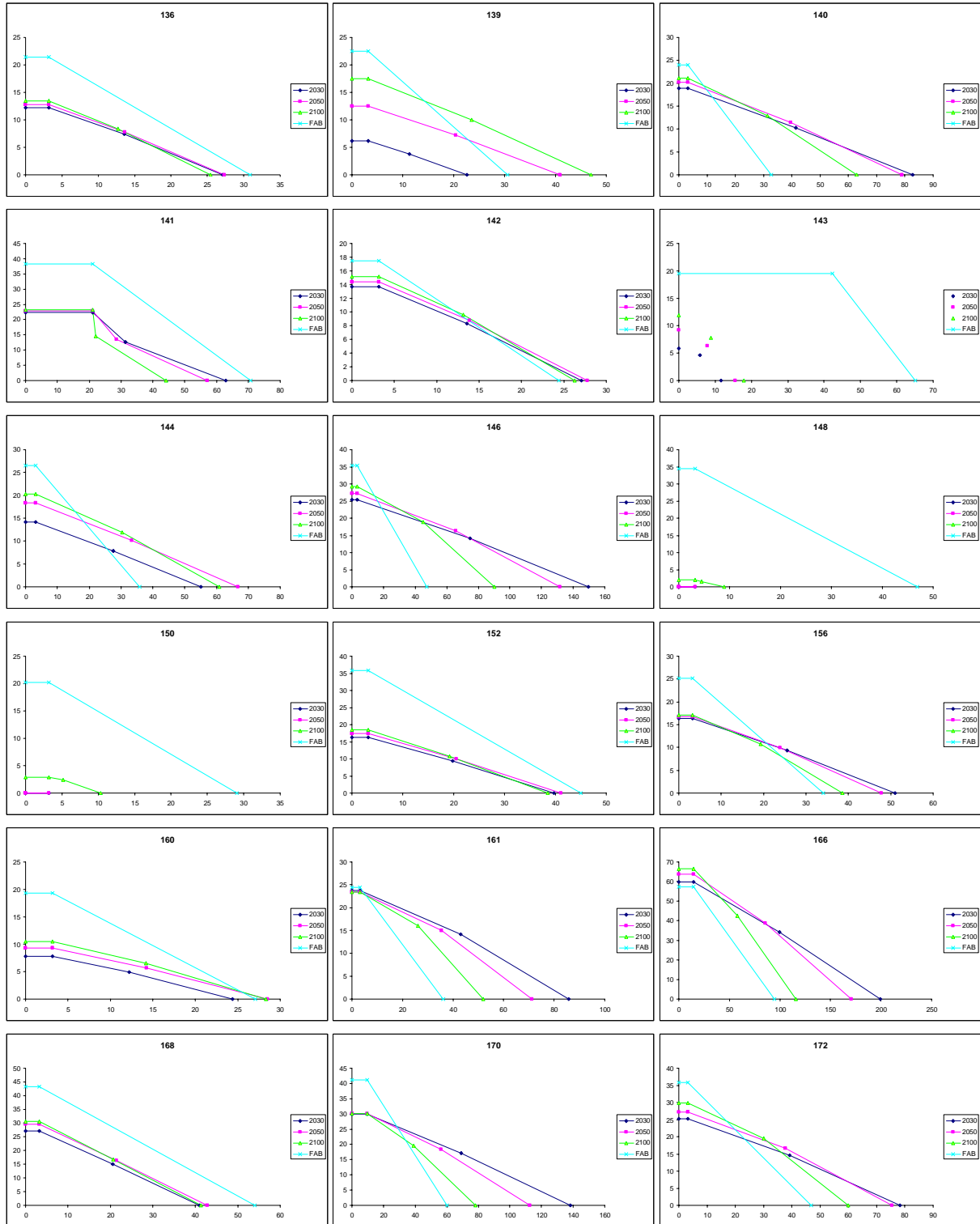
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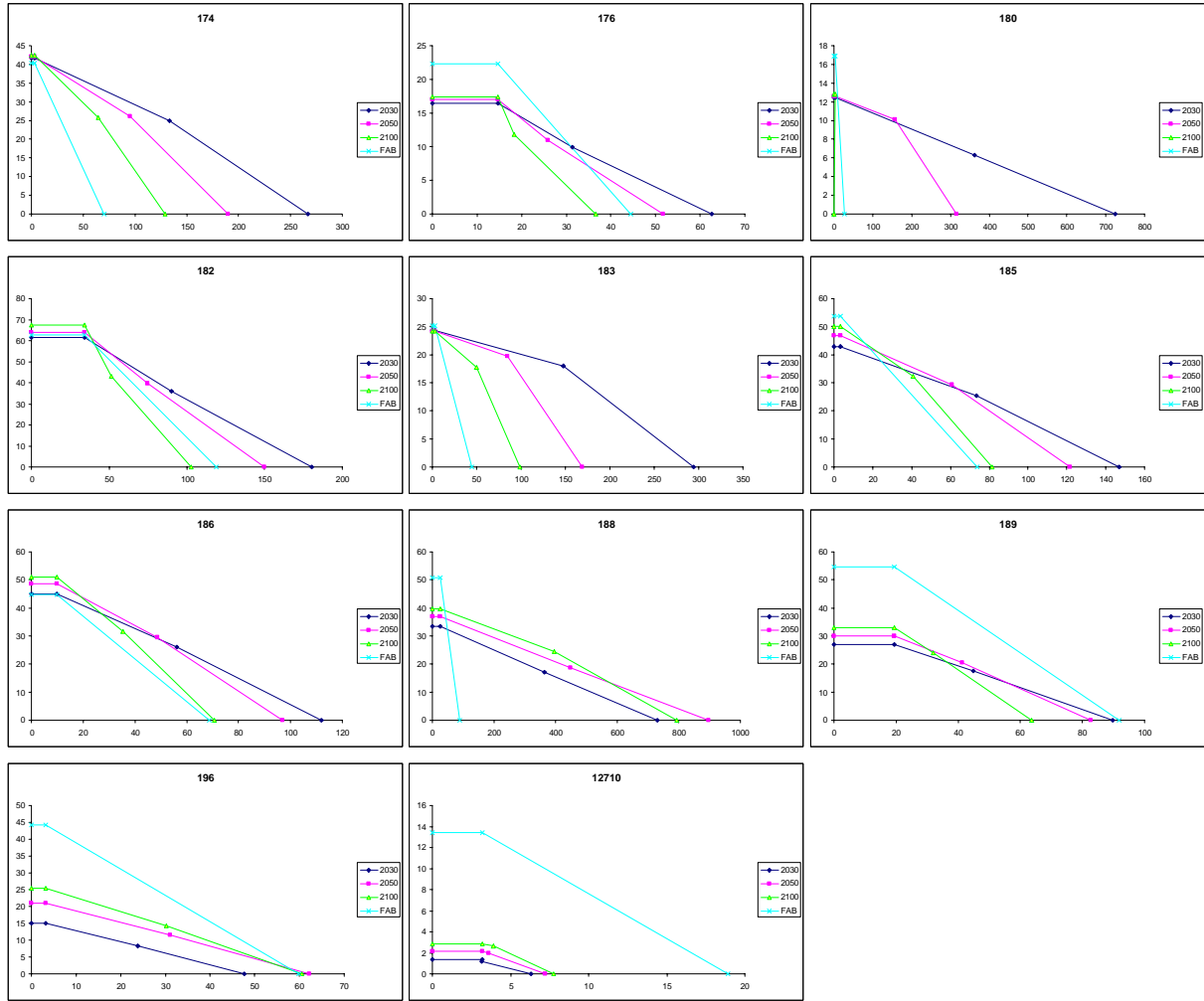
# Appendix A. Figures of individual target load and critical load functions for all modelled lakes













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