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TRANSBOUNDARY AIR POLLUTION**

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**DYNAMIC MODELLING, TARGET LOAD FUNCTIONS AND CRITICAL LOADS
FOR SURFACE WATERS AND ICP WATERS SITES**

Report prepared by the Programme Centre of the International Cooperative Programme on
Assessment and Monitoring of Acidification of Rivers and Lakes (ICP Waters)

INTRODUCTION

1. This study updated the critical load (CL) estimates for sites in the International Cooperative Programme on Assessment and Monitoring of Acidification of Rivers and Lakes (ICP Waters) sites and compared these with the gridded CL data for waters held by the Coordination Centre for Effects (CCE). Data for the period 2000–2002 were used. The study also considered features used in determining target load functions (TLF) for surface waters, as well as sources of uncertainty in CL and TLF.

I. UPDATE OF CRITICAL LOADS FOR ICP WATERS SITES

2. CLs has been an area of work within ICP Waters, as the data collected by the Programme were well suited for calculating CLs using static models. Henriksen and Posch (1998) calculated CLs and exceedances for ICP Waters sites using the static models SSWC (steady-state water chemistry model) and FAB (first-order acidity balance model). They used water chemistry data for the period 1992–1995.

3. More recent data (2000–2002) from the ICP Waters sites have shown that the CL estimates based on them were very similar to those based on the 1992–1995 data (figure 1). For sulphur (S) the points fell very close to the 1:1 line. As was expected, the deviation was largest for the sites with the highest CL ($CL_{\max S}$). These sites had the highest concentrations of ions and thus were most subject to natural variations in concentration due to dilution effects caused by variations in discharge. For nitrogen (N) the points also fell close to the 1:1 line, but in many cases slightly below the line. This was because more conservative values for N uptake (set to zero) were used for the 2000–2002 estimates.

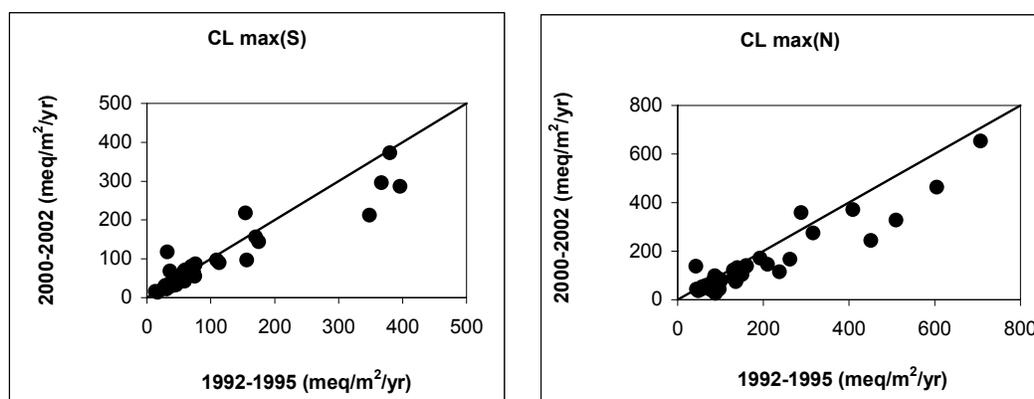


Figure 1. Critical loads for ICP Waters sites calculated using the FAB model and based on data for the periods 1992–1995 (from Henriksen and Posch 1998) and 2000–2002. *Left-hand panel:* maximum CL for sulphur; *right-hand panel:* maximum CL for nitrogen.

II. COMPARISON OF CRITICAL LOADS FOR ICP WATERS SITES WITH GRIDDED DATA FROM THE CCE DATABASE

4. The ICP Waters sites were not specifically included in the gridded data used by CCE in compiling maps for Europe. The CLs for the ICP Waters sites in Europe were close to the 5th-percentile value for the EMEP 50 km × 50 km grid cell in which the sites were located (figure 2). This was the same result found by Henriksen and Posch (1998) for the 1992–1995 data. ICP Waters sites thus generally were at the most sensitive end of the range of waters within each EMEP grid cell. Both the CL estimates for the ICP Waters sites and the 5th-percentile were based on new data. The ICP Waters data were for 2000–2002 and the EMEP grid cell data were

the results for surface waters from the 2005 call for data by CCE. Two sites were exceptions to this general result (see figure 2).

5. Most ICP Waters sites were at the sensitive end of the range within each grid cell. This was expected, as the ICP Waters sites were originally chosen largely to monitor the acidification process. The sites were similarly well suited for following the recovery in response to decreases in S and N deposition.

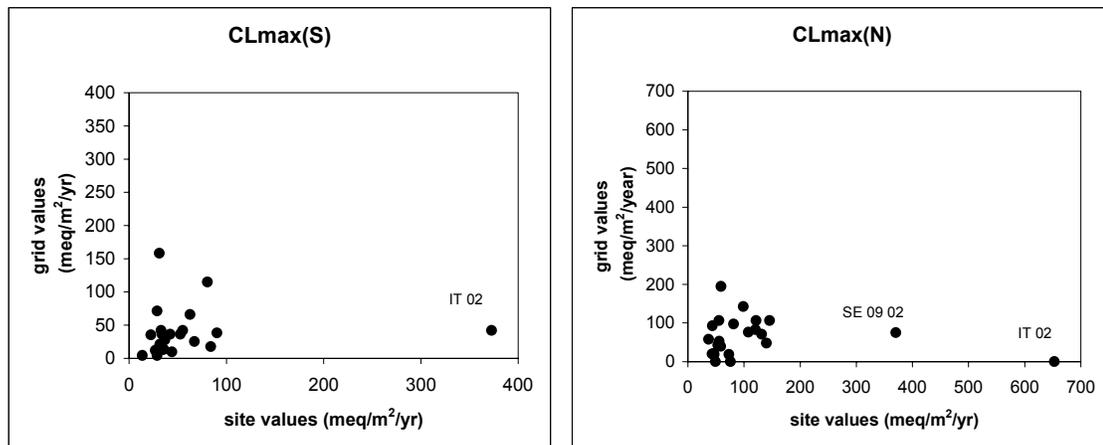


Figure 2. CLs for ICP Waters sites in Europe compared to the 5th-percentile grid values of maximum CL for sulphur (*left-hand panel*) and maximum CL for nitrogen (*right-hand panel*) of CCE.

III. CATCHMENT PROCESSES LEADING TO TIME LAGS

6. Static (steady-state) models were used to calculate CLs, whereas dynamic models were used to calculate target loads (TL). The key difference between these approaches is related to the response times between changes in acid deposition and damage to biota.

A. Time delay: sulphur

7. It has long been recognized that in some ecosystems S is strongly retained in soil. Thus there is a long delay between changes in S deposition and the response of sulphate (SO₄) concentrations in runoff. SO₄ adsorption is the main cause for the delay. The acidification history at White Oak Run in the state of Virginia (United States) well illustrates the time delay caused by SO₄ adsorption. The MAGIC model calibration indicated that S deposition had been above 50 meq/m²/year since about 1920, and yet the stream in 1990 still had acid-neutralizing capacity (ANC) of nearly 20 µeq/l. The high SO₄ adsorption capacity of the soil caused it to retain a large fraction of the incoming SO₄. As the capacity gradually became filled, the concentration of SO₄ in streamwater rose and, during the past 20–30 years, led to the paradoxical situation where SO₄ concentrations showed an increasing trend despite a decreasing trend in SO₄ deposition.

8. In young soils developed on glaciated terrain, SO_4 adsorption is usually small. SO_4 concentrations in surface waters closely follow S deposition, with lag times of only a few years. This was the case in most surface waters in glaciated terrain, as is shown by the trend analyses conducted as part of the ICP Waters work (Skjelkvale 2003) as well as other studies (Evans et al. 2001).

B. Time delay: nitrogen

9. Nitrogen is also strongly retained in terrestrial ecosystems. Usually N deposition (the sum of reduced and oxidized N) greatly exceeds the output of inorganic N (mostly as nitrate (NO_3)) in runoff. Ammonium concentrations in runoff are usually negligible. This situation is clearly not sustainable over the long term, as terrestrial ecosystems have a finite capacity to store N. Terrestrial ecosystems subjected to chronically high levels of N deposition thus begin to leach more NO_3 over time. This condition is conventionally termed “nitrogen saturation”.

10. Birkenes provided an example of a forested catchment, which retained nearly all of incoming N deposition. The 30-year record of deposition and runoff chemistry at Birkenes indicated that the catchment was proceeding very slowly towards N saturation. At Birkenes, a simulation using the MAGIC model suggested that several hundred years of N deposition would be required to reach the FAB steady-state condition in which all incoming N was lost from the catchment.

11. While the response of runoff to increased N deposition might be delayed by many decades, the response to decreased N deposition can be quite rapid. In contrast to the situation for S deposition, N deposition has not decreased dramatically during the past 20 years, and thus there are few good examples of ecosystem response to decreased N deposition. Here the best evidence was from large-scale whole-ecosystem experiments with roofs, such as those conducted as part of the RAIN project at Risdalsheia, Norway (Wright et al. 1993). A dramatic decrease in N deposition resulted in a rapid decrease in NO_3 in runoff.

C. Time delay: base cations

12. Acid deposition causes a long-term slow depletion of base cations from the soil. The increased flux of strong acid anions (SO_4 and NO_3) from soil is accompanied by cations, the acid cations H^+ and Al^{3+} and the base cations Ca, Mg, Na and K. The relative concentrations of these two groups of cations depend largely on the base saturation (BS) of the soil. Soil with high BS release more base cations than soil with low BS.

13. Recovery of soil BS can first begin when the rate of base cation leaching and net uptake in vegetations falls below the rate of base cation supply from deposition and weathering. In acidified catchments, therefore, a moderate decrease in acid deposition might simply slow the

rate of depletion of base cations from the soil, but not reverse the trend. The long-term pattern of soil BS is often asymmetric; the decrease can be rapid (halving the BS within only a few decades), while replenishment following a major decline in acid deposition might require centuries.

IV. TARGET LOAD FUNCTIONS VERSUS CRITICAL LOAD FUNCTIONS

A. Birkenes

14. Birkenes was a typical acidified surface water, which required substantial reduction in acid deposition to allow recovery. At Birkenes the TL for S was below the CL (figure 3). Recovery of the stream's acid-neutralizing capacity (ANC) to the target $0 \mu\text{eq/l}$ would require a larger reduction in S deposition if the target was to be achieved soon (i.e. in the year 2030) rather than later (e.g. in 2090). At very long time scales, the TL for S approaches the steady-state CL.

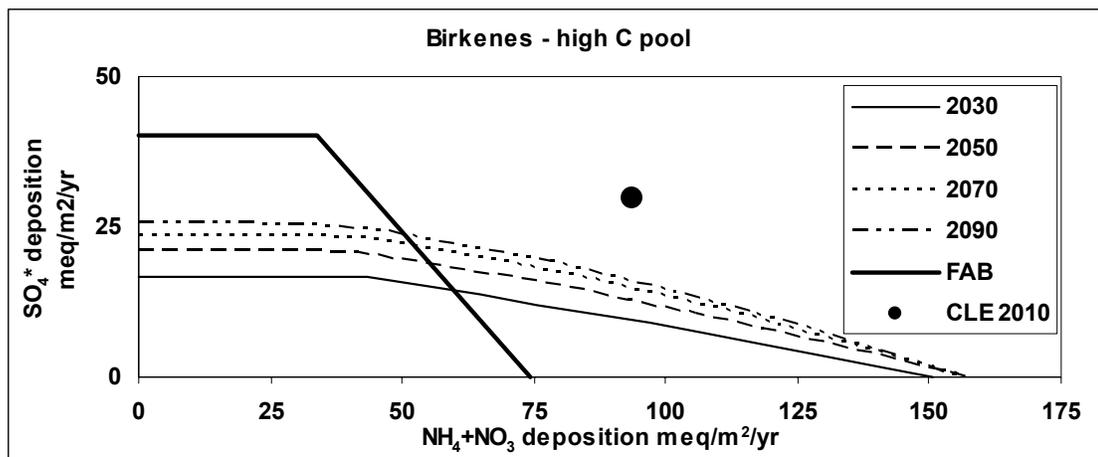


Figure 3. TLFs and critical load functions (CLF) for surface water at Birkenes, Norway. The TLFs were calculated using the MAGIC model. The CLF was calculated using the FAB model. Four TLFs were calculated for achievement of the criterion of $\text{ANC} = 0 \mu\text{eq/l}$ by the years 2030, 2050, 2070 and 2090, respectively. CLE 2010 shows the deposition estimated for the year 2010 assuming full implementation of the current legislation (CLE) scenario.

15. For N the situation was the opposite (figure 3). Over the short term the site could accommodate large amounts of N deposition, as most N was retained in the soil and did not contribute to acidification of runoff. But over the long term, if the concept of N saturation held, the catchment ecosystem would retain less and less of the incoming N and the TL would be lower. Over very long time scales, the TL would approach the steady-state CL. The TL functions thus crossed the CL function ($\text{TL} < \text{CL}$ for S and $\text{TL} > \text{CL}$ for N). The method used by the CCE was based on the precautionary principle, and thus in all cases the minimum of the target load

function and the critical load function was used. In this example the TLF would be used for low values of N deposition, whereas for high values of N deposition the CLF would be used.

B. White Oak Run

16. At White Oak Run the TLF was above the CLF with respect to both S and N (figure 4). In the short term, S deposition could be much larger without causing critically low ANC levels; the TL for S was higher than the CL. Only after nearly 800 years did the TL approach the CL. Again based on the precautionary principle, the minimum of the TLF and CLF would be used. In this case the CLF would be used for all pairs of S and N deposition.

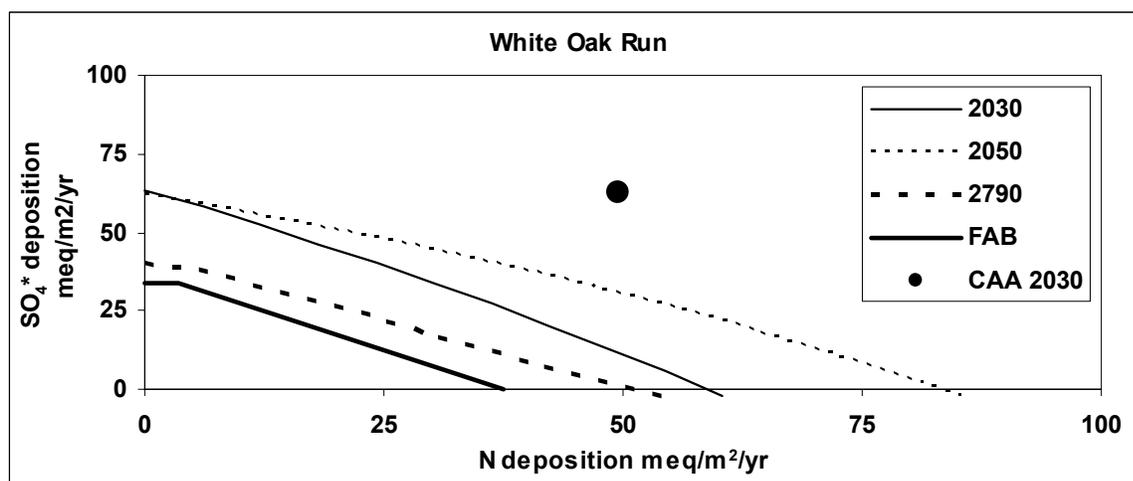


Figure 4. TLFs and CLF for surface water at White Oak Run (Virginia, United States). Three TLFs were calculated using the MAGIC model to achieve the criterion of ANC = 20 µeq/l by the years 2030, 2050 and 2790 (800 years in the future). The CLF was calculated using the FAB model. CAA 2030 shows the deposition expected in year 2030 if the United States Clean Air Act were fully implemented (solid square). The TLFs were calculated assuming implementation of the Clean Air Act by year 2010, and further reductions implemented in 2010.

C. Seasons versus year

17. CLFs and TLFs supplied by the national focal centres to CCE were based on annual data. The calculations used an ANC limit set to protect an indicator organism, such as brown trout. The use of annual values had been adequate in the negotiations of the 1994 Oslo Protocol and the 1999 Gothenburg Protocol, as these protocols were aimed at reducing the deposition of S and N such that exceedance in Europe was minimized. These protocols took a big step towards closing the gap between CL and deposition.

18. As deposition approaches the level of CL and surface waters recover to the point at which indicator organisms can begin to reappear, the seasonal and episodic variations in water quality become increasingly important. Many of the chemical parameters used in the CL and TL calculations showed large annual variation due to such phenomena as snowmelt and high-flow events. The natural biological cycle in the vegetation and soils of the catchment also affects the seasonal pattern in concentrations of many chemical parameters. Nitrate is one of the key parameters that typically has large seasonal variations.

19. The study of Øygardsbekken showed TLFs differ greatly depending upon the month in which the target was to be achieved (figure 5). If the target was to be achieved for the month of September, when NO_3 concentrations were the lowest for the year, the TLF was considerably higher than that of the yearly mean. On the other hand, if the target was to be achieved for March, when NO_3 concentrations peaked, then the TLF was considerably lower (in this case zero which could not be achieved even with zero S and N deposition).

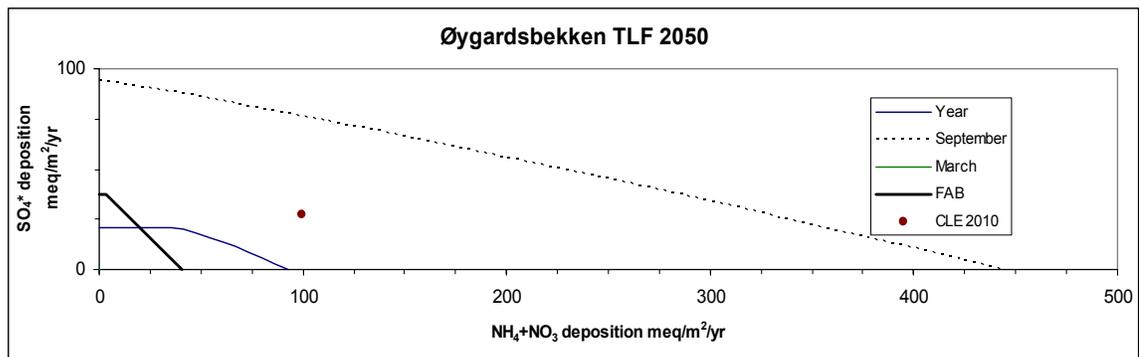


Figure 5. TLFs for the year 2050 and CLF for surface water at Øygardsbekken, Norway, calculated for yearly mean data (solid line), September data (dotted line) and March data (zero, zero; does not appear on the graph). CLF was calculated using the FAB model. CLE 2010 shows the estimated deposition for the year 2010 assuming the CLE scenario.

D. Effects of climate change

20. Climate change is one of several factors that can affect acidification of freshwaters in the future. As a first step in evaluating the potential impact of climate change on the recovery of surface waters from acidification, a series of trials with MAGIC were conducted at 14 sites in Europe and North America (Wright et al. in press). Birkenes (Norway) was one of the sites included. The trials at Birkenes assumed a future increase in temperature, precipitation and storminess. The most important effect was the acceleration of N saturation due to increased mineralization of soil organic matter caused by higher future temperatures.

21. The scenario with future climate change alters the TLF (figure 6). The TL was lower with climate change, and was more pronounced for N than for S.

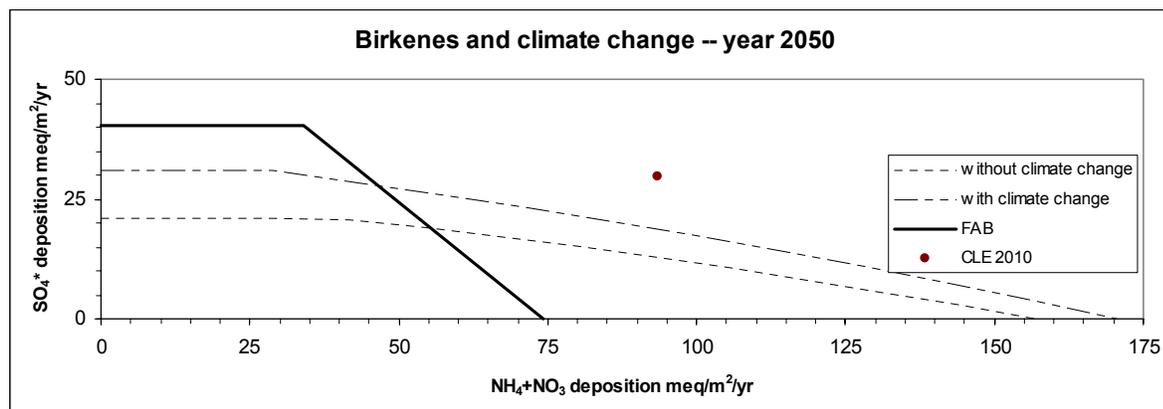


Figure 6. TLFs and CLF for surface water at Birkenes, Norway, for achievement of ANC = 0 $\mu\text{eq/l}$ by the year 2050 assuming present-day climate conditions (without climate change) and given a scenario of future climate change (with climate change). The CLF was calculated using the FAB model. CLE 2010 shows the deposition estimated for the year 2010 assuming that the CLE scenario was fully implemented.

V. CONCLUDING REMARKS

22. The updated CLs for the ICP Waters sites based on 2000–2002 data were very similar to those calculated based on 1992–1995 data. The comparison with the 5th-percentile from the EMEP 50 km \times 50 km grid cells for waters was also very similar. This was reassuring and gave confidence to the robustness of the methods used to calculate CLs and to upscale to the European level. With few exceptions, the ICP Waters sites tested were at the most sensitive end of the scale within each respective grid cell. They were thus well suited for monitoring responses to changes in S and N deposition.

23. Use of dynamic models to set TLs represents a new degree of complexity in the scientific underpinning of work under the Convention. The MAGIC model was used to calculate TLFs for freshwaters in three countries in response to the call for data issued by CCE in 2004. Freshwaters in sensitive regions elsewhere in Europe and North America were modelled, and these applications were used to assess the effects of scenarios for future S and N deposition (Wright et al. 2005).

24. The addition of the time dimension has forced us to face several major uncertainties in the understanding of biogeochemical processes, which affect surface water chemistry. Of these, N retention and loss in catchments continues to be a major unknown factor, despite extensive scientific research on the subject in recent decades. While it is clear that chronic high levels of N deposition cannot be sustained in catchments in the long run, the rate of transition from a high degree of retention (the present-day situation in many catchments) to the steady-state condition

of low retention with no change in pools of N in soil and vegetation (as assumed by the FAB model and in accordance with the precautionary principle) is simply not known in most cases. The records of N deposition and leaching from small catchments from more than 30 years have not yielded a consistent pattern pointing to a progressive N saturation.

25. The large gap between the long-term steady state and the present-day N retention has meant that the TLF has differed from the CLF, especially with respect to N deposition. Catchments that are not currently showing N saturation could receive large N deposition for several decades with little adverse effect on the ANC of surface water.

26. The effects of future climate change on catchments and freshwaters add new levels of complexity to the evaluation of acid deposition scenarios. The research fields of acid deposition and climate change have many areas of overlap. For example, emissions of S gases affect the atmospheric energy balance, and global warming affect the release of NO₃ from soils. Although many of the possible effects of climate change could be simulated by dynamic models such as MAGIC, further development of models is considered necessary. These developments are required in the near future if the full potential of dynamic models is to be realized within the required timescale of the Convention, e.g. the forthcoming review of the 1999 Gothenburg Protocol.

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