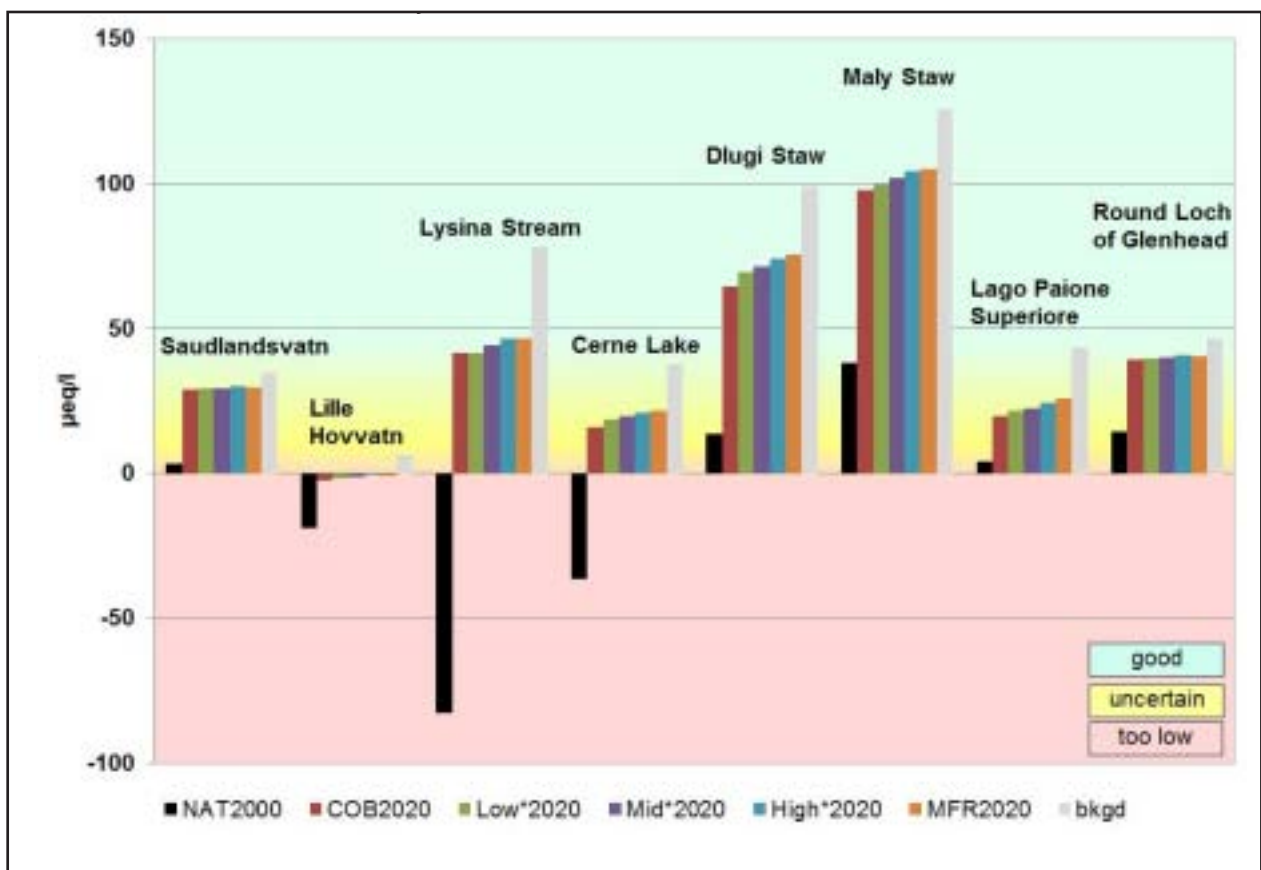**NIVA**

ICP Waters Report 108/2011

Impacts of Air Pollution on Freshwater Acidification under Future Emission Reduction Scenarios; ICP Waters contribution to WGE report

International Cooperative Programme on Assessment and Monitoring Effects of Air Pollution on Rivers and Lakes

Convention on Long-Range Transboundary Air Pollution

LRTAP
Long-range Transboundary Air Pollution

Norwegian Institute for Water Research
– an institute in the Environmental Research Alliance of Norway

REPORT

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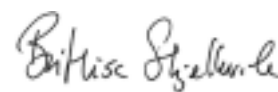| Author(s)	Topic group	Distribution
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Abstract

The UNECE Convention on Long-range Transboundary Air Pollution (LRTAP) is currently working on a revision of the Gothenburg protocol. ICP Waters has used the dynamic model MAGIC to evaluate the effects of future deposition scenarios (COB2020 (current legislation), Low*2020, Mid*2020, High*2020, and MFR2020 (maximum technically feasible reduction) on surface waters. These five deposition scenarios are very similar to one another and represent substantial decreases in deposition for the year 2020 relative to the base year 2000. At all sites the modelled results indicate that chemical recovery will continue into the future. At all but the most acid sensitive sites acid neutralising capacity (ANC) will increase to levels above the critical level for biological damage. Additional improvements in water quality can be obtained in the future with emission reductions beyond MFR2020.

4 keywords, Norwegian	4 keywords, English
1. Sur nedbør	1. Acid rain
2. Dynamisk modellering	2. Dynamic modelling
3. Gøteborgprotokollen	3. Gothenburg Protocol
4.Langtransporterte luftforurensninger	4. Long-range Transboundary Air Pollution

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Impacts of Air Pollution on Freshwater Acidification under Future Emission Reduction Scenarios

ICP Waters contribution to WGE report

Preface

The UNECE Convention on Long-range Transboundary Air Pollution (LRTAP) is currently working on a revision of the Gothenburg protocol. One of the activities involves generating potential future deposition scenarios of S and N for Europe. The Working Group on Effects (WGE) has been asked to evaluate the effects of these future scenarios on forests, waters, vegetation, health and materials. ICP Waters has taken on work with effects on surface waters.

The ICP Waters Programme Centre received the new deposition scenarios from the Coordination Centre for Effects (CCE) 29. August 2011. In addition Max Posch at the CCE kindly provided estimates of background deposition originally generated by EMEP.

In addition to Norway, Czech Republic, Italy, Poland and UK have participated in the work with the scenario analysis.

Thorjørn Larssen has been responsible project manager while Richard F. Wright was responsible for running the MAGIC analyses on the Norwegian sites, and for guiding and discussing results from the participating countries. Espen Lund provided technical assistance with the data, maps and figures.

Oslo, 15 November 2011

Brit Lisa Skjelkvåle
ICP Waters Programme Centre

Contents

Summary

The UNECE Convention on Long-range Transboundary Air Pollution (LRTAP) is currently working on a revision of the Gothenburg protocol. One of the activities involves generating potential future deposition scenarios of S and N for Europe. The Working Group on Effects (WGE) has decided to evaluate the effects of these future scenarios on forests, waters, vegetation, health and materials. ICP Waters has taken on work with effects on surface waters.

In August 2011 the CCE of ICP M&M circulated data for five future scenarios for the year 2020 of S and N deposition to be evaluated (ex-post analysis). In order of reduction these are COB2020 (current legislation), Low*2020, Mid*2020, High*2020, and MFR2020 (maximum technically feasible reduction). The "low" and "high" refer to level of ambition in emission reductions. The CCE asked the various ICPs to evaluate these. We also ran a future scenario with only background deposition, to illustrate the maximum improvement in water quality that could be achieved by emission reductions.

Here we report the evaluation of these five scenarios for eight acid-sensitive freshwater sites in Europe, two in southern Norway, two in the Czech Republic, two in Poland, and one each in Italy and the UK. These waters are included in the ICP Waters monitoring programme for acidification. Chemical and biological parameters are measured. Measurements began in the 1970s or 1980s.

We use the dynamic acidification model MAGIC version 777 to simulate future lake water chemistry under the five scenarios. MAGIC has been used extensively to evaluate acidification and recovery.

The five scenarios for deposition are very similar to one another, and the modelled future ANC levels are very similar among the various scenarios. All represent substantial decreases in deposition for the year 2020 relative to the new base year 2000. At all sites the modelled results indicate that chemical recovery will continue into the future. At all but the most acid sensitive sites (such as Lake Lille Hovvatn, Norway) acid neutralising capacity (ANC) will increase to levels above the critical level for biological damage.

The greatest reductions in deposition are given by the maximum feasible reduction scenario (MFR2020). This is still substantially above the natural background levels of deposition. Additional improvements in water quality can be obtained in the future with emission reductions beyond those envisioned under MFR2020.

Sammendrag

UNECE-LRTAP jobber for tiden med en revisjon av Gøteborgprotokollen. En av aktivitetene er å vurdere ulike scenarier for framtidig utslipp og avsetning av S og N for Europa. The Working Group on Effects (WGE) har besluttet å vurdere virkningene av fem utslippsscenarier på skog, vann, vegetasjon, helse og materialer (ex-post analyse). ICP Waters har tatt på seg arbeidet med effekter på overflatevann.

I august 2011 sendte CCE ut data for fem fremtidige scenarier for S og N avsetning som ICPene skulle vurdere. Ordnet etter strenghetsgrad er disse COB2020 (current legislation), Low*2020, Mid*2020, High*2020 og MFR2020 (maksimum teknisk mulig reduksjon). Programsenteret for ICP Waters har vurdert disse fem scenariene for 8 forsuringssensitive ferskvannslokaliteter i Norge, Tsjekkia, Polen, Italia, og UK. Resultatene vil inngå i en felles rapport fra WGE, som en leveranse fra ICP Waters programmet til WGE.

Vi har brukt den dynamiske forsuringsmodellen MAGIC (Cosby et al. 1985a, Cosby et al. 1985b, Cosby et al. 2001) for å simulere fremtidige vannkjemi i de 8 lokalitetene under de fem gitte deposisjonsscenariene.

Den fem utslippsscenariene er alle relativt like og fremtidig modellert ANC har derfor kun små forskjeller. Alle scenariene gir betydelige utslippsreduksjoner fra 2000 til 2020 betydelige økninger i ANC. Modellresultatene viser at alle lokalitetene vil få fortsatt økt ANC i framtiden. Prediksjonene viser at alle lokalitetene, bortsatt den mest forsuringsfølsomme (Lille Hovvatn), vil få ANC verdier som er høyere enn den kritiske grenseverdien for biologiske effekter.

De største reduksjonene i nedfall oppnås ved scenariet MFR2020. Dette scenariet er fortsatt betydelig høyere enn den naturlige bakgrunnsavsetningen. Ytterlig forbedring av vannkvaliteten kan derfor oppnås i fremtiden med utslippsreduksjoner som er større enn det som ligger i MFR2020.

1. Background

The UNECE Convention on Long-Range Transboundary Pollutants (LRTAP) is currently working on a revision of the Gothenburg protocol. One of the activities involves generating potential future deposition scenarios of S and N for Europe. The Working Group on Effects (WGE) has decided to evaluate the effects of these future scenarios on forests, waters, vegetation, health and materials. ICP Waters has taken on work with effects on surface waters.

In August 2011 the Coordination centre for Effects (CCE) of ICP Modelling and Mapping (ICPM&M) issued data for five future scenarios for the year 2020 of S and N deposition to be evaluated (ex-post analysis). In order of reduction these are
- COB2020 (current legislation),
- Low*2020,
- Mid*2020,
- High*2020, and
- MFR2020 (maximum technically feasible reduction).

The "low" and "high" refer to level of ambition in emission reductions. The CCE asked the various ICPs under the Working Group on Effects (WGE) to evaluate these. We also ran a future scenario with only background deposition, to illustrate the maximum improvement in water quality that could be achieved by emission reductions.

Here we report the evaluation of these five scenarios for eight acid-sensitive freshwater sites in Europe, two in southern Norway, two in the Czech Republic, two in Poland, and one each in Italy and the UK. These waters are included in the ICP Waters monitoring programme for acidification. Chemical and biological parameters are measured. Measurements began in the 1970s or 1980s.

We use the dynamic acidification model MAGIC version 777 (Model for Acidification of Groundwater In Catchments) (Cosby et al. 1985a, Cosby et al. 1985b, Cosby et al. 2001)to simulate future lake water chemistry under the five scenarios. MAGIC has been used extensively to evaluate acidification and recovery. MAGIC was used to calculate target loads for Norwegian lakes in response to the CCE 2006 call for data(Larssen et al. 2005), and to calculate future water chemistry given 14 future deposition scenarios in response to the CCE 2008 call for data (Larssen et al. 2008).

2. Sites

Eight sites were chosen for this study. These come from acid-sensitive areas around Europe. All have been acidified by acid deposition and are in the process of recovery in response to declines in acid deposition during the past 20 years.

Table 1. *Locations of 8 freshwater sites used in assessment of emission reduction scenarios.*

SITE	COUNTRY	LAT	LONG	EMEPi	EMEPj	REFERENCE
Saudlandsvatn	NO	58.20	6.77	50	57	(Hesthagen et al. 2011)
Lille Hovvatn	NO	58.60	8.02	51	59	(Hindar and Wright 2005)
Cerne Lake	CZ	48.97	13.50	71	48	(Vrba et al. 2003)
Lysina Stream	CZ	50.05	12.67	69	49	(Hruska and Kram 2003)
Maly Staw	PL	50.75	15.70	71	53	(Rzychon and Worsztynowicz 2008)
Długi Staw	PL	49.23	20.01	78	56	(Rzychoń et al. 2010)
Lago Paione Superiore	IT	46.17	8.19	70	37	(Rogora 2004)
Round Loch of Glenhead	UK	55.08	-4.42	43	44	(Kernan et al. 2010)

Figure 1. *Map of Europe showing location of the 8 ICP Waters sites used with the MAGIC model for assessment of the scenarios.*

2.1 Lake Saudlandsvatn, Norway

Lake Saudlandsvatn is located in Vest-Agder County, southernmost Norway, about 15 km from the coast (58° 12' 12" N, 6° 46' 30" E). The lake is 106 m above sea level, has surface area of 15 ha, catchment area of 4.5 km^2, and a mean and maximum depth of 6 and 30 m, respectively. Brown trout is the only species of fish present, and no stockings or liming has been carried out.

Lake Saudlandsvatn in southernmost Norway was highly acidified with pH < 5.0 in the 1970s, and sulphur (S) deposition five times greater than the critical load (Figure 5)(Hesthagen et al. 2011). The lake sustained a good brown trout (*Salmo trutta*) population until early 1980s, but then it started to decline and nearly went extinct ten years later. During the 1980s, the acid sensitive caddis fly *Hydropsyche siltalai* disappeared from the lake tributaries. Chemical recovery following reduced deposition of S became evident in the late 1990s, when pH increased to between 5.5 and 6.0. By 2000, S deposition had decreased to the critical load. Acid neutralising capacity (ANC) increased to above the critical limit for brown trout of 9 μeq L^{-1} for the first time in 2001. *H. siltalai* reappeared in 1996, and increased highly in abundance from 2000 and onwards. The zooplankter *Daphnia longispina* reappeared in 2000-2002, and since 2003 a marked recovery of the brown trout population also occurred (Hesthagen et al. 2011).

2.2 Lake Lille Hovvatn, Norway

Lake Lille Hovvatn (58° 36' 05" N, 8° 01' 05" E) is situated at 494 m elevation in Birkenes municipality, Aust-Agder County in southern Norway. The lake has surface area of 19 ha, catchment area of 0.75 km^2, and a mean and maximum depth of 4 and 20 m, respectively. The catchment is characterised by thin organic-rich and podsolic soils on massive gneissic-granitic bedrock with much exposed bedrock surface and smaller bog areas. Vegetation is a sparse unproductive mixed forest.

The earliest water chemistry measurements at the neighbouring Lake Store Hovvatn date from 1961 and indicated that the lake was already severely acidified (pH 4.6–5.1). Lake Store Hovvatn was the most acidic lake in the 1974 national survey of lakes in Norway (Wright and Henriksen 1978). Beginning in 1980 Lake Store Hovvatn has been used for extensive research on mitigation by liming and restocking of fish. Lake Lille Hovvatn has served as untreated reference. Regular monitoring of Lake Lille Hovvatn began in 1980; the two lakes have nearly identical water chemistry. Since 1995 the lake has been included in the Norwegian national monitoring programme for long-range air pollutants, and results reported annually (SFT 2009). The data show that chemical recovery began in the early 1980s and has resulted in sharp decrease of SO$_4$ concentrations accompanied by increases in pH and ANC and decreases in labile aluminium. By the year 2003 ANC was close to zero, and pH reached about 4.8 (Hindar and Wright 2005).

Anecdotal information on the fish in Lake Store Hovvatn suggests that the native population of lake-spawning brown trout began to experience reproductive failure already in the 1920s. Repeated attempts to re-introduce the fish stock failed in the 1940s. Paleolimnological data indicate acidification-induced changes occurred in the 1920s. By the year 2003 the recovery of water chemistry at Lake Lille Hovvatn may have reached levels at which survival of adult fish is possible. But conditions are still insufficient for reproduction, however, as egg survival at pH close to 5.0 is unlikely (Barlaup et al. 1998).

2.3 Lysina, Czech Republic

The Lysina catchment (stream water site) is located in the large spruce forest on the unglaciated plateau of the Slavkov Forest in western Czech Republic (Figure 2, Table 1). The catchment has been monitored since 1989 and 1990 for runoff (stream water) and deposition (bulk and throughfall),

respectively. The chronically acidic stream at Lysina experienced marked declines of sulphate (SO_4), nitrate (NO_3), calcium (Ca) and magnesium (Mg) concentrations in the 1990s (Hruska and Kram 2003).

2.4 Cerne Lake, Czech Republic

Cerne Lake is a small forest lake located at 1008 m a.s.l. in the Bohemian Forest, southwestern Czech Republic. The lake is nutrient-poor and acidified. The catchment is mostly spruce forest. It has been monitored since 1984 (Vrba et al. 2003). It was severely acidified in the 1980s and has since shown dramatic recovery in both chemistry and biology, driven by the large declines in sulphate and nitrogen deposition.

2.5 Dlugi Staw, Poland

Dlugi Staw is an ultraoligotrophic lake located in the Tatra Mountains of southern Poland. It has extremely low biomass of phytoplankton. Zooplankton is absent in the open water. The lake is barren of fish despite stocking with although brook trout in 1960. Biological investigations in Dlugi Staw have been carried out as part of several EU Projects: AL:PE 2, MOLAR and EMERGE. Diatom communities in Dlugi Staw indicated a slightly acidic environment (Kawecka and Galas 2003). Oligochaeta and Chironomidae dominate the zoobenthos community (Kownacki et al. 2000). The present biota of the lake tolerates episodic changes in pH. Historical data are sparse and make reconstruction of the acidification history difficult (Kownacki et al. 2000). Acidification changes in the past is confirmed by paleolimnological data from lake sediments (Gasiorowski and Sienkiewicz 2010) and from other lakes in the Slovak part of the Tatra Mountains (Stuchlík et al. 2002). These data show the changes in species composition during the late 1970s; organisms more sensitive to acidification were replaced by more tolerant ones.

2.6 Maly Staw, Poland

Maly Staw is an oligotrophic, acidified lake located in the Karkonosze Mountains, southwestern Poland. This area is part of the "The Black Triangle", encompassing the border area of Poland, the Czech Republic and Germany. Air pollution in the region reached a maximum in the early 1980s, due mainly to the operation of brown coal power plants. Maly Staw is one of two Polish lakes included in the ICP Waters Programme. Regular monitoring of this lake was initiated in the 2004 and carried out (except for a break 2007-2008) until now. Samples of lake outflow are collected bimonthly. The lake was previously sampled in 1994 and 1995. Deposition data was obtained from National Deposition Monitoring.

2.7 Lago Paione Superiore, Italy

Lake Paione Superiore (LPS), Italy, is a high-altitude lake located in the Central Alps, at 2269 m a.s.l. The lake underwent acidification in the 1970s due to high deposition of S and N compounds in the area, located North of the main emission sources in Northern Italy (Mosello et al. 1999).

Effects of acidification were evident on both the lake flora and fauna: benthic diatoms assemblage was shifted towards acidophilous species, and zooplankton lost the dominant species, *Arctodiaptomus alpinus*. Paleolimnological studies outlined that lake acidification paralleled the increasing input of long-range transported industrial pollutants, traced by spherical carbonaceous particles(Marchetto et al. 1994, Guilizzoni et al. 1996). In the last 20-25 years, decrease in acid load from the atmosphere led to an improvement in lake water quality, with an increase in both pH and alkalinity(Mosello et al.

1999). First signs of biological recovery were identified, such as change in diatom flora and appearance of sensitive species among benthic insects (Marchetto et al. 2004). Climate change and episodic deposition of Saharan dust were also important driving factors controlling lake water chemistry(Rogora et al. 2003).

LPS is one of the Italian sites included in the ICP Waters Programme. Chemical data are regularly collected at this site since the late 70s, with a varying sampling frequency; since 2000, one or two samples per year have been collected in late summer/autumn. Lake is usually sampled at the deepest point. As no stable thermal stratification is detected, mean values using a weighted average based on the water volume at different depths are calculated (Marchetto et al., 2004). Biological data were gathered in the framework of EU-funded projects on mountain lakes, but they were not collected regularly and do not cover the most recent period (since 2000 onward).

LPS experienced an acidification/recovery pattern starting from the 1970s. Monitoring of chemical data started in 1978 with a varying sampling frequency from year to year. Due to changes in the analytical methods, only data since 1984 are considered for long-term trends. pH and alkalinity of the lake decreased to 5.3 and to negative values respectively in the 1980s; then a recovery begun in the 1990s, as a response to decreasing deposition of acidifying compounds (Mosello et al. 1999). The long-term trends of both H+ and sulphate deposition at the sampling site of Domodossola, located in the same area f LPS, show an evident decrease since the 1980s.Beside the increase in pH and alkalinity, a further evidence of the recovery from acidification in LPS can be found in the trend of aluminium (Al) concentrations: despite marked seasonal fluctuations, Al content in lake water decreased from 60-70 µg l-1 in the 1980s to 15-20 µg l-1 in recent years (Marchetto et al. 2004).

As to biological data, zoobenthos in LPS has been studied from 1991 to 2000. A total of 51 taxa were found in the lake-shore community. 26 out of 51 taxa were Chironomids, the most ubiquitous and the most abundant insect group in high altitude lakes (Marchetto et al. 2004). The most recent data available (2000) suggest that species richness is still poor in LPS, mainly due to physio-chemical conditions that restrict animal survivorship to a few species highly adapted to extreme environments (Marchetto et al. 2004).

In LPS, diatom assemblages in the late 1980s were typical of a clearwater, oligotrophic, acid lake. The diatoms found in 2000 were still dominated by the same *Achnanthes* (15%) and *Pinnularia* (8%) species, but alkaliphilous species such as *Aulacoseira valida* (11%) and *Achnanthidium minutissimum* (11%) were also present, testifying the response of the diatom community to the improving chemical conditions of the lake (Marchetto et al. 2004).

2.8 Round Loch of Glenhead, UK

The Round Loch of Glenhead lies at 298 m.a.s.l. in the Galloway region of south-west Scotland (NX 450804) and drains a catchment of 90 ha. The catchment lies on the Loch Doon granite intrusion and the rocks include tonalite and those of a tonalite/granite transition. Soils are dominated by deep peat and peaty podsols, with skeletal soils and bare rock characterising the steepest slopes. The catchment is characterised by moorland vegetation, dominated by Molinia, Erica, Pteridium and Trichophorum and includes other species commonly associated with upland blanket mires such as Calluna, Nardus and Potentilla. The catchment lies in an area of high rainfall (c. 2300 mm). The loch is naturally acidic but suffered further acidification as a result of acid deposition from the mid-nineteenth century through to the 1980s. A slight increase in pH has occurred since then to its current value of about 5.1. Trout fry densities appear to show an increasing trend between 1997 and 2006. However, parr densities appeared to increase until ca. 1995 after which numbers have declined, with reaches sometimes recording no parr (Kernan et al. 2010).

3. Deposition scenarios

We have used the "grid average" deposition values throughout this study. The deposition scenarios specified in 2011 by the CCE include new values for the year 2000, i.e. "historical" deposition (termed NAT2000). These values differ from those given by the CCE in the 2008 call for data, and these in turn differed from the historical deposition values supplied by IIASA and published by (Schöpp et al. 2003) (*Figure 2*). No values are given for the year 2010, despite the fact that this is the year for full implementation of the Gothenburg protocol. We thus assumed linear reduction from the year 2000 to full implementation year 2020 and constant thereafter. For the year 2020 the new scenarios suggest significantly lower S* deposition than the old CLE (current legislation) scenario.

We chose to normalise the new scenario data to the year 2000 data supplied by the CCE 2007/8. The five scenarios were thus scaled relative to the values for 2000 CCE 2007/8. This means that the reconstruction of acidification history at the various sites is not affected. The acidification of soil and water and the recovery at any given time is a function of the total cumulative acid deposition at the site.

The five scenarios for the year 2020 all indicate large reductions in S and N deposition from year 2000 to year 2020, but they differ very little from one another (*Figure 3*). An interesting curiosity is that for two EMEP grid squares (50-57 Norway and 43-44 UK) the deposition values for maximum feasible reduction for NOx are actually larger than those for the High*2020 scenario.
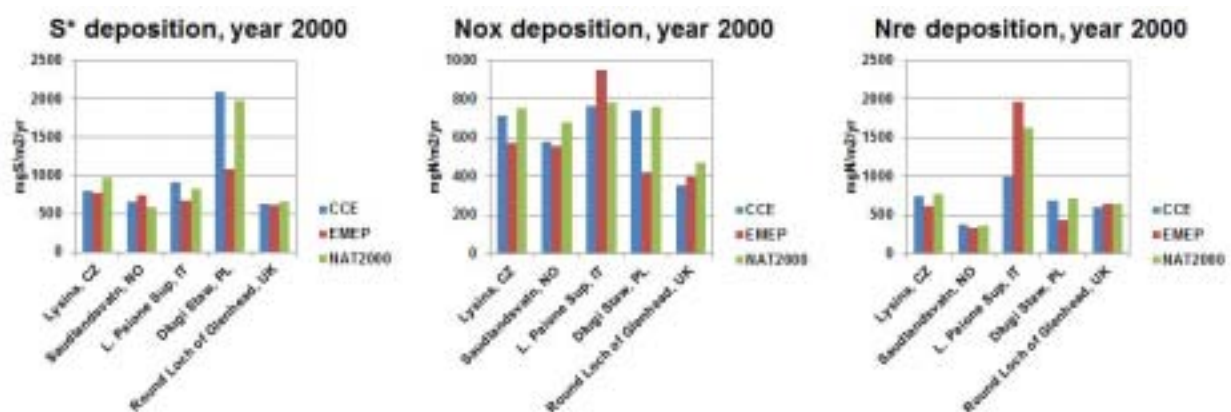

Figure 2. Total deposition in the year 2000 of non-marine sulphur (S), oxidised nitrogen (Nox), and reduced nitrogen (Nre) at five sites in Europe. Shown are grid-average values for the 50X50 km EMEP grid squares in which each of the sites lies. Modelled deposition data for the year 2000 were supplied by the CCE in the 2007/8 call for data (CCE), obtained from the EMEP website[1] (EMEP), and supplied in August 2011 from the CCE for this scenario analysis (NAT2000).*

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[1] *http://webdab.emep.int/Unified_Model_Results/ Specifying in the search: 2000 (met 2008) rep 2010.*
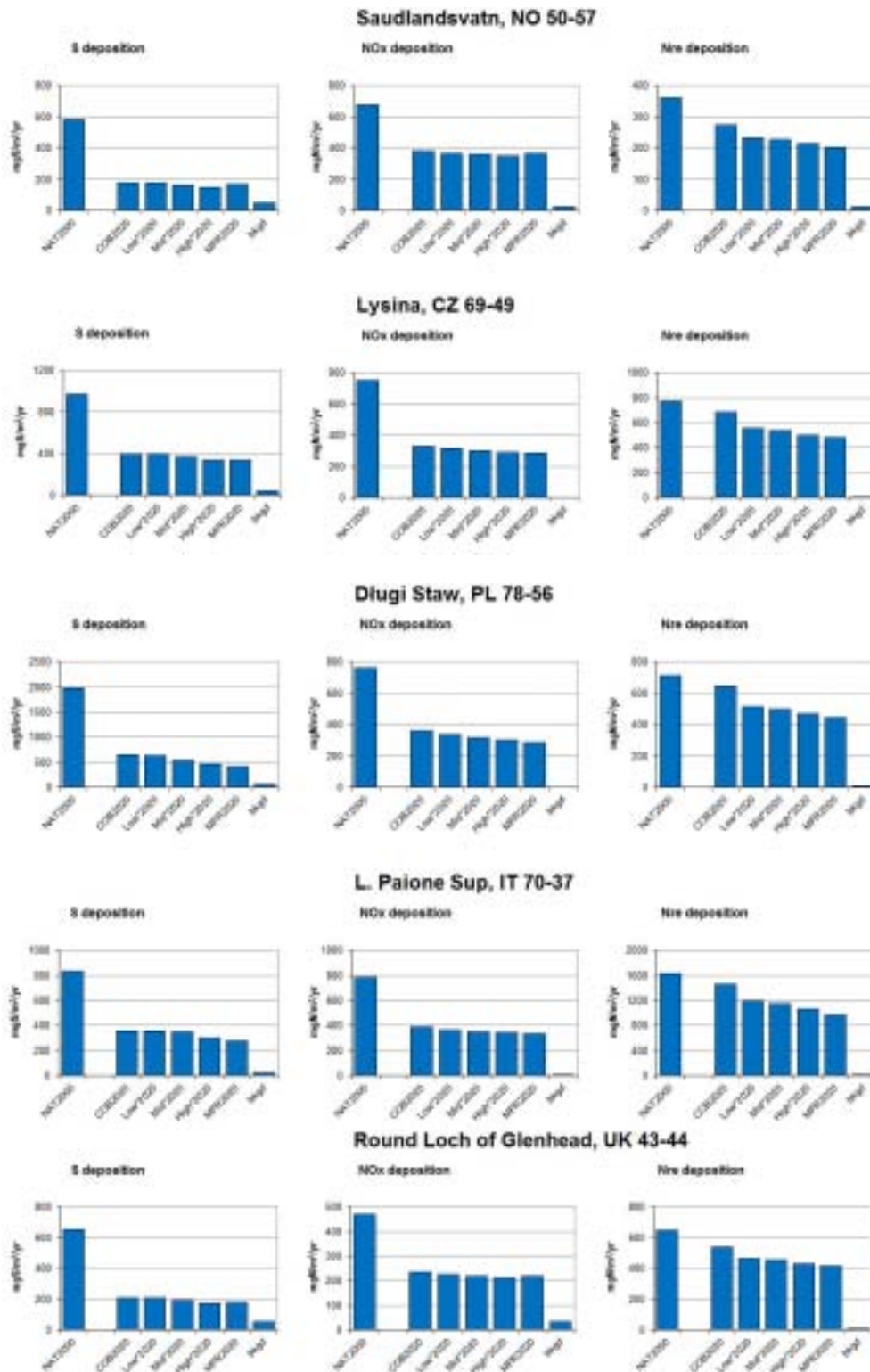
Figure 3. *Deposition scenarios for non-marine sulphur (S), oxidised nitrogen (Nox) and reduced nitrogen (Nre) for the 6 EMEP grid squares (i-j) in which the 8 freshwater sites are located. Shown are values for the year 2000 (COB2020) (left-most column), values for the 5 scenarios for the year 2020, and values for "background" (right-most column).*

4. Results

ICP Waters assessed the effects of the ex-post scenarios by means of the dynamic biogeochemical model MAGIC (Cosby et al. 1985a, Cosby et al. 1985b, Cosby et al. 2001) . MAGIC has been extensively used to assess soil and water acidification, including a major assessment of the implementation of the Gothenburg protocol (CLE scenario) (Wright et al. 2005). MAGIC provides an estimate of surface water acidification status (as indicated by the acid neutralising capacity ANC) in response to a given scenario of S and N deposition over time.

The resulting estimates of ANC were then used to evaluate biological response. There are robust dose-response relationships between ANC and key indicators of ecosystem damage, such as viable population of fish (brown trout, salmon), biodiversity of groups such as diatoms, invertebrates, and aquatic plants. These indicator organisms have been used to set critical limits (ANClimit), which in turn have been used to determine critical loads of acidity (CLA) (Henriksen and Posch 2001).

4.1 Example: Saudlandsvatn, Norway

Lake Saudlandsvatn, southern Norway, provides a 35-year record that illustrates the rise and fall of acid deposition, acidification of water, and damage and recovery to key biota (Hesthagen et al. 2011).

At the start of the monitoring in 1974 the non-marine S deposition (S*) greatly exceeded the critical load for acidity (CLA) and the lake was acidified with negative ANC (far below the ANC_{limit}) and low pH. Short-lived biological acid-sensitive indicator organisms (invertebrates and zooplankton) were absent, and the native brown trout population was on its way to extinction. Since about 1988 S* deposition has decreased sharply, ANC and pH have increased, and starting in the late 1990s the biota has begun to recover (Figure 4).

At Lake Saudlandsvatn more than 90% of deposited N is retained in the lake and catchment, and this situation has not changed during the 35 years of monitoring. Nitrogen deposition does not greatly affect lake acidification at least at present. Focus can thus be placed on S* deposition.

MAGIC was first calibrated to the observed annual water chemistry data 1974-2009 and driven by the historical S and N deposition data for the grid square 50-57 provided by the CCE in the 2007/8 call. The deposition history was scaled to the measured deposition at the site for the year 2000. The calibrated parameter set was then run with the 5 scenarios for future deposition of S and N for the year 2020 (COB2020, Low*2020, Mid*2020, High*2020, MFR2020).
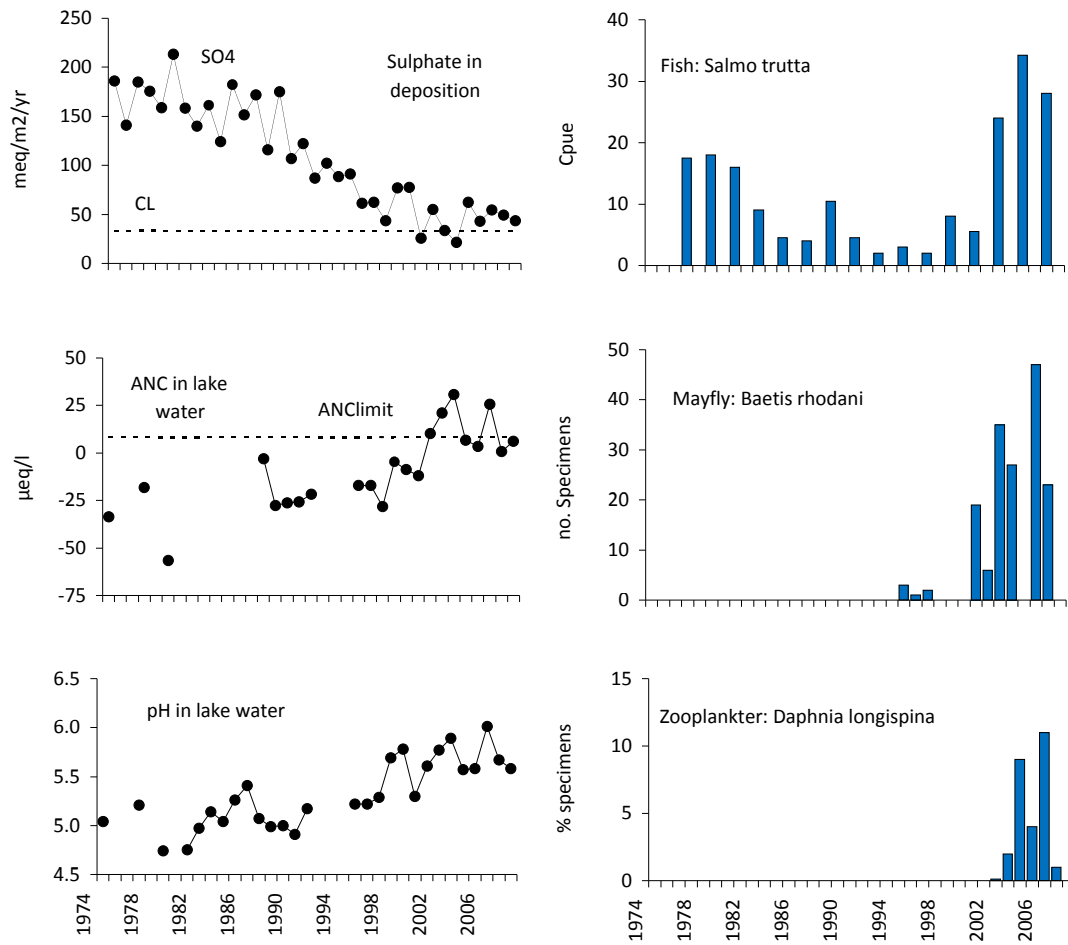
Figure 4. *Long-term deposition, lake chemistry and lake biology monitoring data for Lake Saudlandsvatn, an ICP Waters site in southern Norway. Shown are non-marine S (S*) deposition, lake ANC and pH, catch-per-unit effort of fish, number of specimens collected of the acid-sensitive mayfly B. rhodani, and % specimens collected of the acid-sensitive zooplankton species D. Longispina. Data from (Hesthagen et al. 2011).*
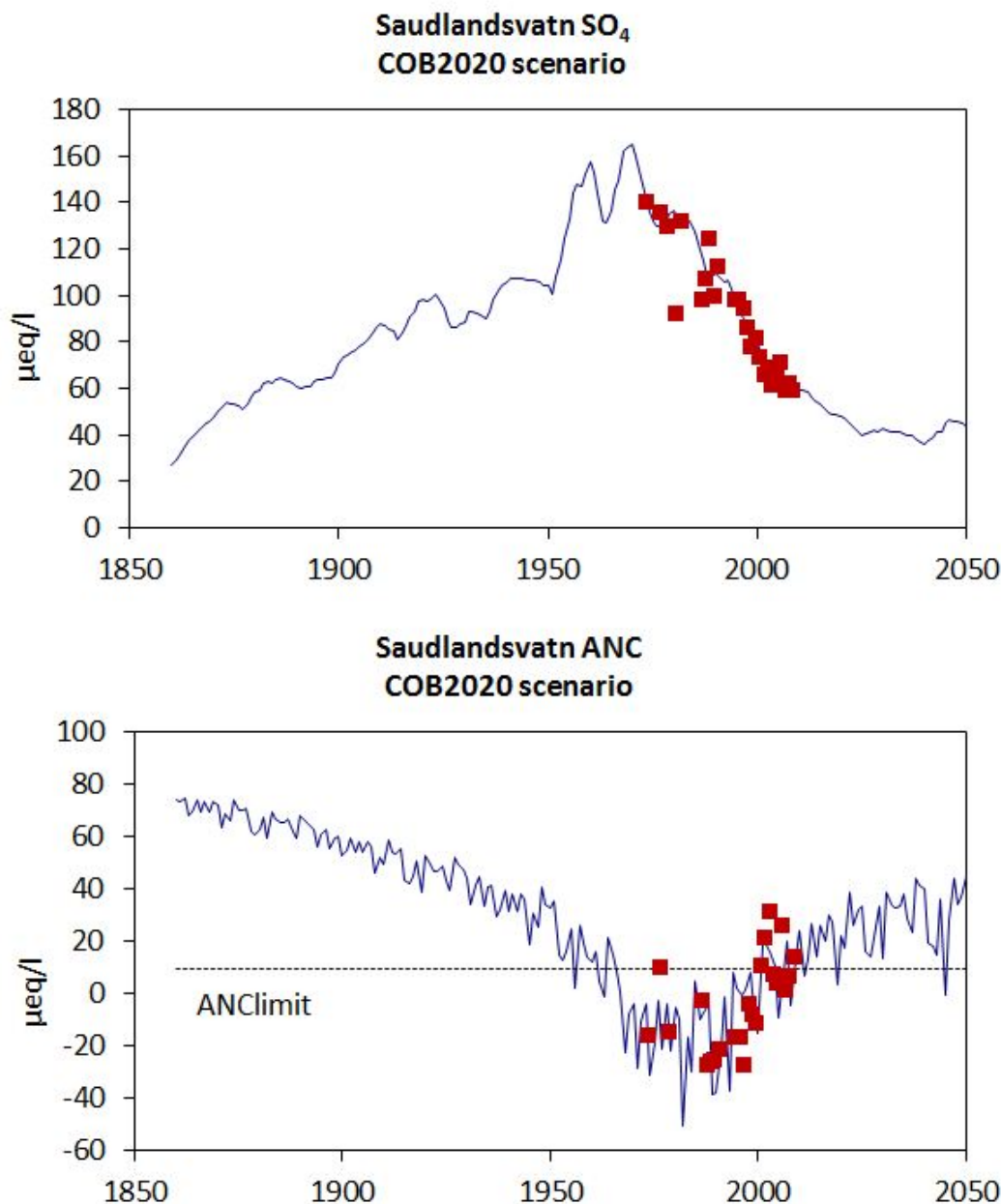
Figure 5. *Concentrations of sulphate (SO₄) and ANC in Lake Saudlandsvatn measured (red squares) and simulated (blue line) with the MAGIC model. The future simulated values assume S* deposition as specified by the NAT2000 scenario for 2000 and 2020, and constant level past the year 2020.*

The long-term reconstructed acidification history at Lake Saudlandsvatn suggests that ANC fell below the ANC$_{limit}$ for fish around 1950, and that ANC was well below the ANC$_{limit}$ until recently (Figure 5). The year-to-year "noise" in ANC with present-day amplitude of about 30 µeq/l reflects natural variations in amounts of precipitation and seasalt inputs.

With the COB2020 scenario (current legislation) ANC levels are expected to continue to increase somewhat over the next 10 years, and then level off at about ANC 30 µeq/l. Year-to-year fluctuations, however, imply that ANC will fall below ANC$_{limit}$ during "bad" years, years with high seasalt inputs (Figure 5).

4.2 Chemical recovery at 8 sites under the 5 scenarios

For all the sites there was little difference between the projected ANC for the year 2020 under the five scenarios COB2020, Low*2020, Mid*2020, High*2020 and MFR2020 (Figure 6, Table 2). In most cases the difference in ANC obtained under the MFR2020 scenario (the most severe of the 5) and the COB2020 scenario (current legislation) is only a few µeq/l, much less than natural year-to-year variations. This is because the future S* deposition is very similar under these scenarios.
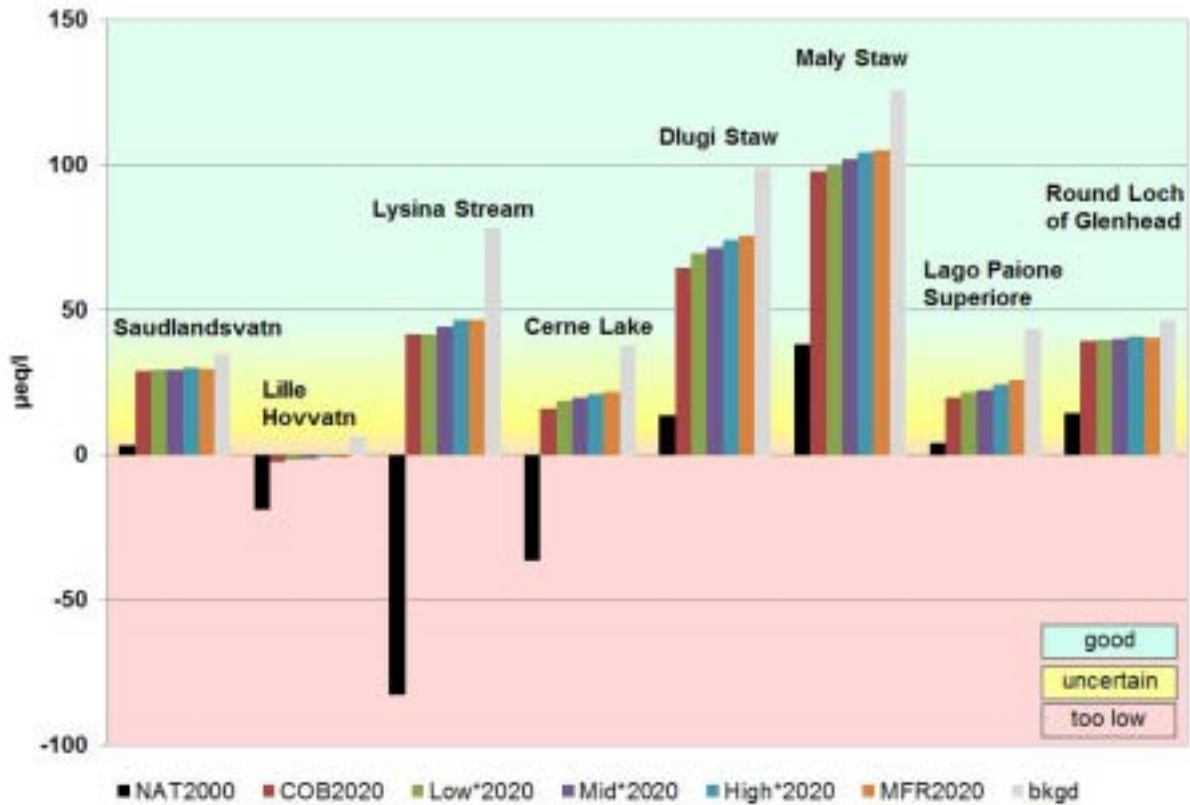
Figure 6. *Modelled ANC (µeq/l) in years 2000 and 2030 under various scenarios of S and N deposition. Values are given for the year 2030, which allows the ecosystems 10 years to respond to the implementation year 2020 for the various scenarios.*

Table 2. *Modelled ANC (µeq/l) in years 2000 and 2030 under various scenarios of S and N deposition. Values are given for the year 2030, which allows the ecosystems 10 years to respond to the implementation year 2020 for the various scenarios.*

Site	2000	COB2020	Low*2020	Mid*2020	High*2020	MFR2020	bkgd
Saudlandsvatn, Norway	3.4	28.8	29.2	29.5	30.0	29.6	34.7
Lille Hovvatn, Norway	-19.0	-2.3	-1.7	-1.2	-0.6	-1.0	6.3
Cerne Lake, Czech rep.	-36.4	15.8	18.5	19.6	20.8	21.6	37.6
Lysina Stream, Czech rep.	-82.7	41.1	41.6	44.1	46.5	46.4	78.4
Maly Staw, Poland	38.3	97.8	99.8	102.1	104.2	105.1	125.8
Długi Staw, Poland	13.7	64.6	69.6	71.5	74.0	75.6	98.9
Lago Paione Superiore , Italy	4.0	19.6	21.8	22.4	24.4	25.8	43.6
Round Loch of Glenhead, UK	14.6	39.2	39.6	40.0	40.7	40.6	46.4

In the case of Lago Paione Superiore, Italy, the simulated ANC differs significantly among the scenarios. This is because nitrogen leaching plays a particularly large role in acidification at this lake. N input from the atmosphere and N dynamics in soils of the catchment and in lake water will be the most relevant processes affecting future recovery at this site. Nitrogen deposition in the Central Alps, where LPS is located, is among the highest in Europe (Rogora et al. 2007) and alpine lakes in this area are affected by quite high NO_3 concentrations with respect to other remote lakes (Rogora et al., 2008). Nitrate concentrations in LPS are still quite high (about 20 µeq/l, with a pronounced seasonal and interannual variability), but measured data show a tendency towards a decrease in the last few years. Anyway reduction of N emission in source regions, located in the lowland, will be crucial in the next few years for the recovery of alpine lakes from acidification and for their nitrogen status.

The background-only scenario was included to illustrate the maximum possible improvement in water quality that can be obtained by reduction in emissions of acidifying air pollutants. In all cases modelled recovery of ANC under the background-only scenario indicates significant and in some cases substantially better recovery than under MFR2020 (Figure *7*). Maximum technically feasible reduction (MFR) is inherently a level which is subject to improvement as pollution control technology and energy use change over time. At present, however, reductions in sulphur and nitrogen emissions (and deposition) beyond MFR are hypothetical. The modelling results indicate that under the background-only scenario at all but one of the sites examined, the ANC will recover to levels well above the critical level for fish populations. Only in the extremely sensitive Lake Lille Hovvatn (Norway) will the ANC be near or at the critical level for fish in the year 2030 under the background-only scenario.
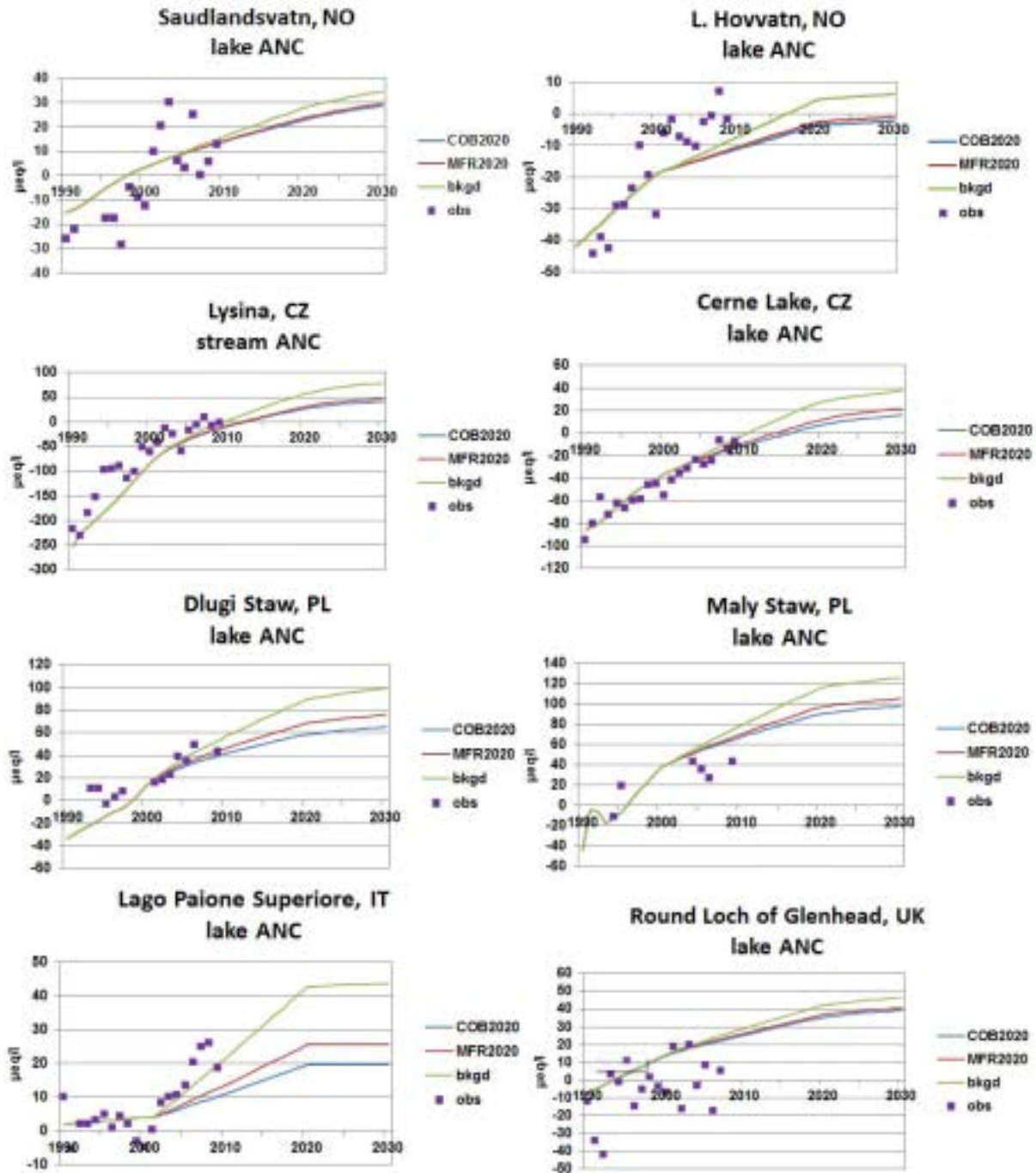
Figure 7. Simulated and observed acid neutralising capacity (ANC) at each of the 8 sites addressed in this report. Three deposition scenarios are presented: COB2020 (current legislation, including the Gothenburg protocol), MFR2020 (maximum feasible reduction) and bkgd (background deposition only). The background deposition scenario was included to illustrate the maximum additional improvement in water quality that can be attained by reductions in emissions of S and N air pollutants.

4.3 Biological recovery

The results indicate that at all sites the future S and N deposition under the future scenarios will result in substantial improvement in water quality in year 2020 relative to year 2000. Whether the lake will fully recover biologically depends, of course, on the degree of acid sensitivity of the site. For example, whereas under COB2020 scenario full recovery at Lake Saudlandsvatn can be expected, at Lake Lille Hovvatn the remaining acid deposition will cause sufficient acidification such that the lake ANC lies below the critical limit (ANC_{limit}), which implies that key indicator organisms such as fish will not fully recover.

In addition come the time lags inherent in both the chemical and biological recovery processes. Response in ANC to decreases in acid deposition is not immediate; the modelled results indicate that gradual improvement can be expected over several decades (Figure 7). Biological recovery cannot start until the ANC increases above the critical limit. Then additional delays can be expected, due to such factors as migration distance and times, false starts caused by occasional acid episodes, competition between species etc.

At most of the sites studied, biological recovery had already begun by the year 2000. Based on the modelled ANC given the various scenarios for 2020 additional recovery can be expected (Table 3). Only at Lake Lille Hovvatn is chemical recovery projected to be insufficient for biological recovery in the year 2020, even given the MFR2020 scenario.

Table 3. *Summary of biological status in the study lakes observed (1990, 2000, 2010) and forecast recovery under two scenarios for 2020. Recovery classes: 0 no recovery; * start recovery; ** partial recovery; *** full recovery. Organism groups: f=fish; zp=zooplankton; zb=zoobenthos; dia=diatoms. NS= not studied.*

	Status 1980	Status 2000	Status 2010	Forecast 2020 COB2020	Forecast 2020 MFR2020	Organism group
Saudlandsvatn	0	*	**	***	***	f, dia
L. Hovvatn	0	0	0	0	0	f, dia
Lysina	0	0	*	***	***	zb
Cerne	0	*	*	**	***	zp, zb
Dlugi Staw	0	0	NS	***	***	dia
Maly Staw	0	NS	NS	***	***	zp, dia
Lago Paione Sup	0	0	0	**	***	zb, dia
Round Loch GH	0	0	*	***	***	f, zb, dia

5. Conclusions

- The five scenarios for deposition are very similar to one another
- The five scenarios all represent substantial decreases in deposition for the year 2020 relative to the new base year 2000.
- The modelled future ANC levels at each site under the five deposition scenarios differ little from one another.
- At all sites the modelled results indicate that chemical recovery will continue into the future under all of the scenarios.
- At all but the most acid sensitive sites (such as Lake Lille Hovvatn, Norway) acid neutralising capacity (ANC) will increase to levels above the critical level for biological damage.
- Year-to-year variations in acid deposition, seasalt inputs or climate can result in variations in ANC. At sites for which the mean ANC is at or near the critical limit, these natural fluctuations can cause acid episodes with biological damages.
- The greatest reductions in deposition are given by the maximum feasible reduction scenario (MFR2020). This is still substantially above the natural background levels of deposition. As pollution control technology improves in the future, additional improvements in water quality can be obtained with emission reductions beyond those envisioned under MFR2020.

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Appendix A. Simulated and observed recovery at the 8 sites

Shown are non-marine S deposition, N deposition (Nox + Nre), and simulated and observed acid neutralising capacity (ANC) at each of the 8 sites addressed in this report. Three deposition scenarios are presented: COB2020 (current legislation, including the Gothenburg protocol), MFR2020 (maximum feasible reduction) and bkgd (background deposition only). The background deposition scenario was included to illustrate the maximum additional improvement in water quality that can be attained by reductions in emissions of S and N air pollutants.
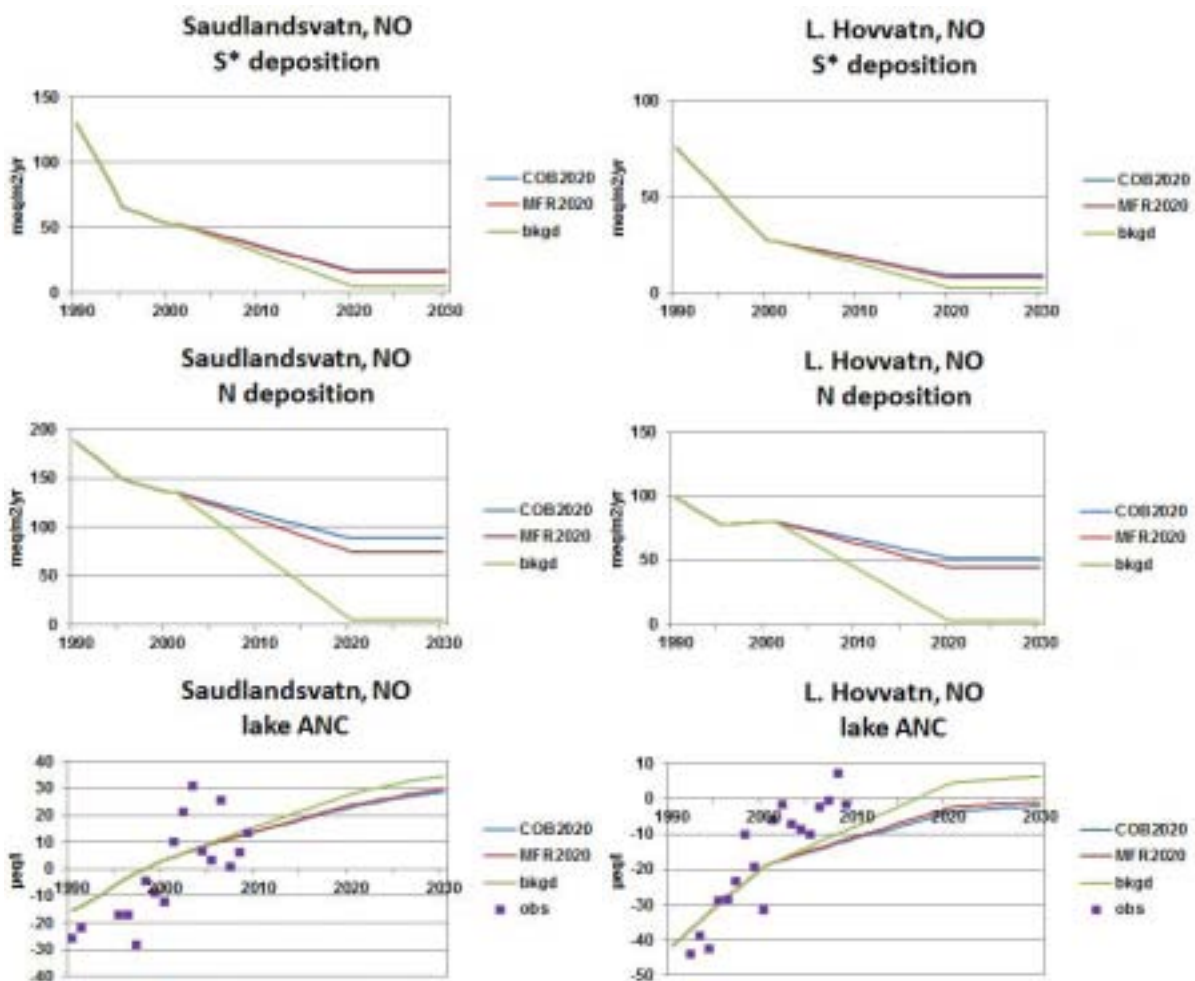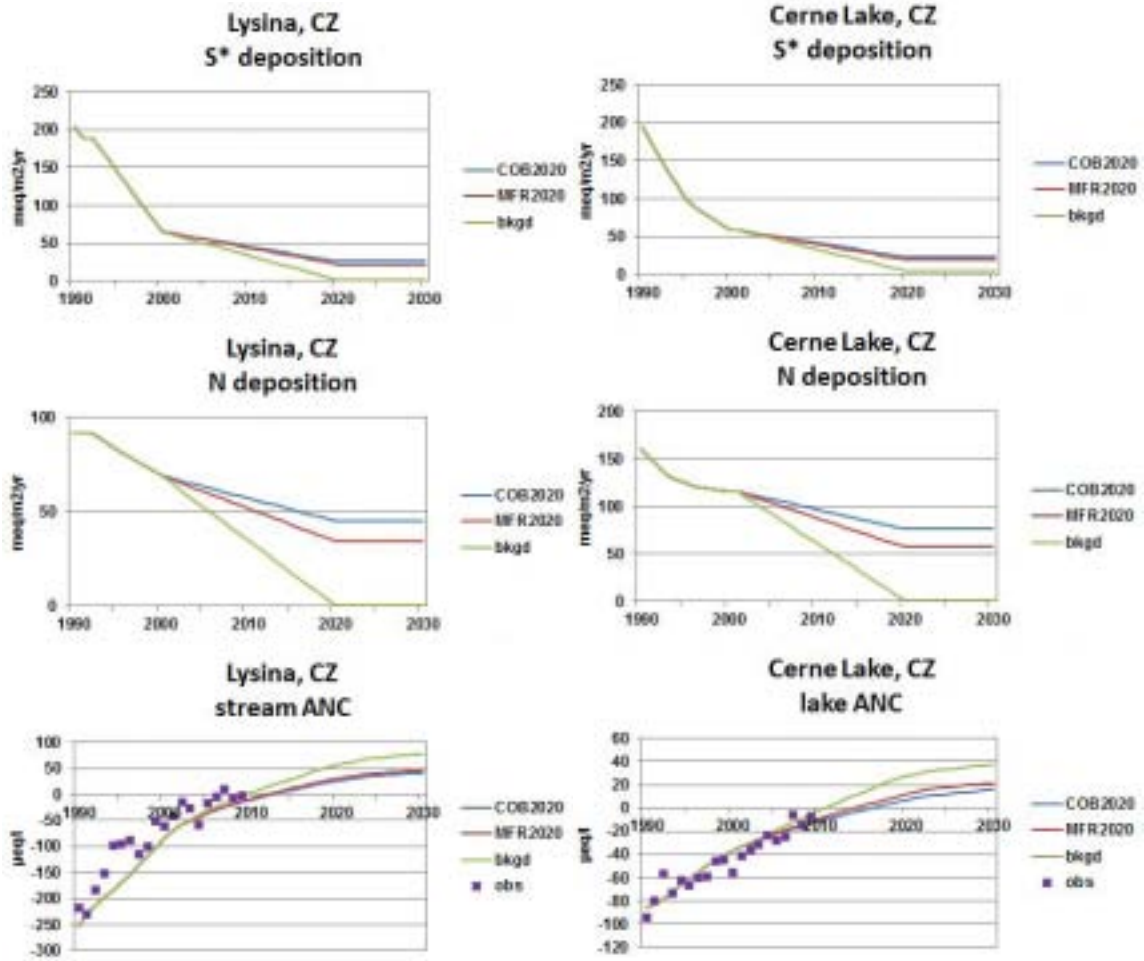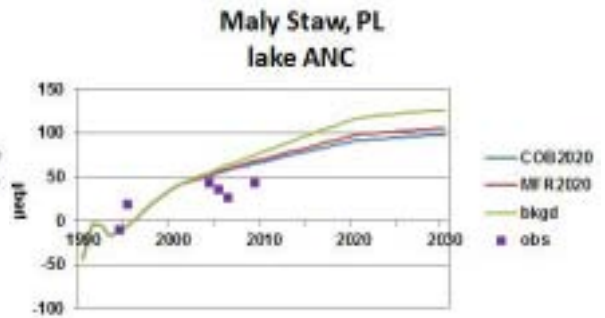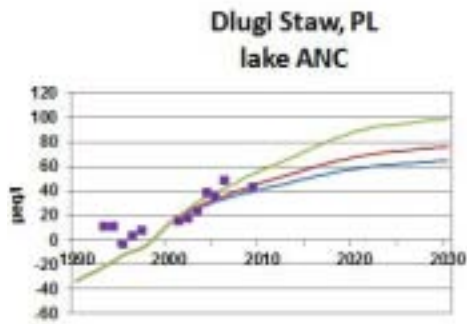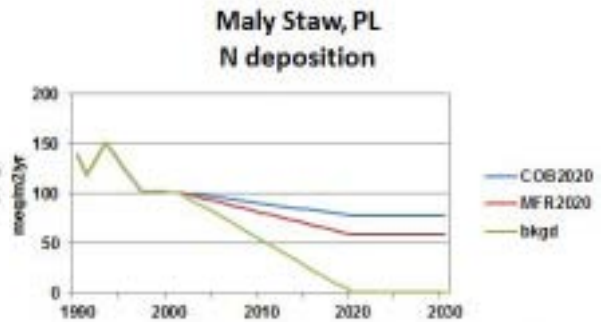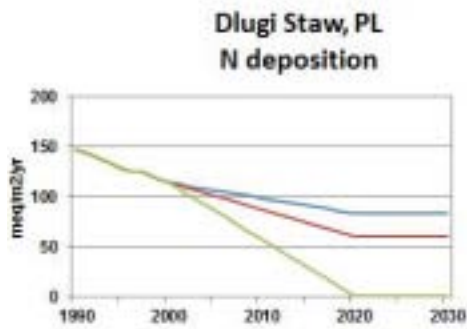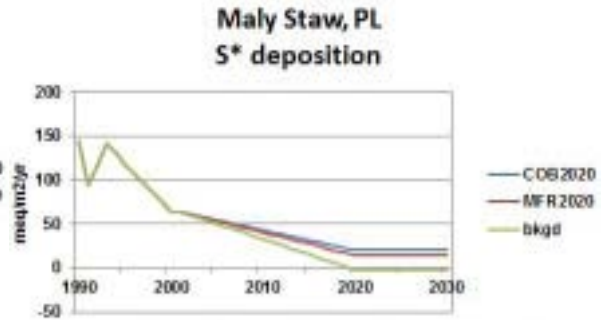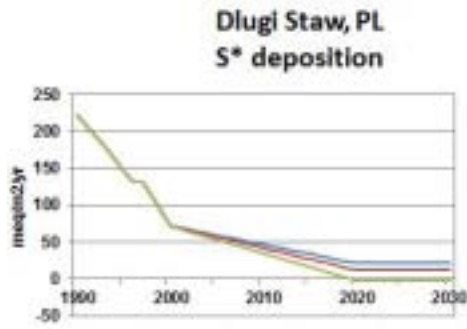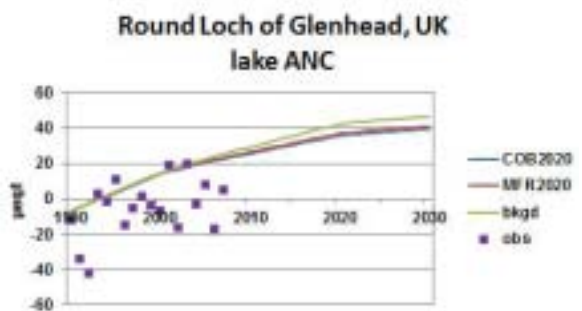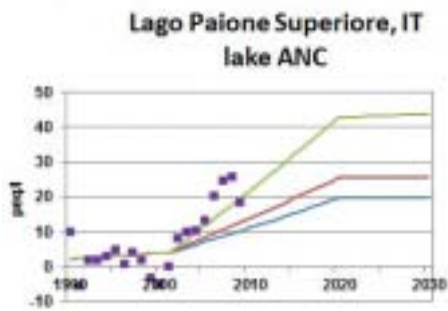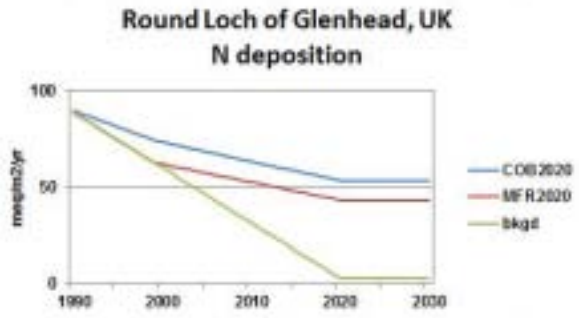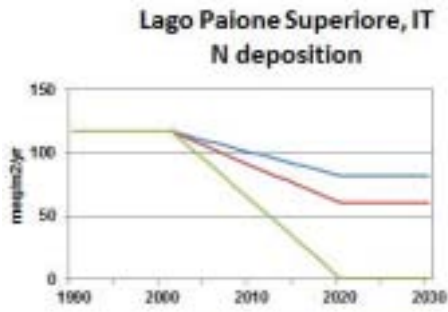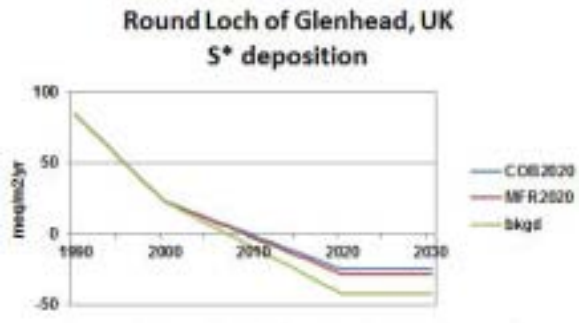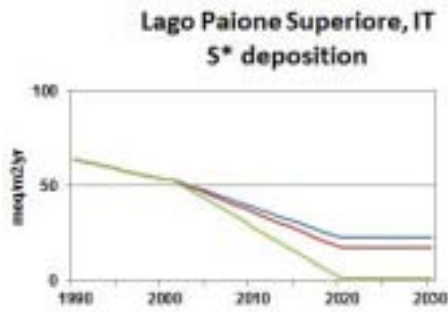
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