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Re-calibration of the MAGIC model with data from the National Lake Survey 2019. Results from phase 2.

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Abstract

The biogeochemical MAGIC model has been applied to the data from the 1995 and 2019 surveys of 1000 Norwegian lakes. The work is a follow-up of a modelling exercise that was done in 2022, with improved input data and with new deposition estimates generated from NILU's deposition station network. The results indicated that the new deposition data from NILU gave slightly better simulated results (compared to the observed) than those with the deposition estimates from EMEP used in 2022. For future work we recommend that the calibrations to the 2019 data driven by the deposition data from NILU's deposition station network are used.

Keywords: Lakes, Atmospheric deposition, Acidification, Modelling
Emneord: Innsjøer, Atmosfæriske avsetninger, Forsuring, Modellering

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Preface

This project is a follow-up of the 2022 calibration of the MAGIC model to data from the 2019 National Lake Survey. The work has been funded by the Norwegian Environment Agency (NEA) and is related to NIVA's role as National Focal Centre under the UNECE International Cooperative Programme on Modelling and Mapping of Critical Loads & Levels and Air Pollution Effects, Risks and Trends (ICP M&M). The work on critical loads and dynamic modelling in the context of acid deposition is central to this role, and the current report provides background for the future work.

We thank Wenche Aas (NILU) for providing deposition estimates for Norway expressed as five-year means for the period 1980-2020, and Hilde Fagerli (met.no) for providing deposition scenarios for 2030 and 2050 from the European Monitoring and Evaluation Programme (EMEP). We also thank Max Posch for re-fitting the historical sulphur and nitrogen deposition data to NILU's deposition estimates for the years 1980-2020. At NIVA we thank our colleague James Sample for assigning grid-based input data including new national runoff data from NVE.

The project has been conducted under the contract 22047070 from the Norwegian Environment Agency (NEA). The contact person at NEA was Gunnar Skotte.

Oslo, 6 December 2023

Summary

We applied the MAGIC model to the data from the 1995 and 2019 surveys of 1000 Norwegian lakes (the "1000-lake surveys"). The simulations used estimates of sulphur (S) and nitrogen (N) deposition provided by NILU and based on NILUs network of monitoring stations. In 2022 we carried out this same exercise using modelled deposition estimates provided by EMEP. The entire input data required for MAGIC applications to the 1000-lake surveys was updated and checked for missing data, inconsistencies, and errors. Specific discharge was updated with values obtained from NVE for the most recent 30-year normal period (1991-2020).

A total of 986 lakes had all the data and information necessary for MAGIC calibrations. Almost all of these were successfully calibrated by MAGIC – both when calibrated to the 1995 data (n=969) and when calibrated to the 2019 data (n=964). In total, 616 lakes were calibrated all four times: in both 2022 (with EMEP) and 2023 (with NILU) and to both the 1995 and 2019 lake data.

The results indicated that deposition data from NILU gave slightly better simulated results (compared to the observed) than those with the deposition estimates from EMEP used in 2022. The simulations captured the observed decreases in SO_4 concentrations and the increases in ANC in acid-sensitive lakes. But the observed recovery in ANC was somewhat greater than modelled. The simulations underestimated the observed Ca concentrations in acid-sensitive lakes in 2019, which indicates that other factors than reduced SO_4 have affected the Ca trend since 1995. The calibrations to the 2019 data were used to forecast ANC to the years 2030 and 2050; only minor changes were forecasted. Analysis of simulated and observed data (1986-2020) for the 12 "trend" lakes that were included in the 1000-lake surveys gave the same general patterns.

We recommend that the calibrations to the 2019 data driven by the deposition data from NILU are used for future work. The NILU data are preferred as they are based on measured deposition, they extend back to 1978, and they indicate a lower total acid stress over the entire acidification period starting in the late 1800s. These MAGIC calibrations to the 2019 data now offer a platform for a possible extension of the Swedish "MAGIC bibliotek" to also include Norwegian lakes. The calibrations provide a basis for evaluating and forecasting scenarios of future climate and land-use changes.

Sammendrag

Vi har anvendt MAGIC-modellen på dataene fra de norske 1000-sjøers undersøkelsene i 1995 og 2019. Simuleringene er basert på estimater av atmosfærisk avsetning av svovel (S) og nitrogen (N) fra NILUs nettverk av overvåkingsstasjoner. I 2022 utførte vi det samme modelleringsarbeidet ved å bruke modellerte avsetningsestimater levert av EMEP. Alle inngangsdata for MAGIC-modelleringen av 1000-sjøene ble oppdatert på nytt og sjekket for feil eller mangler. Spesifikk avrenning for innsjøenes nedbørfelter ble også oppdatert til den nye 30-års normalen fra NVE (1991-2020).

Totalt 986 innsjøer hadde all nødvendig informasjon til å kalibrere MAGIC-modellen. Nesten alle ble vellykket kalibrert – både til 1995-dataene (n=969) og til 2019-dataene (n=964). I alt er 616 innsjøer kalibrert fire ganger: Med EMEP-data i 2022 og NILU-data i 2023 for begge innsjødatasettene (1995 og 2019).

Resultatene indikerte at NILUs deposisjonsdata ga litt bedre simulerte resultater (sammenlignet med observert vannkjemi) enn de modellerte deposisjonsdataene fra EMEP som ble brukt i 2022. Simuleringene fanget opp de observerte reduksjonene i konsentrasjonene av sulfat (SO_4) og økningen i ANC i de forsuringsfølsomme innsjøene. Men den observerte økningen i ANC i innsjøene var noe større enn modellert. Simuleringene underestimerte kalsiumkonsentrasjonen i de forsuringsfølsomme innsjøene i 2019, noe som indikerer at andre faktorer enn redusert SO_4 har påvirket kalsium-trenden siden 1995. Kalibreringene til 2019-dataene ble brukt til å gjøre prediksjoner for ANC i 2030 og 2050. Resultatene viste bare mindre endringer i forhold til 2019. En analyse av simulerte og observerte data (1986-2020) for 12 «trend-innsjøer» som var inkludert blant 1000-sjøene ga de samme generelle mønstrene.

Vi anbefaler at kalibreringen til 2019-datasettet med deposisjonsdata fra NILU brukes i det videre arbeidet med modellering av 1000-sjøene. NILU-dataene foretrekkes framfor EMEP-dataene da de er basert på faktiske målinger, strekker seg tilbake til 1978 og indikerer et lavere nivå på historisk deposisjon siden slutten av 1800-tallet. Kalibreringen til 2019-dataene vil egne seg som plattform for en mulig utvidelse av det svenske “MAGIC biblioteket” der også norske innsjøer inkluderes. Den vil også kunne brukes til å lage nye prognoser for 2030, 2050 og eventuelt videre, samt gi grunnlag for å kunne vurdere effekter av fremtidige endringer i klima og arealbruk.

1 Introduction

The MAGIC model (Model for Acidification of Groundwater In Catchments) (Cosby et al. 1985ab, Cosby et al. 2001) is widely used to simulate the effects of acid deposition on the chemistry of surface waters, and to estimate the expected changes given future rates of acid deposition. MAGIC has recently been recoded and transferred to NIVA's model platform Mobius (Norling et al. 2021, Norling et al., in review). This provides more flexibility and simpler routines for auto-calibration and sensitivity analysis, and for calibration to data from more than one point in time.

In 2022 we applied MAGIC to data from the 1995 survey and the 2019 re-survey of 1000 Norwegian lakes (de Wit et al. 2023) to evaluate the ability of the model to satisfactorily simulate the observed lake chemistry data measured in 1995 and 2019 (Kaste et al. 2022). The results suggested that the EMEP deposition data used to drive the model may overestimate the actual decline in sulphur (S) deposition over the period 1995-2019. Here we repeat the analyses but now use deposition estimates generated from NILU’s deposition station network.

The aim was to provide the best possible basis for forecasting changes in lake chemistry given future changes in drivers such as acid deposition, climate change and land-use change.

2 Materials and methods

2.1 Modelling tools and techniques

We used the same procedures and MAGIC and Mobius software as described in the 2022 report (Kaste et al. 2022).

2.2 Update of input data

2.2.1. Selection of lakes and lake information

The lake chemistry data from the 1995 1000-lake survey are reported by Skjelkvåle et al. (1996) and from the 2019 survey by Hindar et al. (2020). In the previous application of the MAGIC model to the 1000-lakes (Kaste et al. 2022) some of the lakes had to be omitted due to inconsistencies in the input data. In 2023, the entire input data was again updated and checked for missing data, inconsistencies, and errors. As a result, a total of 986 lakes had all the data and information necessary for MAGIC calibrations.

In 2022, a preliminary dataset for specific discharge according to the new normal period 1991-2020 was used for the MAGIC calibrations. The "official" dataset from The Norwegian Water Resources and Energy Directorate (NVE) that was used for the 2023 calibrations contains only minor deviations from the preliminary data used in the previous calibration. We used the same catchment area and lake area data as in the 2022 calibration, when catchment areas for all lakes were revised based on digital tools from NVE and NIVA (Kaste et al. 2022).

2.2.2. Deposition data for S and N

For the MAGIC simulations in 2022 we used the EMEP (European Monitoring and Evaluation Programme) modelled deposition values for S and N given for the period 1990-2020. These are based on an emission-dispersion-receptor model. For the simulations in 2023 presented here we used estimates for S and N deposition from NILU (Norwegian Institute for Air Research). These are based on measurements at NILUs precipitation monitoring stations and extrapolated to all of Norway using a kriging routine. The estimates are given as 5-year means with the first period 1978-1982. S* deposition refers to the non-seasalt fraction (also termed excess or pollutant fraction) only.

In both cases, estimates for S*, NH_y and NO_x deposition prior to first year of the data provided (1990 for EMEP; 1980 for NILU) were coupled to estimates of historical deposition 1880-1980 given by (Schöpp et al. 2003). The historical data were scaled to the EMEP or NILU data for each site such that the 1990 or 1980 historical value matched the EMEP 1990 or NILU 1978-82, respectively. Details on this procedure are given in the Appendix to the 2022 report (Kaste et al. 2022).

In the calibration procedure for each lake the S* deposition flux in the calibration year (1995 or 2019) is multiplied by a factor such that it is equal to the SO_4* flux (meq/m^2/yr) in runoff from the lake.

Adjustment factor = SO_4* flux (lake) / S* flux (deposition)

This factor is then used to multiply the historical, EMEP and NILU S* deposition values for all years in the simulations. The same factor is also used to obtain deposition values for NHy and NOx, again for all years, and again based on the historical, EMEP and NILU estimates.

The reasoning is that the SO_4* flux in runoff from the lake gives a better estimate of the S* deposition to the lake and catchment. Local variations in topography, land cover and aspect can all affect precipitation amount, as well as wet and dry deposition of chemical components. Neither the EMEP model estimates nor the NILU kriged extrapolations from measurement stations can take local variations into account. In most Norwegian catchment-lake systems, the output of SO_4 closely follows the S* deposition. Thus, for most lakes in the 1000-lake surveys the lake SO_4 probably provides a better estimate of S deposition than the EMEP or NILU estimate.

2.2.3. Calibration procedures

We calibrated to the 1995 data and examined the simulated vs observed lake chemistry in 2019, and then to the 2019 data and examined the simulated vs observed lake chemistry in 1995. We compared these results with the results obtained in the calibrations from 2022. We did not conduct a 2-point calibration. The results from 2022 indicated that the 2-point calibration did not greatly improve the fit of the simulated to the observed lake chemistry data. Furthermore, the calibrations to the 2019 dataset give the best platform for forecasting future changes in lake chemistry.

The calibrations were conducted as in previous years. We did not introduce a new dependency of SO_4 concentrations on total organic carbon (TOC) concentrations in soil solution and lake water. This is because we have only two measurement points in time for the 1000-lake water chemistry, and no data for the TOC concentrations in soil solution.

As previously the calibrations were conducted stepwise with optimisation first of the strong acid anions chloride (Cl), sulphate (SO_4) and nitrate (NO_3) in that order, and then on the four base cations calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) simultaneously. Prime focus was on the simulated vs observed values for acid neutralizing capacity (ANC). Details on the calibration procedures can be found in Larssen et al. (2008). ANC is defined as the equivalent sum of the base cations subtracted the equivalent sum of strong acid anions; units µeq/l.

2.2.4. Trend lakes

Twelve of the lakes in the 1000-lake survey are also “trend” lakes (Table 1). There are 78 trend lakes in total that have been sampled annually in the autumn since 1986 and are part of the Norwegian Acid Monitoring Programme (in Norwegian: Programmet for Overvåking av langtransportert forurenset luft og nedbør) (Vogt and Skancke 2023). The lakes are acid-sensitive with ANC < 200 µeq/l. Six of the twelve lakes are located in parts of southern Norway that receive acid deposition, five are in mid- and northern Norway, and one is on the Russian border in northeastern Norway (Figure 1).

Table 1. The 12 «trend» lakes that are included in the 1000-lake survey datasets. The "region" refers to the regional groups of trend lakes (Vogt and Skancke 2023).

MAGIC SiteID	Station Name	Aqua monitor Station ID	Aqua monitor Station Code	County	Region	Lat °N	Long °E
36	Lille Hovvatnet	26096	928-2-20	Aust-Agder	4 -Sørlandet-Øst	58.61	8.04
42	Saudlandsvatnet	26100	1003-2-4	Vest-Agder	5 - Sørlandet-Vest	58.20	6.76
50	Lomstjørni	26107	1114-1-34	Rogaland	5 - Sørlandet-Vest	58.68	6.08
115	Brårvatn	26150	831-501	Telemark	4 -Sørlandet-Øst	59.30	7.71
116	Tufsingen	26151	1640-603	Sør-Trøndelag	8 - Midt-Norge	62.61	11.89
166	Kleivsetvannet	26153	1018-4	Vest-Agder	4 -Sørlandet-Øst	58.12	7.66
171	Kjemåvatn	26154	1840-601	Nordland	9 - Nord-Norge	66.75	15.41
187	Holmsjøen	26155	429-601	Hedemark	1 - Østlandet-Nord	61.16	11.62
193	Bjørfarvatnet	26156	1725-3-14	Nord-Trøndelag	8 - Midt-Norge	64.28	10.97
3792	Kapervatnet	26900	1927-3-1	Troms	9 - Nord-Norge	69.25	17.41
3916	St.Valvatnet	45677	2030-607	Finnmark	10 - Øst-Finnmark	69.69	30.66
3453	Røyravatnet	46056	1154-601	Rogaland	6 - Vestlandet-Sør	59.56	6.03

Figure 1. Map of Norway showing locations of the twelve "trend" lakes that are included in the 1000-lake dataset.

3 Results and discussion

3.1 S deposition 1880-2020.

EMEP and NILU give about the same estimates of S* deposition at the 12 trend lakes over the period 1990-2020 but differ in estimates of S deposition for years prior to 1990 (Figure 2). NILUs series starts in 1980 (mean for the 5-year period 1987-1982) whereas the EMEP series starts in 1990. The historical estimates of Schöpp et al. (2003) starting from 1880 are coupled in 1980 to the NILU series, but not until 1990 in the EMEP series. For most of the lakes, this results in larger amounts of S* deposition in years prior to 1990 for the EMEP series as compared to the NILU series. The difference is because the NILU deposition curve for 1980-1990 is flat, whereas the historical estimates of Schöpp et al. (2003) indicate large declines in S* deposition 1980-1990.

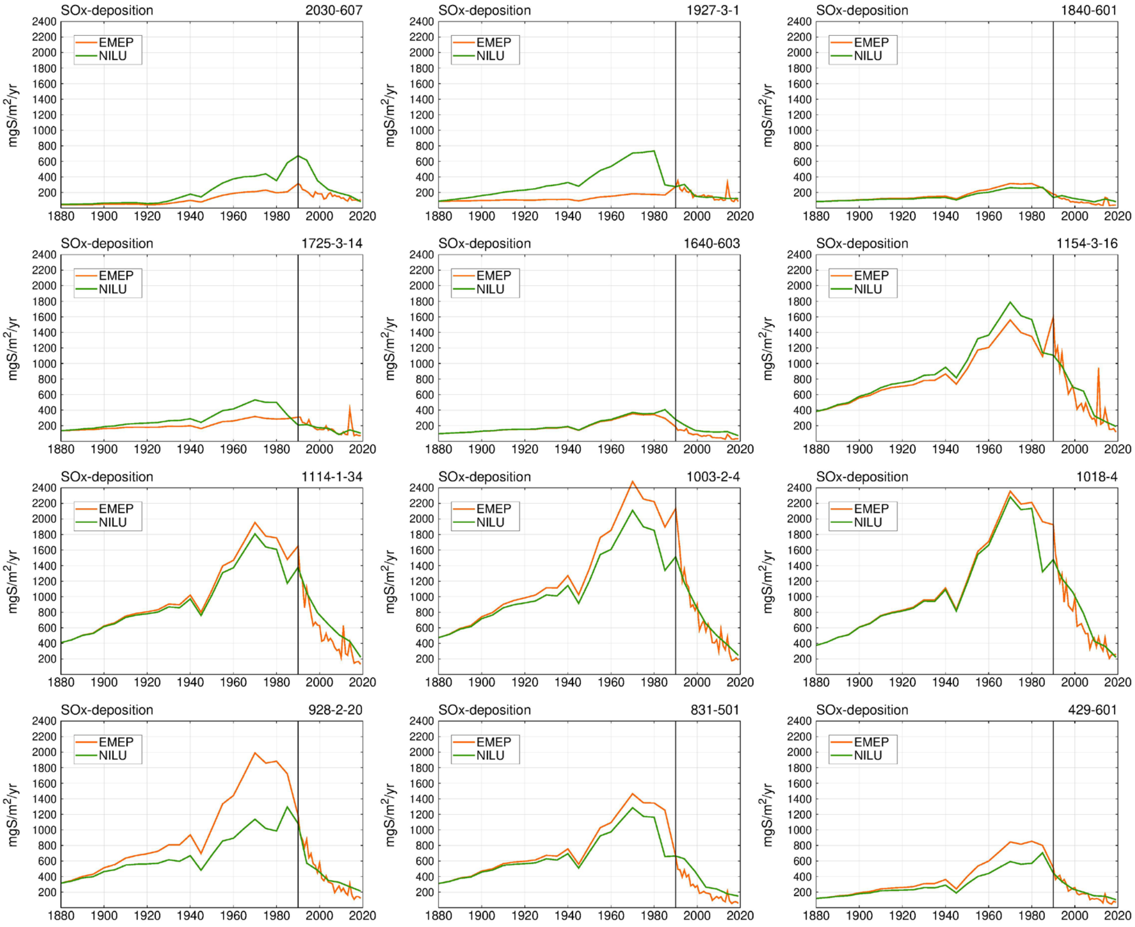


Figure 2. SO_x deposition (mg $S/m^2/yr$) (non seasalt fraction only) at twelve Norwegian "trend" lakes based on estimates from the EMEP model (data from 2022) and from NILUs monitoring stations (data from 2023) and the historical estimates of Schöpp et al. (2003) for the years prior to 1990 (EMEP) or 1980 (NILU).

The EMEP estimates for NOx (Figure 3) and NHy (Figure 4) deposition also differ from the NILU estimates. The lake data from both 1995 and 2019 show that >90% of the incoming N is retained in the catchment and lake or lost to the atmosphere. Compared to the other major ions, concentrations of both NO_3 and NH_4 were generally low in most of the lakes, and thus in most lakes do not greatly influence ANC.

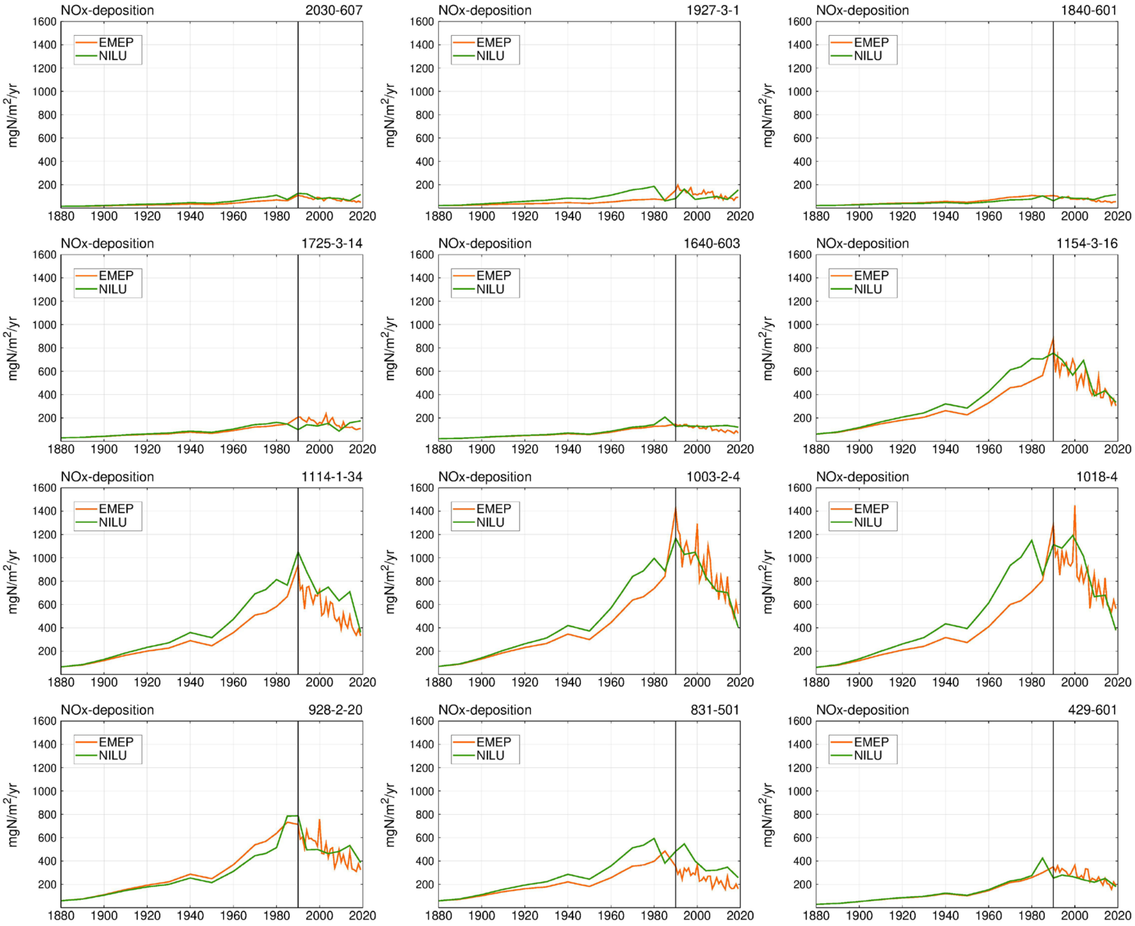


Figure 3. NO_x deposition (mg $N/m^2/yr$) at twelve Norwegian “trend” lakes based on estimates from the EMEP model (data from 2022) and from NILUs monitoring stations (data from 2023) and the historical estimates of Schöpp et al. (2003) for the years prior to 1990 (EMEP) or 1980 (NILU).

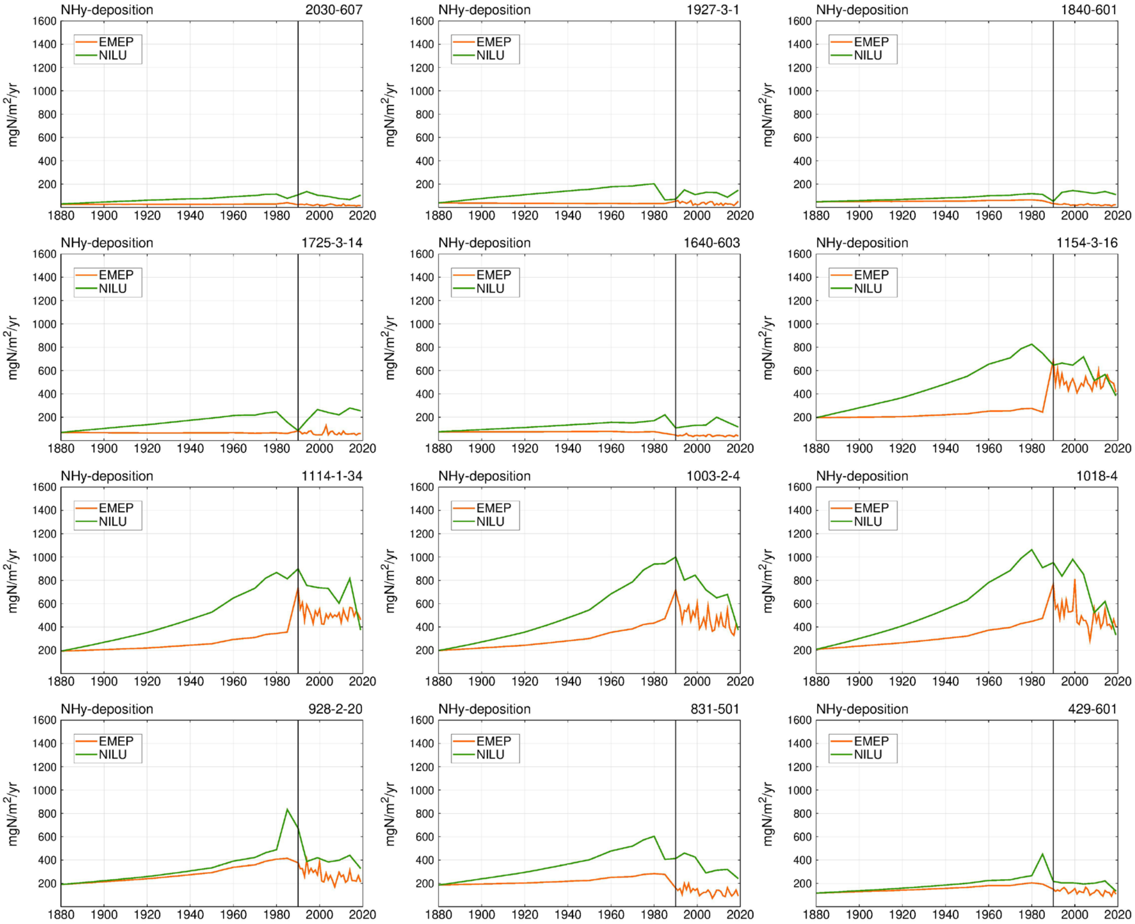


Figure 4. NH_y deposition (mg $N/m^2/yr$) at twelve Norwegian "trend" lakes based on estimates from the EMEP model (data from 2022) and from NILUs monitoring stations (data from 2023) and the historical estimates of Schöpp et al. (2003) for the years prior to 1990 (EMEP) or 1980 (NILU).

3.2 Calibrations to the 1995 and 2019 data

Of the 986 lakes with complete input data, a total of 969 and 964 were successfully calibrated to the 1995 and 2019 data, respectively. The new calibrations using the NILU deposition estimates (and the updated specific discharge estimates from NVE) gave nearly the same simulated lake water chemistry as the calibrations carried out in 2022 using the EMEP deposition estimates (and the previous discharge estimates). For SO_4 (Figure 5), ANC (Figure 7), and Ca (Figure 8) the regressions of simulated vs observed concentrations in 2019 are nearly identical to the calibrations from 2022 with EMEP deposition and 2023 with NILU deposition. The figures show the results for the 616 lakes that were successfully calibrated all four times, and limited to those lakes with observed ANC < 200 µeq/l, and observed non-marine SO_4 greater than 0 and less than 200 µeq/l. The latter limitation excludes lakes with large sources of S from within the catchment.

The calibrations indicated that a slightly better fit to the observed data was obtained when calibrating to the 1995 observed data. This was probably because at many lake sites the deposition of S in 1995 was significantly higher than in 2019. One of the assumptions behind the calibration procedure is that the observed SO_4 flux at each lake reflects the S deposition at that lake. For those lakes at which S deposition declined over the period 1995-2019, the projections forward aim towards lower SO_4

concentrations in 2019. Seasalt deposition and internal sulphur processes in the catchment and lake have greater influence on SO_4 concentrations in 2019 relative to 1995.

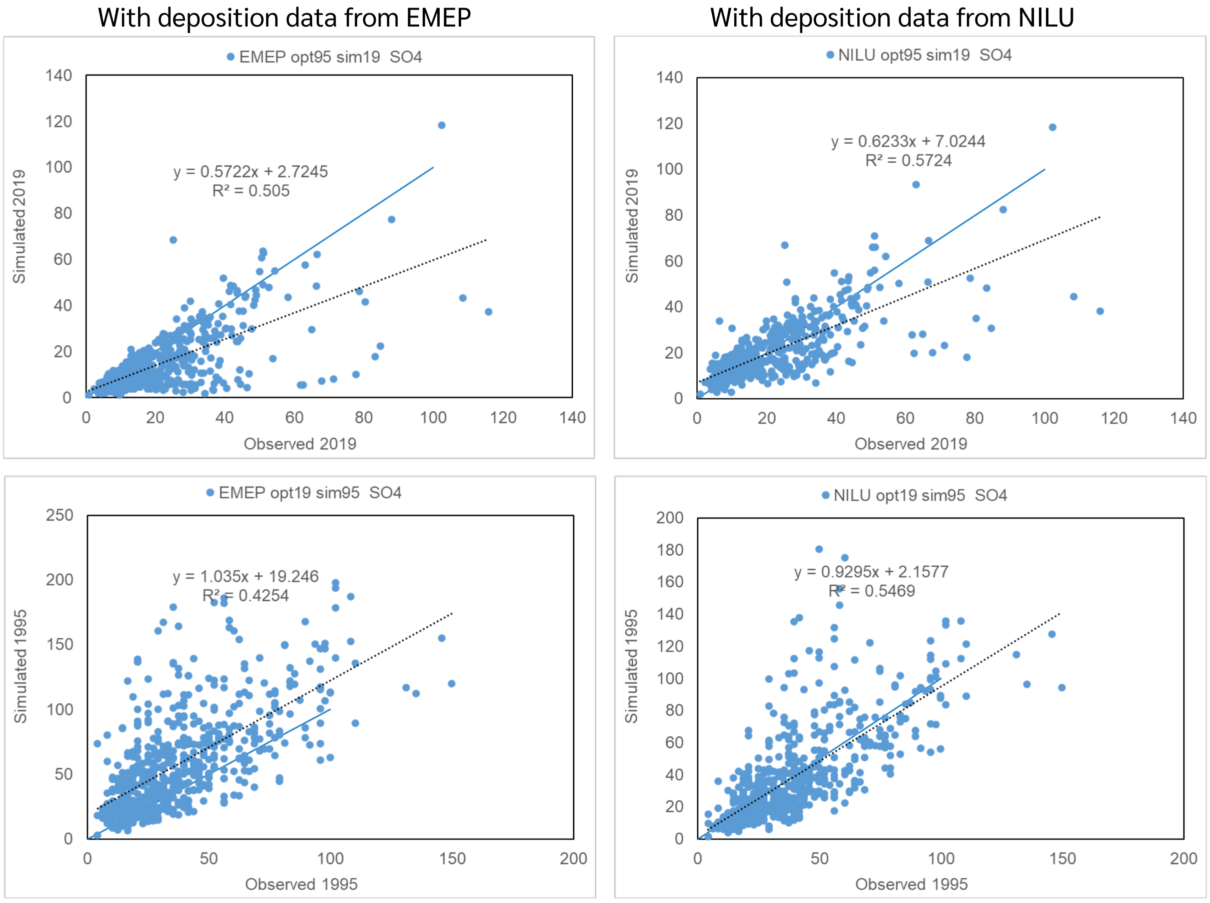


Figure 5. Simulated and observed concentrations in 2019 of SO_4 in 616 lakes with four successful calibrations by MAGIC. Left panels: calibrated to the 1995 or 2019 observed data using EMEP deposition data. Right panels: calibrated to the 1995 or 2019 observed data using NILU deposition data. Shown are data for the acid-sensitive lakes, i.e. those with ANC below 200 µeq/l in both 1995 and 2019. Excluded are lakes that had concentrations of non-marine SO_4 less than zero or more than 200 µeq/l. Solid lines (1:1); dotted lines (least-squares linear regression).

The concept behind MAGIC is that changes in S deposition drive changes in water chemistry. The decrease in S* deposition from 1995 to 2019 given by the EMEP and NILU estimates should therefore be reflected in proportional changes in SO_4 concentrations in the lakes. This assumption assumes no internal catchment or lake sources and sinks of S, and that S deposition moves through the catchment and lake system with lag times of less than one year. That the simulated changes in SO_4 concentrations in the lakes differ from the observed, may be due to both inaccurate S* deposition estimates or to these catchment and lake factors.

The simulated changes from 1995 to 2019 in SO_4 concentrations were somewhat less than the observed (Figure 6). The simulations based on the 1995 data gave better fit to the observed changes. The slopes of the regression were all less than 1; the observed change was larger than simulated. This could indicate that the change in S deposition from 1995 to 2019 was underestimated by both the EMEP and NILU data. SO_4 concentrations *increased* from 1995 to 2019 in 49 of the 616 lakes, most likely due to internal sources of S (such as weathering from soil minerals).

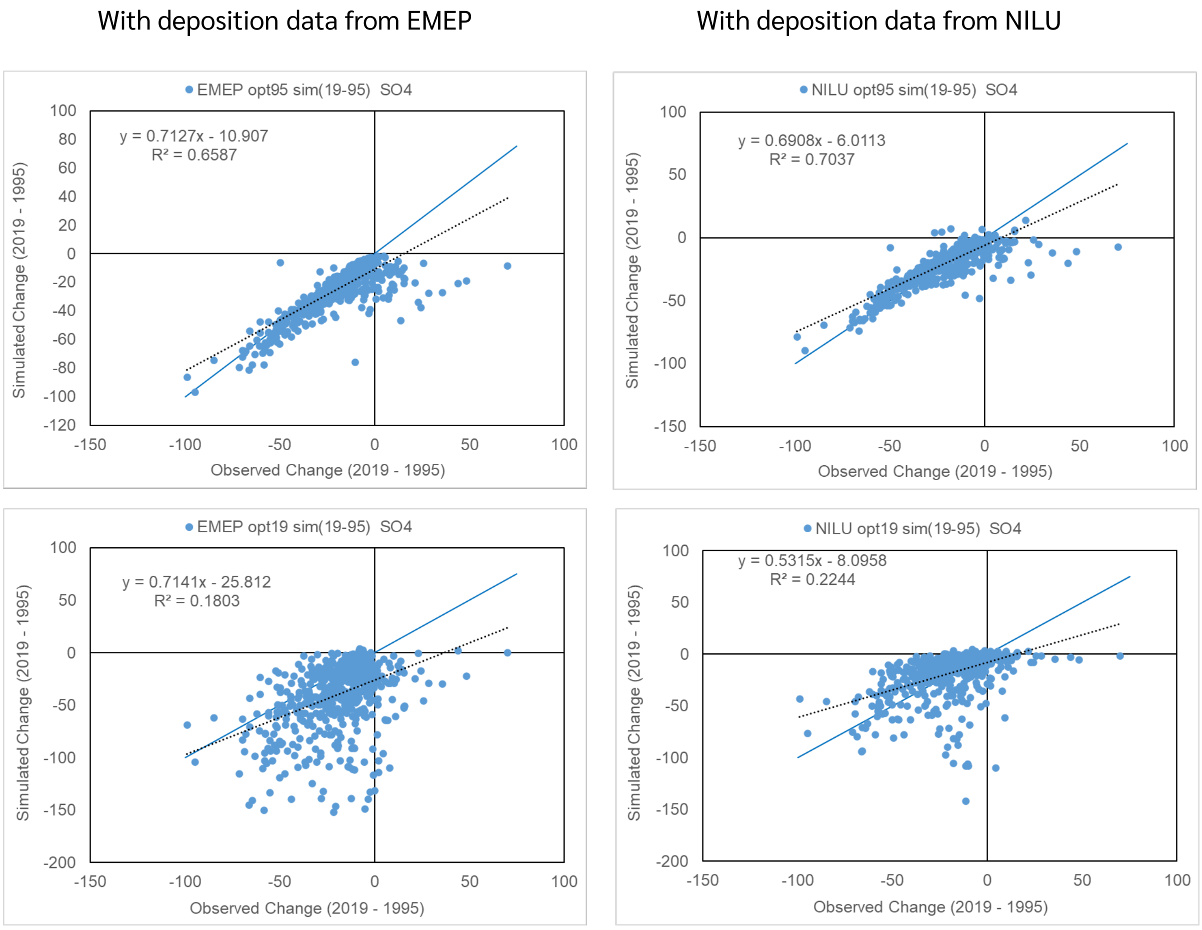
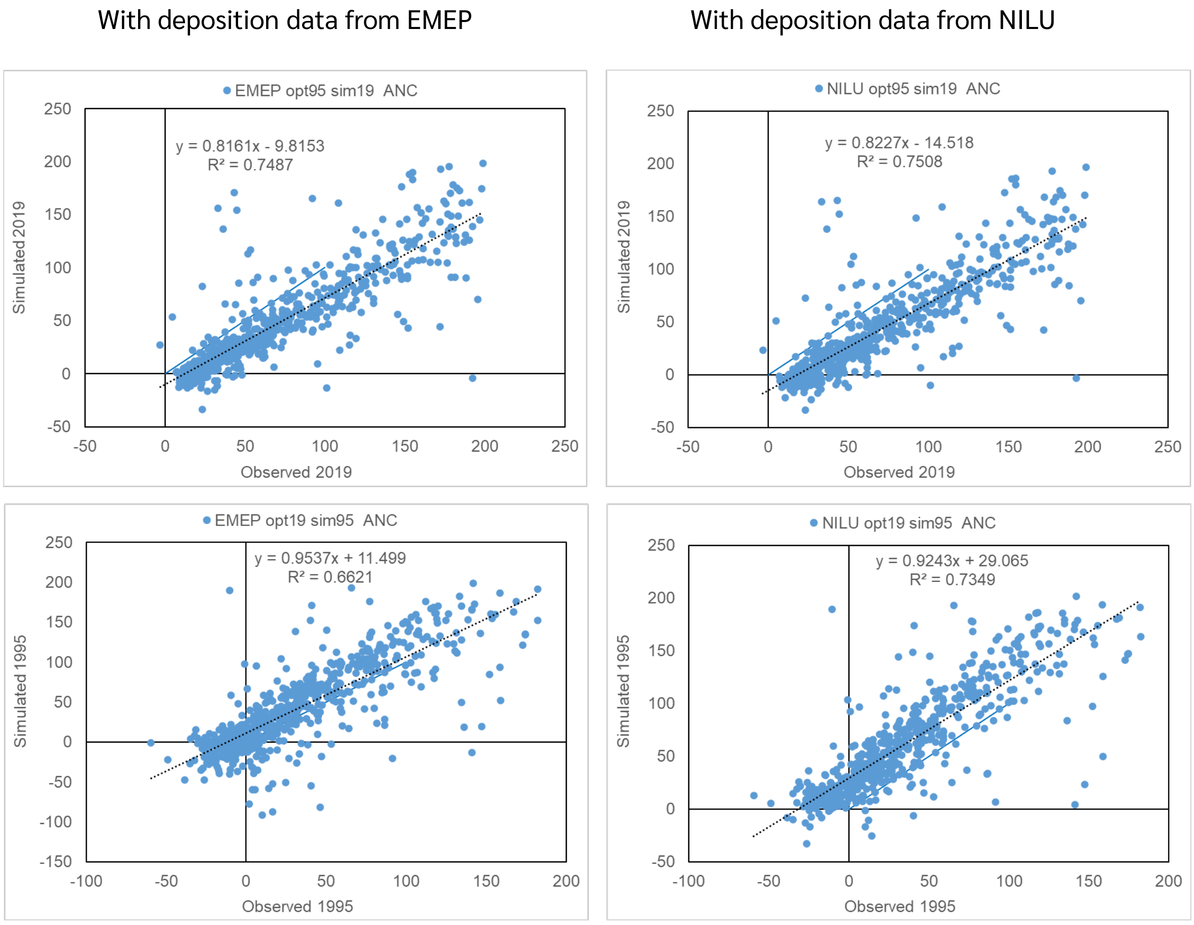


Figure 6. Simulated and observed change in concentrations 1995 to 2019 of SO_4 in 616 lakes with four successful calibrations by MAGIC. Left panels: calibrated to the 1995 or 2019 observed data using deposition data from EMEP. Right panels: calibrated to the 1995 or 2019 observed data using deposition data from NILU. Shown are data for the acid-sensitive lakes, i.e. those with ANC below 200 µeq/l in both 1995 and 2019. Excluded are lakes that had concentrations of non-marine SO_4 less than zero or more than 200 µeq/l. Solid lines (1:1); dotted lines (least-squares linear regression).

The MAGIC calibrations with the NILU data gave about the same simulated ANC results as with the EMEP data. In both cases the simulated ANC underestimated the observed increase in ANC between 1995 and 2019 (Figure 7). This was clearly the case for 105 of the 616 lakes that were forecast to have negative ANC in 2019, whereas only one of the lakes had observed negative ANC.

The increases in ANC from 1995 to 2019 were driven primarily by decreased concentrations of SO_4. The simulated changes in concentrations of SO_4 were generally less than the observed changes (Figure 6). When calibrated to the 1995 data, the simulated SO_4 concentrations in 2019 were lower than the observed (Figure 5, upper panels), and when calibrated to 2019 the simulated SO_4 concentrations in 1995 were equal or slightly higher than the observed (Figure 5). The picture is a bit unclear, however, due to several lakes that appear as outliers, perhaps due to internal sources or sinks of SO_4 in the catchment and lake, lag times between S deposition and SO_4 flux from the lake, and year-to-year variations in seasalt deposition. These factors are relatively more important in 2019 as the pollutant S deposition was much lower than in 1995.

The NILU deposition data gave somewhat better simulated SO_4 concentrations in the lakes relative to the EMEP deposition data (Figure 5). Of the four sets of calibrations, those to the 2019 data driven by the NILU deposition data give the best fit of the simulated to the observed SO_4 concentrations in the lakes in 1995.


With deposition data from EMEP

With deposition data from NILU

Figure 7. Simulated and observed concentrations in 2019 of ANC in 616 lakes with four successful calibrations by MAGIC. Left panels: calibrated to the 1995 or 2019 observed data using EMEP deposition data. Right panels: calibrated to the 1995 or 2019 observed data using NILU deposition data. Shown are data for the acid-sensitive lakes, i.e. those with ANC below 200 µeq/l in both 1995 and 2019. Excluded are lakes that had concentrations of non-marine SO_4 less than zero or more than 200 µeq/l. Solid lines (1:1); dotted lines (least-squares linear regression).

The explanation for the underestimated change in ANC appeared to lie in unexpected changes in cation concentrations. The simulated Ca concentrations in 2019 were lower than the observed (Figure 8). The simulated agreed well with the observed for the other three base cations (Mg, Na, K) (not shown).

The conventional view of the recovery process is that decreased S deposition gives reduced flux of SO_4 from the catchment to the lake, and the flux of cations also decreases. A fraction of the cation decrease is of the base cations (Ca is the most prominent), and a fraction is decrease in acid cations (H^+ and inorganic Al^{n+}). These concepts are central to MAGIC. The MAGIC simulations thus are expected to produce declines in Ca concentrations in lake that have had significant decreases in S* deposition over the period 1995 to 2019. MAGIC simulations would indicate no change in Ca concentration in lakes that have not had significant change in S* deposition.

The measured data indicate that the decrease in Ca concentration over the period 1995 to 2019 has been less than forecast by MAGIC (**Error! Reference source not found.**). MAGIC calibrated to the 1995 data and driven by either EMEP or NILU S deposition data underestimated concentrations of Ca. The unexpected higher concentrations of Ca were identified by (de Wit et al. 2023) in their analyses of the 1995 and 2019 surveys.

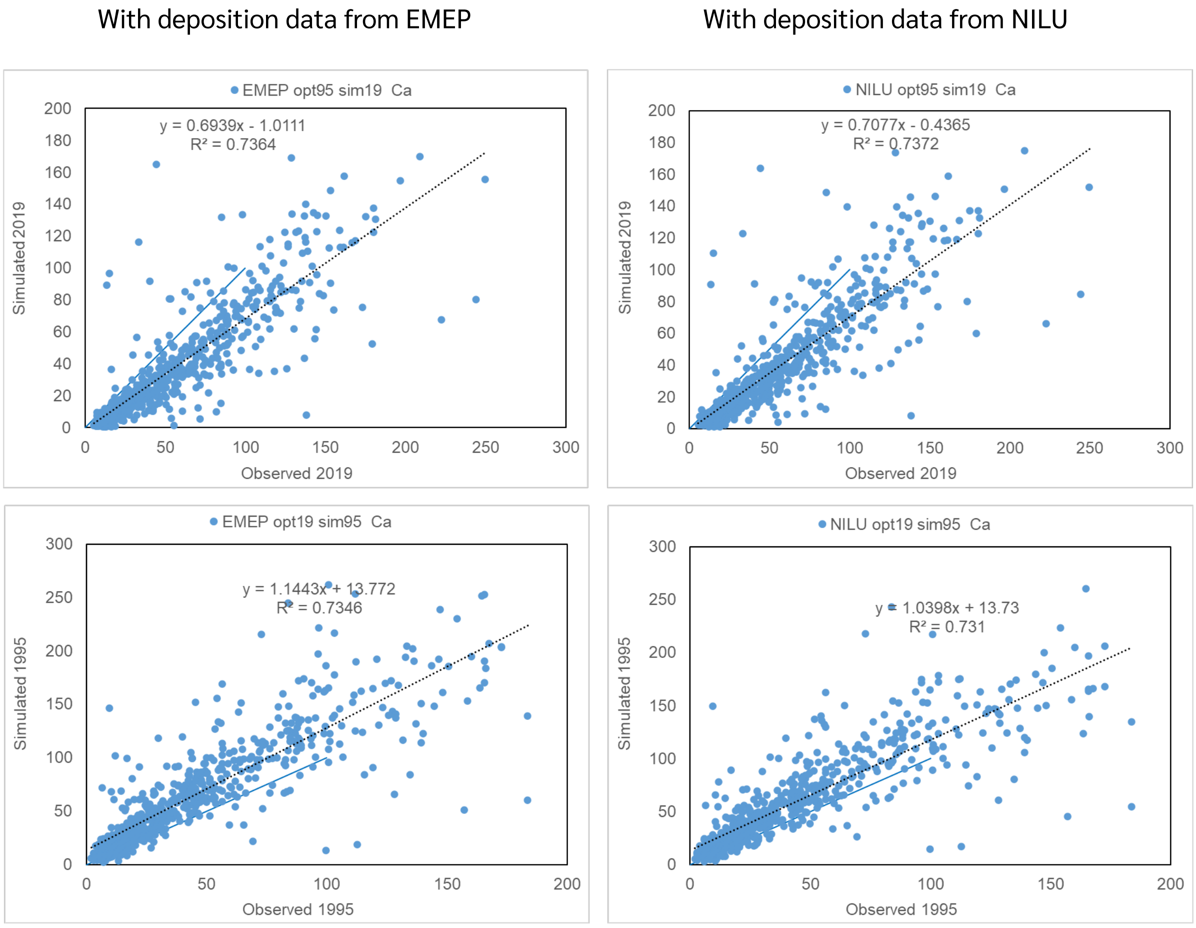


Figure 8. Simulated and observed concentrations in 2019 of Ca in 616 lakes with four successful calibrations by MAGIC. Left panels: calibrated to the 1995 or 2019 observed data using EMEP deposition data. Right panels: calibrated to the 1995 or 2019 observed data using NILU deposition data. Shown are data for the acid-sensitive lakes, i.e. those with ANC below 200 µeq/l in both 1995 and 2019. Excluded are lakes that had concentrations of non-marine SO_4 less than zero or more than 200 µeq/l. Solid lines (1:1); dotted lines (least-squares linear regression).

3.3 Forecasts to year 2030 and 2050

EMEP has updated prognoses for future S and N deposition for the years 2030 and 2050 given that the current legislation and other international agreements are fulfilled. For S* deposition the EMEP estimates indicate an 8% decrease from 2019 to 2030 and 10% decrease from 2019 to 2050. We ran the MAGIC calibrations to the observed 2019 data for the 1000 lakes to estimate future water chemistry in the lakes given these EMEP prognoses for future deposition. The results suggested only minor further improvements to ANC in the lakes from 2019 to 2030 and 2050 (Figure 9).

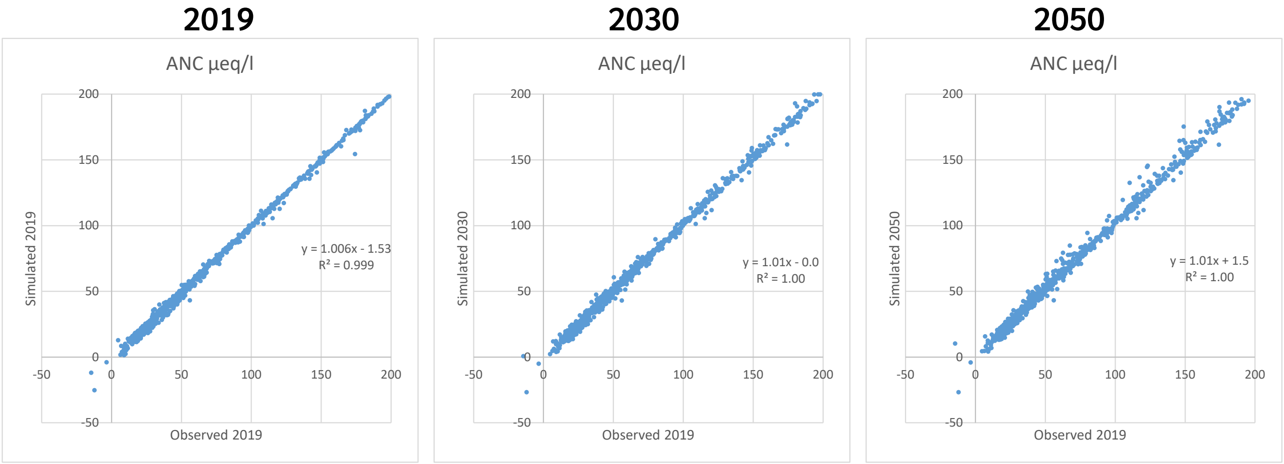


Figure 9. Simulated vs observed ANC (µeq/l) in 2019, 2030 and 2050 in 984 lakes calibrated to the observed 2019 data.

3.4 Simulated and observed lake water chemistry for 12 “trend” lakes

The observed changes in SO_4 concentrations in the 12 trend lakes show regional differences; SO_4 concentrations decreased markedly 1986 to 2019 in the 7 lakes in southern Norway and to a lesser extent to the 5 lakes in mid- and northern Norway (Figure 10). The lake St.Valvatnet (2030-607) in northeastern Norway on the Russian border appears clearly influenced by the S emissions from the smelters in Nikel. The simulated SO_4 concentrations from the calibration to the 1995 data (blue lines in figure 9) follow the observed closer than the simulations from the calibrations to the 2019 data (green lines in figure 9). This is probably due in part to the fact that small uncertainty in the 2019 observed SO_4 concentration will give a relatively large uncertainty in the back-calculated 1995 SO_4 concentration.

ANC concentrations have increased in the 7 trend lakes in southernmost Norway and also in the 5 lakes in mid- and northern Norway (Figure 11). The observed increases are larger than the simulated. This agrees with the conclusion from the entire 616 lake dataset that observed recovery has been greater than simulated.

Ca concentrations in the 7 lakes in southern Norway have declined somewhat over the period 1986-2019; the simulated concentrations gave greater declines than the observed (Figure 12). A portion of the observed recovery in ANC in these lakes is apparently due to more moderate declines in Ca concentration. Again, this agrees with the general picture obtained from the entire lake dataset.

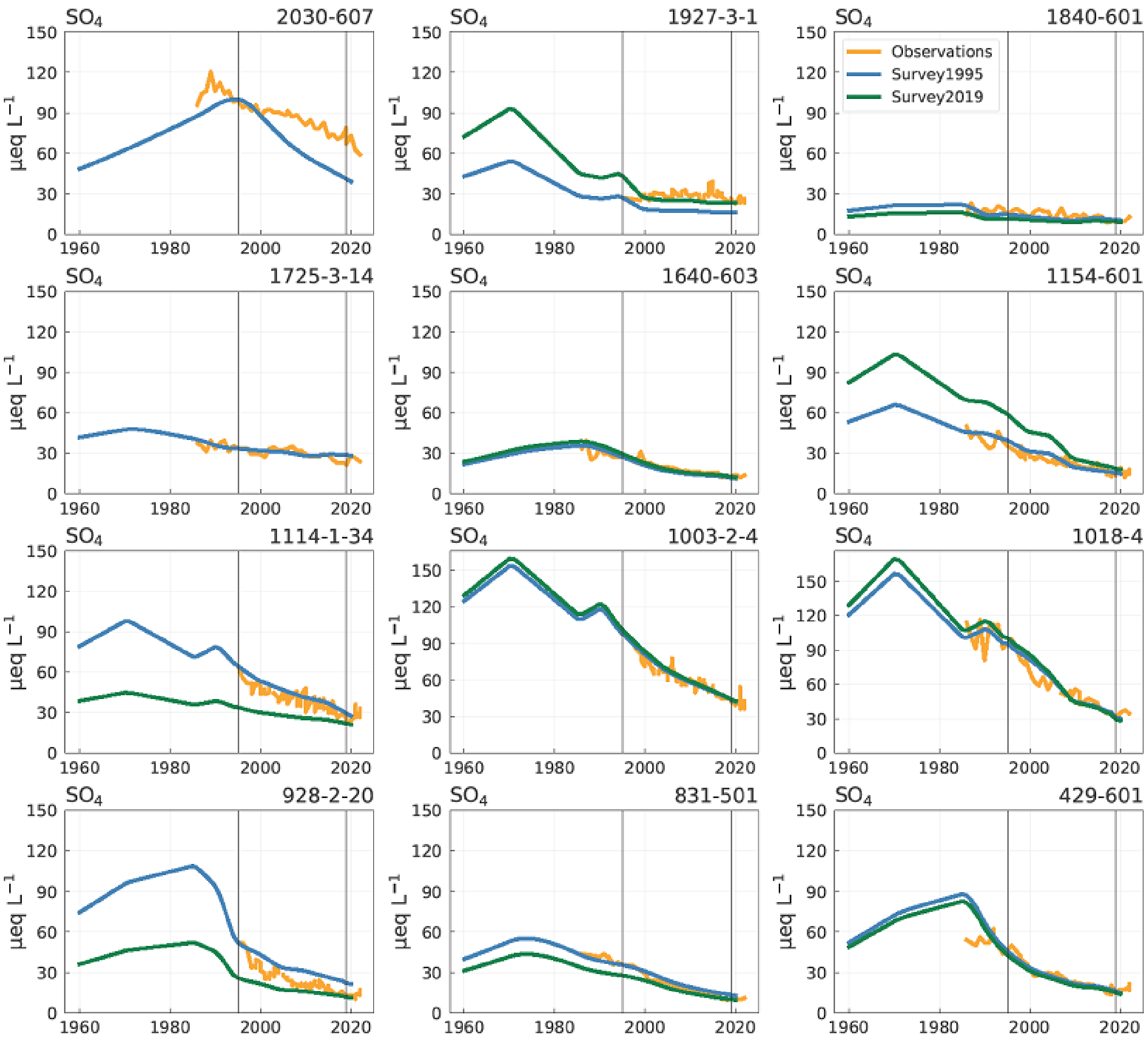


Figure 10. Simulated and observed SO₄ (µeq/l) in 12 trend lakes. Shown are simulations based on the 1995 survey (blue line) the 2019 survey (green line) and the observed (orange line). The vertical lines mark the years 1995 and 2019.

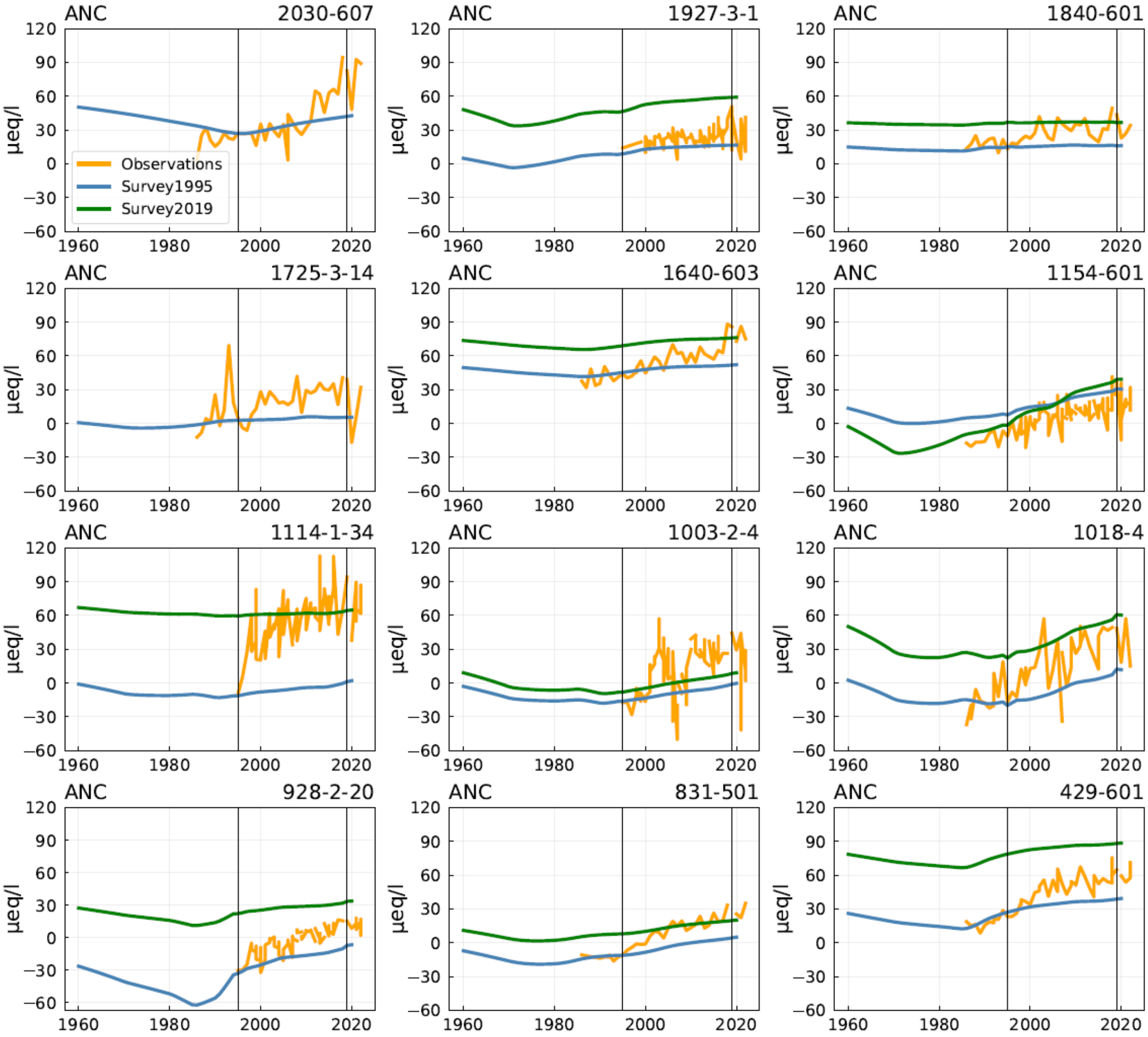


Figure 11. Simulated and observed ANC (µeq/l) in 12 trend lakes. Shown are simulations based on the 1995 survey (blue line) the 2019 survey (green line) and the observed (orange line). The vertical lines mark the years 1995 and 2019.

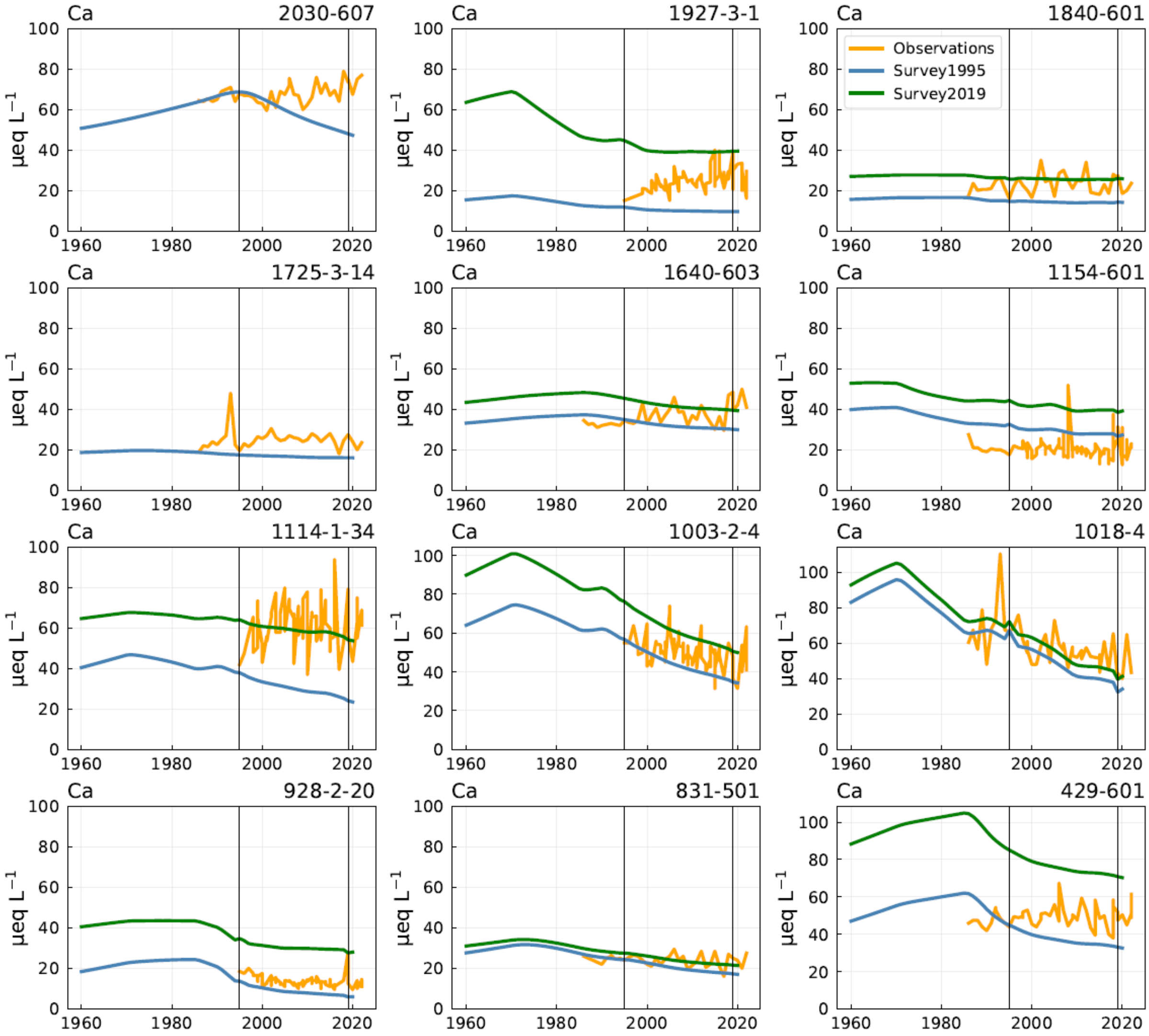


Figure 12. Simulated and observed Ca (µeq/l) in 12 trend lakes. Shown are simulations based on the 1995 survey (blue line) the 2019 survey (green line) and the observed (orange line). The vertical lines mark the years 1995 and 2019.

4 Conclusions and recommendations

In this report we present the results from applying the MAGIC model to the data from the 1995 and 2019 Norwegian "1000-lake surveys". The work has the following conclusions:

- Estimates of S and N deposition derived from NILUs network of monitoring stations has been obtained from NILU and used as inputs to the MAGIC simulations. The deposition data from NILU gave slightly better simulated results (compared to the observed) than those with the deposition estimates from EMEP used in 2022.
- The simulations captured the observed decreases in SO_4 concentrations and the increases in ANC in acid-sensitive lakes. But the observed recovery in ANC was somewhat greater than expected.
- The simulations underestimated the observed Ca concentrations in acid-sensitive lakes in 2019, which indicates that other factors than reduced SO_4 have affected the Ca trend since 1995.
- Predictions for ANC in 2030 and 2050 showed only minor changes compared to 2019.
- The simulations are supported by annual data 1986-2020 from the 12 "trend" lakes that were included in the 1000-lake surveys.

For future work we recommend the following:

- The calibrations to the 2019 data driven by the deposition data from NILU should be used for future work. The NILU data are preferred as they are based on measured deposition, they extend back to 1978, and they indicate a lower total acid stress over the entire acidification period starting in the 1800s.
- The MAGIC calibrations to the 2019 data offer a platform for a possible extension of the Swedish "MAGIC bibliotek" to also include Norwegian lakes.
- The calibrations provide a basis for evaluating and forecasting scenarios of future climate and land-use changes.

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