7. An application of the MAGIC model to four high altitude lakes in Ticino, Switzerland

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1. Introduction

This report presents the results of a modelling exercise applied to four high altitude lakes in the Ticino region, Switzerland. In this area, acidification of high-altitude lakes situated in granitic areas was first reported in the early 1980s, as an effect of acid deposition (Mosello et al., 1992). Successively, as an effect of decreasing emission and deposition of acidifying compounds, several lakes showed signs of acidification recovery (Steingruber & Colombo, 2010a).

The aim of the modelling was to reconstruct and predict lake chemistry in response to atmospheric deposition change. The applied model is MAGIC, which was specifically developed for the long term reconstruction and future prediction of soil and surface water acidification at the catchment scale (Cosby et al., 2001).

The study lakes were selected on the basis of available data for the model application, and in order to be representative of the high altitude lake population in the Ticino region. They span a wide range of chemical characteristics and cover varying level of sensitivity to acidification, from highly (Starlaresc, Tomè) to moderately sensitive (Laghetto Inferiore, Laghetto Superiore) lakes.

This study represents the first attempt to model long term changes in lake water chemistry, trying to evaluate the effective level of recovery (in terms of pH, ANC or other key variables) with respect to pre-acidification conditions. The model allowed a reconstruction (hindcast) of lake chemistry since 1960, and a prediction (forecast) for the period 2010-2050. The projections of future lake chemistry were obtained by applying different scenarios of atmospheric deposition reduction.

2. Study lakes

The characteristics of the lakes selected for the modelling (Fig. 1) are shown in table 1, while their average chemical characteristics (mean values of 2010-2011) are shown in table 2. Lake Starlaresc (STA) and Tomè (TOM) have low pH and alkalinity values (5.6-5.7 and 3-4 µeq L⁻¹, respectively), and may be considered representative of the category of highly sensitive lakes. Indeed ANC levels below 20 µeq l⁻¹, as those affecting these lakes, are usually assumed as “critical” for the biota and indicative of a high acidification risk. On the other hand Laghetto Inferiore (LAI) and Superiore (LAS) may be classified as moderately sensitive, with ANC values between 30 and 40 µeq L⁻¹.

<table>
<thead>
<tr>
<th>Lake</th>
<th>Acronym</th>
<th>Lat.</th>
<th>Long.</th>
<th>Alt.</th>
<th>Catchment area</th>
<th>Lake area</th>
<th>Max depth</th>
<th>Catchment cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starlaresc da Sgiof</td>
<td>STA</td>
<td>8°46′25″</td>
<td>46°16′26″</td>
<td>1875</td>
<td>23</td>
<td>1.1</td>
<td>6</td>
<td>29 67</td>
</tr>
<tr>
<td>Tomè</td>
<td>TOM</td>
<td>8°41′23″</td>
<td>46°21′47″</td>
<td>1692</td>
<td>294</td>
<td>5.8</td>
<td>38</td>
<td>57 41</td>
</tr>
<tr>
<td>Laghetto Inferiore</td>
<td>LAI</td>
<td>8°35′34″</td>
<td>46°28′34″</td>
<td>2074</td>
<td>182</td>
<td>8.3</td>
<td>5.6</td>
<td>65 27</td>
</tr>
<tr>
<td>Laghetto Superiore</td>
<td>LAS</td>
<td>8°35′05″</td>
<td>46°28′34″</td>
<td>2128</td>
<td>125</td>
<td>12.7</td>
<td>8.3</td>
<td>65 29</td>
</tr>
</tbody>
</table>

Tab. 1 – Main characteristics of the lakes selected for the modelling and their catchments.
The study lakes have been monitored for water chemistry since the 1980s, so that a long term series of chemical data exist. Similarly, atmospheric deposition chemistry has been studied in the Ticino region since the late 1980s and a network of 9 sites is still operating (Steingruber & Colombo, 2010b).

Fig. 1: Lakes selected for the modelling. a) Starlaresc da Sgiof; b) Tomè; c) Laghetto Inferiore; d) Laghetto Superiore (Pictures by G.A. Tartari & M. Veronesi).

<table>
<thead>
<tr>
<th>Lake</th>
<th>pH</th>
<th>Cond. µS cm⁻¹</th>
<th>Alk µeq L⁻¹</th>
<th>BC µeq L⁻¹</th>
<th>SO₄ µeq L⁻¹</th>
<th>NO₃ µeq L⁻¹</th>
<th>Cl µeq L⁻¹</th>
<th>Si mg L⁻¹</th>
<th>DOC mg C L⁻¹</th>
<th>Al tot µg L⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>STA</td>
<td>5.59</td>
<td>7.2</td>
<td>4</td>
<td>48</td>
<td>26</td>
<td>17</td>
<td>3</td>
<td>0.73</td>
<td>0.9</td>
<td>52</td>
</tr>
<tr>
<td>TOM</td>
<td>5.66</td>
<td>7.8</td>
<td>3</td>
<td>61</td>
<td>27</td>
<td>27</td>
<td>3</td>
<td>1.0</td>
<td>0.4</td>
<td>25</td>
</tr>
<tr>
<td>LAI</td>
<td>6.79</td>
<td>8.4</td>
<td>36</td>
<td>85</td>
<td>27</td>
<td>13</td>
<td>2</td>
<td>0.75</td>
<td>0.6</td>
<td>17</td>
</tr>
<tr>
<td>LAS</td>
<td>6.78</td>
<td>7.9</td>
<td>35</td>
<td>81</td>
<td>23</td>
<td>12</td>
<td>3</td>
<td>0.66</td>
<td>0.7</td>
<td>12</td>
</tr>
</tbody>
</table>

Tab. 2 – Mean chemical characteristics (2010-11) of the selected lakes. Cond.: conductivity at 20 °C. Alk: alkalinity. BC: sum of base cations (Ca²⁺, Mg²⁺, Na⁺, K⁺). Si: Reactive silica. DOC: dissolved organic carbon.

2.1. MAGIC calibration and application to the study sites

In this study the dynamic acidification model MAGIC version 777 was used. The main peculiarities in the study area (Southern Switzerland), where the studied sites are located, are:
1. the climate features, with high amount of deposition due to the orographic effect and at the same time high load of N and S compounds due to the location of the area north to the Po plain in Italy (Steingruber & Colombo, 2010a);
2. the heterogeneity in the lithological, vegetation and soil cover in the lake catchments;
3. the chemical characteristics of lake water, showing very low solute concentrations and limited buffer capacity, due to the dominance of acidic, low weatherable rocks in the catchments.

The target year chosen for the calibration was 2010. Atmospheric deposition chemical data were mean values of 2009-2011, and precipitation volume (2200 mm) was the long-term average of the period covered by available data at Robiei (1996-2011). The hindcast period was of 150 years (1860-2010) and the forecast simulations were run for 20 years (2011-2030).

2.2. Scale factors for atmospheric deposition

The study lakes are all located in the cell i=70, j=38 of the EMEP grid (50 km x 50 km). Deposition sequences for this cell covering the period 1980-2010 are available from the WebDab-EMEP DB. Successively, to reconstruct the scale factors for the whole hindcast period (since 1860), the “historical” deposition data, provided by the Coordinating Centre for Effects (CCE) of the ICP Modelling & Mapping, were used. These data were issued in 2011 for selected ICP WATERS sites in the framework of the so-called “ex-post analysis” (Wright et al., 2011).

Data issued by CCE also included deposition scenarios for the period 2010-2030. These scenarios are COB 2020 (current legislation), and MFR 2020 (maximum feasible reduction).

Because the study lakes in Ticino are part of the ICP WATERS network, two scenarios in the present modelling exercises were applied, so that this report may be a further contribution to the evaluation of the effects of potential future deposition reduction on surface waters. Sulphate deposition is supposed to decrease of 37% and 55% with respect to the present level (2010) under the COB and MFR scenarios respectively. A relevant reduction is foreseen also for oxidised N deposition, which will decrease of 34% and 38% under COB and MFR, respectively. On the other hand, reduced N deposition will change slightly (5%) under the current legislation; only implementing the maximum feasible technologies a 38% reduction may be achieved.

3. Results and discussion

3.1. Calibration and hindcast

Generally a good agreement between modelled and measured concentrations of SO4, NO3 and base cations was achieved at all sites. The study lakes showed slightly different SO4 pattern, with the highest maxima (100-110 µeq L-1) at the most acidified sites STA and TOM. Base cations decreased in the lakes, as an effect of the acidification recovery: as simulated by the model, leaching of BC increased in correspondence with the increase of acidifying anion, and peaked in the 1980s. Afterwards a decreasing trend began, more evident at the most acidified sites. A negative trend also affected nitrate concentrations in lakes, even if measured values are much more scattered with respect to SO4 or BC. This is related to the fact the N compounds are affected by biological processes taking place both in the soil and in lake water. With respect to sulphate, measured NO3 did not show a clear decreasing trend: concentrations tend to be lower only in the last few years of the record (2008-2010). This is related to the fact that atmospheric input of N did not change as the same rate as S deposition in the study area.

The decrease of NO3 in lake water is more evident in LAS and LAI, where concentrations passed from about 25 to 10-15 µeq L-1. TOM is the lake showing the highest present concentrations of NO3 (25 µeq L-1 as mean value of 2010-11). This can be due to the larger catchment area and the higher catchment.

3.2. Forecast simulation

The future changes in lake chemistry according to three different scenarios are compared in fig. 2 for Lake Starlarasc da Sgiof. MFR represents the best case scenario with the emission reduction offered by a full implementation of the best available technologies. The COB or “current Legislation” scenario reflects the current perspectives of individual countries (Cofala et al., 2006).

As can be expected, the greatest improvement in the lake chemical status is foreseen under the background deposition scenario, followed by MFR and COB for all the variables considered. Under the Bkgd scenario, lakes will essentially recover to the pre-acidification condition, with pH and ANC coming back to the values of the early 1900s.
Fig. 2 – Simulated (MAGIC) and observed (Obs) pH-, ANC, sulphate and nitrate values in the Starlaresc da Sgiof lake. Three deposition scenarios are considered: COB2020 (actual legislation, including the Gothenburg Protocol), MFR2020 (maximum feasible reduction) and Bkgd (background deposition only).

The relative changes in the values of the chemical variables between 2020 and 2010 under the various scenarios are shown in tab. 3. Lakes STA and TOM, which have been affected by a more pronounced acidification in the 1980s, showed a more evident recovery pattern with respect to LAS and LAI: for instance ANC passed from strongly negative values (-20 µeq L\(^{-1}\)) to positive ones (0-5 and 0-10 µeq L\(^{-1}\) in STA and TOM, respectively). ANC will more than double by 2020 in both the two lakes (Tab. 3). However, safety values of ANC (above 20 µeq L\(^{-1}\)) would be reached only under the MFR scenario. In the more realistic hypothesis of the COB scenario the two lakes will recover to ANC values around 15 µeq L\(^{-1}\). In Europe the value of 20 µeq L\(^{-1}\) has been identified as the level needed to meet the critical loads exceedance target under UNECE protocols and a 30 µeq L\(^{-1}\) value estimated as the pre-acidification reference value. It has to be emphasised that the most sensitive lakes STA and TOM would never reach ANC values above 40 µeq L\(^{-1}\), even under the hypothesis of background deposition. Hence specific target values for this category of lakes (with extremely dilute, low buffered waters due to crystalline bedrock) should have been identified.

The recovery rates, in terms of pH and ANC values, have been markedly lower in LAI and LAS with respect to STA and TOM. ANC has probably never reached negative values in the lakes, and it recovered to values above 40 µeq L\(^{-1}\) in recent years (up to 60-70 µeq l\(^{-1}\) in LAS).

As to sulphate, most of the expected change in response to decreasing deposition has already taken place in the lakes (within 1980 and 2010). However, the decrease of concentration will continue also in the next two decades, and it will be of about 30-40% and 40-50% with respect to the present levels under the COB and MFR scenarios, respectively (Tab. 3).

The biggest differences among the considered scenarios are found in the forecast of NO\(_3\) concentrations. Indeed both COB and MFR foreseen a decrease of NO\(_x\) and NH\(_3\) emissions, but these are still far from the estimated levels of background deposition. In particular, NH\(_3\) emissions are supposed to decrease slightly under the COB scenario (only 5% with respect to present level). NO\(_3\) levels will decrease to about 10 µeq L\(^{-1}\) in LAS and LAI by 2020; they will remain slightly higher (13 µeq L\(^{-1}\) under the COB scenario) in STA, and above 20 µeq L\(^{-1}\) in TOM.
N deposition will be the dominant driving force in the acidification of the study lakes in the next future (Curtis et al., 2005). Ammonium deposition will be particularly important, since it represents now the dominant form of N in atmospheric deposition in the study area (Rogora et al., 2012). For this reason, the MAGIC model was also run assuming (i) progressive decrease of NO$_3$ deposition (from -20% to -50% in 2020 with respect to 2010, and no change in NH$_4$ deposition) and (ii) progressive decrease of both NO$_3$ and NH$_4$ deposition (Fig. 3). Only the most sensitive lake STA was considered. The aim of this modelling exercise was indeed to put in evidence the relative gain of reducing both oxidised and reduced N deposition with respect to changing NO$_3$ deposition only.

Tab. 3 – Relative changes (%) in the values of ANC, SO$_4$, NO$_3$ and base cations (BC) in 2020 (and 2030) with respect to the present status (2010) under the three scenarios.

The results clearly show the necessity to reduce both forms of N deposition if a significant change in the ANC levels has to be obtained. The relative gain of a coupled reduction compared to NO$_3$ reduction only in terms of ANC in the lake is between 1.5 (20% emission decrease in 2020) and 3.7 (50% emission decrease) µeq L$^{-1}$. Despite the decrease of NO$_3$ concentrations foreseen for the next future, NO$_3$ levels in the lakes will remain quite high (10-20 µeq L$^{-1}$). The study area is affected by high N deposition with respect to those found in other parts of the Alps or in other mountain areas of the world (Rogora et al., 2006; 2008). Hence N emission in the source region located in the lowlands...
has necessarily to be reduced to reach a substantial decline of N deposition in the alpine and subalpine areas of both Italy and Switzerland and a further decrease of NO\(_3\) levels in alpine lakes.

4. Concluding remarks

This modelling exercise represents the first application of the dynamic model MAGIC to high altitude lakes in the Ticino area. Previous application of MAGIC to other high altitude lakes in the Central Alps (Rogora 2004; Rogora et al., 2003a) as well as application of the SMB and FAB models to the Ticino lakes (Posch et al., 2007) already put in evidence the usefulness of dynamic modelling for both hindcast and forecast ecosystem response to atmospheric deposition scenarios. In the Ticino area several lakes are still acidic or present a high sensitivity to acidification (Steingruber & Colombo, 2010a). MAGIC was successfully calibrated for a few lakes in this area, representative of varying levels of sensitivity to acidification. The model allowed a reconstruction of pre-acidification condition and a simulation of the future chemical changes in lake water in relation to different deposition scenarios, as those adopted in the so-called “ex-post analysis” performed within the ICP WATERS (Wright et al., 2011).

The output of the modelling confirmed a rather critical situation for the most sensitive lakes, with ANC values which will remain below the critical limit of 20 µeq L\(^{-1}\) in the next decades according to the most realistic scenario. This study also put in evidence that the ANC critical levels normally adopted in the evaluation of acidification recovery are probably too low for this category of lakes. The simulations performed with MAGIC clearly demonstrated the benefits of achieving the emission reductions in both S and N agreed under the Gothenburg Protocol. But current levels of S and particularly N emissions must be reduced even more to protect freshwaters from episodic acidification and guarantee a stable recovery. The modelling results put in evidence the relevance of N deposition in determining the present status of the lakes and their chemical evolution in the next two decades. Beside atmospheric deposition, other actors affect the long-term changes in surface water chemistry. Alpine lakes in particular have proved to be highly sensitive to climate change (e.g. Psenner & Schmidt, 1992; Rogora et al., 2003b; Hobbs et al., 2001). A further step in the modelling of high altitude lake chemistry could be an attempt to incorporate and represent climate change and its impacts using dynamic modelling, as done for instance by Wright et al. (2006).

References


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