Water ecosystems affected by human impact within the protected area of the Tatra National Park (Poland)

Iwona Kurzyca¹*, Adam Choiński², Alfred Kaniecki², Jerzy Siepak¹

¹Department of Water and Soil Analysis, Adam Mickiewicz University
ul. Drzymały 24, 60-613 Poznań, Poland
²Department of Hydrology and Water Management
Adam Mickiewicz University
ul. Dziegielowa 24, 61-680 Poznań, Poland

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Abstract

The subjects of the study were two high-mountain lakes, Morskie Oko and Czarny Staw pod Rysami, in the Tatra range of the Carpathian Mountains located within the protected area of the Tatra National Park. This paper presents results of the analytical study of the lake water composition and compares this with relevant data from earlier years. The impact of the following factors was distinguished and discussed: atmospheric deposition (dry and wet), migration of pollutants with runoff water supplying both reservoirs, tourism (hiking, climbing), and the influence of mountain hostels. The resistance and sensitivity of the lakes to human impact is described in terms of water quality changes and characteristics of the catchments and the region.
INTRODUCTION

The Tatra National Park (TPN) is the area of profound natural value within which natural habitats, plant communities, animals, various features of the mountain landscape, including water reservoirs and water-courses, are protected. However, this area is exposed to particularly strong and long-lasting anthropogenic pressure of a diverse character.

Mountainous areas receive larger quantities of pollutants relative to lowlands because of the orographic effects (Kopacek et al. 2005). Morphological characteristics of the area as well as climatic conditions are conductive to the intensification of the atmospheric deposition of pollutants. Air masses, easily halted above mountain peaks contribute dry deposition, whereas abundant atmospheric precipitation and hazes additionally favor the wash-out of pollutants from the atmosphere (wet deposition). Snow cover (lasting over half of the year and absorbing considerable amount of pollutants) also contributes largely to the overall contamination of lake water, because melting snows is one of the main sources of their water supply (Mirek 1996).

In the 1980s and 1990s this area was exposed to particular acidification caused by industrial pollution emitted by industrial districts and coal-mines located either in the immediate vicinity or farther away. In these decades, NO₂ and SO₂ emissions were 280 and 160 mmol m⁻² y⁻¹, respectively (Kopacek et al. 2004). However, by the late 1990s, emission levels had fallen to 75 and 90 mmol m⁻² y⁻¹, respectively, by reducing pollutant emission according to the terms of the Gutenberg Protocol signed by Poland and neighboring countries (Kopacek et al. 2004).

The atmospheric deposition of acidifying pollutants is particularly dangerous to Tatra lakes because of their small buffer capacity related to the low mineralization of the water and the specific geological structure of the drainage area (Rzychoń 1998). A study of European mountain lakes also meet all these conditions (Wilander 2005).

Water ecosystems in the Tatra Mountains are subjected to various forms of anthropogenic stress. Eutrophication caused by nutrient enrichment occurs as a result of the effect of the structure and shape of the drainage area, the type of flora occurring there, water body characteristics, stocking, high intensity mountain tourism, and the location of mountain hostels (Czocharański and Borowiak 2000, Kownacki et al. 2002).

The aim of this study was to determine the current chemical composition of the water from lakes Morskie Oko and Czarny Staw (the Tatra National Park) and to assess the effect of human impact on these water ecosystems.
MATERIALS AND METHODS

Characteristic of the study area

The lakes Czarny Staw and Morskie Oko lie on the northern side of the High Tatra Mountains in the Rybi Potok Valley and are surrounded by the highest peaks of the Polish Tatra Mountains. These two reservoirs are situated in the area of the springs of Rybi Potok in the granite range of the Tatra Mountains and occupy the lowest parts of the post-glacial hollows closed with a rock step (Czarny Staw) or moraine step (Morskie Oko). The borders of the post-glacial cirques and lower parts of the slopes are covered with stone rubble and glacial till. As far as Morskie Oko is concerned, dwarf pine separated by naked scree reaches its rim. The main characteristics of these are presented in Table 1. The first bathymetric measurements of the lakes in the Tatra Mountains were made in 1934 (Śliwierski 1934), while the maximum depths of these lakes were measured by Choiński (Choiński 2000). According to the area occupied, Lake Morskie Oko is the largest lake in the Tatra Mountains and Czarny Staw is the third largest, whereas according to the depth, Czarny Staw is the second and Morskie Oko is the fifth deepest lake.

Table 1

<table>
<thead>
<tr>
<th>Lake</th>
<th>Altitude [m a.s.l.]</th>
<th>Volume [10^3 m³]</th>
<th>Maximum depth [m]</th>
<th>Lake area [ha]</th>
<th>Catchment area [ha]</th>
<th>Catchment area of rock [%]</th>
<th>moraine [%]</th>
<th>meadow [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morskie Oko</td>
<td>1395</td>
<td>9935</td>
<td>51.8</td>
<td>34.9</td>
<td>595</td>
<td>40</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Czarny Staw</td>
<td>1580</td>
<td>7762</td>
<td>77.0</td>
<td>20.6</td>
<td>158</td>
<td>50</td>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>

These two reservoirs are supplied mainly by precipitation, directly and indirectly from surface runoff and rock mantle runoff. Great contribution to the lake water supply comes from snow and ice melt. The area where the lakes lie is in the zone of the highest annual precipitation in Poland. Mean, annual precipitation is usually greater than 1600 mm, and in the period from May to October, precipitation is over 1000 mm. The contribution of solid precipitation (e.g. snow, hail) to the mean annual precipitation is as high as 24%.

The mean annual specific runoff is close to 50 dm³ s⁻¹ km⁻², which corresponds to an annual runoff layer of about 1500 mm, which is the highest in Poland. The denudation runoff index exceeds 100 t km⁻², and is also the highest in Poland.
The unique character of these lakes is manifested by the exceptional transparency of their waters. The transparency of Czarny Staw measured with a Secchi disk by Choiński (Choiński 2000) on Sept. 15, 1999 was 23.0 meters, which was the greatest measured in Poland. The transparency of Morskie Oko was lower at 15 meters, which was related to the fact that the catchment area of Morskie Oko is much larger so it received greater loads of suspensions.

Methods

Water samples were collected three times in 2006; in spring (April) from under the ice cover, in summer (June), and in fall (September) from the surface. Samples were collected from the surface at a distance of 5 m from the shoreline. Measurements of pH (pH-meter Elmetron PT-215; Poland) and electric conductivity (conductometer Commet 1; USA) were taken at the collection site. Then the samples were placed in polyethylene vessels and transported to the laboratory where they were filtered (0.45 μm) and subjected to chromatographic analysis. During transport and prior to analyses, the samples were stored at +4°C in darkness. Their ionic composition was determined on an ion chromatograph (Dionex 120; USA) with conductometric detection. The anions determined included F-, Cl-, NO₃-, PO₄³⁻, SO₄²⁻ and the cations Na⁺, K⁺, Mg²⁺, Ca²⁺, NH₄⁺. In order to verify the traceability and to evaluate the correctness and accuracy of the physicochemical analyses, a series of measurements was performed on certified reference material with satisfactory results. A detailed description of the experimental methods, their calibration, and validation can be found elsewhere (Walna 2004).

RESULTS AND DISCUSSION

The analysis of the water samples from Morskie Oko and Czarny Staw pod Rysami indicates some similarities (Table 2). The parameters describing physicochemical characteristics of water samples collected in the summer and fall in the two lakes were of similar ranges. The parameters characterizing the samples collected during the thaw season took elevated values in the two lakes studied, because of the effect of ice-cover and snow-cover melting and intensive runoff into lakes basins.

The pH values measured ranged from 5.9 to 7.1 for Morskie Oko and 5.9 to 6.9 for Czarny Staw. Usually, the slightly lower pH of Czarny Staw water corresponded to its higher electric conductivity. The electric conductivity was very low for the samples from both reservoirs and did not exceed 30 μS cm⁻¹, which was evidence of their low mineralization.
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Similar values of pH, as well as electric conductivity were noted in the samples from the Rybi Potok in the section linking both reservoirs and at the outflow from Morskie Oko.

All samples had low concentrations of fluorides that did not exceed 20 μg l⁻¹. As far as other acid-forming ions are concerned, in the summer and fall water samples from Czarny Staw the contents of sulphate and nitrate ions were higher and the content of chloride ions was lower than in the water of Morskie Oko. A comparison of the current data with those available from earlier years was made only for the samples collected in summer and fall as previously measurements were made mainly during this period (Table 3). As follows from this table, concentrations of chloride, sulphate, and nitrate ions have decreased in recent years. The maximum concentrations of these ions were noted in the 1980s, which is also the period in which the highest depositions of these ions were noted in the area (Fig. 1). This fact was also mentioned by Kopacek et al. (2002, 2005) and Stuchlik et al. (2006). The reduction of depositions of these pollutants observed from the early 1990s led to a gradual decrease in the concentrations of SO₄²⁻ and Cl⁻, and a recovery of the water of Morskie Oko and Czarny Staw was observed, as evidenced by the study with the MAGIC model (Kopacek et al. 2004). Nevertheless, the concentrations of the NO₃⁻ ions in the water of both lakes are still distressingly high, along with an elevated level of NH₄⁺ (Table 3).

Concentrations of nitrites in the Tatra Mountains lake water correlated negatively with parameters characterizing catchment-weighted mean pools of soil, i.e., with the percent of land cover with meadow and soil depth, and

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**Table 2**

Concentrations of particular ions in April, June, September 2006 in Morskie Oko and Czarny Staw pod Rysami [mg l⁻¹].

<table>
<thead>
<tr>
<th>Month 2006</th>
<th>F⁻</th>
<th>Cl⁻</th>
<th>SO₄²⁻</th>
<th>NO₃⁻</th>
<th>NH₄⁺</th>
<th>Na⁺</th>
<th>K⁺</th>
<th>Mg²⁺</th>
<th>Ca²⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Morskie Oko</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>0.015</td>
<td>0.59</td>
<td>2.54</td>
<td>2.21</td>
<td>0.09</td>
<td>0.37</td>
<td>0.11</td>
<td>0.07</td>
<td>1.61</td>
</tr>
<tr>
<td>June</td>
<td>0.014</td>
<td>0.27</td>
<td>3.01</td>
<td>1.71</td>
<td>0.03</td>
<td>0.33</td>
<td>0.09</td>
<td>0.09</td>
<td>3.12</td>
</tr>
<tr>
<td>September</td>
<td>0.020</td>
<td>0.26</td>
<td>2.94</td>
<td>1.50</td>
<td>0.02</td>
<td>0.35</td>
<td>0.10</td>
<td>0.10</td>
<td>3.78</td>
</tr>
<tr>
<td><strong>Czarny Staw pod Rysami</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>April</td>
<td>0.003</td>
<td>0.89</td>
<td>2.82</td>
<td>1.90</td>
<td>0.29</td>
<td>0.31</td>
<td>0.20</td>
<td>0.20</td>
<td>0.58</td>
</tr>
<tr>
<td>June</td>
<td>0.011</td>
<td>0.21</td>
<td>3.13</td>
<td>1.98</td>
<td>0.01</td>
<td>0.24</td>
<td>0.07</td>
<td>0.10</td>
<td>3.21</td>
</tr>
<tr>
<td>September</td>
<td>0.012</td>
<td>0.18</td>
<td>3.12</td>
<td>1.86</td>
<td>0.02</td>
<td>0.26</td>
<td>0.07</td>
<td>0.09</td>
<td>3.45</td>
</tr>
</tbody>
</table>

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positively correlated with the grade of the terrain, annual precipitation, and the highest elevation in the catchment (Kopacek et al. 2005). High-mountain catchments with their sparse and thin soils usually exhibit limited ability to retain N and are extremely sensitive to elevated N deposition (Williams et al. 1996), which may cause transition from N-limitation to N-saturation status (Stoddard et al. 1994). This problem is really important because of the nitrogen overloading of the natural environment (Galloway 1998).

The deposition of other cations analyzed, including Na⁺, K⁺, Mg²⁺, Ca²⁺, has also decreased from the maximum values observed in the 1980s (Fig. 1). The samples collected in the summer and fall of 2006 contained very low concentrations of potassium and magnesium; in Czarny Staw they were 0.07 mg l⁻¹ and 0.10 mg l⁻¹ respectively, while in Morskie Oko they were 0.10 mg l⁻¹ and 0.10 mg l⁻¹, and slightly higher concentrations of Na⁺, of 0.35 mg l⁻¹ were noted in Morskie Oko and 0.25 mg l⁻¹ in Czarny Staw. The concentrations of calcium ions were much higher at 3.45 mg l⁻¹ in Morskie Oko and 3.30 mg l⁻¹ in Czarny Staw.

**Table 3**

Comparison of concentrations of particular ions in the two lakes studied [mg l⁻¹].

<table>
<thead>
<tr>
<th></th>
<th>F⁻</th>
<th>Cl⁻</th>
<th>SO₄²⁻</th>
<th>NO₃⁻</th>
<th>NH₄⁺</th>
<th>Na⁺</th>
<th>K⁺</th>
<th>Mg²⁺</th>
<th>Ca²⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Morskie Oko</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1963ᵇ</td>
<td>-</td>
<td>0.79</td>
<td>1.57</td>
<td>1.62</td>
<td>0.03</td>
<td>0.47</td>
<td>0.08</td>
<td>0.64</td>
<td>4.27</td>
</tr>
<tr>
<td>1985ᵇ</td>
<td>-</td>
<td>1.43</td>
<td>4.17</td>
<td>2.69</td>
<td>0.29</td>
<td>-</td>
<td>-</td>
<td>0.71</td>
<td>4.34</td>
</tr>
<tr>
<td>1991ᶜ</td>
<td>-</td>
<td>0.30</td>
<td>4.50</td>
<td>0.55</td>
<td>-</td>
<td>0.42</td>
<td>0.15</td>
<td>0.20</td>
<td>4.40</td>
</tr>
<tr>
<td>1994ᵈ</td>
<td>-</td>
<td>0.20</td>
<td>3.84</td>
<td>0.70</td>
<td>-</td>
<td>0.90</td>
<td>0.30</td>
<td>0.19</td>
<td>5.40</td>
</tr>
<tr>
<td>1994⁹</td>
<td>-</td>
<td>0.21</td>
<td>3.46</td>
<td>1.86</td>
<td>-</td>
<td>0.37</td>
<td>0.09</td>
<td>0.15</td>
<td>4.12</td>
</tr>
<tr>
<td>2000ᶠ</td>
<td>-</td>
<td>0.20</td>
<td>2.70</td>
<td>1.51</td>
<td>0.05</td>
<td>0.43</td>
<td>0.12</td>
<td>0.16</td>
<td>3.64</td>
</tr>
<tr>
<td>2006ᵍ</td>
<td>0.017</td>
<td>0.27</td>
<td>2.98</td>
<td>1.61</td>
<td>0.03</td>
<td>0.34</td>
<td>0.10</td>
<td>0.10</td>
<td>3.45</td>
</tr>
<tr>
<td><strong>Czarny Staw pod Rysami</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1991ᶜ</td>
<td>-</td>
<td>0.25</td>
<td>5.25</td>
<td>0.67</td>
<td>-</td>
<td>0.36</td>
<td>0.14</td>
<td>0.19</td>
<td>4.79</td>
</tr>
<tr>
<td>1994ᵈ</td>
<td>-</td>
<td>0.30</td>
<td>4.45</td>
<td>0.7</td>
<td>-</td>
<td>0.80</td>
<td>0.30</td>
<td>0.10</td>
<td>5.34</td>
</tr>
<tr>
<td>1994⁹</td>
<td>-</td>
<td>0.35</td>
<td>4.22</td>
<td>2.73</td>
<td>0.02</td>
<td>0.71</td>
<td>0.19</td>
<td>0.20</td>
<td>4.80</td>
</tr>
<tr>
<td>2000ʰ</td>
<td>-</td>
<td>0.17</td>
<td>3.32</td>
<td>1.99</td>
<td>0.01</td>
<td>0.37</td>
<td>0.10</td>
<td>0.17</td>
<td>4.25</td>
</tr>
<tr>
<td>2006ᵍ</td>
<td>0.012</td>
<td>0.20</td>
<td>3.13</td>
<td>1.92</td>
<td>0.02</td>
<td>0.25</td>
<td>0.07</td>
<td>0.10</td>
<td>3.33</td>
</tr>
</tbody>
</table>

a,b- Bambówna and Wojtan (1996), c- Henriksen (1992), d- Czochański and Borowiak (2000), e- Stuchlik et al. (2006), f- Kasza et al. (1997), g- mean summer/fall sampling; authors’ own results, h- Kopacek et al. (2004)
Rock cover leaching and dissolving processes lead to the neutralization of water, and in particular to the neutralization of acids deposited from the atmosphere. However, long-term washout of the buffering compounds (e.g., carbonate buffer – calcium) in the high alpine catchments such as that of Rybi Potok, may lead to the exhaustion of the buffer capabilities of the catchment area, leading to a permanent change in the pH of the waters relative to their pH values recorded in the 1930s and 1950s (Kot 1996).

Among the factors leading to degradation of the water ecosystems of Morskie Oko and Czarny Staw tourism plays a significant role. The problem is especially severe as in the warm seasons Morskie Oko is visited by about 2,000 tourists daily, so nearly 2 million tourists per year (www.tpn.pl).

The impact of tourism on the natural environment in the Tatra National Park has been presented in detail by Czochański and Borowiak (2000). The scale of pollution becomes clear when the bottoms of Morskie Oko and Czarny Staw are cleaned annually by divers (www.krab.agh.edu.pl) when huge quantities of plastic bottles, bags, glass, food packages, and coins are retrieved. The areas in the vicinity of tourist trails and hostels are biologically contaminated (Czapski and Mızgajska 1996). Fortunately, the water in the two lakes studied did not contain soluble phosphates in concentrations >0.01 mg l⁻¹, which proves they are insulated from sewage.

**Fig. 1.** Long–term trends in the total deposition of SO₄²⁻, Cl⁻, NO₃⁻, NH₄⁺ and base cations (BC) in the Tatra Mountains (according to Kopacek et al. 2004, modified).
Because of their intensity, these factors can contribute to the eutrophication of waters in the studied lakes despite the fact they are oligotrophic and insignificantly loaded with nutrients and the presence of nitrates in them in summer attests to the lack of significant sorption by organic matter (Czochański and Borowiak 2000). In contrast to Czarny Staw, the character of the catchment area of Morskie Oko (partly covered with vegetation) permits some runoff of eutrophic substances (Czochański and Borowiak 2000). Moreover, the presence of fish (mainly trout) in Morskie Oko stimulates an increase in the mass of algae by increasing the level of available nutrients (Gliwicz 1985). The problem of tourists feeding fish should also be mentioned. Moreover, results of measurements of the thermal and optical conditions made by Borowiak (Czochański and Borowiak 2000) show considerable similarity of the Morskie Oko water characteristics to that of the water of located nearby Przedni Czarny Staw subjected to eutrophication.

CONCLUSIONS

The effects of anthropogenic stress manifested as the acidification and eutrophication of lakes in the high Tatra Mountains pose a threat to the abiotic features of these limnic habitats. Although global measures (e.g., Gotenberg Protocol) have reduced considerably the emission of pollution into the atmosphere, it still exerts a significant influence on the conditions in sensitive high-alpine ecosystems.

- The waters from the lakes studied are characterized by a low degree of mineralization, low hardness, low contents of calcium and magnesium, and low electric conductivity.
- The quality of the water in Morskie Oko and Czarny Staw has improved over the last twenty years as the result of decreasing contents of acid-forming ions.
- The high deposition of nitrogen compounds and globally-observed overloading with nitrogen lead to increasing levels of nitrate and ammonium ions, which poses a threat to the equilibrium of the ecosystems of the lakes studied.
- Elevated levels of dissolved phosphates were not noted, which proves the isolation of the lakes from sewage; however, reports in the literature indicate that there is biological contamination in the vicinity of the lakes.
- The low buffer capacity of the reservoirs studied and hence their high sensitivity to pollution suggest the need for the systematic monitoring of the quality of the lake waters to be able to estimate the tendency of
changes in the chemical properties of the waters and the impact of particular processes determining their composition.

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