Chapter 4

Environmental and anthropogenic factors affecting water chemistry in the Polish Tatra Mountains

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Abstract: The aim of the chapter is to analyze the environmental and anthropogenic factors affecting groundwater, stream water and lake water chemistry in the Polish Tatra Mountains. Geology is the most important environmental factor determining water chemistry in the Polish Tatra Mountains. In the crystalline portion of the Tatra Mountains formed of poorly soluble granite and gneiss rocks, the total dissolved solids and concentration of main cations and anions are many times lower than that in the sedimentary portion of the Tatra Mountains formed of highly soluble carbonate rocks. Hydrologic factor (changes in discharge) drives stream water and spring water chemistry changes in the course of the year and during rainfall and snowmelt events. Soil cover properties such as their thickness and chemistry are additional environmental factors affecting water chemistry in the Tatra Mountains. Anthropogenic factors influencing water chemistry in the Tatra Mountains include acid rain, deforestation, and tourist traffic.

Key words: groundwater, streams, lakes, geology, lithology, human impact

INTRODUCTION

The chemistry of both surface water and groundwater is affected by many different environmental and anthropogenic factors. The most important environmental factors are usually lithology, soil cover, vegetation, and hydrology, while the most important anthropogenic factors are wastewater discharge and fertilizer use (Hem 1985). The Tatra Mountains are located within the borders of a large national park in Poland and Slovakia and are an area experiencing relatively little human pressure. Therefore, this region provides favorable conditions for the identification of natural factors controlling water chemistry. However, water in this region remains under the strong impact of tourist traffic and the impact of long-distance air pollutants (Rzychoń, Worsztynowicz 2008). The identification of factors controlling water chemistry in high mountains in the broadly defined Baltic Sea region, for example in the Tatra Mountains, is an important issue because of the crucial role of mountains in the water chemistry of rivers flowing further downstream.

Geology

Groundwater, stream water and lake water chemistry varies across the Polish Tatra Mountains (Fig. 2.5). This is the result of large geologic variation in the region. The southern part of the Tatra Mountains is made of poorly soluble crystalline rocks: metamorphic rocks (mainly gneiss and crystalline shale) and alaskite in the Western Tatra Mountains, and granitoids (granodiorites) in the High Tatra Mountains. The northern part of the Tatra Mountains is formed of well-soluble sedimentary rocks: dolomitic limestone, limestone, dolomite, sandstone, shale, and conglomerates (Passendorfer 1996). Total dissolved solids (TDS) and the concentration of main ions in groundwater, stream water and lake water are very low in the crystalline part of the Tatra Mountains (Małecka 1989; Oleksynowa; Komornicki 1996; Żelazny 2012; Sajdak et al. 2018a). For example, the mean TDS of spring water (n = 489) across this part of the Tatra Mountains is only 33.7 $mg \cdot dm^{-3}$ (Żelazny 2012). TDS and the concentration of main ions in the crystalline Western Tatra Mountains are about twice as high as in the crystalline High Tatra Mountains (Photo 4.1). This is due to the slightly better solubility of crystalline rocks in the Western Tatra Mountains than in the High Tatra Mountains. In the northern sedimentary part of the Polish Tatra Mountains, TDS and the concentrations of main ions of groundwater and stream water are distinctly higher than in the southern crystalline part of the Tatra Mountains. For example, according to Żelazny (2012), the mean TDS of spring water in this part of the Tatra Mountains is 245.1 $mg \cdot dm^{-3}$ (Fig. 4.1). According to Małecka (1989) and Małecka et al. (2007), the chemistry of precipitation affects ap. 90% of groundwater and stream water chemistry at high elevations in the southern parts of the Tatra Mountains where the solubility of crystalline rocks is very low. The effect of precipitation on water chemistry did not exceed 30% at lower elevations in the sedimentary part of the Tatra Mountains.

Photo. 4.1. Field measurements of physical properties of water in the Tatra Mountains (Photo. J. Pociask-Karteczka).

Spatial diversity of water chemistry in the Tatra Mountains are determined by local geology and have been used thus far as the basis for the hydrochemical regionalization of the Polish Tatra Mountains. The first regionalization was performed by Oleksynowa (1970) who identified three hydrochemical regions: (1) crystalline Tatra Mountains area, (2) transitional region of crystalline and sedimentary rocks, (3) sedimentary Tatra Mountains area. Another regionalization was done by Małecka (1989) who identified three hydrochemical regions characterized by a belt-type pattern related to the tectonic and geologic structure in the Polish Tatra Mountains. The first region includes areas formed of both crystalline rocks and quartzite sandstone. The second region includes areas formed of the High-Tatric Units sedimentary rocks – mainly limestone. The third region includes areas formed of the Sub-Tatric Units sedimentary rocks – mostly conglomerates, dolomitic limestone, as well as nummulites of the Eocene. There is a newest hydrochemical regionalization developed by Żelazny (2012), who used multidimensional analysis of variances in spring water chemistry. He recognized two main hydrogeochemical environments associated with (Fig. 4.2):

1. sedimentary rocks,
2. crystalline rocks.

For the studied sedimentary rock environment, he identified three distinct sub-types: (1) dolomite-limestone, (2) dolomite-limestone-sulfate, (3) limestone. For the crystalline rock environment, he distinguished two sub-types: (1) granitoid environment, (2) metamorphic environment (Fig. 4.2). Spring water in the Tatra Mountains may be placed in 15 hydrochemical categories. The most common water categories are HCO_3^-–Ca^{2+}–Mg^{2+} (45.4%) and HCO_3^-–Ca^{2+} (24.3%). The degree of hydrochemical variation is greater in the crystalline core (13 types) versus the sedimentary core (9 types). The most common components of the crystalline core are SO_4^{2-} (53.2%), quite frequently Mg^{2+} (41.3%), and less frequently Na^+ (14.1%). On the other hand, the most common component of the sedimentary rocks is Mg^{2+} (74.7%), and to a much lesser extent, SO_4^{2-} (8.1%). Spring hydro-geochemical types follow a mosaic-type spatial pattern that is linked closely to lithologic determinants (Żelazny 2012).

Soils

Soil properties such as their thickness, texture and chemistry usually control the ion influx to lakes and streams (e.g. Mulder et al. 1995; Seibert et al. 2009; McDowell, Liptzin 2014). According to Sajdak et al. (2018b), the high concentration of Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^- and NO_3^- in the stream water in crystalline part

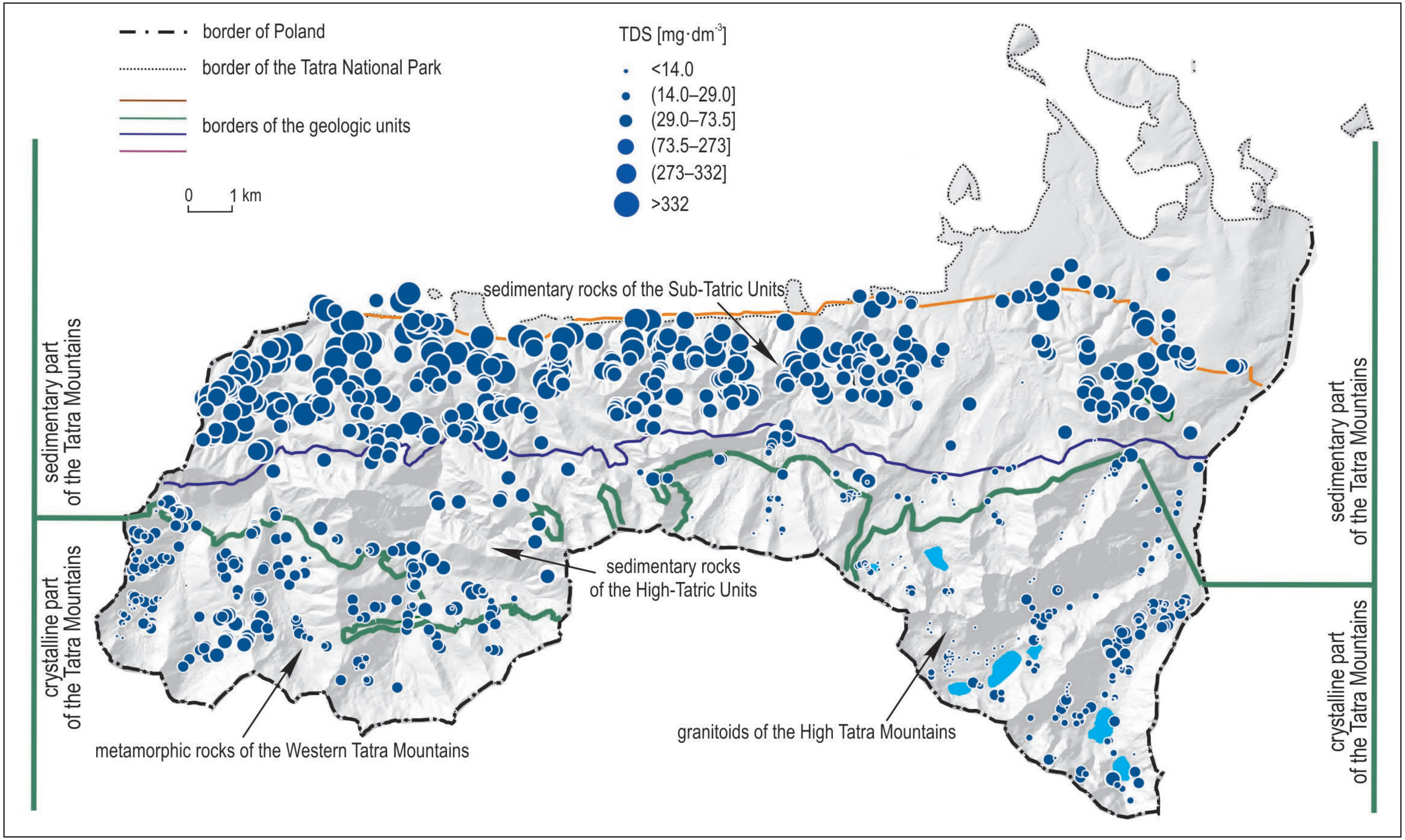

Fig. 4.1. Total dissolved solids (TDS) of spring water in the Polish Tatra Mountains (Żelazny 2012, modified).

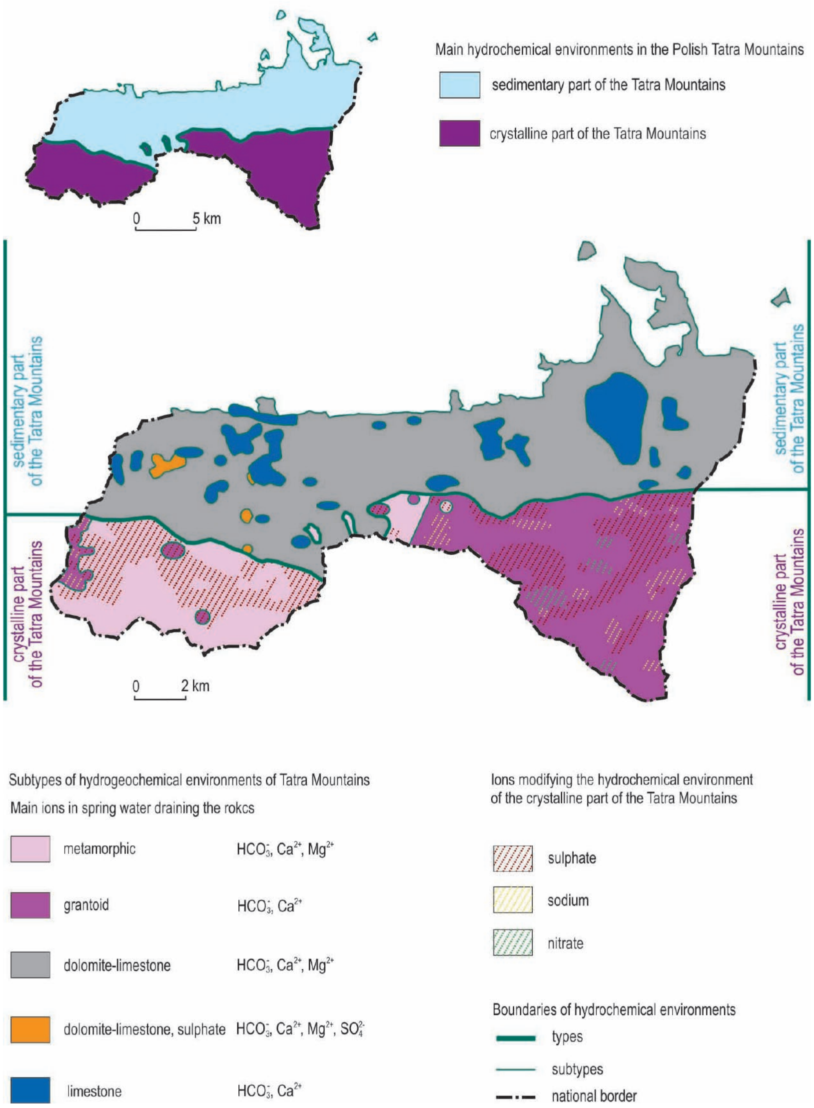

Fig. 4.2. Hydro-geochemical environments in the Polish Tatra Mountains (Żelazny 2012, 2015c, modified).

of the Tatra Mountains at the beginning of rain-on-snow events results from ion leaching from shallow soils: Regosols, Entic Podzols, Leptic Podzols, Folic Leptosols, and Haplic Podzols. However, Kopáček et al. (2004a) found no significant correlation between soil chemistry and the concentration of some main ions and nutrients in Tatra lakes. They found a correlation between organic matter concentration in soils and nutrient (C, N, and P) concentrations in lakes. The amount of soil and soil exchangeable base cation capacity determines the sensitivity of Tatra lakes to acidification (Kopáček et al. 2004b; Stuchlík et al. 2006). Lakes draining catchments with a large amount of soil and high soil exchangeable base cation capacity are more resistant to acidification than lakes draining catchments with a small amount of soil and low soil exchangeable base cation capacity. A small amount of soil results in a low ability of catchments to retain acidic nitrogen derived from atmospheric deposition, thus leading to a high concentration of NO_3^- in lake water. Low soil exchangeable base cation capacity results in a low acid neutralizing capacity of lakes and low pH of lake water (Kopáček et al. 2004b).

Hydrology

Changes in discharge over the course of the year are the most important factor controlling the seasonal variation of stream water and spring water chemistry in the Tatra Mountains. The influx of snowmelt water in the spring and rainwater in the summer is characterized by low TDS and a low concentration of most main ions, which results in a decrease of these parameters in stream water and spring water with increasing discharge. The rate of seasonal change in spring water chemistry depends on the amount of rainfall as well as the thickness, density, and melting rate of snow cover (Wolanin, Żelazny 2010; Wójcik 2012; Żelazny 2012; Wolanin 2014; Sajdak et al. 2018a). There are two types of stream hydrochemical regimes in the Tatra Mountains:

– high mountain regime,
– middle mountain regime.

For both regimes, the lowest TDS and concentration of most main ions occur during the spring snowmelt season. However, in streams characterized by a high mountain regime, the lowest TDS, lowest conductivity, and lowest ion concentrations occur later than in streams characterized by a middle mountain regime. This is due to the snowmelt season occurring later and lasting longer at higher elevations than at lower elevations (Żelazny 2012).

The most dynamic changes in stream water chemistry in the Tatra Mountains occurred during rainfall and snowmelt events. Streams are supplied by groundwater alike throughflow and overland flow. Throughflow and overland flow water are characterized by a distinctly lower concentration of most main ions than groundwater due to less contact time with parent material. Hence, dilution is the main factor controlling stream water chemistry during events in the Tatra Mountains (Sajdak et al. 2018b). Changes in some ion concentrations triggered mainly by dilution sometimes are also affected by other processes. For example, an unexpectedly large increase in HCO_3^- at the beginning of a rain-on-snow event in the mountain creek may be triggered by a rapid influx of pre-event ("old") water from the local karst system (Sajdak et al. 2018b).

Acid rain

There is a decline in the concentration of main cations in some lakes in the High Tatra Mountains (Zielony Staw lake and Długi Staw lake) due to the long-term acidification of precipitation in the area. The pH of bulk precipitation ranged from 4.39 to 5.16 and an increasing trend in the pH of atmospheric precipitation occurred in the Tatra Mountains in the years 1992–2005 (Rzychoń, Worsztynowicz 2008). Acid rain pollution originates mostly in locations far away from the mountain range. There are seasonal fluctuations in precipitation acidity: lower pH was noted during the winter than during the summer. This was explained by unique meteorologic conditions in winter causing an inflow of industrial pollution from faraway locations and higher local sulfur deposition in the heating season (Grodzińska-Jurczak 1995). The lowest pH of snow occurs near cities such as Zakopane and Kościelisko, and near tourist lodges (Żelazny, Kasina 2009).

Deforestation by windfalls and bark beetle outbreaks

Forests in the Tatra Mountains are artificially dominated by spruce monocultures (Grodzki, Guzik 2009). Spruce monocultures occupy nearly 80% of the lower montane zone while natural mixed beech-fir forest occupy less than 10% of the zone (Mirek 1996). The spruce monocultures are characterized by low resistance to summer drought, heavy winds, bark beetle infestation, and fungus expansion (Małek et al. 2012, 2014). Hillslope deforestation triggered by hurricane-force winds in 2013 (Photo 4.2) and tree stand decline due to bark beetle infestation has led to significant changes in the water chemistry of springs and streams in the mountain stream catchment in the West Tatra Mountains (Żelazny et al. 2017a, b). Research conducted one and a half years

Photo. 4.2. The Western Tatra after windfall in December 2013 (Photo M. Żelazny).

after deforestation revealed that the mean concentration of NO_3^- in water in areas deforested by winds was 15.44 mg·dm^{-3}, in areas deforested by bark beetle infestation – 6.17 mg·dm^{-3} while in forested areas – only 3.26 mg·dm^{-3}. Hence, the increase of NO_3^- concentration in stream water and spring water caused by deforestation was more than fivefold (Żelazny et al. 2017a). The mean water concentration of NO_3^- on deforested hillslopes continued to increase over time. In the period 2015–2016 the mean concentration of NO_3^- in stream water and spring water in areas deforested by winds equaled 16.53 mg·dm^{-3}, in areas deforested by bark beetle infestation 6.69 while in forested areas 3.06 mg·dm^{-3} (Żelazny et al. 2017b). Such a large increase in the concentration of NO_3^- in deforested areas results in a change in the position of NO_3^- in the sequence of anions from the natural sequence occurring in forested carbonate-type catchments ($HCO_3^- > SO_4^{2-} > NO_3^- > Cl^-$) to the now predominant sequence $HCO_3^- > SO_4^{2-} > NO_3^- > Cl^-$ (Żelazny et al. 2017a, b).

Tourism

The number of visitors in Tatra National Park has remained at about 2.5 million per year for the last two decades (Siwek, Biernacki 2016). The impact of tourist traffic on the natural environment in the Tatra Mountains is distinctly larger than that in other mountain national parks in Europe. For instance tourist traffic in Berchtes gaden National Park in the German Alps equals 57,000 tourists per hectare per year, in Swiss National Park and Hohe Tauern National Park in the Austrian Alps – 9000, while in Tatra National Park – 120,000 tourists per hectare per year (Kurek 2007). Borowiak et al. (2006) found that the water chemistry of some Tatra Mountains lakes located close to mountain lodges is strongly affected by tourist traffic. The shores of these lakes are used as a stopover for many people. Tourist lodges are a major threat to stream water quality *via* their frequent release of wastewater into local streams (Siwek, Biernacki 2015, 2016). Wastewater produced by the mountain lodges in the years 2008–2009 caused significant changes in the concentrations of some nutrients found in streams into which the wastewater was released: the concentration of NH_4^+ in stream water downstream of the wastewater release site was roughly 200 times greater than the concentration upstream of that site, while PO_4^{3-} concentrations were 30 times greater. The NO_3^- content increased substantially also. The largest loads of nutrients were released into streams in the summer season when the discharge of streams is very low. This causes serious ecological threat to stream water quality due to weak wastewater dilution. Wastewater releases from tourist lodges into streams and stream water pollution have been a leading problem in the Tatra National Park for many years. The wastewater management situation in the Tatra National Park has improved markedly since 2009. In 2010 and 2011 wastewater treatment plants at the Murowaniec Lodge and Polana Chochołowska Lodge were fully modernized (Fig. 5.2). In 2011 a new treatment plant was opened at the lodge in the Valley of Five Polish Lakes (Siwek, Biernacki 2015).

Conclusions

The chemical composition of water in the Tatra Mountains has been controlling both by environmental and anthropogenic factors. Complex geology has a crucial significance. For example, the total dissolved solids of spring water in the crystalline part of the Tatra Mountains formed of poorly soluble granite and gneiss rocks is many times smaller than that in the sedimentary portion of the Tatra Mountains formed of highly soluble limestones and dolomites. Other factors, apart from geology, affect water chemistry in the Tatra Mountains to some extent (Fig. 4.3).

Hydrologic factor – changes in discharge – is responsible for seasonal stream water and spring water chemistry changes as well as changes during rainfall and snowmelt events. The influx of meltwater and rain water results in a decrease of TDS and concentration of most main ions in stream water and spring water according to increasing discharge. Soils are an additional environmental factor influencing water chemistry in the Tatra Mountains. Some ions are flushed out of the soil at the beginning of rainfall and snowmelt events. The amount of soil and soil exchangeable base cation capacity determines the sensitivity of lakes to acidification. The Tatra Mountains have been affected by acidic pollution of long-distance transport. The impact of acid rain on water chemistry in the Tatra Mountains results in a decline of main cations concentration. The decline of spruce monocultures in the Tatra Mountains results mostly in substantial increasing of NO_3^- concentrations – even one and a half years after deforestation. Wastewater released from tourist lodges affects stream water chemistry leading to excessive nitrogen and phosphorus concentration. The quality of water in the Tatra Mountains has improved since 2009 owing to modernization wastewater treatment plants in mountain lodges.

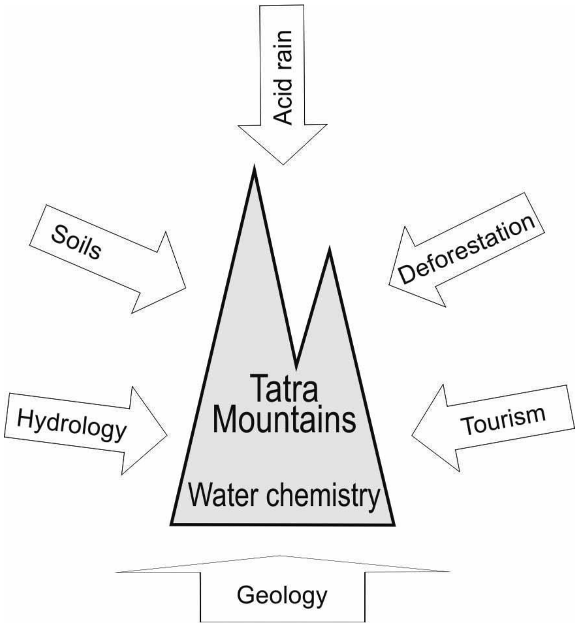

Fig. 4.3. Factors controlling water chemistry in the Tatra Mountains.