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Long-term changes of lake - watershed systems in the Šumava, Jizera, and Tatra Mountains affected by acid atmospheric deposition

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Ph.D. Thesis
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I declare that for all of the publications submitted as a part of this doctoral thesis, Zuzana Hořická (Stuchlíková) was a key member of the teams responsible, and significantly participated in data collection, chemical and biological analyses, and in preparation of the manuscripts.

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I affirm that neither this thesis, nor any of the publications attached within, have been submitted for the purpose of obtaining the title of Ph.D., or any other title, at another institution.

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I wish to thank Evžen Stuchlík, who originally brought me to hydrobiology and awakened my enthusiasm for the study of mountain lakes and the alarming phenomenon of "acid rain", for long years of beautiful and exciting work together, and for his care and support during my whole professional life. My teacher of limnology (and much more), and the intellectual leader of our small "lake team" (for the Šumava and High Tatra Mountains) in the 1980s, was Jan Fott, to whom I am very grateful for his kind and elegant guidance.

Later, I was invited by Josef Křeček to take part in highly interesting research in the Jizera Mountains, heavily damaged by anthropogenic acidification and drastic forestry practices. Josef has enlarged my view of a lake (reservoir) to include also the watershed and its complexity. He and our daughter Kamilka Marie showed much understanding during my preparation of some of the older data from the Tatras for publication, and during completion of this thesis, which I greatly value.

The work presented in the attached articles would not have been possible without the enthusiasm and the conscientious assistance in the field of many colleagues, friends, and Earthwatch (Boston, U.S.A.) volunteers.

At the moment of finalizing the thesis, though, I feel most obliged to my father Karel Hořický and to those of my closest ones, friends, and colleagues, who never stopped believing in my successful accomplishment of the Ph.D. level, and who truly stood by me. A friend once said, "Think of the day you will have it done"; so I did.

Contents

Publications

Introduction

This thesis is based on seven articles, bringing together the main results of a long-term study of waters in the Tatra Mountains (1978-1996) and the Jizera Mountains (1992-2000), and their watersheds, that were heavily damaged by anthropogenic acidification during the second half of the last century. One of the papers also summarizes the results of the research of three lakes in the Šumava Mountains (1978-1992). The decades of the 1980s and 1990s were the peak of acidification in all the studied areas, due to the maximum acid deposition in Central Europe in that time (Kopáček *et al.*, 2001), while from the middle of 1990s, the process of their recovery from acidification has been recorded (Kopáček *et al.*, 1998; Hruška *et al.*, 2002).

The aims of the work developed during the whole research period; the main tasks and findings are represented by the attached papers. Since the end of the 1970s, we tried subsequently to answer the following questions:

1. Did acidification of surface waters occur on the territory of Czechoslovakia?
2. Which areas were affected, and what was the character and extent of their damage?
3. Were the drastic changes that we found a consequence of anthropogenic acidification caused by sulphur deposition, or did they result merely from changes in the forest management in lake watersheds (in the structure of the vegetation cover)?
4. What was the proportion of sulphur and nitrogen emissions in the acidification?
5. What was the impact of acidification on the phytoplankton and zooplankton of mountain lakes?
6. What were the key factors and mechanisms in this influence?

List of attached publications

The Šumava and the Tatra Mountains:

Stuchlík, E., Z. Stuchlíková, J. Fott, L. Růžička & J. Vrba, 1985: Vliv kyselých srážek na vody na území Tatranského národního parku (Effect of acid precipitations on waters of the TANAP territory). In: Zborník prác o Tatranskom národnom parku (Treatises concerning the Tatra National Park) 26: 173-211. [In Czech, with summary in Russian, German, and English.]

Fott, J., M. Pražáková, E. Stuchlík & Z. Stuchlíková, 1994: Acidification of lakes in Šumava (Bohemia) and in the High Tatra Mountains (Slovakia). Hydrobiologia 274: 37-47.

Stuchlík, E., J. Kopáček, J. Fott & Z. Hořická, 2006: Chemical composition of the Tatra Mountain lakes: Response to acidification. Biologia, Bratislava, 61/Suppl. 18: S11-S20.

Hořická, Z., E. Stuchlík, I. Hudec, M. Černý & J. Fott, 2006: Acidification and the structure of crustacean zooplankton in mountain lakes: The Tatra Mountains (Slovakia, Poland). Biologia, Bratislava, 61/Suppl. 18: S121-S134.

Sacherová, V., R. Kršková, E. Stuchlík, Z. Hořická, I. Hudec & J. Fott, 2006: Long-term change of the littoral Cladocera in the Tatra Mountain lakes through a major acidification event. Biologia, Bratislava, 61/Suppl. 18: S109-S119.

The Jizera Mountains:

Stuchlík, E., Z. Hořická, M. Prchalová, J. Křeček & J. Barica, 1997: Hydrobiological investigation of three acidified reservoirs in the Jizera Mountains, the Czech Republic, during the summer stratification. Can. Tech. Rep. Fish. Aquat. Sci. 2155: 56-64.

Křeček, J. & Z. Hořická, 2001: Degradation and recovery of mountain watersheds: the Jizera Mountains, Czech Republic. Unasylva 207 (52): 43-49.

Summary of the attached publications

Effect of acid precipitations on waters of the TANAP territory

Due to the acidity of rain water and acidification of the Lake Černé in the Šumava Mts (SW Bohemia), found in 1978 (Fott *et al.*, 1980; Růžička *et al.*, 1981), we decided to find out the *status quo* of mountain lakes and running waters on the territory of the Tatra National Park (TANAP) in Slovakia. The paper summarizes results from the years 1978-1983, when we carried out repeated synoptic samplings from 268 locations in the High Tatra Mts for determination of pH, alkalinity, and conductivity. In 7 lakes, we determined concentrations of major ions and chlorophyll-*a*, and identified zooplankton.

Our data clearly confirmed that the process of acidification of the Tatra waters had begun. In comparison with data from lakes of a similar character in the Polish part of the High Tatra Mts in the years 1937 and 1963, concentration of bicarbonate decreased and concentration of sulphate and nitrate increased several times. The concentrations of sulphate in both rain and lake water, though, were lower than estimated from average values of pH of rain water, due to a high proportion on nitrate (up to 40%) in the rain water and in the lakes.

According to alkalinity (A, in μeq l^{-1}, the non-dystrophic waters were divided into four categories: 1. Acidified waters (A < 20): 42% of lakes and small standing waters (n = 132), 21% of streams (n = 113); 2. Waters endangered by acidification (A = 20-100): 44% of lakes and small standing waters, 39% of streams; 3. Waters not endangered then (A = 100-500); 4. Calcareous waters (A > 500).

The pH vs. alkalinity relation showed that any drop in alkalinity below the value 25 μeq l^{-1} was accompanied with a sharp drop in pH.

Besides the value of alkalinity, the character of a lake's watershed (geological background and the extent of weathering), the size of the watershed, and the residence time of the water in the watershed area, were suggested to influence the susceptibility of a lake to acidification.

The most acidified standing waters were small shallow basins with a very small watershed, fed with the rain water.

We assessed the impact of acidification on mountain lake ecosystems. We did not find any effect on direct counts of bacteria, but concentration of chlorophyll-*a* was extremely low ($< 0.2\ \mu\mathrm{g\ l}^{-1}$) in acidified lakes, and crustacean zooplankton (*Arctodiaptomus alpinus*, *Cyclops abyssorum tatricus*, *Daphnia pulicaria*, *Mixodiaptomus taricus*) were missing in acidified lakes above the forest line, where their previous occurrence was recorded. The results of this study corresponded with data from other areas of the world affected by acidification, but for the biota, the consequences were much more drastic in the Tatra lakes: planktonic Crustacea were not reduced but extinct, and replaced by littoral species like *Chydorus sphaericus*.

Acidification of lakes in Šumava (Bohemia) and in the High Tatra Mountains (Slovakia)

The next publication of our results on acidification of lakes in the Šumava Mts and the High Tatra Mts (the studies started in both areas in 1978) clearly stated that due to acid precipitation and sensitive geology, the Šumava lakes were acidic at the beginning of the 1990s. pH values ranged between 4.3-4.8 in the surface layer of the lakes Černé, Čertovo, and Prášilské within the 1980s. Phytoplankton were poor in the number of species, with flagellates dominating, and similar to acidified lakes elsewhere. Older findings by B. Fott from the mid-1930s (unpublished data), however, showed that many species of algae from oligotrophic lakes can occur in the lake water even when it turns acidic.

The work discussed a possible contribution of a change in the vegetation cover in the watershed to the acidification of lakes, concluding that the determining factor had to be acid precipitation, and mentioned the explanation of a change in the zooplankton species composition by fish predation in the 1890s by Frič & Vávra (1897). Planktonic Crustacea were extinct in the lakes Černé and Čertovo, in contrast to the Lake Prášilské. We found much less labile monomeric aluminium in this lake which has *Cyclops abyssorum* and *Daphnia longispina* in its zooplankton, although it is also acidic, than in the other two lakes. This confirmed the hypothesis by Hörnström *et al.* (1984) saying that a high Al content is responsible for the sparse zooplankton fauna, through oligotrophication and toxicity.

A possible contribution of other metals than Al to the toxicity of the water was admitted, e.g. beryllium (Veselý *et al.*, 1989).

Alpine lakes in the High Tatra Mts were described as affected by acidification to a different degree, where the sensitivity of a lake to acidification and its stage in the acidification process were determined by the level of calcium (Fott *et al.*, 1987; Fott *et al.*, 1992; Kopáček & Stuchlík, 1994). The acidification status of a lake, based on the lake water chemistry, was assigned to the occurrence or absence of planktonic Crustacea. Thus, the lakes above the forest line were divided also according to the zooplankton status into lakes where zooplankton were 1. unchanged, 2. extinct, 3. modified (replaced by *Chydorus sphaericus*). A theory of precipitation of phosphorus in the range of pH of lake water 5-6 (Almer *et al.*, 1978), and, thus, starvation of zooplankton or also a physiological stress accompanying starvation (Nillsen *et al.*, 1984), were mentioned.

Chemical composition of the Tatra Mountain lakes: Response to acidification

This work assessed the spatial variability in water chemistry throughout the Tatra lake district in the period of maximum acid deposition in Europe, and defined the main factors causing differences in the amount of ions and nutrients in the lakes during that time. Data from two extensive surveys of lakes on the territory of the Tatra Mts, performed in the autumns of 1984 (maximum acidification; 53 lakes) and 1993-1994 (the beginning of chemical recovery from acidification; 92 lakes), were used. This article was followed by the work of Kopáček *et al.* (2006) on chemical recovery from acidification, comparing these data sets with results from the autumn of 2004 (15 years after reduction in acid deposition).

During the peak of acidification (in 1984), water chemistry of the Tatra lakes exhibited signs typical for a region affected by atmospheric acidification, with a high variability in pH, concentrations of alkalinity and nitrate, and significantly elevated concentrations of sulphate compared to the values from lakes on the Polish side of the Tatra Mts in the 1930s (Stangenberg, 1938). Among ions, SO_4^{2-} concentrations showed the lowest spatial variability, and were higher in lakes with forested watersheds than in alpine lakes, thus suggesting elevated SO_4^{2-} input by throughfall deposition under tree canopies.

In general, the study showed a low ionic content of the lakes, with conductivity (at 20 °C) ranging from 1.1 to 4.7 mS m^{-1}. The majority of them belonged to acidified or strongly acidified lakes, according to our previous works (Stuchlík *et al.*, 1985; Fott *et al.*, 1992; Kopáček & Stuchlík, 1994). The chemical composition of the Tatra lakes in 1984-1994 was similar to that of lakes in other high-mountain areas of Europe (the Alps, the Pyrenees), with two exceptions: 1. The lakes in the Tatra Mts were more acidic (median alkalinity of 40 μeq l^{-1}, median pH of 5.3; 23% of the lakes had a depleted carbonate buffering system), and 2. watersheds in the alpine zone were N saturated, with high NO_3^- concentrations (median of 32 μeq l^{-1}).

Major factors governing differences in the lake water chemistry were bedrock composition and the amount of soil and vegetation in their watersheds. Compared to lakes in the predominantly granitic central part of the mountains (the High Tatra Mts), lakes in the West Tatra Mts had higher concentrations of base cations and alkalinity due to the presence of metamorphic rocks in the bedrock. Concentrations of phosphorus, organic nitrogen, organic carbon, and chlorophyll-*a* were highest in forest lakes and lowest in lakes with rocky watersheds. Concentrations of nitrate and Ca:Mg ratios showed an opposite trend.

The work mentions several exceptions to these general patterns in chemical and biological composition, due to exceptional geology or hydrology of the lake watersheds.

Acidification and the structure of crustacean zooplankton in mountain lakes: The Tatra Mountains (Slovakia, Poland)

Zooplankton of lakes in the Tatra Mts have been closely investigated since the middle of the 19th century, which later enabled the recognition of lake acidification and the assessment of its influence on the biota of lake ecosystems. Species composition of planktonic Crustacea in 102 lakes in the West and High Tatra Mts, studied during the peak of anthropogenic acidification (1978-1996), was presented in this paper. The work identified factors determining the original and present altitudinal distribution of zooplankton species throughout the Tatra Mts, specified the role of the acidification-induced processes of oligotrophication and aluminium toxicity in the extinction of Crustacea from plankton of alpine lakes, and explained differences in the zooplankton response to acidification in different types of lake ecosystems.

In the pre-acidification period, the distribution of zooplankton was determined namely by the lake altitude and orientation (north vs. south) and by the watershed character. Crustacean zooplankton in larger lakes consisted of a limited number of species, with *Acanthodiaptomus denticornis* and *Daphnia longispina* dominating lakes in the forest zone, and *Arctodiaptomus alpinus*, *Cyclops abyssorum*, *Daphnia longispina*, *Daphnia pulicaria*, and *Holopedium gibberum* dominating lakes in the alpine zone. *Ceriodaphnia quadrangula*, *Daphnia obtusa*, *Daphnia pulex*, and *Mixodiaptomus tatricus* occurred in lakes with high concentrations of dissolved organic matter and in strongly acidified waters.

This work showed that anthropogenic acidification caused drastic changes in both the chemistry and biology of the Tatra lakes. The species composition of crustacean zooplankton was not affected by acidification in non-acidified lakes (distributed along the whole altitudinal gradient), while planktonic Crustacea disappeared from acidified lakes with meadow-rocky watersheds, and in strongly acidified lakes with meadow-rocky watersheds, original Crustacea disappeared and were replaced by populations of acid-tolerant littoral species *Acanthocyclops vernalis*, *Chydorus sphaericus*, and *Eucyclops serrulatus*.

As stated already in previous studies (e.g. Fott *et al.*, 1992, 1994, 1999), acidification significantly influenced not only the species composition, but also the quantity of phytoplankton and zooplankton. The key role of acidification-induced oligotrophication and aluminium toxicity, possibly also acidification-induced eutrophication, in the extinction of crustaceans from plankton of alpine lakes, was discussed in the paper.

It was concluded that despite the first signs of biological recovery observed in the early 2000s, acidification remains the most important factor governing the structure of plankton in the Tatra lakes.

Long-term change of the littoral Cladocera in the Tatra Mountain lakes through a major acidification event

This study focused on Cladocera inhabiting the littoral zone of lakes, neglected in most previous research in comparison with pelagic zooplankton. It compiled the occurrence of littoral Cladocera in 46 lakes in the West and High Tatra Mts (Slovakia and Poland) in seven periods of a different human impact on the lakes. A paleolimnological study was included – findings of Cladocera remains from the surface layer (0-0.5 cm) and a deeper (15-17 cm) layer of sediment cores, representing the recent community and a pre-industrial period, respectively, historical data from the beginning of the last century (Minkiewicz, 1917), and our data from 1980 to 2004. The chosen lakes that passed through anthropogenic acidification in the 1980s and are now in the process of recovery from acidification belonged into the three categories after Kopáček *et al.* (2004): lakes extremely sensitive to acidification, acid sensitive, and non-sensitive lakes. These categories are identical to the earlier defined categories of strongly acidified, acidified, and non-acidified lakes.

Altogether, eleven species of littoral Cladocera were found in the Tatra lakes: *Acroperus harpae*, *Alona affinis*, *Alona quadrangularis*, *Alona rectangula*, *Alona guttata*, *Alonella excisa*, *Alonella nana*, *Chydorus sphaericus*, *Eurycercus lamellatus* (Chydoridae), *Ceriodaphnia quadrangula* (Daphniidae), and *Polyphemus pediculus* (Polyphemidae). The most numerous species were *Chydorus sphaericus*, *Alona affinis*, *Acroperus harpae*, and *Alona quadrangularis*.

The work discussed the problematic detection of littoral cladoceran species, especially those living in or on the surface layer of the sediment or feeding near the bottom, and the fact that their absence in samples taken by a plankton net from the shore did not necessarily indicate their absence in lakes. Among other factors complicating the detection of littoral species, there are e.g. their low abundances with possible seasonal peaks, or the size of a lake, in combination with the character of the littoral zone. On the other hand, the suitability of a sediment core taken from the central part of a lake, to represent the occurrence of both pelagic and littoral species of Cladocera, was mentioned.

Attention was paid to the response of littoral Cladocera to characteristics of their environment (lake and shoreline morphology, size, altitude, and exposure of a lake, the littoral and watershed cover, lake water chemistry) and its changes, including acidification and recovery from acidification. The number of species was highest in lakes of all categories with a high portion of the vegetation and soil cover (i.e. with dwarf pine in their watersheds). On the whole, the littoral community was richest in lakes non-sensitive to acidification.

Except for *Chydorus sphaericus*, littoral Cladocera disappeared from all the lakes, including non-sensitive lakes, at the peak of acidification in the 1980s. Most species returned to the lakes when pH started to increase in the 1990s, but in acid sensitive (least productive) lakes, their return was noticeably slower.

The persistence of *Chydorus sphaericus* in all categories of lakes during the peak of anthropogenic acidification was probably enabled by a high tolerance of this species to low pH and low temperatures, and by its wide niche, covering both the littoral and pelagic zones. In strongly acidified alpine lakes where original pelagic Crustacea disappeared, *Chydorus sphaericus* was often the only species inhabiting the open water (Stuchlík *et al.*, 1985; Fott *et al.*, 1994; Hořická *et al.*, 2006).

Hydrobiological investigation of three acidified reservoirs in the Jizera Mountains, the Czech Republic, during the summer stratification

The region of the Jizera Mts (Northern Bohemia, Czech Republic) is another geologically sensitive area strongly affected by acid deposition. The analysis of historical data showed that the natural acidity of waters in the Jizera Mts, caused by humic acids, was altered by acid deposition in the early 1950s. Anthropogenic acidification brought about a decrease in pH of surface waters and degradation of life in streams and reservoirs; the number of zooplankton species was reduced and the fish disappeared from the reservoirs, as it was shown by investigations conducted in the 1950s and 1960s. In that time, however, the acidity of water in the reservoirs and the changes in biota were still partially attributed to the dystrophic character of the watersheds. In the 1980s, acid deposition caused a mass die-back of coniferous forests in the whole region of the Jizera Mts and a large-scale deforestation of the watersheds. Liming of waters in the Jizera Mts was probably conducted since the beginning of the 20th century, to maintain fish populations. During the 1980s, intensive liming of both watersheds and reservoirs was conducted for many years, but did not eliminate the acidification problem.

Drinking water reservoirs Bedřichov (1905), Souš (1915), and Josefův Důl (1982) were studied in the summer of 1992, to assess the present state of their acidification. Stratification of temperature, conductivity, oxygen, pH, alkalinity, concentration of chlorophyll-*a*, and biovolume of the main species of phytoplankton were analyzed in vertical profiles, and species composition of phytoplankton and zooplankton were determined.

Acidification was recognized as a factor which significantly influenced both chemistry and plankton communities of all three reservoirs. The values of pH ($pH > 5$ in the epilimnion) were nevertheless higher than in the 1980s (Bednářová, 1988). We explained the change by liming (alkalization of the epilimnion by tributaries from the watersheds and/or a direct effect of liming), and by the reduction of acid deposition following the deforestation of watersheds.

The species composition of phytoplankton (with a low number of taxa, as it is common in acidified lakes throughout the world, and Dinophyceae dominating – namely genera *Peridinium* and *Gymnodinium*) was similar in all reservoirs, and did not change significantly during the last 30 years before the beginning of our study. The biomass of phytoplankton was low; most of it was concentrated in the upper 5 m layer in each reservoir.

The major species of zooplankton were *Brachionus sericus*, *Keratella valga*, *Microcodon clavus* (Rotatoria), *Ceriodaphnia quadrangula* (Crustacea: Cladocera), and *Acanthocyclops vernalis* (Crustacea: Copepoda). These species exhibit a wide range of pH tolerance and were present in the Souš reservoir since the 1920s (Gessner, 1925), while the rotifer *Keratella cochlearis* and crustaceans *Bosmina longirostris* and *Eudiaptomus gracilis* disappeared with the increasing acidity of the water in the reservoirs.

We concluded that the only significant effect of liming of the watersheds was a partial (limited to the epilimnion) and temporary (lasting until the autumnal circulation) increase in pH of the water, accompanied by an increase in the phytoplankton biomass, and that the seasonal instability of water chemistry and changes in biota such as unpredictable peaks of algae, made the drinking water treatment of these waters difficult.

Degradation and recovery of mountain watersheds: the Jizera Mountains, Czech Republic

The Jizera Mts, together with the Giant Mts and the Ore Mts, are a part of the so-called Black Triangle, the epicentre of acid atmospheric deposition in Europe. The slow-weathering bedrock (granite) and shallow podzolic soils of low buffering capacity if the Jizera Mts are extremely sensitive to acidification. Moreover, the native tree species composition of the forest cover (83%) in the region (common beech, *Fagus sylvatica*, Norway spruce, *Picea abies*, and common silver fir, *Abies alba*) was replaced during the 20th century by spruce monocultures. In the 1980s, the watersheds of the Jizera Mts, namely in the high plateau, were significantly declined as a consequence of acid atmospheric deposition and inappropriate forestry practices – developing spruce plantations of lower ecological stability, extensive clear-cut harvesting using heavy mechanization, and ineffective control of insect epidemies. Reforestation was for long unsuccessful, mainly because of competition from invasive grass species (*Calamagrostis villosa* dominating). Erosion and sediment runoff resulted in deterioration of the quality of surface waters. Low pH values and a high content of aluminium and heavy metals in reservoirs and streams led to extinction of fish and a reduction of water biota.

This work summarized the damage of watersheds in the Jizera Mts, and described the fast improvement of surface waters in the 1990s, which was a consequence of both the decrease in air pollution and reduction of the leaf area (reduction in acid deposition under the canopy) by the clear-cutting of spruce stands, partially also a result of liming.

The first signs of chemical recovery appeared in the late 1980s, after the clear-cut of mature spruce stands: mean annual pH values increased from 4.0 to 5.0, concentrations of sulphate and nitrate decreased from 13 to 6 mg l^{-1} and from 6 to 4 mg l^{-1}, respectively. In 1991 (Bedřichov) and 1996-1999 (Souš and Josefův Důl), brook char (brook trout, *Salvelinus fontinalis*) and brown trout (*Salmo trutta* morpha *fario*) were experimentally reintroduced. Brook char (the most acid-tolerant freshwater species) were able to survive and reproduce, although the content of aluminium, lead, mercury, and cadmium in their tissues exceeded the hygienic limit; brown trout evidently starved and did not reproduce. The study mentioned that the survival of fish is endangered by episodic acidification events (in snowmelt and rainstorms) with drops in pH values and an increased level of toxic forms of aluminium.

The article stated that in a long-term perspective, the water quality may be improved by planting forest stands with a nearly native tree species composition, and by the use of traditional environment-friendly forest practices in the mountain watersheds.

Conclusions and perspectives

Surface waters in many areas of Europe with sensitive geology suffered severe anthropogenic acidification during the last century, among them also water ecosystems in remote mountain areas, which are extremely sensitive to global changes. The lake district of the Tatra Mountains on the Slovak-Polish border, as well as lakes in the Šumava Mountains and reservoirs in the Jizera Mountains (Bohemia, Czech Republic), were strongly acidified.

The reasons for acidification were elevated sulphur and nitrogen emissions, transported long distances in the atmosphere. The contribution of nitrogen to acidification was always very high (up to 40%) on the territory of the Czech and Slovak Republics, compared to other acidification areas within Europe. However, the size and character of a watershed (namely the geology and vegetation cover) and forest management in the watersheds were important factors influencing the sensitivity of waters to acidification, the extent of damage, and the dynamics of the acid-driven processes.

The man-made acidification may be combined with a natural acidity (dystrophy) in some waters, caused by a high amount of organic acids.

Acidification led to a change in the water chemistry (a decrease in pH and alkalinity, and an increase in concentrations of sulphate and nitrate), and to a reduction of biodiversity in freshwater ecosystems. Fish and planktonic Crustacea disappeared from many lakes. Acidification-induced oligotrophication, eutrophication, and toxicity of aluminium were recognized as key mechanisms of the effect of anthropogenic acidification on biota. In the areas studied, the consequences of acidification were more drastic than in other mountain areas of the world.

Since the beginning of the 1990s, the water ecosystems in all the areas studied have been rapidly recovering from acidification due to a strong reduction of both sulphur and nitrogen deposition. Recovery of water chemistry from acidification started immediately after the socio-economic changes in Central Europe in 1989, but has been delayed by a hysteresis of pH and elevated concentrations of aluminium in some watersheds (Kopáček *et al.*, 2002). The past water chemistry in these and many other studied areas, as well as predictions for the future, have been extensively modelled using the MAGIC model. Thus, there are different recovery scenarios for areas reforested with Norway spruce monoculture and those planted with a mixed forest, with a tree species composition close to the original forest, and for lakes in the alpine zone (Křeček & Hořická, 2001; Kopáček *et al.*, 2004; Hardekopf *et al.*, *submitted*).

It is much harder, though, to predict the biological recovery. It often followed the changes in water chemistry, but, in general, it was delayed because of the considerable complexity of these processes. The survival of re-stocked salmonid fish (*Salvelinus fontinalis*, *Salmo trutta* morpha *fario*) is determined by water pH and concentration of aluminium, the food supply, and the lake – tributaries system, which enables the survival of fish in periods of snowmelt or flood flows, accompanied with a drop in water pH (Hořická *et al.*, 2005). In planktonic and littoral Cladocera, so far we have seen that in addition to the return of original species to lake ecosystems, we must expect a period of an unstable dynamics in the species composition, where the trophic status of a lake, water temperature and acidity, quality and quantity of food, and predation by fish and invertebrates (e.g. *Notonecta*) will be determining factors in the post-acidification succession (Hořická, 2005; Sacherová *et al.*, 2005). In the first phase of the recovery of biota, we expect small species with a short turnover time, the “right” life strategy, and a high adaptability to win in competition. For many species now missing, like rotifers or planktonic Copepoda, we do not know whether their return is possible (Kohout & Fott, *in press*). The dispersal of water organisms is a stochastic process, especially in isolated and remote from each other environments. While the fish can be re-stocked by man, the ways and mechanisms of water animals' transport are much more complicated and partly still unknown.

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