Original Research

The Relationship between Quality of Ground Waters and Forest Cover in Regions Affected by High Levels of Acid Atmospheric Deposition – a Case Study of the Krušné Hory Mts., Czech Republic

Z. Hrkal[1, 2]*, D. Fottová[3], P. Rosendorf[2]

[1]Charles University, Faculty of Science, Department of Hydrogeology, Albertov 6, 128 43 Praha 2, Czech Republic
[2]Water Research Institute TGM, Podbabská 30, 160 62 Praha 6, Czech Republic
[3]Czech Geological Survey, Geologická 6, 152 00 Praha 5, Czech Republic

Received: 9 December 2008
Accepted: 21 July 2009

Abstract

Our paper is intended to assess the long-term impact of acid atmospheric deposition on the chemistry of ground waters in the Krušné hory Mts., and to explore to what extent forest cover participates in the development of chemical composition of relevant waters. The study was based on the results of long-term monitoring and assessment of mass flow in the Jezeří experimental catchment (1996-2007), and also on the results of investigation of a network of 26 experimental catchments in the Krušné hory Mts. that were affected by prolonged atmospheric deposition of high levels of sulfur and nitrogen. The monitoring of ground water quality and the health of forests at these catchments was not continuous. However, areal systematic sampling of waters characterizing the periods 1959-65, 1965-74, 1979-89 and 2000-02 enabled us to reconstruct the development of ground waters chemistry in the Krušné hory region during the last 40 years. The changes in chemical composition of waters were compared with data on atmospheric deposition. The obtained results proved the worst quality of ground waters to have occurred in the 1980s, which was manifested by the depletion of HCO_3 contents, a decrease in pH and increase in SO_4 and NO_3 concentrations. Significant damage to the forest cover was recorded during this period of time. The results indicate that in the presence of a coniferous forest the negative impacts of acid atmospheric deposition on groundwater quality are greater. Simultaneously, the deterioration in the quality of groundwater, indicated by increased concentrations of aluminum, plays a part in damaging the health of the forest.

Keywords: groundwater quality, forest health, atmospheric deposition

Introduction

The quality of groundwater arises from a complex process governed by a range of factors among which the chemical composition of atmospheric precipitation plays an essential role at the very beginning of its formation. Atmospheric precipitation influenced by anthropogenic activities resulting in low pH and high contents of NOx and SO_2 comes first into contact with the vegetation cover. The rain washes down into dry soil deposition, dust particles and aerosols caught on leaves and needles of trees. These particles represent in the Czech Republic 2/3 of the total dry

*e-mail: hrkal@vuv.cz

deposition [1]. The intensity of this process is closely connected with the age and type of the forest [2]. Old conifers in general exhibit the highest ability to catch dry atmospheric deposition [3]. The acidification is accelerated in particular by spruce conifers that mostly intensify the deposition of H^+ ions [4]. For instance, Bergkvist and Folkeson [5] found throughfall in spruce forest in comparison with beech trees and birch to have exhibited three times greater deposition of SO_4^{2-} and even eight times greater deposition of H^+. Also, Jezeří catchment in the Krušné hory exhibited 49.3 kg S ha/yr under conifers and only 11.6 kg S under deciduous trees in 2000, while bulk deposition in an open area was only 8.1 kg S [6]. These data support the argument against planting coniferous monocultures in areas with elevated air pollution. However, apart from this the quality of groundwater is also influenced by the internal biological cycle of the forest [7].

Atmospheric precipitation, only after its passage through vegetation cover, is infiltrated into the ground being first in contact with soil, unsaturated and finally with saturated zone of the rock massif. The groundwater gradually changes its chemical composition and the acidity of atmospheric deposition is attenuated by ongoing buffer reactions. During the first stage of acidification, which is more or less discreet, the pH remains stable because the acid deposition is buffered by HCO_3^- ions, of which concentrations gradually decrease. Once the bicarbonates are consumed during this process the pH decreases, and further progress in acidification is buffered by humic compounds and aluminum [6, 8].

However, changes taking place in groundwater also have a backward effect on the health of the given forest. Low contents of calcium and magnesium and high concentrations of metals mobilized by low pH pose the first problem. Aluminum and beryllium appear to be the most dangerous elements for a root system of trees as far as toxicity is concerned [9, 10]. According to Ebben [11], particularly spruce forest (*Picea abies*) is extremely sensitive to high concentrations of toxic metals.

The disproportion in nutrition of a tree is one of a range of factors playing a role in the whole process. High concentrations of nitrogen are functioning as a fertilizer, thus stimulating the growth of vegetation, but magnesium, an absolutely essential component of chlorophyll, is missing in the forest. As a consequence, the trees are weakened as they succumb to climatic stress, insects or diseases that would otherwise be able to cope with easily under common conditions. Therefore, the acidification is occasionally compared with AIDS, because similarly to this human disease, it does not kill the victim outright but fatally weakens its system over time.

It is therefore obvious that the forest, through its ability to catch dry atmospheric deposition, actually intensifies the acidification of ground waters. On the other hand, the quantitative changes taking place in ground waters have a negative impact on the health of the forest.

The Krušné hory Mts. belong to the areas where the impact of acid atmospheric deposition was manifested and followed by extreme processes, resulting in mass extinction of forest cover on a regional scale. As emerges from previous

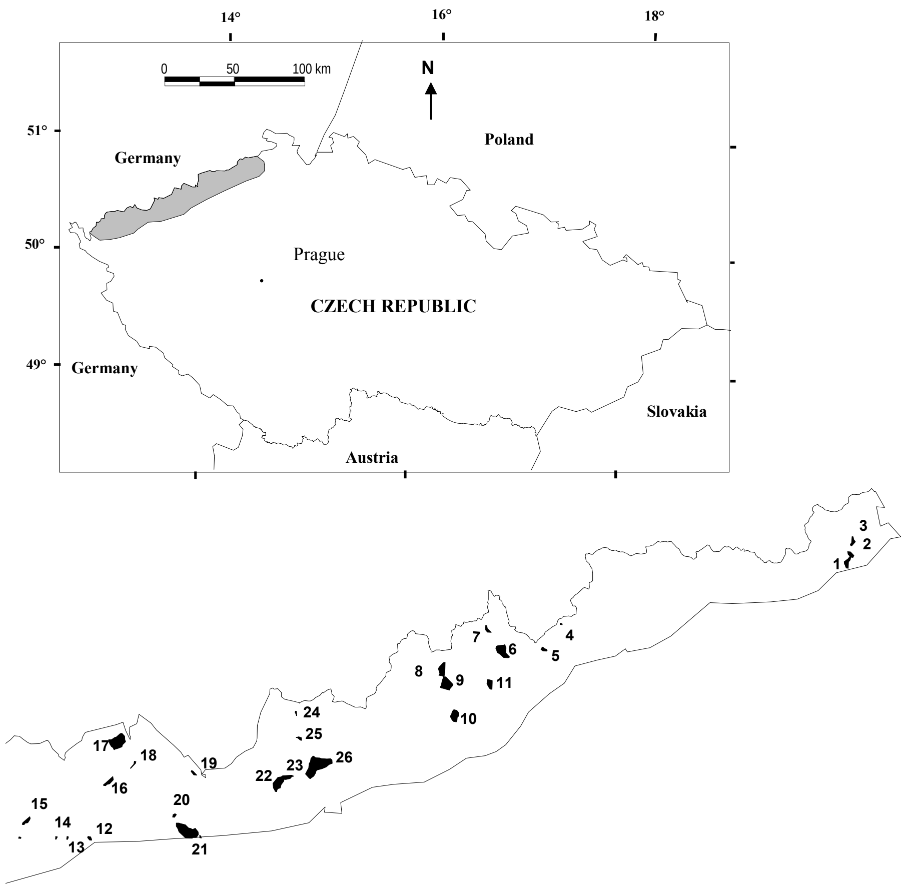

Fig. 1. Position of the region investigated, showing the location of select experimental sites.

studies, the forest may amplify negative impacts of acid atmospheric deposition on the quality of waters. However, these assumptions were so far based exclusively on data of monitoring of small catchments only a few hectares in size. The question arises as to whether a kind of mutual relationship between certain types of forest and its health and ground water quality also exists on a regional scale? What role does the forest play in the chemistry of ground waters in areas affected by acid atmospheric deposition? Does feedback between the quality of ground waters and the health of the given forest also exist? This was the range of questions which the present investigation carried out by the Water Research Institute was focused on. The method for answering these questions involved a comparison of the development of groundwater chemistry in 26 springs revealing their chemistry with the development of health and/or mortality of the forest cover in respective catchments since the late 1950s until the present.

System

The Krušné hory Mts. form a natural topographic boundary between the Czech Republic and Germany (Fig. 1). The higher parts of the range are formed by a high plateau, the altitude of which is around 800 m a.s.l. The total area of the investigated part of Krušné hory Mts. is 1392 km^2. The main rocks are mica schists, two-mica and biotite paragneisses, granodiorite orthogneisses, migmatites, migmatitic gneisses and muscovite to two-mica orthogneisses. Several granite massifs of Variscan age were emplaced later in the metamorphic complexes of the Krušné hory Mts.

The climate in the area studied is rather cool with high total precipitation mostly in areas exceeding 800 m a.s.l., where annual rainfall is close to 1,000 mm. Due to relatively low mean atmospheric temperature (between 5 and 7°C) the precipitation occurs as snow for a considerable part of the year.

The acidification of the Krušné hory Mts. area is ascribed to a prolonged period of extremely high acid atmospheric precipitation caused by industrial emissions, mostly in the form of sulfur and nitrogen compounds. Sulfur dioxide emissions in the Krušné hory Mts. region peaked in the late 1980s. In 1987, nine major sources in the foothills of the Krušné hory Mts. emitted 834,000 tons of sulfur dioxide. This emission rate decreased to 568,000 tons in 1993, i.e. to 67% of the initial value. Emissions of nitrogen oxides in the same area decreased from 274,000 tons in 1987 to 109,000 tons in 1993. Ecological measures were being brought into force in the former East Germany during the same period. In neighboring Saxony, the sulfur dioxide emissions decreased from 2,000,000 t of SO_2 in 1989 to 1,100,000 Mt in 1992. Emission of nitrogen oxides fell from 400,000 tons to 300,000 tons per year [12]. An overall mean value of total sulfur deposition corresponding to 43.6 kg/ha/year in 1999 decreased to 16.5 kg/ha/year in 2001. Sulfur deposition in the Czech Republic is expected to play a much less important role as follows from the projected downward trend in emissions.

The vegetation of the Krušné hory Mts. has changed rapidly over the last hundred years. The original mountain forest consisted of a mixture of European beech, silver fir, and Norway spruce (*Picea Alba*), with a small proportion of birch, oak and maple [13]. This was progressively replaced during the 19th century by fast-growing Norway spruce. By the 1950s, this became the dominant species in the forest of the Krušné hory Mts. The first indications of damage by acid precipitation were recorded as early as the 1920s [14], but a much larger impact of acidification on the health of local vegetation was being recorded by the 1940s and 1950s [15, 16]. However, the real ecological disaster affecting the entire summit region of the mountain range took place as late as 1978. The extent of the damage to the Krušné hory forests is demonstrated in the following graph (Fig. 2).

The lumbered areas were gradually reclaimed. Planting of new forest as fast as possible was intended to stabilize steep slopes and to prevent soil erosion. A search was made for new more acid-resistant species to replace the Norway spruce. As an outcome, the increased proportion of broad-leaved tree species in the overall composition of the forest resulted in a decline in dry atmospheric deposition [18]. Changes in the composition of the Krušné hory forest during the period 1957-91 are indicated in Fig. 3.

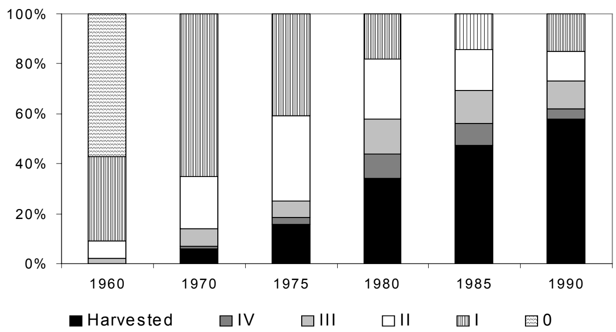

Fig. 2. Damage classes of spruce stands in the Krušné hory, 1960-90 (healthy = 0, dying = IV) after Kubelka et al. 1992.

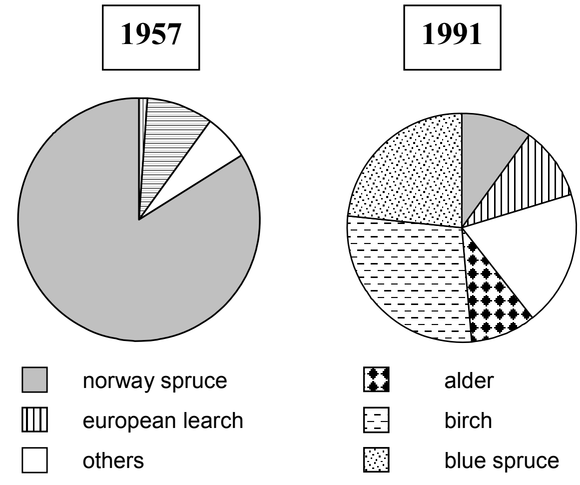

Fig. 3. Tree species composition in the forest of Krušné hory in 1957 (all stands) and 1991 (stands in the age class 1-30 years).

As far as land-use in the studied area is concerned, the forest is the dominant component because 64% of the surface consists of mountainous terrain. Farmland is almost negligible. Arable land constitutes only 4% of the entire area under consideration.

The process of acidification has had a considerable impact on the quality of local groundwater. The alkalinity of the waters fell significantly as compared with the results of chemical analyses from the fifties of the last century. Locally, in the apical parts of the mountain range, the HCO_3^- completely disappeared. At the same time, the concentrations of nitrates and sulfates increased [19].

Materials and Method

The methodology of data processing was based on the fact that two different datasets revealing the development of water chemistry during the last 40 years were available. The first dataset involved long-term systematic monitoring of the Jezeří experimental catchment where monthly data have been available since 1979. This valuable source of information enabled us to assess a long-term trend in the development in groundwater chemistry, including short-term variations. However, this was incoherent information from the viewpoint of the Krušné hory region as a whole.

Another dataset included the chemistry of spring waters covering evenly the whole area under consideration, providing information since the late 1950s. The drawback of this dataset was the fact that it did not provide a continuous series of measurements, but instead irregular single records. This problem was partly eliminated during 2000-02 when all these springs were, similar to the Jezeří catchment, analyzed in monthly periods.

The development of ground waters chemistry in detail, as well as on a regional scale, was reconstructed during the first stage of investigation and the results of groundwater quality were compared with the development of atmospheric deposition.

The second stage of studies was focused on the relationship between the quality of ground waters and the state of health of the forest in relevant catchments. The study was based on a network of catchments forming the infiltration areas of the monitored springs and defined within a Digital Elevation Model (grid 50×50 m) using ARCVIEW 3D Analyst software. All springs drained a shallow subsurface aquifer confined to rock mantle and open fissures in metamorphic and magmatic rocks reaching a maximum depth of 30 m. Therefore, the hydrogeological divide was identical with the hydrological divide defined by local topography. A database of factors influencing groundwater quality and/or governing changes in it was created for each catchment. The database included altitude above sea level of each spring, the areal extent of the catchment and the basic characteristics of the vegetation cover. The characterization of the input data used in considerations is as follows:

Data on Groundwater Quality and Its Development

The earliest data on groundwater quality in the Krušné hory Mts. were gathered during the years 1959-65. A database of analyses of single samples from 130 springs was compiled by the Czech Geological Survey during hydrogeological mapping undertaken at that time. The historical analyses gave only contents of the main cations and anions. A total of 62 springs from this group were re-analyzed for the same elements during 1965-74 and 1979-89 (during the same period of the year). The majority of these springs were again sampled and analyzed in 2000-02 as part of the LOWRGREP 5. FWP EU project [20]. This time, analyses were made at monthly intervals and trace elements and toxic metals were included.

The major problem involved in this kind of information was the different quality of the used data. While the data from 1959-89, acquired from archives, represented only single samplings without specification of sampling method and subsequent laboratory procedures, the data from 2000-02 provide statistically treatable values of fair quality from monthly monitoring. Water samples were analyzed using standard methods in accredited laboratories of the Vodní Zdroje GLS Company. The flame atomic absorption spectrometry or optical emission spectrometry with induced plasma were used for the determination of major and minor cations (Na, Mg, Ca, K, Mn, Li, Fe, Al, Zn, SiO_2), whereas trace elements (Cu, Pb, As, Cd, Be, Al, Co, Cr, Mo, Ni and V) were established by means of atomic absorption spectrometry with electrothermic atomization. Liquid ion chromatography was applied to determine SO_4^{2-}, NO_3^- and Cl^-. A glass electrode combined with pH meter (model Radiometer Copenhagen) were used for measurements of pH.

The chemistry groundwater discharge at the Jezeří catchment was continuously monitored in monthly intervals since 1983, but data from 1978-83 from the Vysoká Pec locality [21] can also be used in our considerations. This is actually the longest series of uninterrupted measurements undertaken in the Krušné hory region that allows us to reconstruct the development of water chemistry. The analytical procedures are the same as methods used in the LOWRGREP project.

All the detailed analyses of relationships between the quality of groundwater and conditions of the forest cover were therefore in particular based on data from recent monitoring undertaken within the LOWRGREP project and the earlier data were taken as supporting.

Development of Species Composition and Forest Health

Maps of defoliation and mortality of conifers derived from Landsat-TM/ETM imagery were compiled by the Institute for Economic Development of Forests. Ten cate-

Table 1. Characteristics of experimental catchments.

cathment No.	altitude of spring (m.a.s.l.)	total surface (ha)	prevailing lithology	forest surface in % (2001-2002)	degree of forest damage (2001-2002)	Al mg/l	Be mg/l	NO_3 mg/l	HCO_3 mg/l	pH
1	436	54	granite	4	3.72	0.20	0.30	5.3	8.80	6.01
2	675	32	ortogneiss	0	-	0.10	0.07	5.6	23.88	6.01
3	639	32	ortogneiss	26	6.21	1.09	1.27	3.0	0.61	4.68
4	738	4	granite	0	-	0.11	0.11	11.7	6.89	5.65
5	692	22	ortogneiss	0	-	0.07	0.08	3.7	23.84	6.01
6	787	152	paragneiss	8	5.86	0.70	0.65	6.7	4.55	4.63
7	725	27	paragneiss	67	4.38	0.10	0.08	2.2	8.39	6.00
8	755	101	ortogneiss	1	5.67	0.18	0.40	7.1	6.44	5.68
9	773	151	paragneiss	10	5.94	0.22	0.08	9.8	10.50	5.99
10	564	103	paragneiss	1	3.57	0.09	0.07	7.2	30.93	6.46
11	706	59	paragneiss	0	0	0.08	0.07	4.6	12.45	6.17
12	576	15	granite	61	3.96	0.17	1.33	4.5	8.95	5.65
13	613	6	granite	0	-	0.08	0.08	14.5	12.72	5.67
14	648	5	granite	95	3.02	0.22	1.36	3.9	11.07	5.67
15	690	36	granite	34	3.24	0.24	1.41	1.8	6.37	5.06
16	895	45	phyllite	88	4.02	0.41	0.45	3.3	1.59	4.57
17	859	239	phyllite	76	3.47	0.35	0.53	1.6	4.59	4.92
18	927	11	phyllite	9	4	0.08	0.08	1.3	21.8	6.25
19	1,023	17	micaschist	0	-	0.15	0.12	6.1	8.37	5.44
20	881	11	granite	7	2.33	0.07	0.07	1.8	9.28	5.78
21	447	5	tuffite	0	-	0.07	0.08	12.6	25.00	6.42
22	690	139	micaschists	12	4.47	0.07	0.07	2.7	8.56	5.95
23	864	52	micaschists	5	5.76	0.09	0.62	7.6	12.12	5.62
24	724	7	micaschists	17%	6.87	0.22	0.22	9.6	7.06	5.62
25	853	14	micaschists	6%	-	0.11	0.20	7.9	24.75	5.55
26	766	419	micaschists	5%	5.63	0.13	0.07	11.3	17.00	5.38

gories (graded in 10% divisions) expressing the degree of damage to conifers and also defining the average defoliation of conifers in the vegetation cover were used to assist interpretation of the analytical results. Category 1 indicates completely healthy forests, and category 10 indicates dead forests. Three series of aerial photographs from 1984-85, 1994 and 2001-02 enabled detailed analysis of changes in the areal extent of forest in individual catchments, and could also be used to assess their health.

Data on the Development of Atmospheric Precipitation

The Krušné hory Mts. region has probably been suffering from acid atmospheric precipitation for more than a hundred years. This conclusion is indirectly based on data concerning the extraction of lignite containing high concentrations of sulfur that was mostly burnt in the foothills of the Krušné hory Mts. The mining operations and the atmospheric deposition resulting from combustion of lignite for industrial purposes culminated in the second half of the 1950s, but the first quantitative data on the extent of atmospheric precipitation date from 1978-83. At this time, the Czech Geological Survey began to monitor the fluxes of chemical components in the experimental catchments of Jezeří X-14 and, later, X-14 [22]. Wet deposition has been monitored at the Vysoká Pec station since 1978, and the earliest data on dry deposition from the Rudoltice meteorological station date from 1993 [22]. As part of the Geomon project, the Jezeří catchment is currently still under investigation [23, 24].

Results

The results revealed a high level of acidification in numerous springs. The alkalinity in a number of springs was found to be close to zero in the 1980s. The measurements of pH were not carried out, but by analogy with the results acquired in 2000-02, it is likely that the value of pH in these springs was close to 4. Data on concentrations of aluminum became available from the 1990s. The mean concentrations of Al in the most acidified springs (HCO_3 < 1 mg/l) were equal to 0.9 mg/l.

Regardless of the significant reduction in atmospheric precipitation by the end of the last century (Fig. 4), the quality of ground waters did not improve as would have been expected. The ground waters have maintained their acid character into the first decade of the new millennium (springs Nos 3, 4, 16, and 17, see Table 1). In 2000-02, the contents of HCO_3 increased slightly compared to those of the 1980s, reaching a mean value of 15 mg/l, (compared with 9.5 mg/l between 1979-89), but the concentrations of aluminum and beryllium dissolved in the groundwater in some springs remain high (Table 1).

The secondary concentration of sulfur in the soil horizon during the recent decades of atmospheric precipitation is believed to be responsible for this situation. At present, this accumulation is being progressively washed out again [25, 26]. The study [24] has shown that approximately 30% of total sulfur content in the drained water comes from organic matter in the upper humic layer of the soil horizon. Consequently, the return of groundwater quality to the so-called "natural state" may take quite a long time.

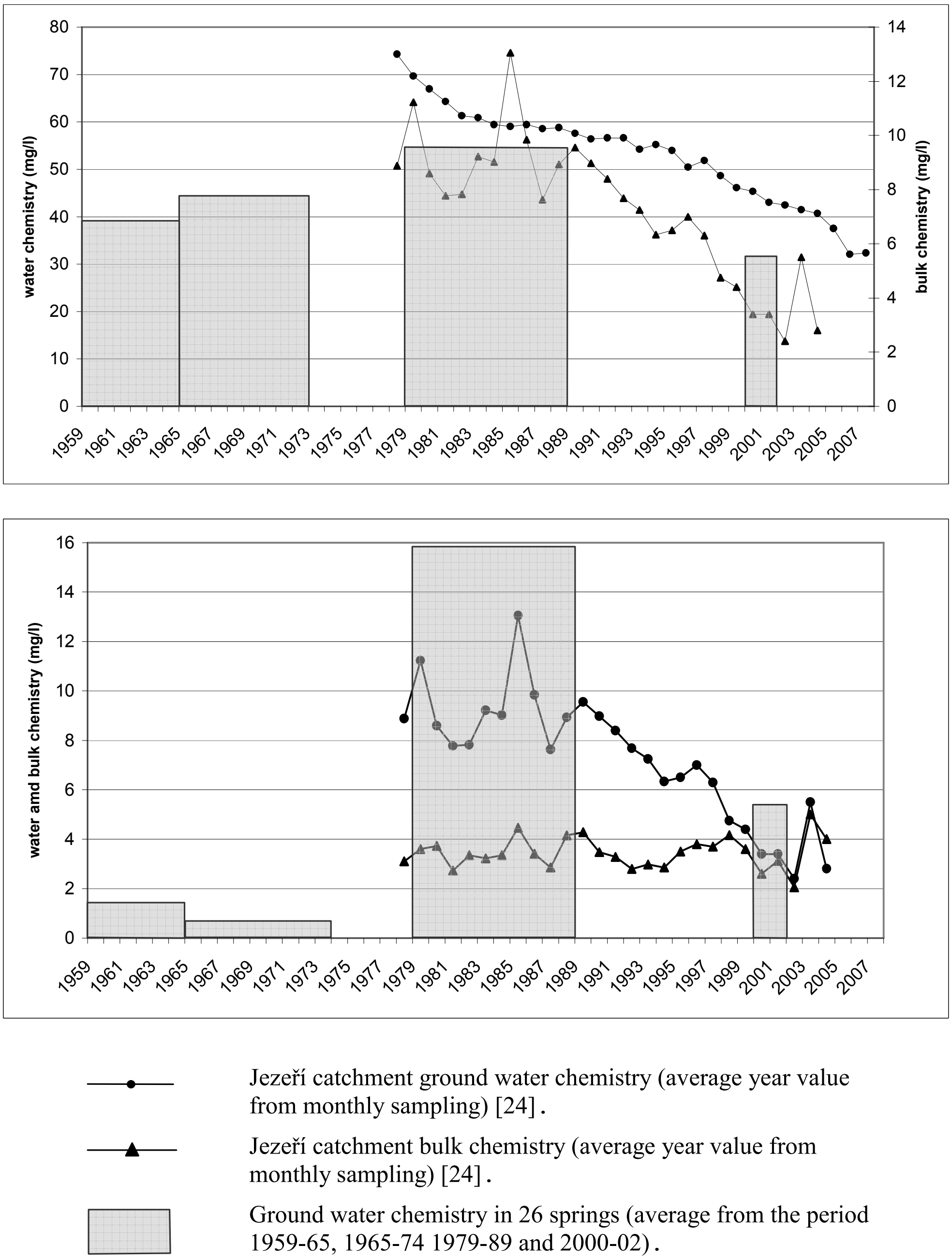

Fig. 4. Trends of groundwater and bulk chemistry in Krušné hory Mts. between 1959 and 2007.

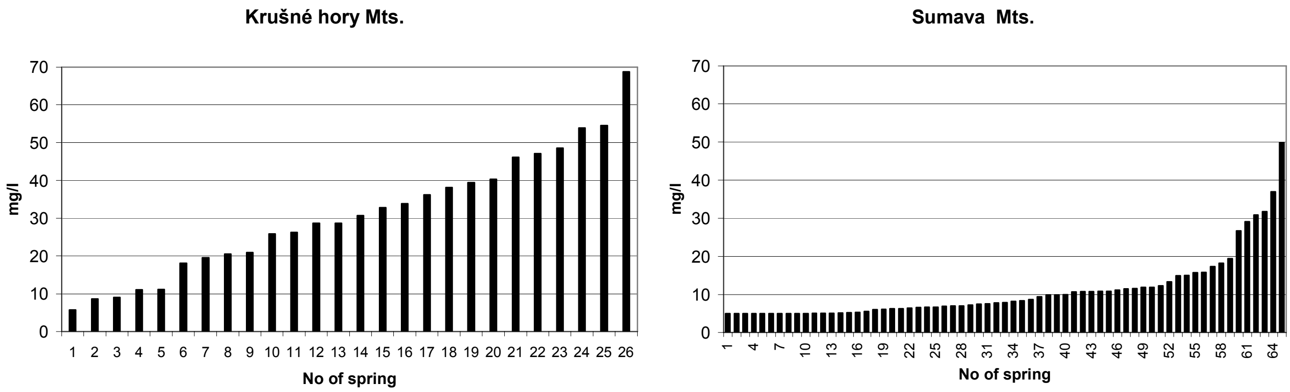

Fig. 5. Monthly average concentration of SO_4 in 2000-02 in Krušné hory Mts. (26 springs) and Sumava Mts. (65 springs).

This fact can be demonstrated by comparing the Krušné hory Mts. with the Šumava Mts. in SW Bohemia. The latter region is built by rocks similar to the Krušné hory region, but a fundamental difference between the two areas is the markedly lower level of acid atmospheric deposition in the Šumava Mts. The mean concentrations of sulfates in the Šumava ground waters established during the LOWRGREP project in 2000-02 revealed only 17 mg/l against 35 mg/l in the Krušné hory region. If we accept a range of 10-20 mg/l as a "natural background" value, then 90% of all the monitored springs in Šumava Mts. fall into this category, while in the Krušné hory it is only 25% (Fig. 5).

The worst effects of acid precipitation on the forest cover of the Krušné hory were recorded in the 1980s. The forest in catchment No. 22 (Fig. 6) serves as an example of these conditions. The spruce forest in 1985 covered 27% of the total area of the catchment occupying 1.39 km^2, and the average degree of damage corresponded to 6.12. In the course of subsequent years the dead and heavily damaged forest was gradually cut down and its area in 1992 was reduced to 19% and in 2000 to 12%, although the dead trees were replaced by new seedlings. The regeneration of the forest obviously led to improvements in its health, but the conditions are still far from being optimal. The mean value of the index of forest damage in this catchment stabilized at 4.76 in 1992 and at 4.47 in 2000. However, a gradual worsening of the health of the forest was observed in numerous catchments in the second half of the nineties. This is not as severe as in the 1980s, but it is a warning that the local environment is still far from normal. In addition to other factors, one important reason for this state of affairs is the slow recovery of ground waters to optimum quality for the reasons explained above.

In the next stage of investigation the results of analysis of forest health in individual catchments was compared with hydrochemical data.

Attention was first focused on the assessment of the presence of the forest and its extent vs. the quality of ground waters. The coniferous forest has a significant ability to capture dry atmospheric precipitation that forms more than 2/3 of the total burden of deposition in the Krušné hory Mts. This is indicated by the results of throughfall monitoring in the Jezeří catchment undertaken in 2000 (Fig. 7). Another factor that should increase the SO_4 concentration in groundwater - canopy leaching was not taken into account due to lack of data.

Another subject for investigation was the relationship between groundwater quality and the health of the forest. The principle used for this analysis was similar to that used in the preceding case – but this time the quality of groundwater was monitored in relation to variations in the health of the forest. Three of the indicators of groundwater acidification clearly showed a close relationship to the health of the forest. In catchments where the forest showed a low level of damage (max. 4), the pH of the groundwater was up to half an order higher than in areas showing a greater degree of damage. In catchments with severely damaged forest, the groundwater had enhanced concentrations of aluminum and low alkalinity. The behavior of nitrates again corresponds with their use as fertilizers. Only a relatively healthy forest is able to eliminate the impacts of atmospheric nitrogen. Therefore, the enhanced concentrations of nitrates occur in areas without forest vegetation or in those with heavily damaged forest.

The results of the investigation are ambiguous as far as beryllium is concerned because beryllium content did not show a direct correlation with the health of the forest.

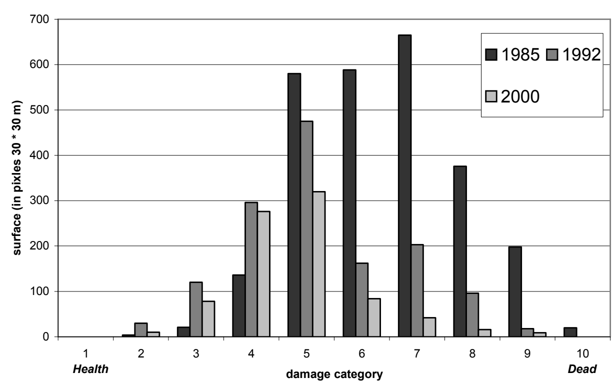

Fig. 6. An example of development of the health of spruce forest in catchment No. 22 during the period 1985-2002.

The concentration of this toxic element evidently increases with decreasing pH, but significant contents of Be were found in ground waters, even in catchments with healthy forest. It is possible that concentrations of Be around 1 ug/l may be indicative of increased acidification, but such levels still may not have a negative impact on the state of forest health.

Discussion

The analysis of data show that marked changes had taken place in the environment of the Krušné hory Mts. during the last 40 years. The study of qualitative changes in groundwater was based on monitoring HCO_3 concentrations, the decrease of which indicates unambiguously the reduction of

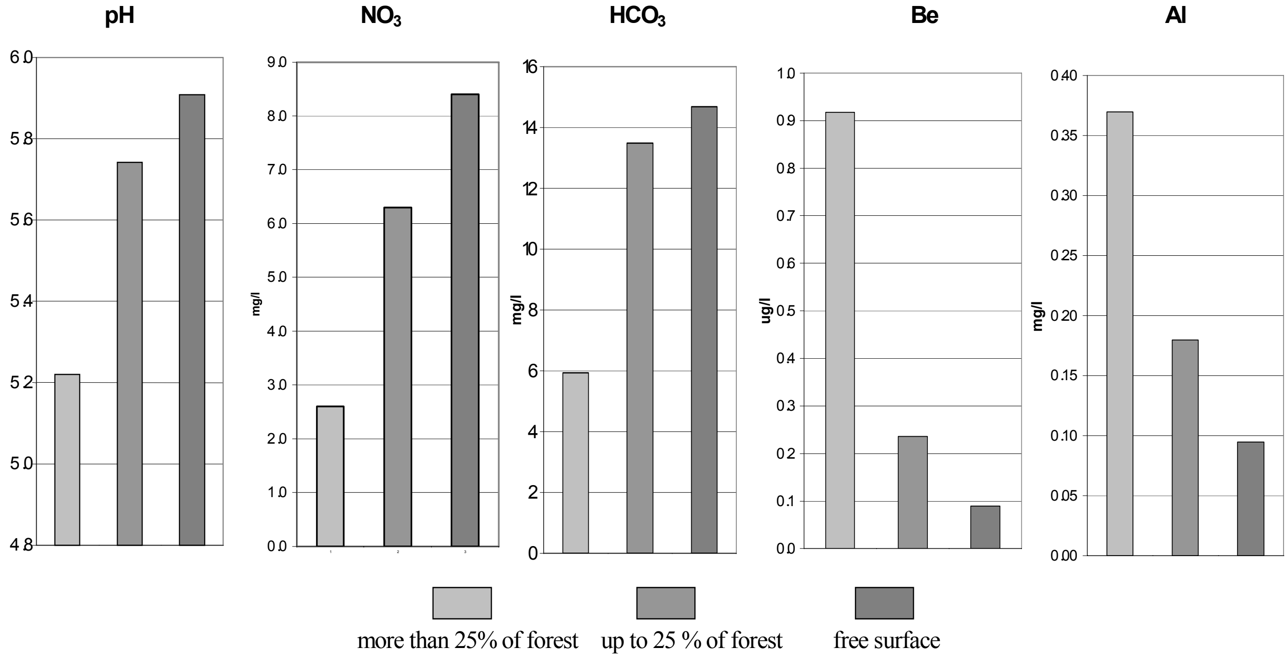

Fig. 7. The dependence of mean values of the major indicators of groundwater acidification on the presence of forest in 26 monitored catchments.

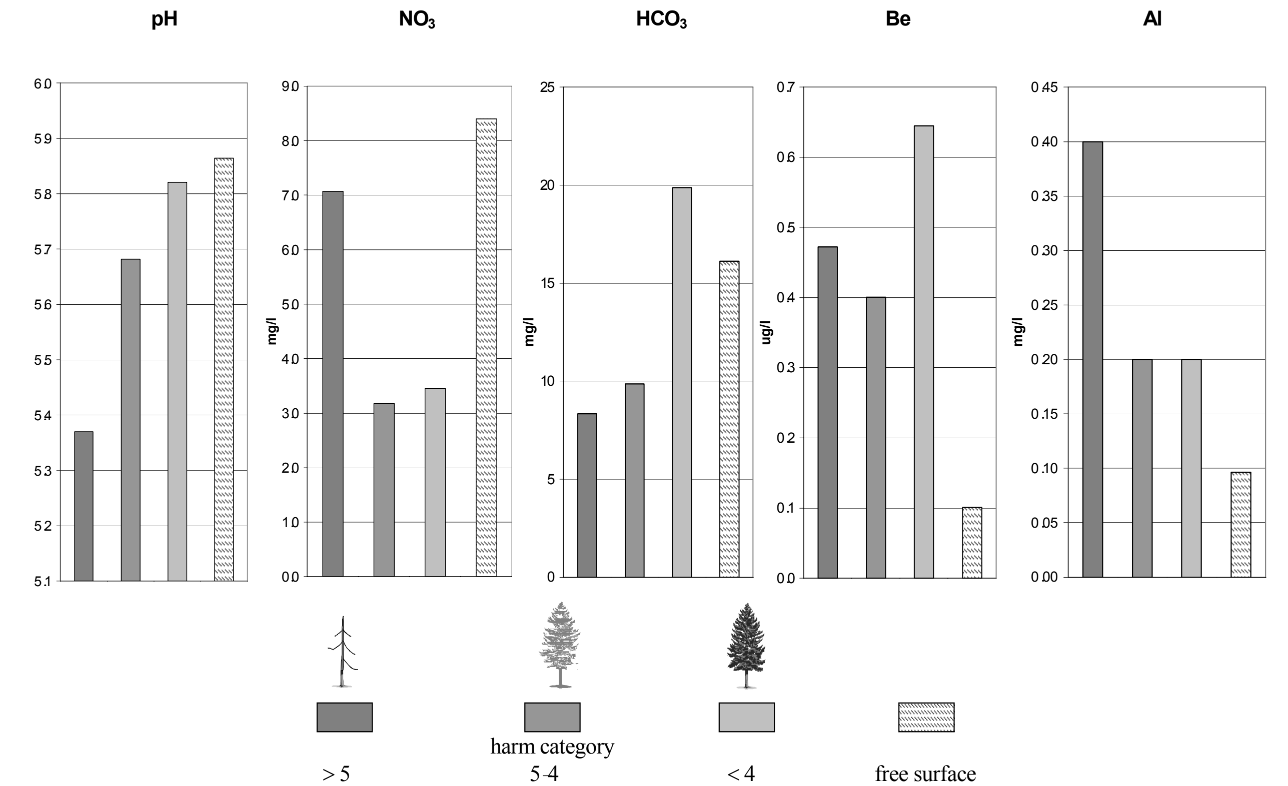

Fig. 8. Relationship between mean values of major indicators of groundwater acidification and the state of health of the forest in 26 monitored catchments.

the buffer capacity of the rock environment. The reduction of pH subsequently increases the solubility of aluminum and beryllium [27]. The concentrations of SO_4 and NO_3 were used as another marker. It is notable that the catchments studied were almost free of any agricultural activities, so that the enhanced contents of nitrates could particularly have been due to atmospheric precipitation and partly (during the process of forest decay) from SOM mineralization.

The presence of forest is therefore generally assumed to be one of the major factors contributing to acidification. This assumption has been confirmed by the results of data acquired from studies on a regional scale: the forested catchments were found to have a pH one order lower than those with grass cover; such catchments also have lower contents of HCO_3 and markedly higher concentrations of aluminum and beryllium in their ground waters (Fig. 8).

The contents of NO_3 do not show the pattern that would be expected – a dense cover of vegetation should increase the capture of dry atmospheric precipitation in the form of aerosols and dust particles that form the dominant contribution to the total deposition in the Krušné hory Mts. area. The situation, however, is quite different: the contents of NO_3 in groundwater from forested parts of catchments are lower than in the meadows. These results may serve as an example of the positive role the forest can play in water quality. Dry deposition of nitrogen in areas covered with forest is really higher than in those lacking vegetation, but the forest can enhance contents of nitrogen successfully consumed as nutrients, so that the atmospheric deposition is converted effectively to a fertilizer.

Conclusions

1. A gradual rehabilitation of forest cover that was heavily damaged in the 1980s also takes place. The investigation of a network of 26 experimental catchments showed that there is a dependence between the forest cover and groundwater quality in areas subjected to a high burden of acid atmospheric deposition. It is also evident that the groundwater quality and the health of the forest are governed by an interactive process in which the water affects the forest and vice versa.
2. The forest, coniferous in particular, in areas suffering from acid atmospheric deposition, amplifies the negative impact of dry deposition. As a consequence, changes of the forest composition leads to local improvements in the quality of ground waters. In the case of nitrogen, the role of the forest is positive because nitrates contained in ground waters are taken up as nutrients and behave as a fertilizer.
3. It is obvious that Integrated Water Management is to be understood as a multidisciplinary activity in which experts in forestry have to play an essential role. Optimization of the generic structure of the forest appears to be necessary in order to minimize negative impacts of acid atmospheric deposition. Unnatural spruce monoculture is to be avoided and priority should be given to the initial Central European mixed woods.

Acknowledgements

This work was supported by projects of the Czech Ministry of the Environment: MZP 0002071101 and SP/1a6/151/07.

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