

Climate change in Central Europe and the sensitivity of the hard rock aquifer in the Bohemian Massif to decline of recharge: case study from the Bohemian Massif

Zbyněk Hrkal · Martin Milický · Miroslav Tesař

Received: 19 August 2008 / Accepted: 19 January 2009 / Published online: 10 February 2009
© Springer-Verlag 2009

Abstract Climate change in Central Europe is manifested by periods of drought during the summer months of years when there is a reduction in atmospheric precipitation and temporary accumulation of water in the form of snow during winter period. The shallow sub-surface aquifer in crystalline rocks is very vulnerable to this decline in rainfall. Monitoring and subsequent model simulations revealed that the groundwater level in recharge areas had been lowered by almost 10 m, but the study also showed that levels in discharge areas are significantly more stable. The transmissivity of hard rock aquifers evidently shows changes in both space and time. The temperature rise results in increasing values of evapotranspiration that is manifested by a gentle but long-lasting groundwater-level decline.

Keywords Climate change · Hard rock · Transmissivity variation

Z. Hrkal (✉)

Department of Hydrogeology,
Charles University in Prague,
Albertov 6, 12843 Praha 2, Czech Republic
e-mail: hrkal@vuv.cz

Z. Hrkal

Water Research Institute TGM, Podbabská 2582/30,
16062 Praha 6, Czech Republic

M. Milický

Progeo Ltd., Tiché údolí 113,
25263 Roztoky u Prahy,
Czech Republic

M. Tesař

The Institute of Hydrodynamics of the Academy
of Sciences of the Czech Republic,
Pod Paňankou 5, 16612 Praha 6,
Czech Republic

Foreword

Global climate change is a phenomenon that has attracted much scientific attention and vigorous debate in recent years. The supply of water for domestic and industrial use is one of the first resources to suffer when warming takes place and seasonal patterns of temperature and precipitation are altered. The present study was designed to assess the vulnerability of the shallow sub-surface aquifer in crystalline rocks to the decline in atmospheric precipitation caused by climate change in Central Europe. Monitoring of precipitation over a period of 3 years was carried out at two localities in the Bohemian Massif and, subsequently, model simulations were carried out. The results obtained are believed to be generally applicable to hard rock aquifers in other areas. The terrain composed of metamorphic and plutonic rocks was selected deliberately because it forms almost three-fourth of the total territory of the Bohemian Massif (Fig. 1). Similar rocks also make up other important tracts of Europe (Krásný 2007).

A characteristic feature of the Bohemian Massif is the accumulation and circulation of groundwater in a relatively shallow aquifer zone formed by weathered rocks containing open fractures. This zone extends below surface to variable depths, locally reaching up to several tens of meters. Under normal climatic conditions in the Bohemian Massif, higher total precipitation and high hydraulic gradients caused by the rough morphology of the aquifer result in extensive and dynamic groundwater circulation. The range of groundwater discharge in mountainous areas often varies between 8 and 15 l/(s km²) (Krásný et al. 1982). The values of groundwater discharge in areas built of hard rocks comparable with those recorded in the Czech Republic were also monitored and computed in other regions of temperate zone of Europe, specifically on the

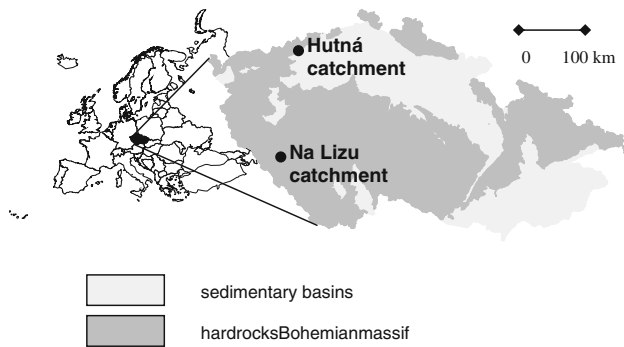


Fig. 1 Extent of hard rocks in Czech Republic and situation of experimental sites

German side of the Šumava Mts. and the Český les Mts. in Bavaria (Apel et al. 1996), in Polish part of the Krkonoše Mts. (Bocheńska et al. 1997; Kryza and Kryza 1997) and elsewhere (Watkins 2007).

However, this environment has a low accumulation capacity and is therefore more sensitive to prolonged periods of reduced atmospheric precipitation than aquifers with deeper basin circulation. Therefore, any delay in the precipitation that recharges this shallow zone results in a rapid decline in the exploitable yields of groundwater from the shallow aquifer.

The climate in Central Europe and its possible further development

It can be stated without much exaggeration that climatic conditions and their changes have determined the course of European history during the last 2,000 years. Human culture developed dynamically during the warm period that began in 800 A.D. and lasted 500 years until the end of the twelfth century. During that time, coastal areas of southern Greenland were covered by forests and fertile soil. In the fourteenth century, the climate began to deteriorate (Fig. 2a). Compared with the dramatic changes that affected our planet several times during the last few hundreds of thousands of years when the average temperature dropped by 8°C (Fig. 2c), the change that took place in the fourteenth century appears quite minor because the average drop in temperature was less than 1°C. This episode of climate change is best documented on the northern hemisphere, in Europe, Asia and North America, whereas manifestations of the change in the southern regions of the Earth are much less obvious. Based on the studies by Bradley and Jones (1993) and Crowley and Lowery (2000), the Intergovernmental Panel on Climate Change (IPCC) argued that the “Little Ice Age” appears to have limited utility in describing trends in hemispheric or global mean temperature changes in the past centuries”.

The cool period was manifested for the first time during the years 1315–1322 when Europe suffered from the first wave of famine (Jordan et al. 1996). As much as 25% of the population died in some areas of Europe because of the lack of food. Subsequently, famines and plague epidemics decimated the population that had been weakened by diseases to such an extent that mortality reached up to 70%. The lowest temperatures in Europe were recorded in the seventeenth century (Moberg et al. 2005) and again during the Thirty Year War, and mortality increased significantly as a result.

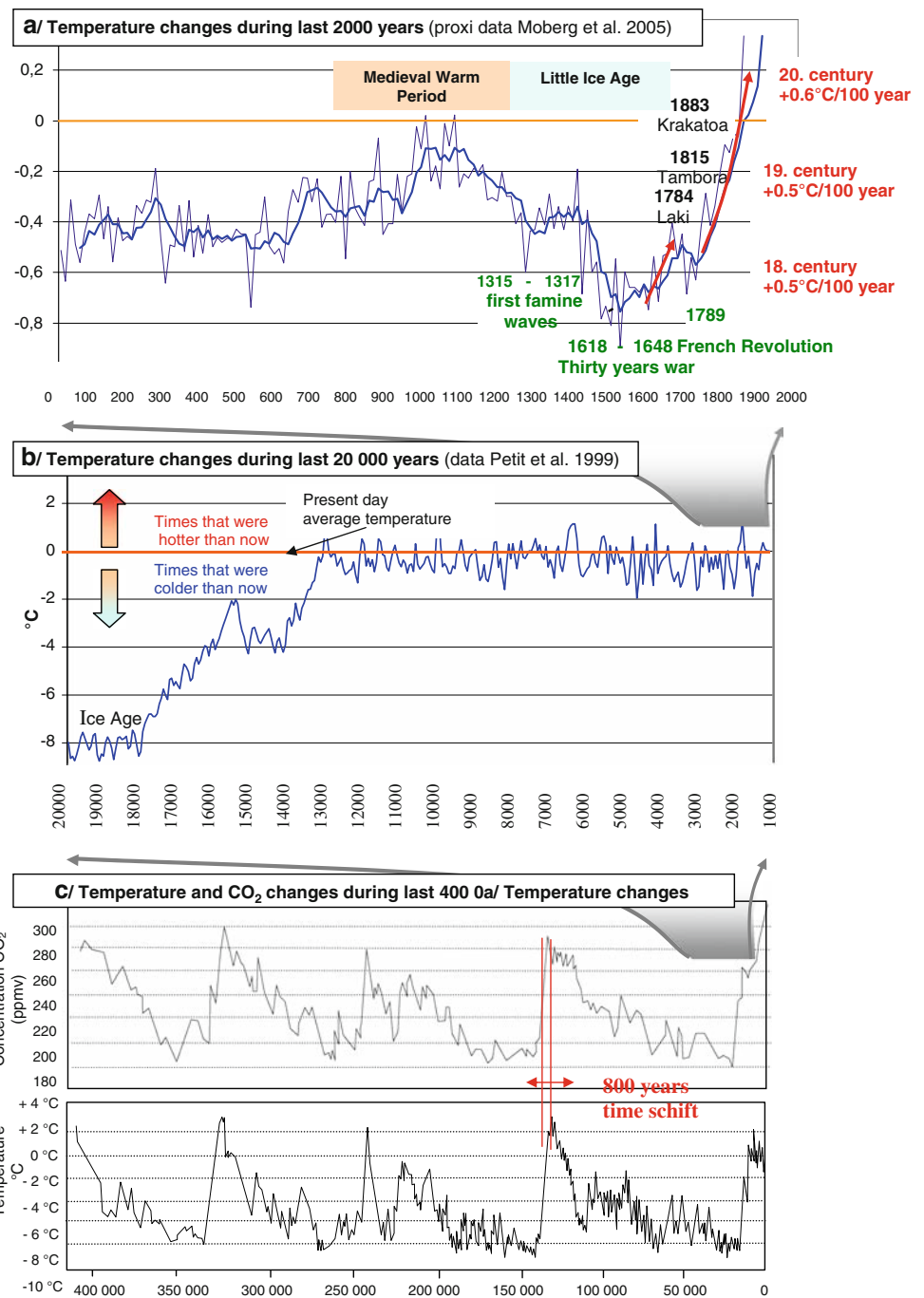
A gentle warming occurred as late as at the end of the seventeenth century, followed by another short cool period in the middle of the nineteenth century. Short-term fluctuations in climate were caused by very intense volcanic activity, as when effusion of basic lava from the Laki fissure took place in Iceland between 1783 and 1784, followed by the gigantic explosive eruptions of stratovolcanos in Indonesia, Tambora in 1815 and the eruption of Krakatoa in 1883.

Against the pattern of these perturbations caused by volcanic activity, the mean temperature on the Earth has been rising since the eighteenth century (Akasofu 2007). Warming is not a phenomenon of the last few decades only, because average temperatures were already rising at the rate of 0.5°C per century in the eighteenth and nineteenth centuries during a period when emissions of greenhouse gases due to industrialization were insignificant (Burroughs 2001; Trand and Nordli 2001; van Engelen et al. 2001). For example, the alpine and continental glaciers were already thawing at the end of the eighteenth century and by 1790 this phenomenon had also been observed in the Antarctic (Vinje 2001). According to the IPCC 2007, the rate of warming during the twentieth century increased by 0.6°C, and within the last decade by as much as 0.75°C.

No doubt, global climate change must be a complex natural phenomenon that cannot be oversimplified to show direct correspondence between CO₂ concentrations in the atmosphere and the average air temperature. For example, in terms of cause and effect, it is apparent at higher resolution of Fig. 2c that the changes in temperature precede the changes in carbon dioxide by about 800 years (Mudelsee 2001).

It is known that very dramatic changes in the temperature and the concentration of greenhouse gases occurred during the geological history of the Earth quite apart from any influence by human beings (Fig. 2c). For instance, in the Eocene, the CO₂ contents were threefold greater than today and the temperature on the Earth was by 12°C higher. During the Earth evolution, the concentrations of CO₂ decreased because carbon was deposited during the formation of coal, crude oil and in particular of limestone, while the oxygen escaped into the atmosphere. As a

Fig. 2 **a** Temperature changes during last 2,000 years (proxi data: Moberg et al. 2005). **b** Temperature changes during last 20,000 years (data: Petit et al. 1999). **c** Temperature and CO₂ changes during last 400,000 years



consequence, the present contents of the former gas are at historical minimum.

In contrast, the temperature in the Miocene was by 8°C lower than today, which gave rise to new glaciation, i.e., the remnants of which we still admire observing them in the mountains and on both poles. We talk about remnants because 10,000 years ago it began to get warmer so that the glaciers were largely melted and the sea levels swelled by 120 m. However, the question is whether this inversion is an another short-term deviation because during the last 1 million years we recorded eight glacial ages and the same number of

warm periods. The present period is believed to be the coolest one on the Earth during the last 450 million years!

The present high level of emissions arising from industrial activities is likely to have accelerated the natural process of warming, but the contribution made by human activities to global warming is difficult to establish precisely.

The trends described above are based on the observations worldwide, however, reliable information about the climate in Bohemia dates only from the year 1777 (Kašpárek 2007). These data indicate that conditions were extremely stable over the period 1847–1987 and a rise in

average temperature has been recorded only during the last two decades (Fig. 3). Nevertheless, average temperatures during the years 1790–1830 were higher than at present.

Notwithstanding the uncertainties that exist, the IPCC (2007) data show that during the next few decades, two phenomena will have a negative impact on water management in Central Europe:

1. The progressive warming recorded during the last two decades has had a marked effect on the replenishment of aquifers by atmospheric precipitation. Although the present average precipitation does not change significantly, the higher rate of evaporation causes a decrease in replenishment of groundwater (Rey 2007). Since the mid-1980s of the last century a statistically significant increase of surface evaporation has been recorded in Central Europe as a result of rising temperatures. The annual increase corresponds to approximately 5 mm/year (Kašpárek 2007).
2. Predicted changes in the seasonal and areal distribution of rainfall. Two scenarios, A2 and B2, have been modeled by the IPCC. These differ from each other in the intensity of the simulated changes. Both scenarios predict a rise in temperatures in Central Europe accompanied by a decrease in atmospheric precipitation during the summer months. The main rainfall is shifted into the winter months. Consequently, a large proportion of the already diminished precipitation in the summer season is absorbed by vegetation or is evaporated so that the summer deficit in the aquifer progressively increases and this unfavorable trend cannot be compensated by greater rainfall in winter. This process has actually been recorded in Central

Fig. 3 Temperature changes between 1777 and 2005 in Elbe river basin (Central Bohemia)

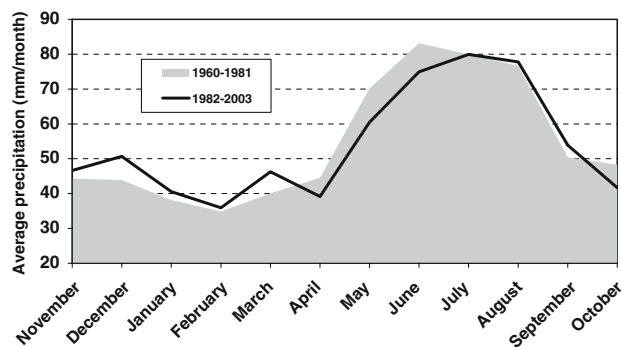
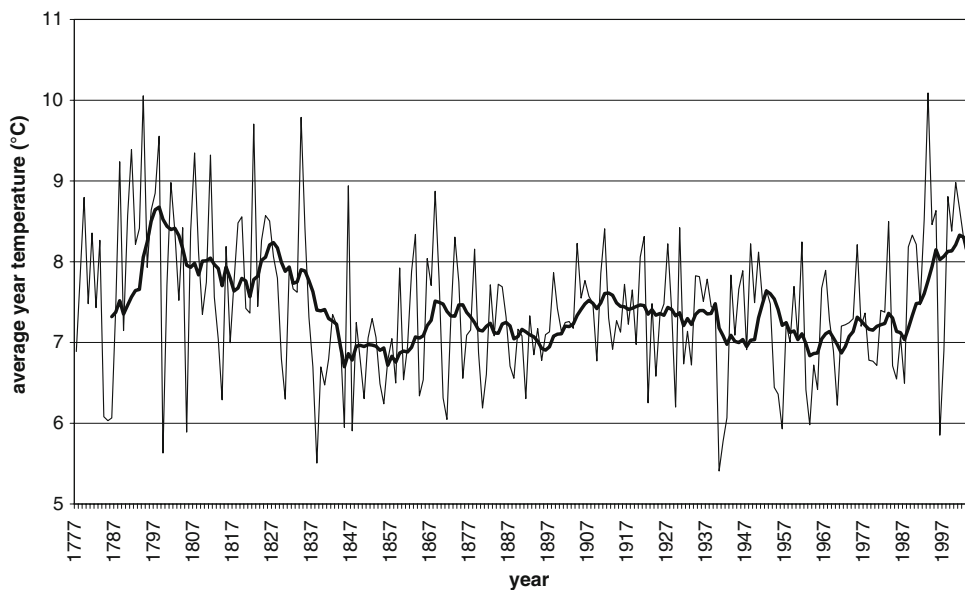


Fig. 4 Monthly precipitation distribution change between 1960 and 2003 (Kašpárek 2007)

Bohemia and is demonstrated in Fig. 4 (Kašpárek 2007).

The project objectives

The major objective of the project has been to assess the vulnerability of the shallow aquifer confined to the hard rock in the Bohemian Massif to ongoing climate change. The investigation was based on the working hypothesis that a reduction of effective atmospheric precipitation would result in erratic lowering of groundwater level, specifically faster on slopes in areas of recharge and slower in valleys in discharge zones. Consequently, spatial and also temporal changes in transmissivity should result.

Another objective has been to answer a question whether the changes in distribution of atmospheric precipitation are reflected only in short-term declines in groundwater levels,

or whether it is a signal indicating a long-term trend. A monitoring borehole VP 1140 of the Czech Hydrometeorological Institute served as a tool in implementation of the second, regional type of project. The borehole was monitoring continuously the groundwater level in sub-surface zone in Proterozoic paragneisses since 1972. It is located at an elevation of 551 m a.s.l. about 10 km away from the Na Lizu catchment that during the monitoring and measurements was not affected by human activities.

Applied methods of investigation

The value of transmissivity is defined by the product of the thickness of the groundwater body and the coefficient of hydraulic conductivity. Changes in groundwater level in space and over time result in reduction of the thickness of the groundwater body, followed by a change in the hydraulic gradient. Moreover, the lowering of the groundwater level has also another consequence. The decrease in permeability with depth as fractures tighten is a characteristic feature of hard rocks. Therefore, the reduction in groundwater level changes not only the hydraulic gradient and the thickness of the saturated zone but also the mean value of the hydraulic conductivity coefficient of the entire water-bearing horizon. This further leads to the reduction of transmissivity during prolonged dry periods.

In order to test this hypothesis and to quantify the anticipated changes, two mountain catchments (Hutná in the Krušné hory Mts. and Na Lizu in the Šumava Mts.) were monitored experimentally during three consecutive years

(Figs. 1, 5). A summary of the basic characteristics of both these localities is given in Table 1. Two pairs of monitoring boreholes were drilled in each of the catchments. Using a rotary-percussion full hole drilling method, two wells 25 and 10 m deep with a diameter of 165 mm in closing profile were drilled within the discharge area of each catchment. Two other wells of the same depth were drilled in the recharge area of each catchment, specifically on the crest of the mountain range close to the watershed. The upper sections of the deeper wells were sealed so that the measurements would be characteristic of the deeper part of the groundwater body in the aquifer where fracture permeability prevailed. The open sections of the wells were examined by logging (Kobr in Hrkal et al. 2007). All the wells are equipped with automatic data loggers, which record groundwater level and water temperature every hour.

In the Na Lizu catchment, the atmospheric precipitation and temperatures were monitored in a closing profile, whereas in the Hutná catchment, because of rough topography, the monitoring was carried out both in the valleys and in the upper parts. Discharge of rivers was also measured at the closing profile during the monitoring. Hydraulic parameters for monitored boreholes were established using 3-day pumping tests (Table 2).

By comparing both the catchments, it is evident that the two mountain localities investigated showed very similar geological and hydrogeological parameters, but differ significantly from each other in their topography. The closing profile of the Na Lizu catchment lies at the same elevation as the apical part of the Hutná catchment, while the Hutná catchment has markedly steeper slopes so that the

Fig. 5 Map of experimental catchments

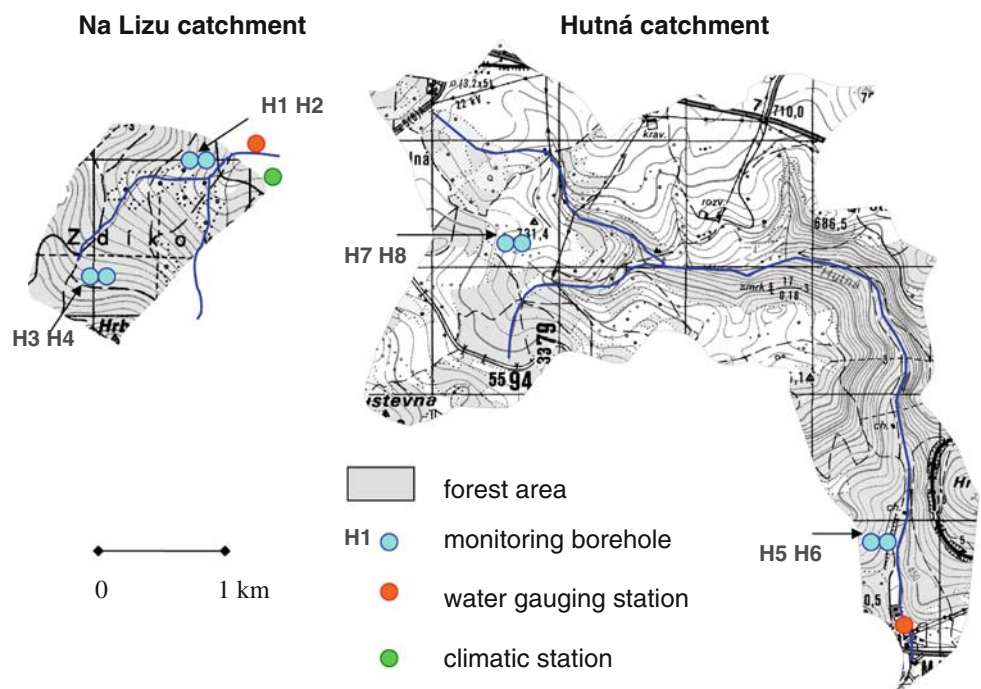


Table 1 Characteristics of the Na Lizu and Hutná catchment

	Catchment	
	Na Lizu	Hutná
Altitude min/max (m a.s.l.)	828/1,075	400/825
Surface (km ²)	0.99	10.78
Lithology	Proterozoic biotite paragneisses and migmatites	Proterozoic paragneisses and ortogneisses
Landuse	71% spruce, 25% beech, 4% meadow	22% spruce, 27% beech, 38% meadow, 9% farmland, 4% others
Average annual temperature (°C) (valley/hill top)	4.9 (at 830 m a.s.l.)/?	8.5 (at 325 m a.s.l.)/5.9 (at 740 m a.s.l.)
Average annual precipitation (mm)	825 (at 830 m a.s.l.)/?	562 (at 410 m a.s.l.)/821 (at 828 m a.s.l.)
Specific total runoff (l/s km ²)	12.0	12.6

Table 2 Transmissivity from pumping tests in the Na Lizu and Hutná catchment

Catchment	Well	Position	Depth (m)	Open section (m)	T (m ² /s)
Na Lizu	H1	Discharge	25	17–21	1.2×10^{-6}
	H2	Discharge	10	2–9	x
	H3	Recharge	25	15–22	1.3×10^{-5}
	H4	Recharge	13	2–12	1.2×10^{-4}
Hutná	H5	Discharge	20	10–18	5.6×10^{-4}
	H6	Discharge	7	2–5	2.3×10^{-4}
	H7	Recharge	20	11–18	1.1×10^{-5}
	H8	Recharge	10	2–8	2.4×10^{-5}

x: no pumping test

hydraulic gradients are higher. The volume of atmospheric precipitation in both catchments is similar but because of the higher altitude of the Na Lizu catchment, the mean temperatures are lower so that evaporation can be expected to be lower. The total specific discharge in both catchments is also identical, but the pattern of vegetation and land use are different. The Na Lizu catchment is completely forested, whereas the proportion of forest in the Hutná catchment (Krušné hory Mts.) is much smaller.

During the next stage of the investigation, a hydraulic model of the Hutná catchment was created using Modflow software. The area of the model solution occupies the whole of the Hutná catchment being constrained by a groundwater divide. The groundwater flow is simulated over an area of 54,072 square elements with a side 20 m long. The hydraulic function of the river Hutná is simulated using boundary condition of the third type and is specified by water level in the stream and by resistance coefficient (characterizing the degree of colmatage of the river bank and the river bed). The boundary condition is submitted in the first model layer.

Vertical profile of typical hard rock areas should be schematised in the following way. An upper weathered zone is composed of regolith and/or Quaternary deposits with dominant intergranular porosity. Below this zone, an intermediate or fractured-bedrock zone with dominant fracture porosity is situated. The fresh unfissured basement, only locally permeable, became at the depth of first tens meters. The upper and intermediate zones form the main “shallow” aquifer, more or less conformable with the land surface. The thickness and character of this aquifer vary according to faulting and fracturing, rock petrography, weathering, morphology and climate (Chilton and Foster 1993). Aquifer thickness is generally in the range of tens of meters.

Simulation model applied in Hutná catchment was based on a conceptual pattern in which the geometry of the model environment was reduced to two layers—an upper aquifer layer in which clayey products of weathering prevail to a depth of 10 m and a lower aquifer layer with increased fracture porosity at a depth between 10 and 25 m below surface. The boundaries stipulated in the model were based on the lithology of rock fragments recovered from the well and recorded by logging.

The simulation of groundwater flow was made in two variants:

- A steady-state simulation of groundwater flow: the input data and boundary conditions were mean values and the results were presented as average values of groundwater level and discharge into a stream under mean conditions of groundwater storages.
- A transient simulation of groundwater flow: the input data and boundary conditions were mean values for defined intervals of 1 month during the monitoring procedure. These data were supplemented by capacity parameters for the rock environment (storage capacity, porosity). The groundwater levels were calculated at

the end of selected time intervals in the simulation and the relevant values of groundwater discharge into a stream were computed.

Hydraulic parameters and the boundary conditions for the area of the model simulation were calibrated during the steady-state simulation of groundwater flow. Data on groundwater levels (the so-called groundwater-level criterion) and on the river discharge (balance criterion) were used for calibration.

The model groundwater levels of the steady-state simulation were used as a precondition at the start of the transient simulation. During this simulation of groundwater flow over the period 1 October 2004 to 30 April 2007 (the time during which the groundwater levels and river discharges in the Hutná catchment were measured), the recharge of rainfall fluctuated from month to month. The water level in the stream remained constant during the whole period of the simulation.

The transient model simulation of groundwater flow provided data on the groundwater levels and data on the discharge of groundwater into the Hutná river over a specific period of time. The simulated groundwater fluctuation was compared with the measured fluctuation of groundwater level in the boreholes. The simulated and measured

data were found to be very similar for all boreholes (Table 3).

Results and the discussion

Altogether, 35,000 measurements of groundwater level were acquired from each monitoring well in both catchments. This set of data together with information on total atmospheric precipitation enabled the pattern of groundwater behavior to be constructed as follows. The general trend in fluctuation of groundwater levels and the reaction of the water-bearing system to the decrease in atmospheric precipitation was found to be the same in both catchments, but there were differences in the intensity of the response (Fig. 6). Differences between the recharge and discharge areas in the Na Lizu catchment were more marked.

Fig. 7 shows that the groundwater levels in all wells during the whole year maintained an identical rhythmic pattern directly dependent on the climatic phenomena. Nevertheless, the intensity of variations observed in each well was different. The groundwater levels in wells H3 and H4 drilled in the recharge area showed an identical pattern but there were notable differences between the highest and lowest groundwater level observed in each of these wells. The groundwater level in the shallow well H2 was fluctuating within the range of 7.5 m, whereas the fluctuation in the deeper well H1 was 5.5 m.

By comparison, the groundwater levels in the two wells H1 and H2 in the discharge area remained more even. The difference between the highest and lowest groundwater level in the shallow well was 1.9 m, whereas the water levels in the deep well fluctuated within the range of only 1.4 m.

In the context of water management, the response of both pairs of wells over longer periods with no precipitation is critical. The decline in groundwater level was observed to be markedly steeper in wells situated in the area of recharge.

Table 3 Comparison of simulated and measured groundwater level in the Hutná catchment

Well	Groundwater level		Difference (m)
	Measured (m a.s.l.)	Simulated (m a.s.l.)	
H5	446.59	446.36	-0.23
H6	447.79	447.97	0.18
H7	750.57	750.32	-0.25
H8	753.34	752.44	-0.90

Measured levels represents average data during monitoring period

Fig. 6 Groundwater level changes in experimental catchments (difference between maximal and minimal level)

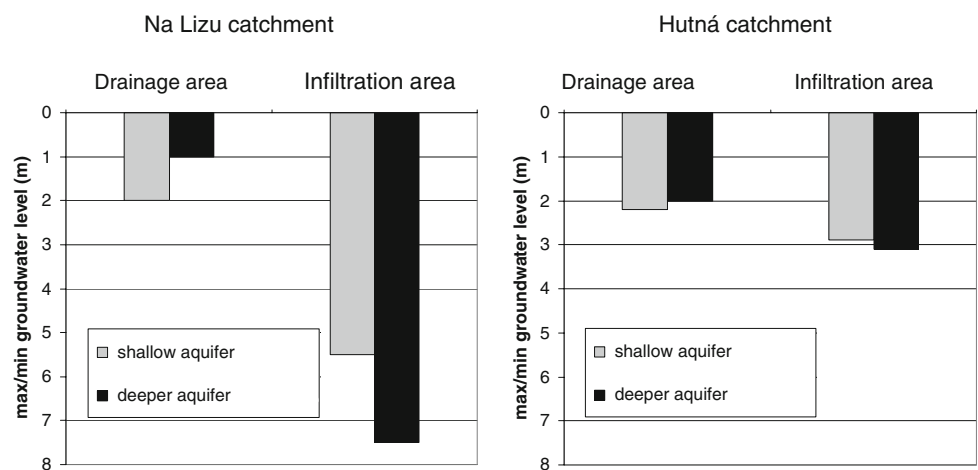
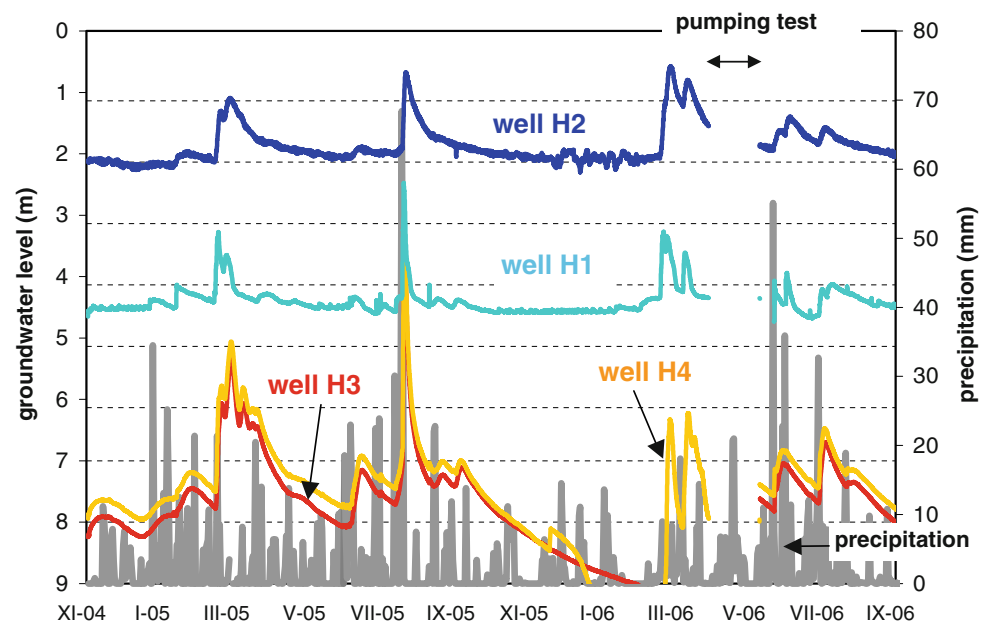


Fig. 7 Groundwater level and precipitation variation between 2004 and 2006 Na Lizu catchment



Both the transient and steady-state forms of simulation demonstrate that the shallow aquifer confined to hard rocks in the Hutná catchment is vulnerable to any reduction in recharge. In both cases, a reduction of infiltration by 25% was noted in comparison to the assessed mean infiltration.

A 1-year period was used for the transient simulation of groundwater conditions during the period of decline in infiltration. The model output indicates (Fig. 8) that the reduction in groundwater levels fluctuates between 1 and 3 m over the major part of the area. The least reduction in groundwater level (max. 0.5 m) occurred in the discharge area along the Hutná river, whereas on steep slopes, the reduction reached as much as 5–6 m and at worst the aquifer dried up.

Areal interpretation of groundwater-level fluctuation provides clear evidence of the importance of topographic position of spot withdrawals of groundwater in hard rocks—i.e. boreholes and wells in discharge areas, close to the valley axis, are believed to be much less vulnerable to climate change than in recharge areas, on slopes and near groundwater divides.

In the steady-state form of simulation, the balance in groundwater volume at reduced infiltration by 25% corresponded to 15.1 l/s (relative to 20.5 l/s as the average infiltration of atmospheric precipitation).

The above-described reaction of groundwater level to the intensity of atmospheric precipitation tends at the first glance to adopt an idea that we are not witnessing an impact of climate change, but it is a response of the groundwater system to short-term variations in net precipitation, i.e. the weather. However, the aforementioned seasonal erratic distribution of atmospheric precipitation causing the decline in yield of shallow wells in particular

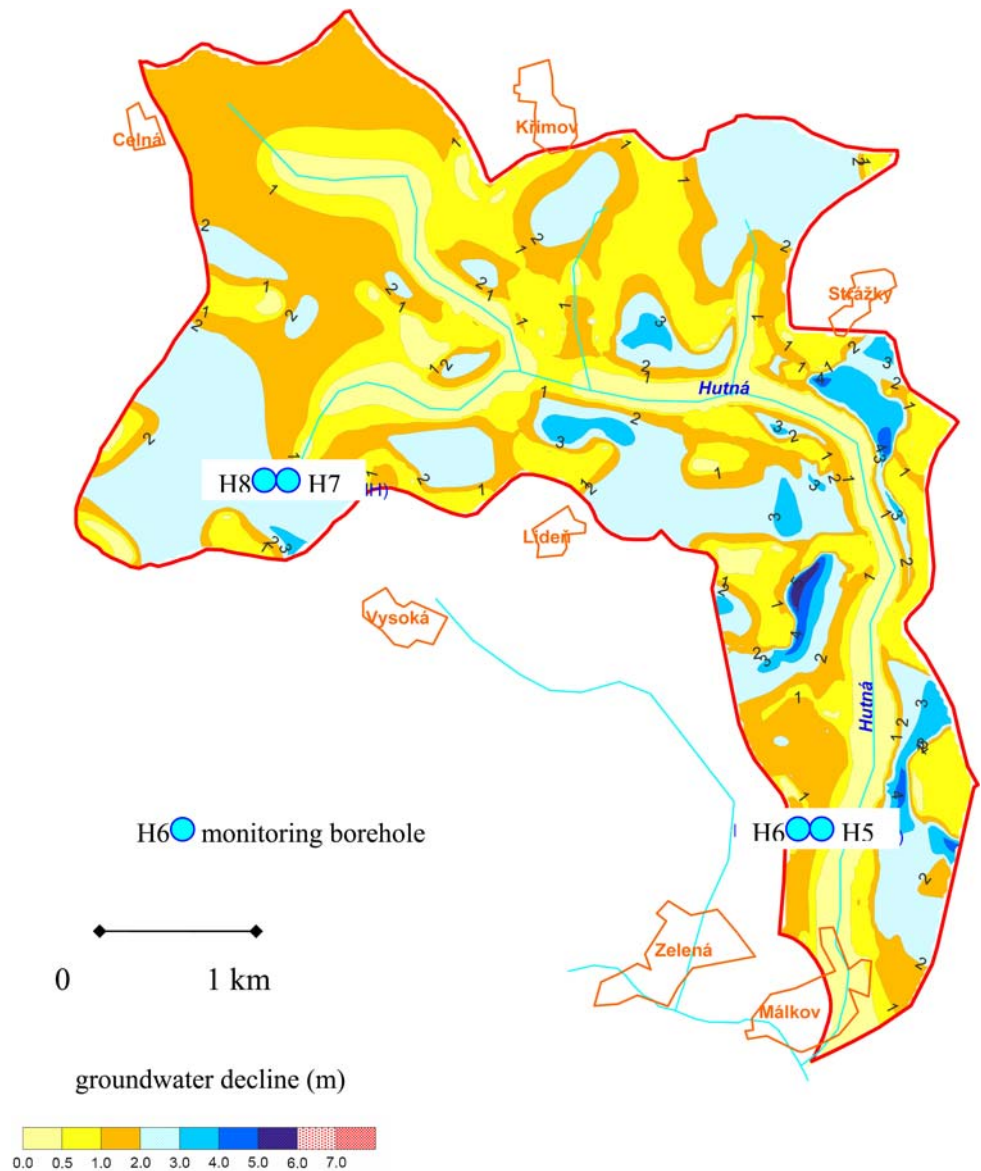
becomes a reflection of climate change in the Central Europe.

As shown from analysis of data from the monitoring borehole VP 1140 drilled by the Czech Hydrometeorological Institute, a long-lasting groundwater-level lowering was recorded since 1976. It is to be pointed out that the average annual values that compensate seasonal variations are of an order of centimeters in groundwater-level lowering. Such a decline can hardly result in serious problems in water management. The actual reason for lower yields appears to be the shift of atmospheric precipitation from the summer period into autumn months (Fig. 4).

Nevertheless, the long-term trend in groundwater-level decline deserves more attention to be paid to it. This decline cannot be explained by simple decrease in rainfall because, as emerges from Fig. 9, the total annual precipitation values during the monitored period were on the contrary growing. The reason for that can be found in conclusions of the study by Kašpárek (2007), which showed increase in evaporation by 5 mm/year that in the whole water balance during the 1976–2006 period would result in a difference corresponding to 150 mm. However, in this particular case, we deal with only one of the loss-making components of the water balance, i.e. the evaporation.

On the other hand, numerous studies (Allen and Chapman 2001; Bosch and Hewlett 1982; McCulloch and Robinson 1993) provide evidence that the increase in interception and transpiration has much greater negative impact on groundwater-level decline. The forest occupies ca. one-third of the total territory of the Czech Republic where it covers mainly the mountainous border areas. The reduction in water quantity by forest is due to interception

Fig. 8 Model groundwater decline in Hutná catchment



of rainfall by forest canopy leading to loss of rainwater reaching the ground surface. For instance, Calder and Newson (1980) showed decline in surface discharge by as much as 20%, due to interception that has taken place in mountainous regions of Great Britain. Nevertheless, the transpiration, i.e. the transfer of water from the soil to the atmosphere through the tree roots, trunks and leaves is responsible for even greater loss of groundwater. For instance, Roberts (1983) published transpiration values corresponding to 330 ± 35 mm for mixed forest in the NE parts of Europe, and similarly Harding et al. (1992) established a forest with ash-tree and beech-tree, a transpiration of 380 mm. Potential evapotranspiration for full-grown thick forest can, under Central European climatic conditions, reach values around 700 mm (Allen and Chapman 2001).

Therefore, the forest is to be considered a phenomenon playing a double role. On one hand, it attenuates the negative impact of flood waters and on the other hand, it may considerably accelerate the negative impact of climate change on the water balance, because it increases the groundwater-level lowering particularly during the summer season, characteristic of lower rainfall totals.

Conclusions

The results of monitoring and model simulations showed that a shallow aquifer confined to crystalline rocks in the Bohemian Massif is very vulnerable to a decline in atmospheric precipitation and infiltration. Monitoring showed that there were notable differences in the range of

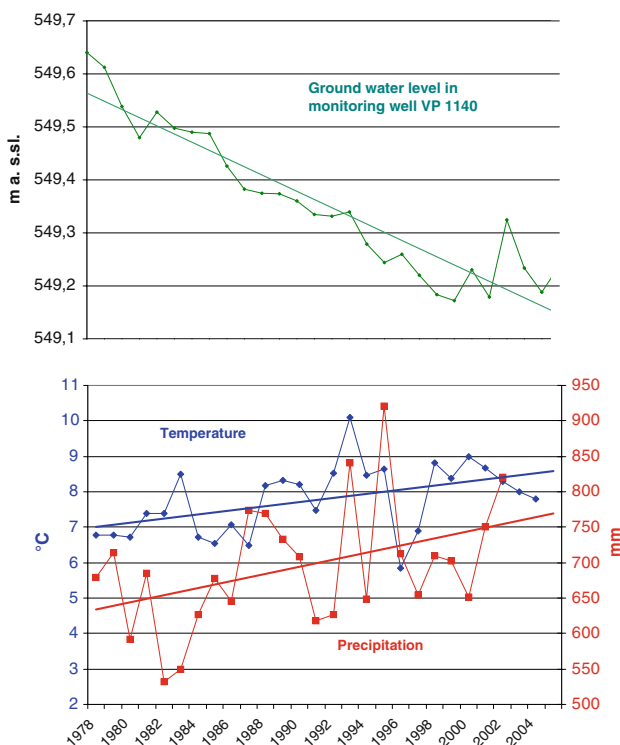


Fig. 9 Groundwater level vs. climatic characteristics in monitoring well 1140

fluctuation of the groundwater level depending on the topographic position of the well.

Rapid decrease in groundwater level in the order of 10 m was recorded in the recharge area and on steep slopes, whereas the decrease in the discharge zone is in the range of meters only.

The thickness of the groundwater body in the area of recharge is reduced much more than that in the discharge area where the groundwater level is connected with the local stream. The monitored catchments thus provide evidence that transmissivity in hard rocks varies both in space and with time. Climate change, which is likely to result in reduced infiltration of precipitation in the hard rock environment, will create serious problems for water management. It is difficult to mitigate the negative impacts of climate change on a shallow aquifer in hard rocks, but a combination of the following measures would help. They include:

1. Increased efficiency of tapping that involves the replacement of spot withdrawals using wells and boreholes by linear drains. It is a very simple but efficient method of tapping groundwater flowing off from a shallow sub-surface zone in hard rocks that is used in numerous regions. A drain laid perpendicular to groundwater streamline diverts the groundwater by gravity into central surface inlets so that it can benefit from the advantage of hard rocks in morphologically

rugged areas. The advantage includes the increased dynamics of groundwater circulation expressed by high values of groundwater discharge exceeding in the Bohemian Massif as much as $10 \text{ l/(s km}^2\text{)}$.

2. Increased recharge by deceleration of a surface stream. A massive regulation of surface streams took place during the last decades in the Czech Republic. The aim of suggested measures is the return to initial state, the renewal of meanders and natural conditions of riverbeds.
3. Reduction of losses through optimization of composition of the vegetation cover. This measure includes mainly the constraint of losses caused by evapotranspiration that in some types of forest represents quite a dominant component of water balance. This step would require a very comprehensive approach that would include close cooperation of water management authorities, hydrologists, hydrogeologists and experts in forestry. The objective of this stage should be the selection of the best generic composition of the forest, which would exhibit the lowest value of evapotranspiration. For instance, a 45-year old pine forest shows evapotranspiration value around 290 mm, but the birch forest of the same age exhibits as much as 460 mm. The forest should be maintained to be of optimum age and thickness, in other words to be in such a condition to play positive role in regulation of catchments, and at the same time its interception would be reduced to minimum.

Acknowledgments The authors acknowledge financial support from the Charles University Grant Agency project “Impact of climatic changes on the hydrogeological condition of hardrocks” and the Czech Science Foundation project 205/05/0177 “Natural resources of groundwater in mountain regions of the Czech Republic under the conditions of global change”.

References

- Akasofu SI (2007) Is the Earth still recovering from the “Little Ice Age”? A possible cause of global warming. http://www.iarc.uaf.edu/highlights/2007/akasofu_3_07/Earth_recovering_ffom_LIA.pdf
- Allen A, Chapman D (2001) Impacts of afforestation on groundwater resources and quality. *Hydrogeol J* 9(4):390–400
- Apel R, Klemm A, Rüdiger F (1996) Grundlagen zum Wasserwirtschaftlichen Rahmenplan, Naab-Regen. *Hydrogeologie*. Bayerisches Geologisches Landesamt, München
- Bocheńska T, Marszałek H, Staško S (1997) Hard rocks of the Sudety Mts. as a groundwater collector and its vulnerability. In: Bocheńska T, Staško S (eds) *Hydrogeology*. 2nd workshop on hardrock hydrogeology of the Bohemian Massif, vol 2052, Acta Universitatis Wratislaviensis, pp 11–19
- Bosch JM, Hewlett JD (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *J Hydrol* 55:3–23
- Bradley RS, Jones PD (1993) “Little Ice Age” summer temperature variations: their nature and relevance to recent global warming trends. *Holocene* 3:367–376

- Burroughs WJ (2001) *Climate change*. Cambridge University Press, London, p 2001
- Calder IR, Newson MD (1980) The effects of afforestation on water resources in Scotland. In: *Land assessment in Scotland*. Proc Symp R Geogr Soc, Edinburgh, pp 51–62
- Chilton PJ, Foster SSD (1993) Hydrogeological characterisation and water-supply potential of basement aquifer in tropical Africa (keynote paper). In: Banks S, Banks D (eds) *Hydrogeology of hard rocks*. Mem. XXIVth Congr. IAH, pp 1083–1100
- Crowley TJ, Lowery T (2000) How warm was the medieval warm period? *Ambio* 29:51–54
- Harding RJ, Neal C, Whitehead PG (1992) Hydrological effects of plantation forestry in north-western Europe. In: Teller A, Mathy P, Jeffers JNR (eds) *Responses of forest ecosystems to environmental changes*. Elsevier, New York, pp 445–455
- Hrkal Z, Kobr M, Nedvěďová E, Tesař M, Vilhelm Z (2007) Impact of global climate change on transmissivity of shallow hard-rock aquifers. In: Marszałek H (ed) *Selected hydrogeologic problems of the Bohemian Massif and of other hardrock terrains in Europe*. Acta Universitatis Wratislaviensis, Poland
- Intergovernmental Panel on Climate Change (IPCC) (2007) Fourth assessment report climate change 2007: synthesis report. <http://www.ipcc.ch/ipccreports/ar4-syr.htm>
- Jordan WJ, Lopez O, van Meijgaard P, Botzet M (1996) The HIRHAM4 regional atmospheric climatic model, Sci. Rep. 96-4. DMI, Copenhagen, 51 pp
- Kašpárek L (2007) Research and protection of hydrosphere—investigation of relations and processes in aqueous component of the environment focused on anthropogenic effects, permanent exploitation of hydrosphere, its protection including legislative measures. MS. Water Research Institute TGM, Prague (in Czech)
- Krásný J (2007) Spatial distribution of permeability in hard rocks: consequences for groundwater flow and chemical composition. In: Marszałek H (ed) *Selected hydrogeologic problems of the Bohemian Massif and of other hardrock terrains in Europe*. Acta Universitatis Wratislaviensis, Poland
- Krásný J, Kněžek M, Šubová A, Danková H, Matuška M, Hanzel V (1982) Groundwater runoff in Czech Republic. Czech Hydro-meteorological Institute, Prague (in Czech)
- Kryza J, Kryza H (1997) Renewal rate of groundwater in the Sudety Mts.—its disposable and exploited resources. In: Bocheńska T, Staško S (eds) *Hydrogeology*. 2nd workshop on hardrock hydrogeology of the Bohemian Massif, vol 2052, Acta Universitatis Wratislaviensis, pp 223–227
- McCulloch JSG, Robinson M (1993) History of forest hydrology. *J Hydrol* 150:189–216
- Moberg A, Sonechkin DM, Holmgren K, Datsenko NM, Karlén W (2005) Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. *Nature* 443:613–617
- Mudelsee M (2001) The phase relations among atmospheric CO₂ content, temperature and global ice volume over the past 420 ka. *Quat Sci Rev* 20:583–589
- Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola JM, Basile I, Bender M, Chappellaz J, Davis J, Delaygue G, Delmotte M, Kotlyakov VM, Legrand M, Lipenkov V, Lorius C, Pépin L, Ritz C, Saltzman E, Stievenard M (1999) Climate and atmospheric history of the past 420,000 years from the Vostok Ice Core, Antarctica. *Nature* 399:429–436
- Rey F (2007) Groundwater resources in Chaînons Béarnais. Thèse Doctorale, Université Bordeaux I, France (in French)
- Roberts JM (1983) Forest transpiration: a conservative hydrological process. *J Hydrol* 66:133–141
- Trand A, Nordli PO (2001) The Tallinn temperature series reconstructed back half a millennium by use of proxy data. *Climate Change* 48:189
- van Engelen AFV, Buisman J, Ijnsen F (2001) *History and climate—memories of the future, a millennium of weather, winds, and water in the lower countries*. Kluwer Academic Press, New York
- Vinje T (2001) Anomalies and trends of sea-ice extent and atmospheric circulation in the Nordic seas during the period 1864–1998. *J Climate* 14:255–267
- Watkins DC (2007) Determining a representative hydraulic conductivity of the Carnmenellis Granite of Cornwall, UK, based on a range of sources of information. In: Krásný J, Sharp JM (eds) *Groundwater in fractured rocks*. IAH Selected Papers 9. Taylor and Francis, London, pp 151–162