XXXVIII IAH Congress

Groundwater Quality Sustainability

Krakow, 12–17 September 2010

Extended Abstracts

Editors:
Andrzej Zuber
Jarosław Kania
Ewa Kmiecik

University of Silesia Press 2010

abstract id: **229**

topic: **1**
Groundwater quality sustainability

1.9
Sustainable management of groundwater

title: **Climate change and groundwater vulnerability in the Czech Republic**

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keywords: climate change, groundwater, Czech Republic

INTRODUCTION

In case of development according to climate change scenarios, the flow as well as baseflow characterising the groundwater discharge will decrease in future. The quantification of groundwater regime is therefore necessary for rational groundwater management. The aim of this paper is therefore to show the options for groundwater regime quantification by using examples of hydrological regime in Polická basin (Metuje River basin), which is area characterised by deep groundwater circulation, and in Divoká Orlice River basin upstream from Klášterec n. O. water gauging station, which was selected as an example of area characterised by relatively shallow groundwater circulation in the crystalline geological formations.

STUDY BASIN AND METHODS

Study basin

A hydrogeological study was focused on comparison of hydrogeological conditions in Policka basin and in Divoká Orlice River basin (Fig. 1). Polická basin is hydrogeologically closed Cretaceous formation. The system on an area of 240 km^2 is formed by 3 main aquifers. Depths of the cretaceous layers of the aquifers exceed 200 m. For these conditions, the calculation of water balance and its simulation are fully reliable. Its closing site is monitored by Hronov water gauging station located on the Metuje River. Its part, the Adršpašsko-Teplická formation is also hydrogeologically closed due the Skalský fault enclosing the hydrologic head of the aquifer. The streamflow is monitored by Teplice nad Metují water gauging station (M XII) located at its closing site.

Figure 1. Site Polická basin and Divoká Orlice River basin.

The area of Divoká Orlice River basin upstream from Klášterec n. O. is 155 km^2, which corresponds approximately to the area of the Metuje catchment in Polická basin, but it is formed by crystalline deposits and therefore its hydrogeological conditions are quite different. It is mostly mountainous catchment with high precipitation (annual precipitation exceeds 1100 mm while it is only 732 mm in Polická basin), which allows frequent replenishment of groundwater. The maximum groundwater storage is approximately from 40 to 50 10^6 m^3 but consequently to high slopes in relation to the erosion bases the available storage is about 10% of the maximum volume.

Bilan water balance model

Modelling changes in groundwater level was conducted using the hydrological model Bilan developed by T.G. Masaryk Water Research Institute, p.r.i. Input data of Bilan model include primarily time series of monthly precipitation, temperature and relative air humidity. The model simulates time series of monthly potential evapotranspiration, actual evapotranspiration, infiltration across the land surface and recharge from the soil to the aquifer. The output of the model includes monthly series of water storages in the snow pack, soil and aquifer. All these hydrological variables apply to the whole catchment. Furthermore, three runoff components, i.e. surface runoff, interflow and base flow (groundwater discharge) are calculated at the outlet of the catchment. The eight free parameters of the Bilan model are calibrated by minimising the differences between simulated and observed outflow from the basin.

RESULTS

Polická basin

First, the simulated baseflow was compared with the baseflow determined by using the separation equation based on interrelationship between the flow regime and groundwater levels. The fit between the results was good and therefore the groundwater storage simulated by the model could be used in further steps. Interesting experience was that of the five boreholes used for derivation of separation equation, VS3 Adršpach borehole (situated in the formation above Skalský fault) produced the best results for both of the water gauging stations. For Teplice nad Metují water gauging station it is not surprising. But in the second case, the catchment above the Skalský fault represents only 30% of the basin of the Hronov water gauging station. It indicates that the borehole used for flow separation as an indicator of groundwater regime need not necessarily represent the real variability in groundwater levels.

The following step was focused on derivation of the relationship between the variability in the groundwater storage (groundwater flow) and changes in groundwater levels. For reliable derivation of real changes in groundwater levels, relatively uninterrupted data series from the period 1976 to 1990 were available from 8 boreholes for Teplice n. M. water gauging station (with the catchment of 89 km^2) and 10 boreholes for Hronov station (with the catchment of 240 km^2).

Mean values of changes in groundwater levels in the periods when groundwater storage changed substantially were used for derivation of the general relationship between the groundwater level and simulated water storage. The knowledge of hydrogeological areas of individual boreholes was insufficient for derivation of their weights for calculation of mean changes in groundwater level and therefore identical weights were used. The results showed that the relationship derived for data from VS3 borehole was most suitable for estimation of groundwater deficit (Figures 2). It is important with respect to the fact that the operational monitoring in the majority of other boreholes has been already finished.

The calculated results were compared with groundwater storage values (the groundwater storage over the erosion base level) derived for the basins by using a mathematical model, which was developed by Milický and Uhlík (2001). The groundwater storage values are 24 x 10^6 m^3 for the Teplice n. M. station and 79 10^6 m^3 for Hronov station.

a) derived at Teplice n. M

b) derived at Hronov

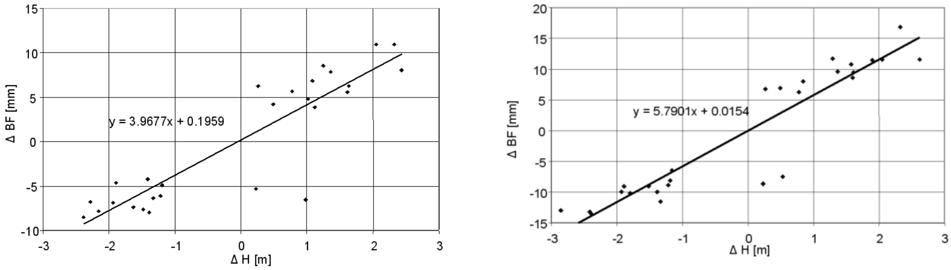

Figure 2. Relation between change in groundwater level in the VS 3 Adršpach borehole (Δ H) and change in groundwater storage (simulated baseflow) derived for the basin of the Metuje River at Teplice n. M (Δ BF) and at Hronov (Δ BF) , period 1974-1990.

For Teplice n. M. station the largest simulated decrease in groundwater storage in the evaluated period was 9.0 mm or 0.80 10^6 m^3. The relevant mean decrease in groundwater level ΔH is 2.21 m. Similar results were derived for Hronov station: 17.04 mm – 4.09 10^6 m^3, ΔH = 2.94 m.

It can therefore be concluded that the largest groundwater decrease in the observation period is small compared to the large groundwater storage in the Adršpašsko-Teplická formation. The maximum decrease was 3.3% of the storage for Teplice n. M. station and 5.2% of storage for Hronov station.

In addition to the observation period (1976–1990), the groundwater storage was also compared with its decrease in dry year 2004. The decrease in groundwater storage for Teplice n. M. station was 6.48 10^6 m^3, i.e. 27% of the whole storage, and 29.44 10^6 m^3, i.e. 37% of the storage for Hronov station. Figure 3 shows permanent decrease in groundwater level during the latest years. In 2004, the groundwater level was 2.26 m below that in 2002. It corresponds approximately to the annual groundwater flow (base flow) but on the other hand it represents only 5% of the whole storage. The situation is not therefore critical for the current conditions (the groundwater levels in 2005 exceeded by 15 their maxima in 2004). However, warning conditions would occur if the trends from the latest 3 to 5 years continue in future as suggested by climate change scenarios.

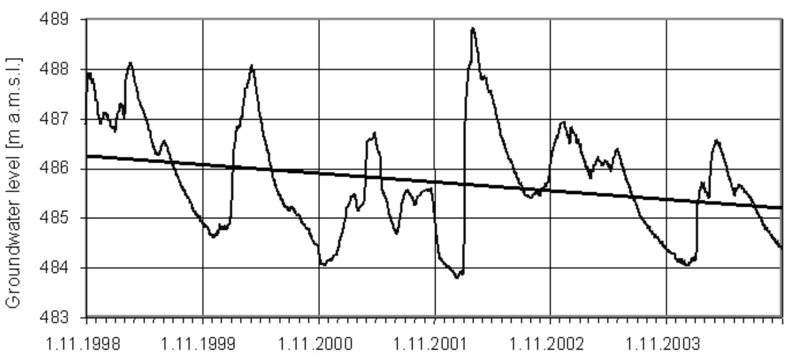

Figure 3. Trend in groundwater level in the VS 3 Adršpach borehole, period 1999-2004.

Divoka Orlice river basin

For the assessment of the natural storage capacity of the catchment we have derived relationships between decrease in the groundwater storage (simulated by the water balance model) and decrease in yields of three observed springs.

The maximum yields of mountainous springs are influenced by surface runoff and interflow, this effect was eliminated by using the method developed by Kille (Figure 4). The resulting spring yields permitted derivation of the relationship between the spring yields and decrease in groundwater storage, which was applicable in practice (Figure 5).

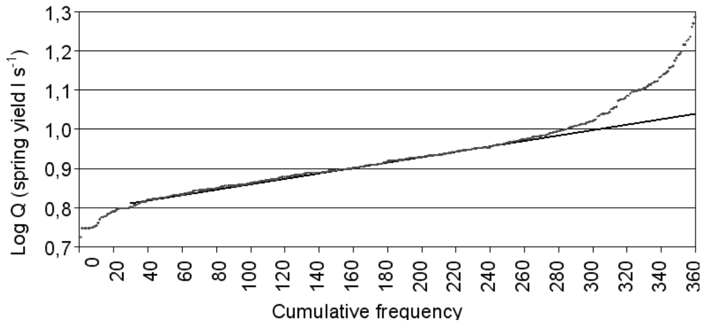

Figure 4. Separation of baseflow by using spring yield (Kille method), Klášterec n. O. water gauging station, spring no. PP0043, monthly values from the period 1971-2000.

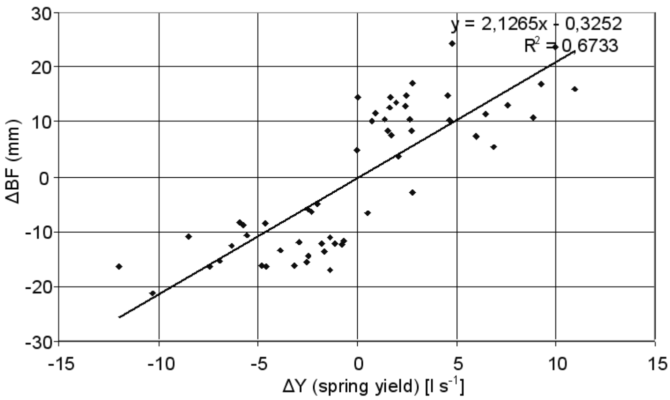

Figure 5. Relation between change in spring yield (spring no. PP0043) and change in groundwater storage (simulated baseflow) derived for the basin of the Divoká Orlice River at Klášterec n. O., period 1971-2000.

Maximum decrease in the groundwater storage in the period from 1971 to 2000 was 22 mm, which is 3.41 10^6 m^3.

The interesting fact is that for minimum groundwater storage the simulated flow was 0.42 m^3s^{-1} (2.7 l $s^{-1}km^{-2}$), which is consistent with values given in a report on Hydrological Conditions of the Czech Republic (Q_{355} = 0.44 m^3 s^{-1}). The mean groundwater flow simulated by the water balance model and also derived from the relationship with spring yield is 1.05 m^3s^{-1} (6.8 l s^{-1} km^{-2}), which is 33% of total runoff. These values are also consistent with long-term characteristics (CHMI, 1982).

A comparison of the maximum decrease in groundwater storage (3.41 10^6 m^3) and estimated available storage (from 4 to 5 10^6 m^3) shows that groundwater contribution to the flow is almost exhausted and the groundwater would not have any additional compensation effect in case of climate change.

Changes in regime of groundwater recharge and groundwater flow are predictable by using low flow tails of runoff hydrographs, whose initial parts are reduced relevantly to a decrease in groundwater level derived by the presented method.

CONCLUSION

The quantification of groundwater regime is indispensable for the purpose of groundwater management planning. In the present study we have determined the active storage of groundwater (the groundwater storage over the threshold of corresponding erosion base) for two pilot water gauging stations on the Metuje River, Teplice n. M. (89 km^2) station and Hronov (240 km^2) in Police Cretaceous basin (geologic formation characterised by deep circulation and high accumulation of groundwater), and for Klášterec n. O. (155 km^2) water gauging station situated on the Divoká Orlice River in the Orlické Mountains (crystalline geologic formation with shallow groundwater circulation). The groundwater storage was determined by the use of water balance model for the periods of decreasing flows, when the only component of the total runoff is baseflow. The results of the study showed that deficits in active storage of groundwater are acceptable even in extreme situations in the Cretaceous layers while in the mountain crystalline formations the groundwater storage can be fully exhausted. In addition, the decrease of groundwater storage would be considerable in both basins, if the recent trend in climate conditions continues as suggested by the climate change scenarios. The study included also derivation of relationships between changes in groundwater storage and changes in groundwater level in Cretaceous deposits of the Polická basin and between changes in groundwater storage and spring yields in the crystalline formations. It was shown that quantification of the groundwater regime should be included as a component of all water management schemes.

ACKNOWLEDGEMENTS

This paper was prepared from the results of the research project on Refining of current estimates of impacts of climate change in sectors of water management, agriculture and forestry and proposals of adaptation measures (project No. SP/1a6/108/07) sponsored by Ministry of the Environment of the Czech Republic.

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International Association of Hydrogeologists

AGH University of Science and Technology

2-vol. set + CD
ISSN 0208-6336
ISBN 978-83-226-1979-0