GROUNDWATER DROUGHT IN DIFFERENT GEOLOGICAL CONDITIONS

Andrej Machlica, Michaela Stojkovova
Department of Hydrogeology, Faculty of Natural Sciences, Comenius University in Bratislava
Bratislava, Slovak republic
machlica@fns.uniba.sk, stojkovova@fns.uniba.sk

Abstract

The identification of hydrological extremes (drought) arising is very actual at present. The knowledge about mechanism of hydrological extremes development could be useful on many levels of human society, such as scientific, agricultural, local governmental, political and others. The research was performed in the Upper part of Nitra River catchment (central part of Slovakia) and in Topla and Ondava River catchments (eastern part of Slovakia). Lumped hydrological model BILAN was used to identify relationships among compounds of the water balance. Presented results are focused on drought in groundwater storage, soil moisture, base flow and discharges. BFI model for baseflow estimation was used and results were compared with those gained by BILAN model. Another item of the research was to compare results of hydrological balance model application on catchment with different geological conditions.

Keywords: *hydrological drought, baseflow, groundwater storage, soil water storage, model Bilan, model BFI.*

1 INTRODUCTION

The problem of drought identification is considered to be one of the most important hydrological research problems. The problems related to the definition, identification and prediction of drought have not been solved yet (Bonacci, 1993).

The primary cause of drought is the lack of precipitation over a large area and for an extensive time period. Such a drought is called a meteorological drought. Water deficit in the atmosphere propagates through the whole hydrological cycle and gives rise to different types of droughts. Combined with high evaporation rates a soil water deficiency might cause a soil moisture drought to be developed. The term agricultural drought is used when soil moisture is insufficient to support crops. Subsequently, groundwater recharge and streamflow will be reduced and a hydrological drought may develop. A reduced recharge leads to lower groundwater heads and storage (Tallaksen and van Lanen, Eds., 2004).

Within the hydrological cycle, groundwater is normally the last to react to a drought situation, unless surface water is mainly fed by groundwater. In deep aquifers the slow reaction of groundwater implies that only major meteorological droughts will finally show up as groundwater droughts. The lag between a meteorological and a groundwater drought may amount to months or even years, whereas the lag between a meteorological and a streamflow drought varies from days in a flashy catchment to months in a groundwater-fed catchment (Tallaksen and van Lanen, Eds., 2004).

The aim of our work was evaluate the occurrence of hydrological drought and its influences to hydrological balance components in the upper part of Nitra catchment (central part of Slovakia) and in the Topla and Ondava catchment (eastern part of Slovakia) with the focus on groundwater compounds of the hydrological cycle. Primary attention was paid to the individual water balance components in the zone of aeration and possible influence on the aquifers. We were also looking for decrease or increase in groundwater runoff.

2 METHODOLOGY

Database creation was the first step of our work. It was necessary for compiling of the hydrological models. Data were acquired from the Slovak Hydrometeorological Institute (SHMU) in Bratislava. All the data were verified and edited according to requirements of BILAN and BFI models.

The BILAN model has been developed for assessing the water balance components of catchment using a monthly step. The structure of the model is formed by a system of relationships describing basic principles of the water balance on the land surface, in the zone of aeration, including the effect of vegetation cover, and in aquifers bearing the groundwater. The input data of the model are monthly series of catchment precipitation and air temperatures. Furthermore, relative air humidity or potential evapotranspiration series are required. Monthly runoff series at the outlet of the catchment are used to calibrate eight model parameters. Model uses an optimization algorithm for calibration of these parameters. Several optimization criteria are available to attain the best fit between the observed a simulated runoff series.

Model simulates monthly series of potential evapotranspiration, actual evaporation, and infiltration into the zone of aeration, percolation of water towards the groundwater aquifer and water storage in the snow cover, zone of aeration (soil) and groundwater aquifer for a catchment. All these variables are used for a catchment as a unit (lumped physically based model). The total runoff consists in three components which are direct runoff, through flow (interflow) and base flow.

The output from the model can be expressed in two types of series – monthly value series and monthly averages (monthly characteristic). Monthly characteristics include average monthly values, monthly minimum and maximum. These were derived from monthly value series for each month in the year and for each variable. Series of outputs can be save in different forms (numeric and graphics data series) (Kasparek in Tallaksen, van Lanen Eds., 2004).

Model BFI performs a separation of the base flow from the total streamflow and calculates the Base Flow Index (BFI). It is written as a Visual Basic Application within Excel. The index gives the ratio of base flow to total flow calculated from a hydrograph smoothing and separation procedure using daily discharges. The BFI is thus considered a measure of the river's runoff that derives from stored sources and as a general catchment descriptor it has found many areas of application, including low flow estimation and groundwater recharge assessment (Morawietz in Tallaksen and van Lanen, Eds., 2004).

Input data are time series of daily streamflow data. The time series must be continuous and should not contain missing data. The output is a graph of the base flow separation, showing the total streamflow (input data) and the calculated base flow values (Morawietz in Tallaksen and van Lanen, Eds., 2004).

One of the hydrological balance components is also groundwater runoff. This component is not measured directly and the most often is separated from hydrograph of discharges using separation methods or mathematic-statistic procedures. The Castany's method (Castany et al., 1970) was used for the groundwater runoff estimation. The method of Castany was used for comparison of groundwater runoff estimation results gained by BFI and BILAN model. The method was chosen because it gives the lowest estimates of groundwater runoff among the most often used methods. In hydrogeology, groundwater runoff values estimated by the method of Castany are considered for the minimum groundwater runoff values from a catchment and under certain conditions (low precipitation totals) they can be considered as manifestation of lack of the groundwater in the aquifer. The method is based on selection of 30 minimum daily discharges following one after another in each year and on calculation of the average value of them. Average groundwater runoff for certain time period (usually for a decade of 10 years) is calculated as a median value from the average values of all years of the assessed period. Groundwater runoff values were calculated for the period of hydrological years 1983-2003.

Some of the model input data were modified according to morphology of research areas. These corrections were done with ArcView 3.2 application in GIS system. Using ArcView application, the mean catchment altitude was estimated and according to this mean value, data on air temperature were recalculated.

The model Bilan was run after modification and verification all model inputs. It was necessary to verify if the model is working properly and if the optimization criterion does no have a very high value. In the case of optimization criterion closest to zero the model setting of parameters is very good and the model conditions are close to real conditions. In the case that the optimization criterion is farther from the zero value, the model conditions not correspond to reality. After finishing the calibration process, creating of hypothesis, analyzes of different curves of water balance compounds in more details has started. The observed time series were divided into specific time periods to be able to investigate some relationships describing changes in water balance compounds in extremes conditions. It means that the whole observed time period was classified according to yearly precipitation amounts; very dry, dry, normal, wet and very wet years were defined. The basic period for classification of the wetness character of single years was period from 1950 to 1980.

We were looking for periods of very dry and dry years. Values of the baseflow and total runoff decrease were estimated for dry years and they were expressed in a percentual ratio to the average value. The groundwater storage amount was analyzed in detail considering the influence of the soil water storage.

Time series (1983-2003) of discharges in six discharge gauging stations were processed and analyzed. Four gauging stations were selected in the upper part of the Nitra River catchment, namely profiles: Tuzina on Tuzina brook (catchment area 35.60 km^2), Chvojnica on Chvojnica brook (catchment area 17.82 km^2), Handlova on Handlovka River (catchment area 40.18 km^2), and Chalmova on Nitra River (catchment area 601.11 km^2). Two gauging stations were chosen in the eastern part of Slovakia, namely Bardejov profile on Topla River (catchment area 325.8 km^2) and profile Stropkov on Ondava River (578.4 km^2).

Tuzina and Chvojnica brooks are the right-side tributaries of Nitra River in the mountainous part of the catchment. Handlovka is a left-side tributary. Topla is a right-side tributary of the Bodrog River and Ondava is its left-side tributary.

The upper part of the Nitra River catchment belongs to the moderately warm, humid climatic region (Chvojnica, Tuzina, Handlovka steams) up to warm, moderately humid (Nitra at Chalmova). Mean annual precipitation varies from 600 up to 700 mm for Nitra at Chalmova up to 800-900 mm for Chvojnica, Tuzina and Handlovka streams (observation period 1961-199). Mean annual air temperature varies in the interval from 7-8° C for Chvojnica, Tuzina and Handlovka streams up to 8-9°C for Nitra at Chalmova (the same observation period).

Topla River catchment at Bardejov profile belongs to the moderately warm, moderately humid climatic region, Ondava River catchment at Stropkov belongs to the warm, moderately humid climatic region with a cold winter. Mean annual precipitation ranged from 700 up to 800 mm for both catchments (observation period 1961-1990). Mean annual air temperature ranged from the 7° up to 8° C in the same observation period.

The period of 21 hydrological years (1983-2003) was evaluated. The data on the mean relative air humidity and mean air temperatures from the Prievidza meteorological station were for all four profiles in the upper part of the Nitra River catchment. Mean precipitation totals from Nitrianske Pravno precipitation gauging station were used for Tuzina and Chvojnica catchments. Mean precipitation totals from Prievidza station were used for Handlovka and Nitra at Chalmova profiles.

Meteorological data for Topla River catchment were used from the Bardejov meteorological station and data for Ondava River catchment from the Stropkov meteorological station.

Chvojnica brook catchment has very similar geological, hydrogeological and climatic conditions to Tuzina brook catchment. The upper part of the Nitra River catchment is typical by combination of different geological conditions and human influences. It is characteristic by the lowest terrain altitude and a flashy character. Also Topla and Ondava River catchment have very similar geological, hydrogeological and climatic conditions to each other.

3 RESULTS AND DISCUSION

In our work we tried to get a complex view on hydrological drought problems assessing localities in the upper part of Nitra River catchment (central part of Slovakia) and Topla and Ondava River catchment in the eastern part of Slovakia. Individual subsurface water balance components were analyzed for the zone of aeration looking for possible influences on the aquifer. The decrease or increase of groundwater runoff values was studied. Some of the results follow.

3.1. Analysis of the discharges in the upper part of Nitra River catchment

Similar shapes of the discharges hydrographs were obtained for Tuzina and Chvojnica streams. Both streams have expressive maximum discharges in the spring months March and April (from 1.5 up to 1.9 $m^3.s^{-1}$ on Tuzina brook and from 0.6 up to 1.9 $m^3.s^{-1}$ on Chvojnica brook). Both streams have their minimum discharges from July up to December (from 0.1 up to 0.2 $m^3.s^{-1}$ on Tuzina brook and from 0.03 up to 0.08 $m^3.s^{-1}$ on Chvojnica brook). Shape of the discharge time series graph for Chvojnica brook is almost identical with that one of the Tuzina brook, differing only in generally lower values of discharges (Figure 1).

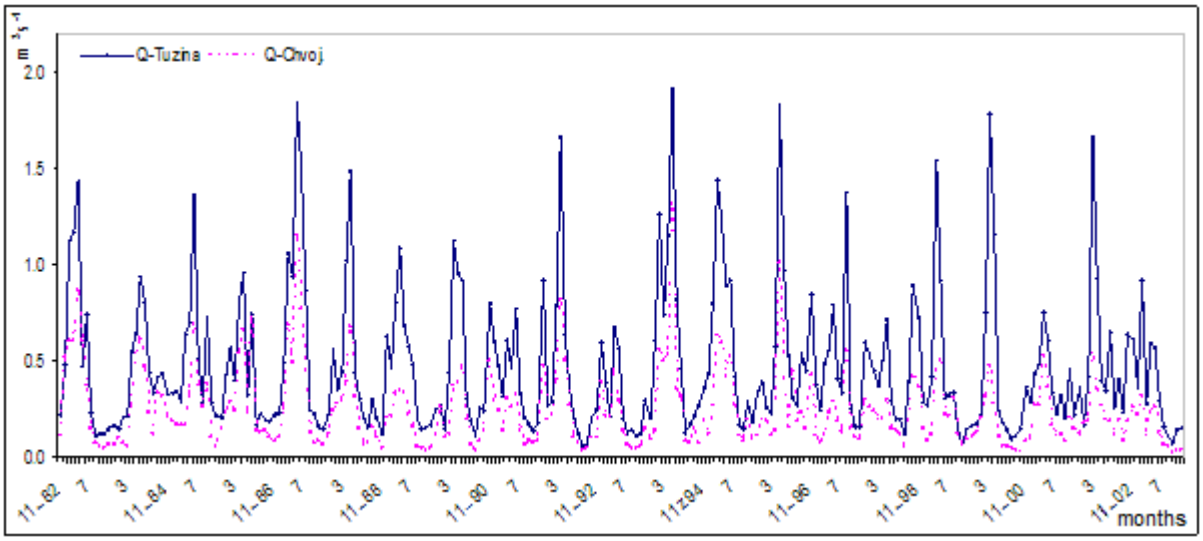

Figure 1: Time series of discharges (Q) on Tuzina and Chvojnica brooks

Maximum discharge values on Handlovka River varies from 1 up to 1.5 $m^3.s^{-1}$ (March and April). Minimum discharge values are in summer and autumn months (from 0.2 up to 0.3 $m^3.s^{-1}$). A similar shape of the flow hydrograph was gained for discharges at the Chalmova profile on the Nitra River. Maximum values are typical for spring months and minimum values for the autumn months (about 2 $m^3.s^{-1}$). Value of the discharge grows downstream. Minimum values at Chalmova are ten-times higher than at Tuzina and Handlova. Nitra River is largely influenced by Handlovka River (Figure 2).

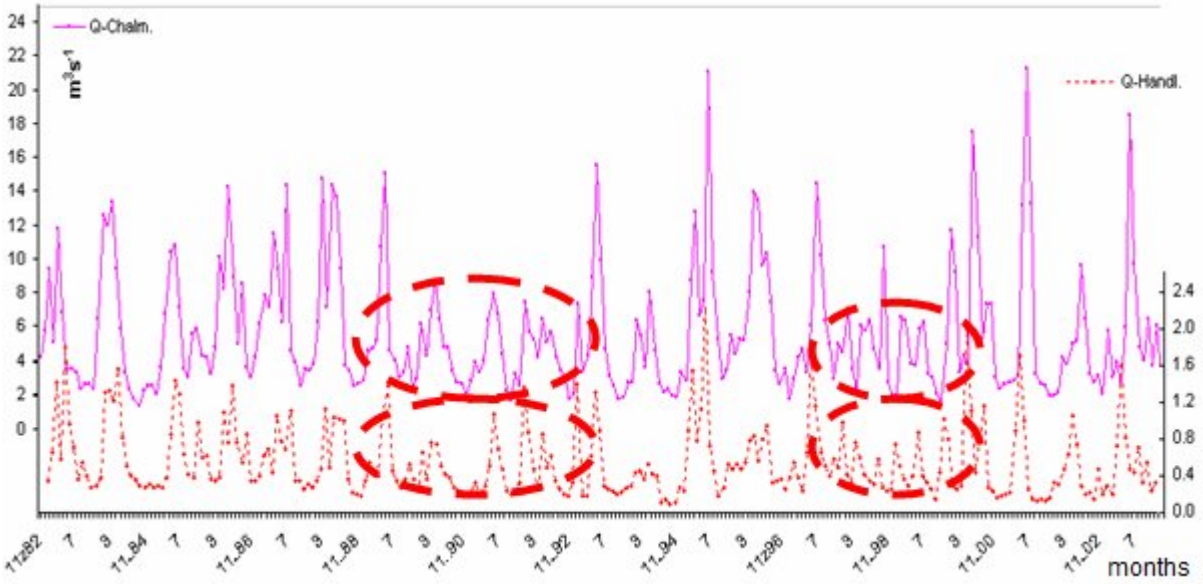

Figure 2: Time series of discharges (Q) on Handlovka and Nitra Rivers

Discharges in Handlova and Chalmova profiles had a similar shape up to year 1997. This situation has repeated again in years 2001 to 2003. All of the streams had a certain regular shape of discharges up to year 1995 with maximum values in spring and minimum values in summer and autumn periods. In the period of years 1987-1992 and 1997-2000, there was an expressive decrease of maximum discharges on Handlovka River, what had a clear influence on discharges in Chalmova profile. Maximum values of discharges increased in years 1994-2002.

Maximum monthly discharge values in Topla River are typical for spring months March and April (influence of snow melting) with the values from 4.55-14.74 $m^3.s^{-1}$. Minimum monthly discharge values occur from October up to December (0.38-1.11 $m^3.s^{-1}$). Periods of minimum discharges on Topla River catchment are showed in Figure 3.

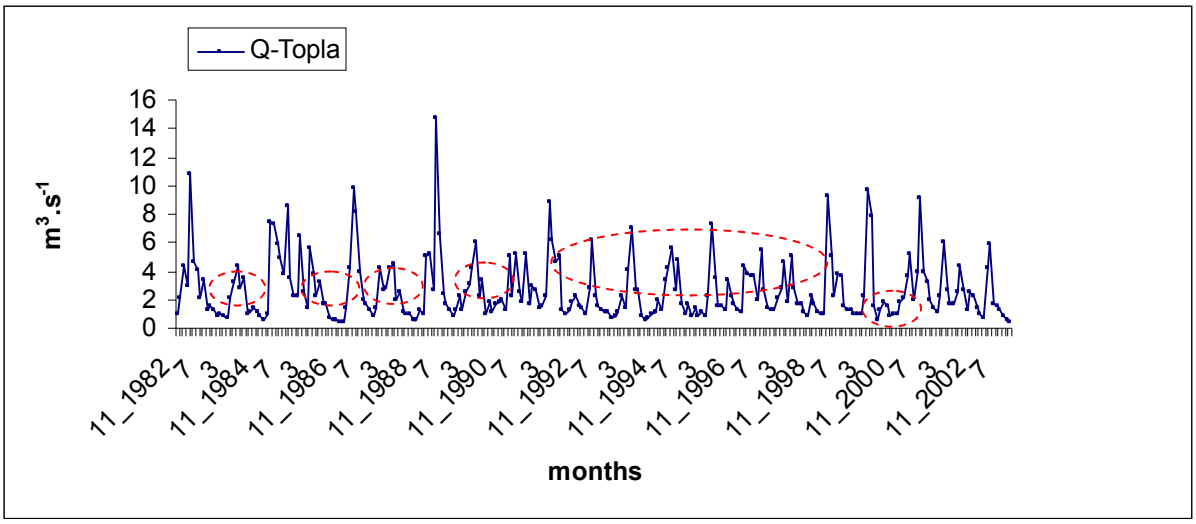

Figure 3: Time series of discharges (Q) on Topla River

Maximum monthly discharge values on Ondava River occur in spring months March and April (influence of snow melting) reaching values from 8 up to 25 $m^3.s^{-1}$. Minimum monthly discharge values occur in August and September ranging from 0.6 up to 0.9 $m^3.s^{-1}$.

Comparison of selected compounds in the time scale

The whole assessed period was classified according to yearly precipitation amounts; very dry, dry and normal years were defined. Topla River catchment is characterized by occurrence of 33 % of very dry years, which is the maximum value among all evaluated catchments. Frequency of dry years reached 33 % in all gauging stations except of Chvojnica and Tuzina. In the case of normal year occurrence, the highest values were estimated for Chvojnica, Tuzina and Ondava (47 %). For the rest of gauging stations it was 33%. Our research was focused on changes in baseflow values in very dry years.

Tuzina Brook

According to modeling results, the groundwater storage (GS) value reaches about 200 mm. In years 1990, 1996 and 1997, groundwater storage (GS) values ranged from 117 to 130 mm per month (Figure 4). This fact points on deficit in snow cover during the winter period. It was also confirmed by snow water storage (SW) parameter which was so low that there was no possibility to display SW value in the time series course. The parameter SW reached the highest value in 1987 and there was a visible positive relationship among snow cover, SW and groundwater storage.

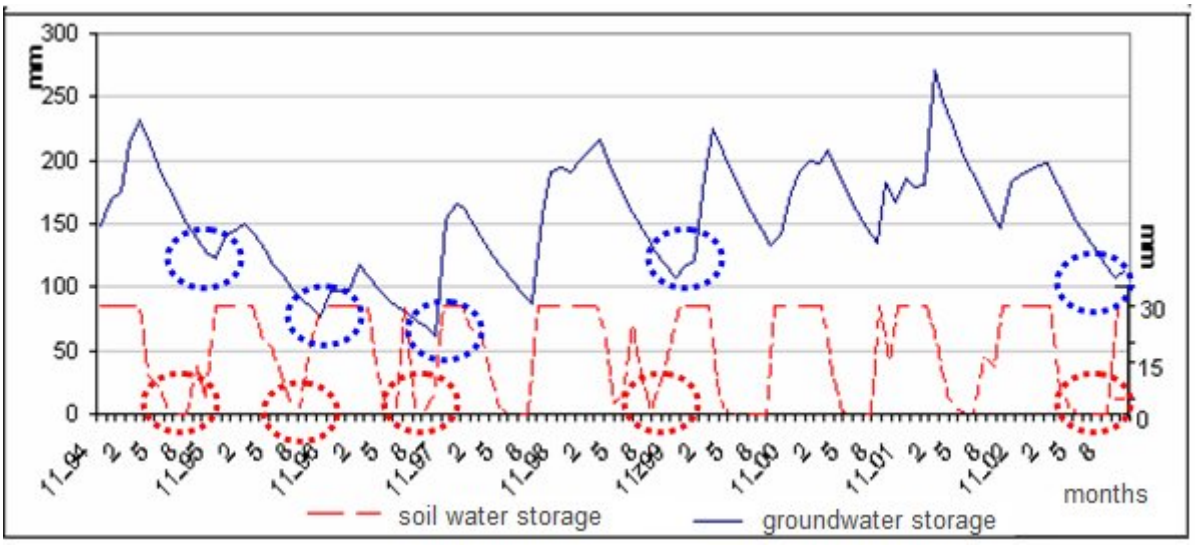

Figure 4: Decrease of soil water storage and ground water storage in summer months

Parameter GS varied in the range from 100 to 130 mm per month in the summer months till 1995. From 1995 to 1997 the GS values were the lowest in the whole observed period. Soil water storage curve (SS) had the similar course within the whole period, with exception of summer months of 1986, 1988, 1997, 1999 and 2001. In those years the soil water storage reached its maximum values in the summer months, the zone of aeration was fully saturated. Precipitation amounts reached the values from 130 to 150 mm per month. Such values are more than two times higher than the average precipitation amount (61 mm per month). The lowest soil water storage values in whole observed period were recorded from 1995 to 1997, what was similar to values of the GS parameter (Figure 4).

Handlovka River

Handlovka River is a stream influenced by mining activities. Average GS value is about 283 mm per month. Average GS is varying around 370 mm per month in winter months and around 200 mm per month in summer months. The more significant decrease of GS values occurred in January and February 1984 (252 mm), 1990 (202 mm) and 1998 (294 mm). An approximately regular course of GS curve was disconnected for the whole period from 1993 to 1997. No clear natural course of runoff can be seen in the whole observed period. This can be caused by anthropogenic activities in the area, most probable by mining activities in brown coal mines. Based on analyzes of GS curves courses we assume that precipitation amount together with water discharged to surface stream from mining works dewatering is the main compound which affects the amount of groundwater in the winter months (Figure 5). Therefore also the significant decrease of GS in summer months does not occur, as it is typical for Paleogene flysch rock environment (Topla, Ondava Rivers) or for areas built by less permeable Neogene rocks (Machlica and Fendeková, 2006).

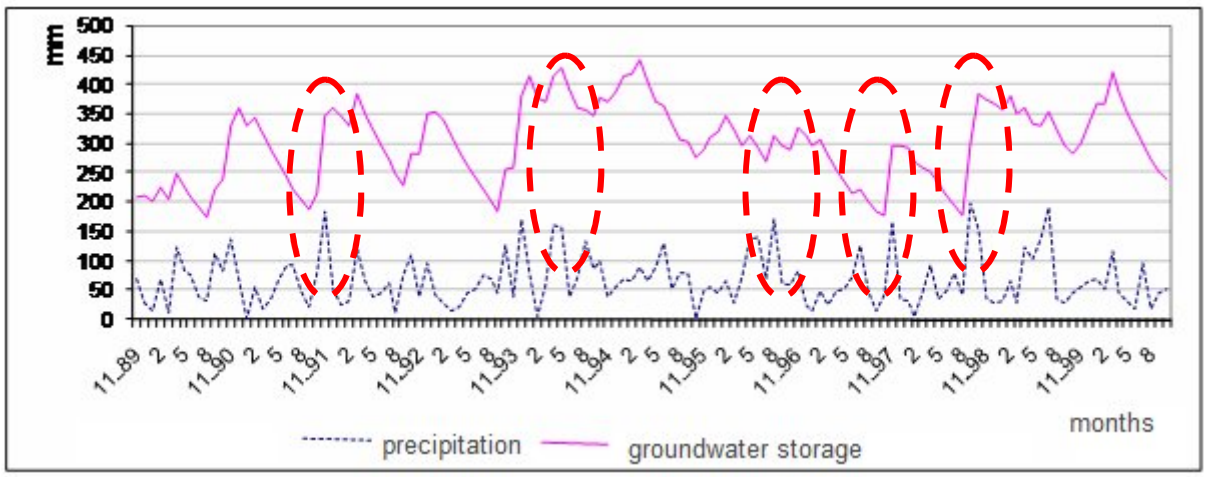

Figure 5: Dependence between precipitation amount and groundwater storage in Handlovka catchment

Topla River

Topla River is situated in a different geological environment. The area is built by Paleogene flysch sediments (alternation of sandstone and claystone), covered by Quaternary alluvial deposits. Climatic conditions are similar to those in the Upper Nitra. Modeling results showed different courses of some water balance compounds (GS, SS and BF – base flow). Groundwater storage reaches the value of about 110 mm per month, in the summer months it varies in the range from 40 to 60 mm per month. Dry periods were visible on courses of GS curves only in 1984, 1990, 1998 and 2003. The courses of SS curves reflected the same situation as GS curves, in dry and very dry years there was the biggest decrease of soil water storage (Figure 6).

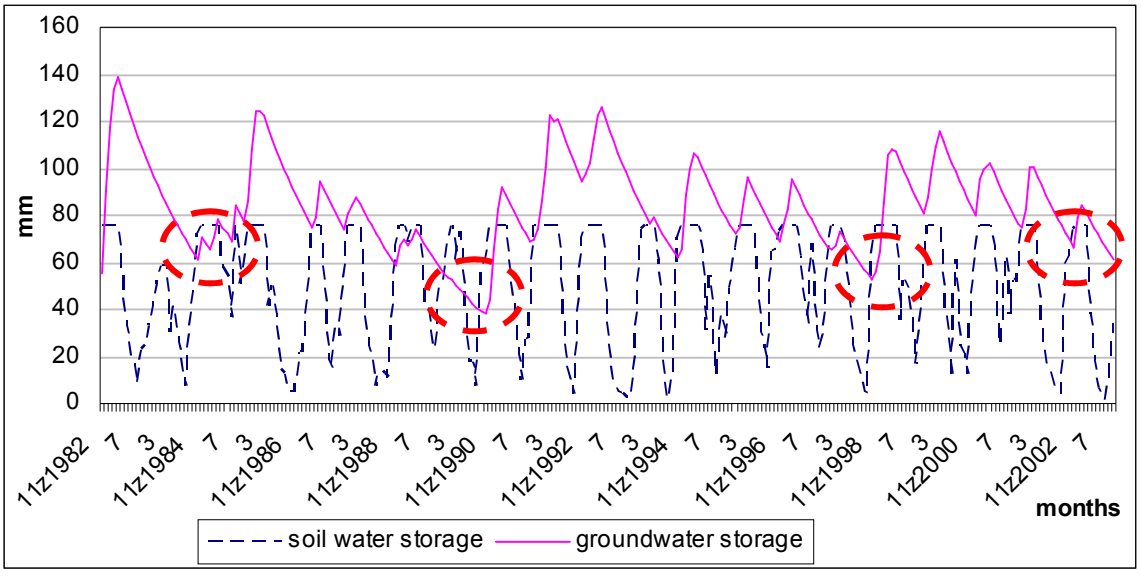

Figure 6: Synchronic decrease of soil water storage and groundwater storage in Topla river catchment

Ondava River

Ondava River has very similar conditions to Topla River. The range of GS values is from 60 to 145 mm per month with the similar seasonal course as for the Topla river (maximum values in the winter, minimum values in the summer period). Very dry and dry years have similar effect on GS and SS curves as on Topla River. The most significant effect was showed in 1984, 1990 and 2003.

Base flow estimation and evaluation

Very similar base flow values were estimated using Bilan and BFI models, the lowest values (Stojkovova 2007) were calculated by the method of Castany (tab.1). Because of different catchments sizes, it was necessary to re-calculate the base flow values into specific groundwater runoff values. The comparison and analysis of base flow courses was done at first for very dry years in the whole observed time period and then especially for winter, spring and summer months.

Table1: Base flow values estimated by different methods

		Baseflow ($m^3.s^{-1}$)			Specific groundwater runoff ($l.s^{-1}km^{-2}$)		
Profile	Stream	BFI	BILAN	Castany	BFI	BILAN	Castany
Chvojnica	Chvojnica	0.15	0.12	0.05	8.19	6.45	2.81
Tuzina	Tuzina	0.28	0.16	0.12	7.95	4.49	3.37
Handlova	Handlovka	0.3	0.35	0.19	7.37	8.7	4.73
Chalmova	Nitra	3.71	3.37	2.05	6.16	5.6	3.41
Bardejov	Topla	1.48	1.49	0.71	4.55	4.57	2.18
Stropkov	Ondava	1.80	2.03	0.65	3.12	3.5	1.12

The lowest values of base flow were estimated for catchments built by flysch sediments (Topla and Ondava catchments). This environment is not able to accumulate bigger amounts of groundwater. The worst conditions of water-saturation has the rock formation with dominance of claystones. They have poor fissure permeability, the infiltration is very limited. Better conditions have rock formations with dominance of sandstones with small portion of micro-conglomerates. Estimated values of base flow correspond to described geological conditions. Influence of external conditions (precipitation amount) manifests with different intensity on courses of base flow curves.

Chvojnica and Tuzina streams have their springs in Mesozoic limestones and dolomites; however the main part of these river courses is located in the area created mainly by granitoids and migmatites. Approaching the Upper Nitra valley, both streams flow through the area built by Quaternary alluvial cones (sand and gravels deposits). Catchments of these streams have the lowest base flow values in the Upper Nitra River catchment. Central part of the area along the Nitra River up to the gauging station at Chalmová is built mainly by fluvial deposits, which are available to store bigger amounts of groundwater what was visible on the base flow values. The highest base flow values in Upper Nitra catchment were estimate on Handlovka

River. Handlovka River has spring in neovolcanic sedimentary rocks along the stream flow during inner Carpathian Paleogene covered by Quaternary sediments. The highest base flow value among all assessed profiles can be affect by mining activities in this area. Artificial recharging of the stream can also be one of the reasons of quite high groundwater storage and base flow values estimated by modeling and Method of Castany (Machlica et al. 2007).

4 CONCLUSION

Presented results document how the drought in surface and subsurface hydrological cycle components could manifested. Factors (in monthly time step) leading to groundwater drought were evaluated by interpretation of shape of the time series generated in BILAN model and by groundwater runoff estimates calculated using BFI model. On the other hand, monthly time step is not satisfactory for detailed monitoring of drought development and propagation in the subsurface compounds of the hydrological cycle. Use of hydrological models with daily time step would be more suitable for such specific analyze. At present, works on re-evaluation results using BILAN model in a daily time step are going on.

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References

Bonacci, O. (1993): Hydrological identification of drought, Hydrological Processes, vol. 7; 249/262.

Castany, G., Margat, J. and Albinet, M. (1970): Evaluation rapide des resource en eaux d´une region, Simposio internacional sobre aguas Subterraneas de Palermo, Asociacion internacional de Hidrogeologos, Ente de Desarrollo Agricola, Palermo, 462-682

Machlica and Fendekova, M (2006): Separation of runoff components using BILAN model in Chvojnica catchment, Podzemna voda, vol. XII, No. 2., SAH Bratislava, 135-147 [in Slovak with English Summary]

Machlica A., Stojkovova M. and Bara M. (2007): Impact of meteorological drought on the base flow formation. 14th Slovak hydrogeological conference. Abstract, p. 100, ISBN 978-80-969342-3-2

Stojkovova, M. (2007): Groundwater runoff on the territory of Slovakia, Podzemna voda, vol. XIII, No.2, SAH Bratislava, 146-152 [in Slovak with English Summary]

Tallaksen, L. M. and van Lanen, H. A. J., Eds. (2004): Hydrological drought, Processes and estimation methods for streamflow and groundwater, Development in water science 48, Elsevier, Netherlands, 579 pp.