J. Hydrol. Hydromech., 62, 2014, 3, 169–176
DOI: 10.2478/johh-2014-0027

Global drivers effect in multi-annual variability of runoff

Miriam Fendeková[1*], Pavla Pekárová[2], Marián Fendek[1], Ján Pekár[3], Peter Škoda[4]

[1] Department of Hydrogeology, Faculty of Natural Sciences of Comenius University in Bratislava, Pav. G, Mlynska dolina, 842 15 Bratislava 4, Slovakia.
[2] Institute of Hydrology, Slovak Academy of Sciences, Racianska 75, 831 02 Bratislava 3, Slovakia.
[3] Department of Applied Mathematics and Statistics, Faculty of Mathematics, Physics and Informatics, Comenius University, 842 48 Bratislava, Slovakia.
[4] Slovak Hydrometeorological Institute, Jeseniova 17, 833 15 Bratislava, Slovakia.
[*] Corresponding author. E-mail: fendekova@fns.uniba.sk

Abstract: Changes in runoff parameters are very important for Slovakia, where stream-flow discharges, being supplied by precipitation and groundwater runoff, are preferentially influenced by climatic conditions. Therefore, teleconnections between runoff parameters, climate parameters and global atmospheric drivers such as North Atlantic Oscillation, Southern Pacific Oscillation, Quasi-biennial oscillation and solar activity were studied in the Nitra River Basin, Slovakia. Research was mostly based on records of 80 years (1931–2010) for discharges and baseflow, and 34 years for groundwater heads. Methods of autocorrelation, spectral analysis, cross-correlation and coherence function were used. Results of auto-correllograms for discharges, groundwater heads and base flow values showed a very distinct 11-year and 21-year periodicity. Spectrogram analysis documented the 11-year, 7.8-year, 3.6-year and 2.4-year periods in the discharge, precipitation and air temperature time series. The same cycles except of 11-years were also identified in the long-term series of the North Atlantic Oscillation and Southern Pacific Oscillation indices. The cycle from approximately 2.3 to 2.4-years is most likely connected with Quasi-biennial oscillation. The close negative correlation between the North Atlantic Oscillation winter index and the hydrological surface and groundwater parameters can be used for their prediction within the same year and also for one year in advance.

Keywords: Runoff variability; Global climatic drivers; Inter-relationships; Nitra River Basin; Slovakia.

INTRODUCTION

Multiannual variability is a very important topic in many studies around the world at present, especially in connection to its possible use in predicting the future development of precipitation and river flows as showed by Wanner et al. (2001), Saris et al. (2010), Lavers et al. (2010), Fritier et al. (2010), Pekarova et al. (2003, 2006, 2010) and others.

The global climate drivers were studied by Burt and Howden (2013) who identified the impact of large-scale climatic variability in the North Atlantic region on seasonal rainfall and river flow across the British Isle. They showed how North Atlantic Oscillation (NAO) dramatically increases orographic enhancement of upland precipitation. Hannaford et al. (2013) documented that recent (post-1960) positive trends of streamflows in northern Europe are not present in longer records, due to decadal variations influenced by the NAO. The inter-annual variability of daily rainfall erosivity in NE Spain during the period 1955–2006, and its connection with atmospheric circulation patterns influencing rainfall in the region, namely the North Atlantic Oscillation, the Mediterranean Oscillation (MO) and the Western Mediterranean Oscillation (WeMO), was studied by Angulo-Martínez and Beguería (2012). They found that the erosive power of rainfall is stronger during negative phases of the three atmospheric circulation indices, and weaker during positive conditions.

The changes in the runoff conditions of Polish rivers in the two NAO stages and their spatial diversity were determined by Wrzesiński (2011) based on the differences between runoff observed in the years of exceptionally high ($NAO_{DJFM} > 2.0$) and low ($NAO_{DJFM} < -2.0$) values of the winter NAO index. The results indicate that the influence of the NAO on the runoff of Polish rivers is diverse in terms of time and space.

De Linage et al. (2013) studied results of ten years of Gravity Recovery and Climate Experiment (GRACE). Values of the terrestrial water storage anomalies (TWSAs) over tropical South America along with seven climate indices linked to equatorial Pacific and tropical Atlantic oceans sea surface temperatures (SSTs) were assessed by a multichannel singular spectrum analysis and by lagged cross correlations. Comparison of the relative distributions of the leading modes helped to identify teleconnections between TWSAs, Pacific and Atlantic SSTs at different time periods. A quasi-biennial mode explains the largest part (27%) of the residual, inter-annual cross covariance and is found both in the El Niño-Southern Oscillation and in the Atlantic meridional mode. A trend-like mode explains the second largest part (24%) of the residual cross covariance and may be caused besides others also by the decadal variability in the North Pacific climate, as expressed by the negative trend in the Pacific decadal oscillation.

The main aim of this study is to analyze the teleconnections between runoff parameters and global atmospheric drivers such as North Atlantic Oscillation, Southern Pacific Oscillation (SO), Quasi-biennial oscillation (QBO) and solar activity in the Nitra River Basin in Slovakia. Inter-relationships were also studied between precipitation and air temperature with these global drivers to form a basic picture of their long-term development. Surface and groundwater parameters in the Nitra River Basin were lately studied by Fendekova and Fendek (2012), Machlica et al. (2010), Van Loon et al. (2010) mostly in connection to drought research.

The present research was established mostly on a discharge time series length of 80 years, representing the period 1931–2010. Shorter time series were used for groundwater head data (1971–2010). Methods of autocorrelation, spectral analysis, cross-correlation and coherence function were employed.

STUDY AREA

The Nitra River Basin is situated in the western part of Slovakia covering an area of 4,501.1 km^2 as seen in Fig. 1. The river has a total length of 169.7 km, with its main right-side tributaries the Nitrica River (319 km^2) and Bebrava River (631 km^2). The main left-side tributary is the Zitava River (907.75 km^2). The upper part of the basin is bordered by the Strazovske vrchy Mts. in the west, by the Mala Fatra Mts. in the north, the Ziar Mts. in the northeast and the Vtacnik Mts. in the east. The Tribec and Pohronsky Inovec Mts. create the eastern border in the central part of the basin. The lower part of this basin has lowland character with the occurrence of some hillylands dividing the Nitra and Hron River Basins in the east.

The upper part of the catchment has a complicated pre-Quaternary geological structure (crystalline core mountains with carbonate envelopes, Neogene volcanic and sedimentary rocks), covered by alluvial sediments in the river valleys, and slope sediments on the mountain foothills. The central and lower part of the basin is flat, filled with sandy and clayey sediments and covered by 5–15 m thick sediments of alluvial plains (Fendekova and Fendek, 2012).

The climate in the basin is typical for Central European larger intra-mountainous depressions and lowland areas, covering the whole range of climatic regions from warm through moderately warm up to cold, depending on the altitude (Landscape Atlas of the Slovak Republic, 2002). According to the Köppen – Geiger classification, the basin has a moderately warm, humid continental climate (Köppen-Geiger climate Dfb). The average altitude is 372 m a.s.l. with the lowest level of 108 m a.s.l. at the closing profile at Nove Zamky and the highest of 1346 m a.s.l. at Vtacnik mount. The average annual areal precipitation was 689.6 mm in 1916–2010, minimum was equal to 467 mm in 1917 and maximum to 1081 in 2010. The long-term annual precipitation decreases from about 1000 mm in the upper part of the basin to 550 mm in the lower part. The average annual runoff was 141 mm (1916–2010) and the evapotranspiration 548 mm. The runoff coefficient is equal to 0.204. The average annual air temperature was 10.1°C (1916–2010) at Hurbanovo station. All climatic elements vary spatially depending on altitude and season.

MATERIAL AND METHODS

The data on precipitation, air temperature, streamflow discharges, baseflow and groundwater heads in monthly intervals, the NAO and SO index values and Wolf numbers were the input data utilized for analysis.

Six precipitation gauging stations (Fig. 1) with a time-series length of 110-years (1901–2010) were used for calculation of the areal precipitation by precipitation gradient approach. The temporal development of air temperature values was assessed using the Hurbanovo meteorological station data (1871–2010).

The daily discharges from five gauging stations with the longest observation time-series were analyzed. The gauging profiles were: (1) Nedozery (1941–2010) in the upper part of the catchment which has the character of a near-natural catchment, (2) Nitrianska Streda (1931–2010) representing the central part of the catchment, (3) Nove Zamky (1916–2010) as the closing profile of the catchment, (4) the Bebrava River at Biskupice (1931–2010) - the most important right tributary and (5) the Zitava River at Vieska nad Zitavou (1931–2010) - the most important left tributary. The courses of long-term monthly runoff are depicted in Fig. 1.

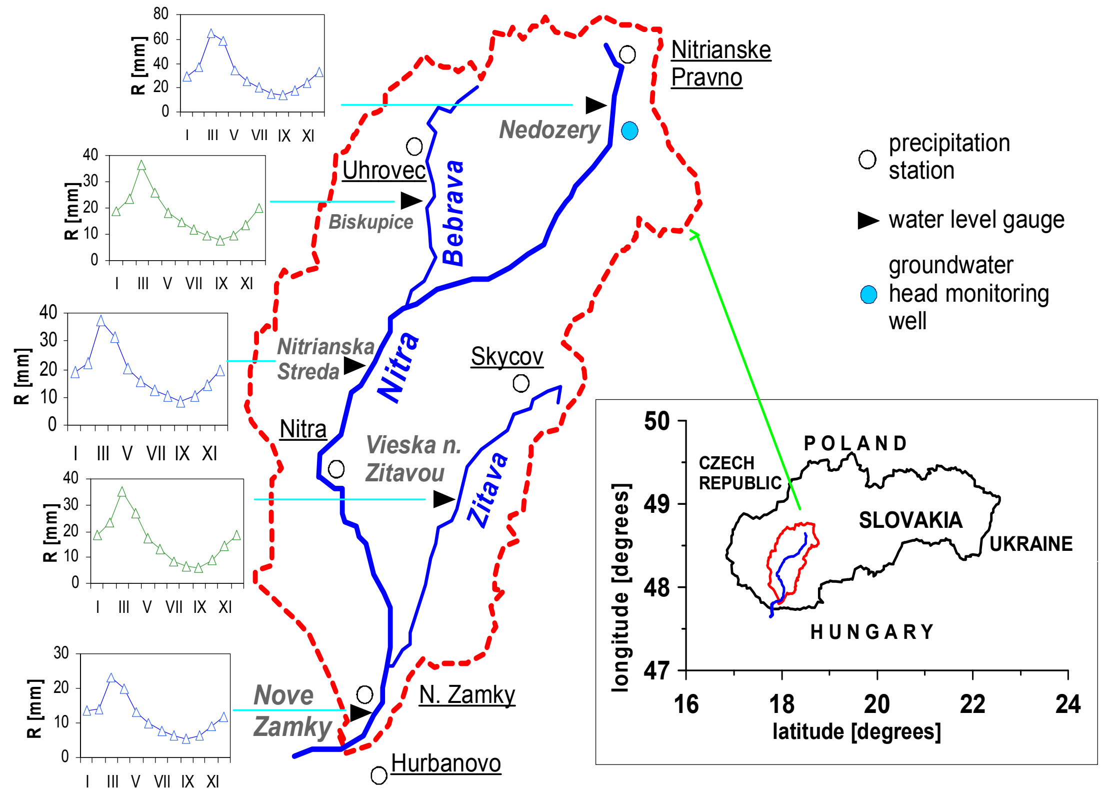

Fig. 1. General location of the Nitra River Basin. Basic river network, water level, groundwater head and precipitation gauging stations used in the study. Runoff (R) seasonality pattern in water level gauging stations http://www.sav.sk/?lang=sk&charset=&doc=services-docs

Base flow values, Q_{97} (97^{th} percentile) from the flow-duration curve of stream flow discharges and the groundwater heads were used as groundwater parameters. Base flow values in daily steps (BF30) were derived from the discharges by the BFI+3 program (Gregor, 2011) based on the local minimum method (Institute of Hydrology, 1980). The 30-day blocks were used for estimation of turning points (Tallaksen and Van Lanen, 2004) enabling separation of the base flow from the direct runoff. The value of Q_{97} was also used as the groundwater runoff parameter. This value represents the discharge, reached or surpassed in 97% of the hydrological year's duration representing approximately 355 days and labelled as Q_{355}. It is considered that this of Q_{355} value represents conditions during which the stream flow is fed only by groundwater runoff. Q_{97} values were estimated by construction of a flow-duration curve for each year of the entire observed period, and separately for the winter-spring period (November-April) and summer-autumn period (May-October). These values were taken to create a derived time series of $Q_{97,}$ representing the groundwater runoff in the winter-spring and summer-autumn periods. Data from monitoring well No. 256 in Nedozery (Fig. 1) in a weekly step were at the disposal, groundwater heads were expressed in m a.s.l. The well is located in the left side alluvial plain of the Nitra River, about 1650 m downstream the gauging profile in Nedozery.

The winter (December through March) index of the NAO based on the difference of normalized sea level pressures (SLP) between Lisabon, Portugal and Stykkisholmur/Reykjavik (Iceland) since 1865 was used in the study according to Hurrell and National Center for Atmospheric Research Staff (2013).

Seasonality and its changes were studied using average monthly data. The analysis of long-term data of hydrological and meteorological variables was followed by the analysis of the time series of average yearly values using autocorrelograms, spectrograms, cross-correlation and coherence analyses in order to assess the influence of global climate drivers on the multi-annual variability in local hydrometeorological data.

The homogeneity of the time series was assessed using the software package AnClim (Stepanek, 2003; Stepanek et al., 2009). Changes in the mean values and variance were tested with standard tests (Student's t-test, Worsley Likelihood Ratio Test, Mann-Whitney-Pettit Test, Standard Normal Homogeneity Test). Some statistical tests and procedures used within this study are based upon the normality requirement of the tested series. Therefore the X^2 and the Kolmogorov-Smirnov tests were used to test the distribution normality of the annual discharge series.

Multiannual variability within the time series was studied by means of autocorrelation. The most significant periods were identified by using periodograms and Blackman-Tukey power spectrum (Herrmann and Egger, 1980). Spectral analysis was studied by means of the MESA method (Pekarova and Pekar, 2007) and long periods were identified using combined periodograms (Pekarova et al., 2010).

Cross-correlograms and coherency coefficients were used to identify the teleconnections of the annual discharges of the Nitra River, annual baseflow values and groundwater heads with the North Atlantic Oscillation (NAO) and the Southern Oscillation (SO) phenomena, as well as the solar activity. The independence between the data series for the period 1931–2005, with lag up to ± 30 years, was tested. Cross-spectral analysis was performed on the basis of the same pairs of time series for this identical purpose.

RESULTS AND DISCUSSION

Precipitation data from five precipitation gauging stations with a time series length of 110 years (1901–2010) and one with 140 years' length (Hurbanovo, 1871–2010) were used in order to assess precipitation long-term variability. The long-term course of average areal annual precipitation on Nitra Basin and runoff at the Nove Zamky station (the closing profile of the basin) is shown in Fig. 2 left. The relationship between annual averages of precipitations and annual runoff is depicted in Fig. 2, right.

Homogenization of time series is widely recognized to be an important step in the process of constructing reliable long-term data sets from original climate observations. The Hurbanovo meteorological station is one of the oldest stations in Europe. For example, the test characteristics *Ti* of the Standard Normal Homogeneity Test (SNHT) of annual precipitation totals for shift in mean level (Alexandersson, 1986; Alexandersson and Moberg, 1997) was just above their critical value 9.35 on the 95% significance level in year 1966 (Fig. 3a). The test characteristics of the changes in standard deviation are similar. Actually, "absolute homogeneity" of long time series is always questionable. The non-homogeneity may result from change in the long-term trend, as it is shown in Fig. 3b. The long-term development of monthly precipitation at the Hurbanovo station shows a decrease of app. 50 mm within period 1871–1976 and an increase within 1977–2010 period. The precipitation began to increase from the early eighties of the last century, in the summer-autumn period.

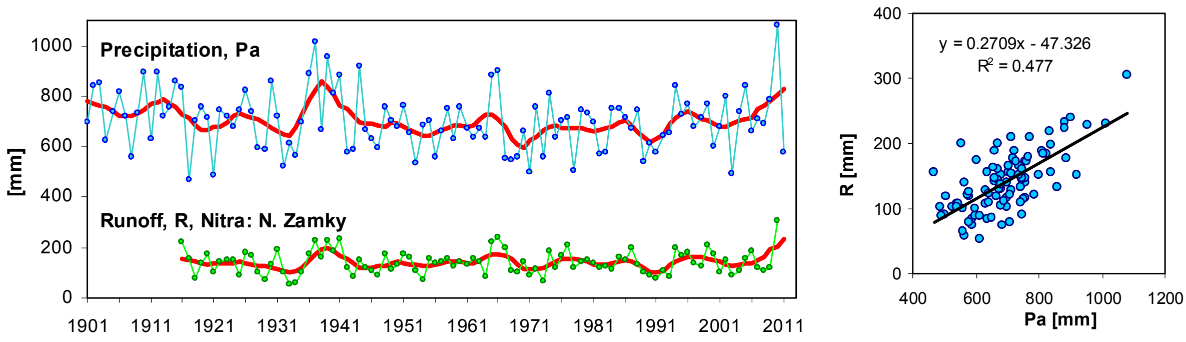

Fig. 2. Temporal development in annual areal precipitations (Pa) and runoff (R) at the Nove Zamky closing profile – left. Dependence of annual runoff (R) on annual precipitations (Pa).

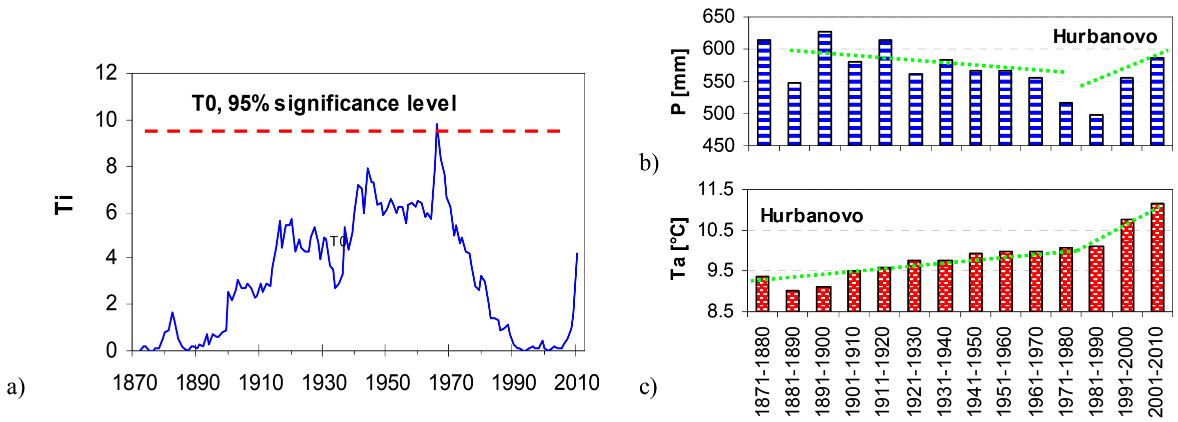

Fig. 3. a) Absolute homogeneity test of annual precipitation series for the Hurbanovo station, changes in the mean level, values of the test statistics *Ti* on y-axis; long-term trend for two periods 1872–1966 and 1967–2011; b) Temporal development of 10-years average of annual precipitation (P), and c) temperature (T). Hurbanovo meteorological station, 1871–2010 period.

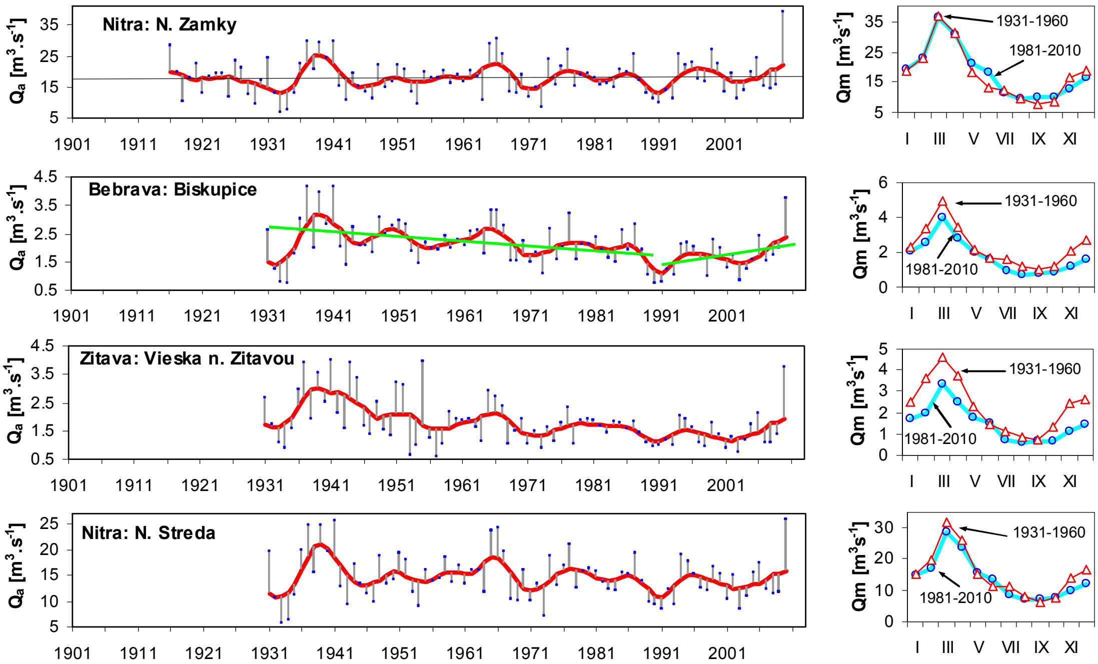

Fig. 4. Average annual discharge differences from 7-years moving averages – left; discharges seasonality for two periods: 1931–1960 and 1981–2010 right for Nitra River at Nove Zamky; Bebrava River at Biskupice; Zitava River at Vieska nad Zitavou; and Nitra River at Nitrianska Streda.

The data on air temperatures at Hurbanovo meteorological station (Fig. 3c) were analyzed because there were only much shorter time series available for the other meteorological stations in the basin. Ten-year averages were used for the evaluation of the air temperature time development during the last century and the beginning of the current one. The increase in air temperatures has been more intense since 1991. The air temperature at Hurbanovo station has increased in 1.3°C during the last 140 years (1871–2010).

Temporal changes in river discharges

The long-term development of annual and seasonal discharges at the assessed discharge gauging stations brought following results. Almost no long-term trend and no seasonality differences can be observed in the Nove Zamky station (the closing profile of the Nitra River Basin) between the 1931–1960 and 1981–2010 periods, as depicted in Fig. 4. On the other hand, there is a visible change in seasonal components in the Nedozery profile in the upper part of the Nitra catchment (Fig. 5, right). Here, the highest discharges in the second period (1981–2010) are shifted from April to March, while the discharges in the winter months (November to February) became lower than in the period 1931–1960. There was no change in the seasonal course of discharges noted in the remaining three evaluated stations (Fig. 4).

A distinct decrease in discharges on both tributaries can be seen, with the Bebrava River and the Zitava River. Only a slight increase in the average discharges for the Nitrianska Streda profile in the central part of the basin was observed in March, November and December.

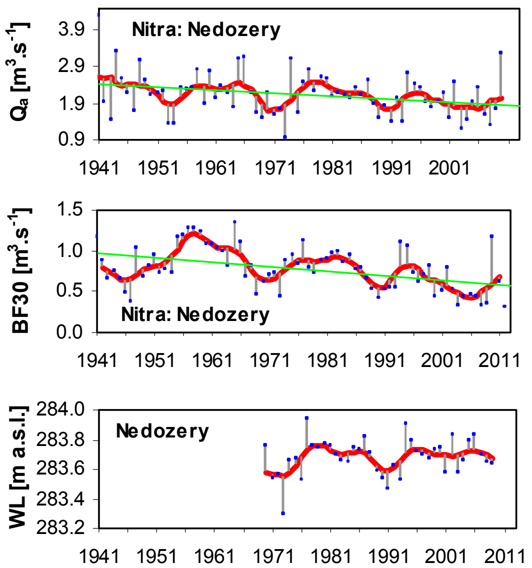

Fig. 5. Average annual discharge (Qa) – Nitra River at Nedozery; base flow (BF30) – Nitra River at Nedozery; annual groundwater head (WL) – near Nedozery. Differences from 7-years moving averages – left, changes in seasonality – right.

Temporal changes in groundwater parameters

Base flow (BF30) data analysis showed that there is a decreasing trend of base flow values visible in Fig. 5. The decrease was found in both, the winter-spring and summer-autumn periods in the Nedozery profile. There is no change in seasonality within the two different time periods of 1946–1975 and 1981–2010, but the decrease within the second period is quite distinct (Fig. 5 right).

Analysis of the weekly groundwater head data showed that the groundwater head varies between 283.12 m a.s.l. and 285.05 m a.s.l., with the long-term value being 283.68 m a.s.l. No significant trend for the whole observed period 1971–2010 was found (Fig. 5). The temporal development of heads in the winter-spring and summer-autumn periods recorded a similar finding.

The seasonality of groundwater head shows a monthly shift compared to the discharge seasonality in the nearest profile in Nedozery. The maximum heads period is shifted to April and the minimum values period to October (Fig. 6).

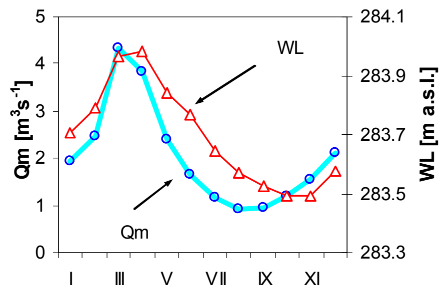

Fig. 6. Discharge and groundwater head seasonality in Nedozery (1971–2010).

Inter-relationships between local hydrometeorological data and global atmospheric drivers

The analysis of auto-correlograms constructed for yearly discharge values showed a distinct 11-year and 28–29-year dependency (Fig. 7). The auto-correlogram of precipitation also showed the 14-year cycle, as well as both the previously mentioned periods.

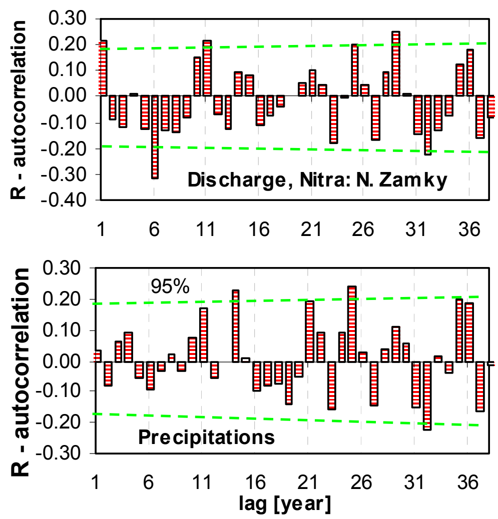

Fig. 7. Auto-correlograms of annual discharge and precipitation.

Because the multiannual cycles do not have their origin in the annual revolution of the Earth around the Sun, we cannot assume that these can be distinguished using auto-correlograms. Therefore the spectral analysis was used. Results from the standardized auto-correlogram and spectrogram for discharges (Q) in the Nitra-Nove Zamky closing profile showed the most distinct period of a length of 11 years, other periods of 7.8, 3.6 and 2.4 years were also distinguished. These same periods were distinguished in time series of precipitation, air temperatures, Southern Pacific Oscillation index (SOi) and North Atlantic Oscillation index (NAOi). The 11- and 21–22-year periods are most likely associated with sun activity as expressed in the Wolf number, while the 2.3- to 2.4-year cycle can be connected with Quasi-biennial oscillation (QBO).

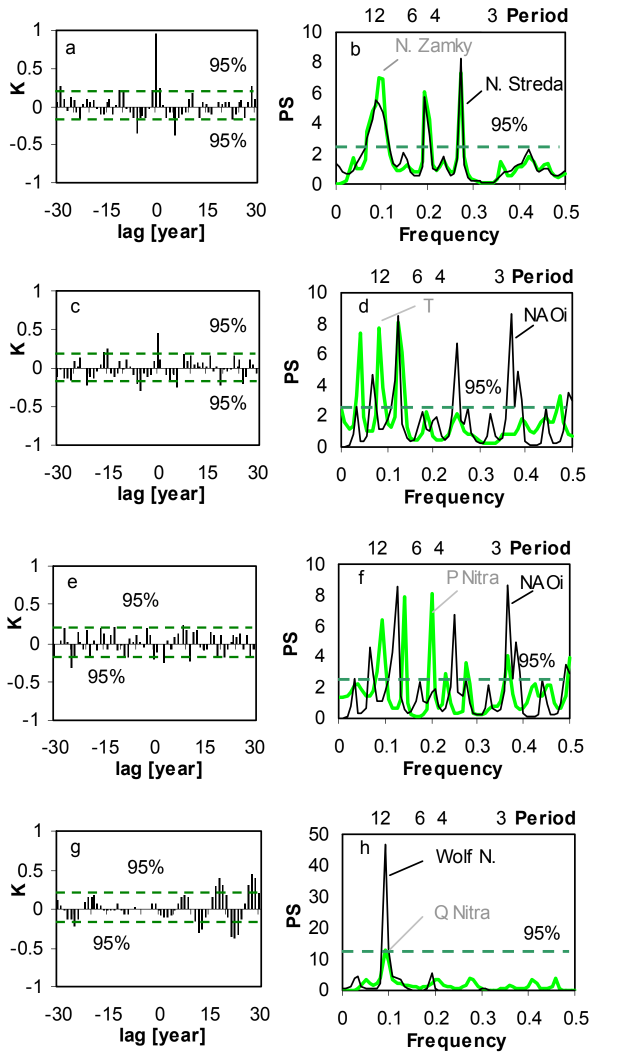

Fig. 8. Results of cross-correlation analysis and spectrograms for selected hydrometeorological variables and global climate drivers:
a-cross-correlogram for discharges in the central and lower part of the basin; b-spectrogram for discharges in the central and lower part of the basin; c-cross-correlogram for NAOi and air temperature; d-spectrogram for NAOi and air temperature; e-cross-correlogram for NAOi and areal precipitation; f-spectrogram for NAOi and areal precipitation; g-cross-correlation of solar activity (Wolf relative number) vs. discharge; h-spectrogram of solar activity (Wolf relative number) vs. discharge.

Cross-correlation analysis together with spectrograms enabled identification of the time shift between single phenomena. Results for discharges in the central (Nitrianska Streda) and lower (Nove Zamky) parts of the catchment are shown in Fig. 8a and 8b, for NAOi and the air temperature in the central part of the basin in Fig. 8c and 8d, for NAOi and the areal precipitation in Fig. 8e and 8f. The last two figures (8g and 8h) show the clear relationship between discharges in Nove Zamky and solar activity within the 11-year periodicity as expressed in Wolf relative numbers.

Cross-correlograms applied on groundwater parameters showed the clear correlation between the winter NAOi (FM: February-March), according to Hurrell (Hurrell and Deser, 2009),

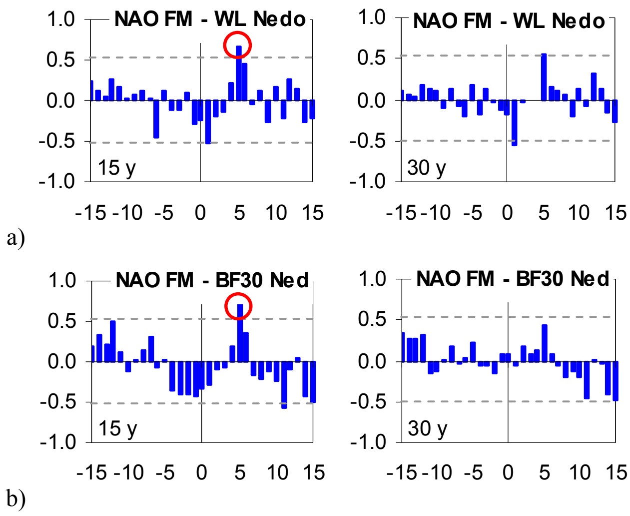

Fig. 9. Cross-correlation between: a) winter NAOi and groundwater heads WL; b) winter NAOi and base flow BF30; Nedozery station.

and the groundwater head (WL) in Nedozery with the one and five-year lag periods (Fig. 9). Results obtained for the last 15-year series are better than those for the last 30-year period. Although the latter are more objective, both are statistically significant on the significance level of 0.05. Results obtained for BF30 were statistically significant at the statistical significance level of 0.05 for the last 15-year period. Results for Q_{97} were less representative, except of Nove Zamky profile, where correlation for the last 15-year period was also statistically significant at the same level of 0.05 (95%).

There is a negative correlation between the winter NAOi according to Hurrell and discharges and groundwater heads within the one-year time shift, as evident in Fig. 9.

High cross-correlation can be used for prediction of discharges and groundwater heads using the winter NAOi according to Hurrell. Similar results were also achieved for Q_{97} for both the winter and summer periods. It means that in the years with the high Hurrell winter NAOi, drought can be expected. Because of autocorrelation pattern, this could be used also for prediction in one year ahead.

Coherence analysis enables us to express the measure of correlation between two time series. An important correlation at the 0.01 significance level was proven between air temperature and the NAOi for frequencies at 3.6 and 11 years. The following correlations were also documented (1) between precipitation periodicity and the NAOi for 2.8 years and for 3.6 years (significant at 0.05 level), (2) between precipitation and SOi for the frequency of 2.4 years (significant at 0.01), (3) between discharges at Nitrianska Streda in the central part of the basin and NAO index for the 2.8-year cycle (significant at 0.01), and for the 3.6-year cycle the significance was 0.05. No correlation between NAOi and SOi was found.

Similar periodicities for 3.6 years were found by Pekarova et al. (2010) for Bela River discharges, while periodicities for 2.35 and 3.6 years were documented by Rysava et al. (2008) for precipitation, Hron River discharges and groundwater heads in the Zvolen Basin in Slovakia. The 3.6-year cycle has already previously been documented for the SO, NAO and AO winter index series (Pekarova et al., 2010).

Results for relation of local hydrometeorological data to SOi were less expressive in all cases.

CONCLUSIONS

The results proved the influence of global climate drivers on precipitation, air temperature, discharges, baseflow and groundwater heads in the study area of the Nitra River Basin. The influence of solar activity was proved by the results of auto-correlograms for discharge time series during the1931–2005 period which showed very distinct 11-year and 21-year periodicity. The same is true for the groundwater head and base flow data. As well as having these periodicities, precipitation data also exhibited a 14-year cycle. Spectrogram analysis documented 11-year, 7.8-year, 3.6-year and 2.4-year periods in discharge, precipitation and air temperature time series. The 7.8- and 3.6-year cycles were also identified in the long-term series of North Atlantic Oscillation and Southern Pacific Oscillation indexes. The cycle determined at 2.3–2.4-year is most likely connected with the Quasi-biennial oscillation. Finally, the close negative correlation between the North Atlantic Oscillation winter index according to Hurrell and the local hydrological surface and groundwater parameters in the Nitra River Basin can confidently be utilized for their prediction within the same year and also for one year in advance.

Acknowledgement. The research supports the work of the UNESCO-IHP VII FRIEND-Water programme. The contribution was prepared within the solution of the FP6 Watch project (contract No.036946), VEGA grant No. 1/1327/12, and APVV-015-10.

REFERENCES

Alexandersson, H., 1986. A homogeneity test applied to precipitation data. J. Climate, 16, 6, 661–675.

Alexandersson, H., Moberg, A., 1997. Homogenization of Swedish temperature data. Part I: Homogeneity test for linear trends. J. Climate, 17, 1, 25–34.

Angulo-Martínez, M., Beguería, S., 2012. Do atmospheric teleconnection patterns influence rainfall erosivity? A study of NAO, MO and WeMO in NE Spain, 1955–2006. J. Hydrol., 450–451, 168–179.

Burt, T.P., Howden, N.J.K, 2013. North Atlantic Oscillation amplifies orographic precipitation and river flow in upland Britain. Water Resour. Res., 49, 6, 3504–3515.

De Linage, C., Kim, H., Famiglietti, J.S., Yu, J.-Y., 2013. Impact of Pacific and Atlantic sea surface temperatures on interannual and decadal variations of GRACE land water storage in tropical South America. Journal of Geophysical Research D: Atmospheres, 118, 19, 10811–10829.

Fendeková, M., Fendek, M., 2012. Groundwater drought in the Nitra River Basin – identification and classification. J. Hydrol. Hydromech., 60, 3, 185–193.

Fritier, N., Massei, N., Durand, A., Laignel, B., Deloffre, J., Fournier, M., 2010. Links between NAO fluctuations and interannual variability of precipitation in the Seine River watershed. In: Servat E., Demuth S., Dezetter A., Daniel T. (Eds): FRIEND 2010: Global Change: Facing Risks and Threats to Water Resources. IAHS Publication No. 340, IAHS Press, Wallingford, pp. 576–583.

Gregor, M., 2011. Možnosti využitia softvérového balíka HydroOffice 2010 pre hydrológov a hydrogeológov. [The usage possibilities of HydroOffice 2010 software for hydrologists and hydrogeologists]. Acta Geol. Slovaca, 3, 1, 95–104. (In Slovak with English Abstract and Summary.)

Hannaford, J., Buys, G., Stahl, K., Tallaksen, L.M., 2013. The influence of decadal-scale variability on trends in long European streamflow records. Hydrol. Earth System Sci., 17, 7, 2717–2733.

Herrmann, A., Egger, F., 1980. Das Abflussverhalten im Flussgebiet der Isar unter Anwendung der Fourier-Analyse. [Runofff behaviour in the Isar Basin using the Fourier analysis]. Deutsche Gewässerkundliche Mitteilungen, 24, 3–4, 81–86. (In German.)

Hurrell, J.W., Deser, C., 2009. North Atlantic climate variability: The role of the North Atlantic Oscillation. J. Mar. Syst., 78, 28–41. DOI:10.1016/j.jmarsys.2008.11.026.

Hurrell, J., National Center for Atmospheric Research Staff (Eds.), 2013. The Climate Data Guide: Hurrell North Atlantic Oscillation (NAO) Index (station-based). Last modified 02 December 2013. Retrieved from https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based

Institute of Hydrology, 1980. Low flow studies. Res. Rep. 1, Institute of Hydrology, Wallingford, UK, 41 p.

Landscape Atlas of the Slovak Republic, 2002. Ministry of the Environment of the Slovak Republic, Bratislava, 344 p.

Lavers, A.D., Prudhomme, C., Hannah, D., 2010. Influence of large scale climatic circulation on precipitation and river discharge for a selection of British catchment. In: Servat, E., Demuth, S., Dezetter, A., Daniel, T. (Eds.): FRIEND 2010: Global Change: Facing Risks and Threats to Water Resources. IAHS Publication No. 340, IAHS Press, Wallingford, pp. 629–636.

Machlica, A., Fendekova, M., Fendek, M., 2010. Modeling of groundwater runoff parameters development in different geological conditions. Acta Geologica Slovaca (AGEOS), 2, 2, 103–112.

Pekarova, P., Pekar, J., 2007. Teleconections of inter-annual streamflow fluctuation in Slovakia with Arctic Oscillation, North Atlantic Oscillation, Southern Oscillation, and Quasi-Biennial Oscillation phenomena. Advances in Atmospheric sciences, 24, 4, 655–663.

Pekarova, P., Miklanek, P., Pekar, J., 2003. Spatial and temporal runoff oscillation analysis of the main rivers of the world during the 19th–20th centuries. J. Hydrol., 274, 62–79.

Pekarova, P., Miklanek, P., Pekar, J., 2006. Long-term trends and runoff fluctuations of European rivers. In: Demuth, S., Gustard, A., Planos, E., Scatena, F., Servat E. (Eds.): FRIEND 2006: Climate Variability and Change - Hydrological Impacts. IAHS Publication No. 308, IAHS Press, Wallingford, pp. 520–525.

Pekarova, P., Miklanek, P., Skoda, P., Pekar, J., Pacl, J., 2010. Multi-annual discharge variability and trend analyses of the Bela River (Slovakia) in 1895–2006. In: Herrmann, A., Schumann, S. (Eds.): Status and Perspectives of Hydrology in Small Basins. IAHS Publication No. 336, IAHS Press, Wallingford, pp. 59–64.

Rysava, Z., Fendekova, M., Pekarova, P., 2008. Rezim hladiny podzemnej vody v casti Zvolenskej kotliny medzi Banskou Bystricou a Zvolenom. [Groundwater level regime in the part of Zvolen Basin between Banska Bystrica and Zvolen]. Podzemna voda, 14, 2, 159–171. (In Slovak.)

Saris, F., Hannah, D.M., Eastwood, W.J., 2010. Changes in precipitation and river flow in northern Turkey: Associations with the North Atlantic Oscillation. In: Servat, E., Demuth, S., Dezetter, A., Daniel, T. (Eds.): FRIEND 2010: Global Change: Facing Risks and Threats to Water Resources. IAHS Publication No. 340, IAHS Press, Wallingford, pp. 568–575.

Stepanek, P., 2003. AnClim - software for time series analysis and homogenization. http://www.climahom.eu/software-solution/anclim

Stepanek, P., Zahradnicek, P., Skalak, P., 2009. Data quality control and homogenization of air temperature and precipitation series in the area of the Czech Republic in the period 1961–2007. Adv. Sci. Res., 3, 23–26. http://www.adv-sci-res.net/3/23/2009/asr-3-23-2009.pdf

Tallaksen, L.M., Van Lanen, H.A.J. (Eds.), 2004. Hydrological drought: processes and estimation methods for streamflow and groundwater. Developments in Water Science, 48, The Netherlands, Amsterdam, Elsevier Science, 579 p.

Van Loon, A.F., Van Lanen, H.A.J., Hisdal, H., Tallaksen, L. M., Fendekova, M., Oosterwijk, J., Horvat, O., Machlica, A., 2010. Understanding hydrological winter drought in Europe. In: Servat, E., Demuth, S., Dezetter, A., Daniel T. (Eds): FRIEND 2010: Global Change: Facing Risks and Threats toWater Resources. IAHS Publication, No. 340, IAHS Press, Oxfordshire, pp. 189–197.

Wanner, G., Brönnimann, S., Casty, C., Gyalistras, D., Luterbacher, J., Schmutz, C., Stephenson, D.B., Xoplaki, E., 2001. North Atlantic oscillation – concepts and studies. Surv. Geophys. 22, 321–382. http://www.climate-impacts.ch/_DGRefPubs/Wann_01_SG_321.pdf

Wrzesiński, D., 2011. Regional differences in the influence of the North Atlantic Oscillation on seasonal river runoff in Poland. Quaestiones Geographicae, 30, 3, 127–136.

Received 12 April 2013
Accepted 5 June 2014