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Multi-Temporal Analysis of Mean Annual and Seasonal Stream Flow Trends, Including Periodicity and Multiple Non-Linear Regression

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Abstract Global warming affects the hydrological cycle and the long-term water budget of river basins. Flow variations have been noticed in the Danube River Basin, especially in its south-western parts where a downward trend in mean annual flows has been prevalent in the past several decades. Time series of mean annual and seasonal flows of the Sava River at hydrological stations Sremska Mitrovica and Zagreb are analysed in this paper. The trend is assessed with the Mann-Kendall test including the effect of serial correlation. Additionally, the trends are assessed in the multi-temporal framework. It is concluded that the long-term periodicity of annual flows has a considerable impact on the time series trend. Long-term component with cycles of 40 years in mean annual flows are detected by the time series analysis in frequency domain. Regression analysis showed a significant correlation between mean annual flows of the Sava River and annual precipitation, mean annual atmospheric pressure and air temperatures at meteorological station Ljubljana, as well as with the North Atlantic Oscillation (NAO) Index.

Keywords Multi-temporal trend analysis · Mann-Kendall test · Periodicity · Multiple non-linear regression · Sava river

1 Introduction

Energy exchange between the Sun, the Earth and the atmosphere is the main driver of the processes that take place in the atmosphere and at the Earth's surface, such as evaporation and runoff. The solar radiation budget is developed at the top of the atmosphere. Outgoing solar

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top-of-atmosphere radiation excludes the heat absorbed by the ground surface and constitutes the difference between the incoming and the reflected solar radiation. The balance of the incoming and outgoing energy at the top of the atmosphere, called the net flux, is 0.6 Wm^{-2} (Hansen et al. 2011; Loeb et al. 2012). This difference is reflected in the overall heat budget of the planet Earth and the atmosphere in a way that leads to changes in the climate formation process. It should be noted that the energy budgets are not unconditionally stable, such that decadal-scale changes are possible (Wong et al. 2006; Wild et al. 2008). Research conducted through measurements of incoming heat at the ground surface has shown an upward trend in the past several decades in the range of+(1.7–2.7) Wm^{-2} (Wild et al. 2008; Wang et al. 2009; Prata 2008).

Increasing heat at the Earth's surface results in increasing mean global temperatures. The Fifth IPCC Assessment Report (IPCC 2013) discusses rising mean global air temperatures during the period from 1880 to 2012. The conclusion is that the complete period exhibits a significant upward trend of mean annual air temperatures, and that the greatest increase is noted from 1979 to 2012, with a 0.25–0.27 °C increment per decade (Jones et al. 2012; Rohde et al. 2013).

In the northern hemisphere, above latitude of 30°, an upward trend of annual precipitation sums has been noted in the period 1901–2008 (IPCC 2013). Contrary to air temperatures, the increasing precipitation trend indicates a broader range of 1.44–3.23 mm by decade (Smith et al. 2012; Becker et al. 2013).

Forty greenhouse gases emission scenarios have been defined for IPCC purposes (Nakićenović and Swart 2000). In the Danube Study (ICPDR 2012), scenarios A1B and A2 were selected. According to scenario A1B, mean annual air temperatures in the Sava River Basin would be higher for 0.5–2 °C in 2050, and for 2.5–4 °C at the end of 2,100. It should be noted that this climate scenario projects a temperature increase in the Danube River Basin with a northwest-to-southeast gradient. Projections under scenario A2 show even higher increases in mean annual temperatures. Regional climate models show increasing annual precipitation sums in northern Europe and downward trends in southern Europe according to A1B and A2 scenarios. In addition to the increasing precipitation sums, the northern part of the Danube River Basin is expected to be affected by more severe precipitation events (ICPDR 2012). The expected increase in the winter months is about +20 %, albeit with considerable variation, such that certain regions can expect+5 % and others+35 %. The anticipated precipitation decrease in southern Europe is in the range from−25 % to−45 %. In central Europe the decrease will be relatively moderate and is expected to be about−20 %. The Alpine region is divided into a wet north and a dry south, such that the south-eastern part of Austria would be in the dry zone.

In past assessments of hydrological and meteorological parameters only a few studies addressed the variation in hydrological parameters as a function of meteorological parameters. Krasovskaia (1996) and Krasovskaia and Sælthun (1997) examined the sensitivity of the hydrological cycle to air temperatures, applying the entropy concept. She conducted her research in northern Europe and found that changes in the hydrological cycle result from a slight air temperature increase and that the changes were primarily reflected in snow formation and melting processes. In the same manner, using the entropy approach, Bower et al. (2004) defined the index of sensitivity to meteorological parameters in the UK and classified seven river regimes. Bouwer et al. (2008) used the linear regression equation with previously normalized hydrological time series to determine the effect of meteorological parameters on time series of annual flows. The correlation coefficient between hydrological and meteorological time series was introduced as a measure of sensitivity. The effect of the global air temperature increase on the hydrological regime was studied by Renner and Bernhofer (2011) using data from 27 hydrological stations in Saxony (Germany). They concluded that all stations have exhibited changes in hydrological characteristics since 1988, and that the average temperature during the hydrological year occurred four days earlier and was 1 °*C* higher. These changes affected river basin runoff as a result of the rising limb of the hydrographs appearing one to three weeks earlier.

The objective of the present research is to determine trends in mean annual and seasonal flows of the Sava River, a tributary to the Danube River, and to establish a relationship between hydrological and meteorological time series. Annual and seasonal flow trends are analysed with the Mann-Kendall test using the multi-temporal approach. This paper also aims at showing that selection of a time interval is important for trend analysis due to the long-term periodicity in time series. Therefore this study is undertaken to define the long-term periodic component of the flows and to establish its effect on the trend.

River flow time series represent the outcome of the atmospheric events in a basin and the characteristics of the basin, such that any changes in these parameters are reflected in the hydrological process (i.e. river flow). It is assumed that the hydrological system can be represented as a simple system using a water balance model (Gudmundsson et al. 2011):

$$\frac{dS}{dS} = P - E - Q, \tag{1}$$

where dS/dt is the change in the reservoir volume (snow, soil moisture, surface water, groundwater, lakes), P is the precipitation, E is actual evapotranspiration and Q is the river flow. Evapotranspiration is generally not measured directly, but derived from air temperature, water vapour pressure, wind speed and other parameters. Air temperatures are used in the present research to define the effect of evapotranspiration on annual and seasonal flows. In addition, the effect of atmospheric pressure and North Atlantic Oscillation (NAO) Index on the river flow is also investigated. In this paper, we applied the multiple non-linear regression in order to describe the relationship between hydrological and meteorological time series.

2 Methods

2.1 Trend Analysis

River trend analyses conducted worldwide show that the Earth's northern hemisphere generally exhibits upward flow trends, while certain parts of Europe, such as southern Europe, exhibit downward trends (Milly et al. 2005; Bates et al. 2008). Birsan et al. (2005) conducted a trend analysis of 48 watersheds in Switzerland under natural streamflow conditions. They detected significant upward trends in winter and spring, and downward trends in summer. Stahl et al. (2010) studied long-term flow variations in 411 natural river basins in Europe. The results show that the downward annual flow trends are present in south-east Europe, while the rest of Europe exhibits upward trends. Hannaford et al. (2013) showed that the long-term flow component results in periodic features of annual and monthly flow trends. Their research was conducted over 132 basins in northern and central Europe.

Many trend analyses are based on the well-known non-parametric Mann-Kendall trend test (e.g. Douglas et al. 2000). This test is based on the Kendall's statistic S, computed as follows (Kendall 1962; Douglas et al. 2000):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\left(Q_i - Q_j\right), \tag{2}$$

where Q is the mean annual flow at time steps i and j, n represents the sample size, and $sign$ (.) is equal to $+1$ if $Q_i > Q_j$ and -1 otherwise. If $S > 0$, the time series has a downward trend and if $S<0$, then there is an upward trend. For an independent data sample without tied values, the mathematical expectation and variance of S are:

$$E(S) = 0,\quad Var(S) = \frac{n(n-1)(2n+5)}{18} = \sigma^2 \tag{3}$$

If tied values are present in the sample, *Var* (*S*) is corrected as follows:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(i)(i-1)(2i+5)}{18}, \tag{4}$$

where t_i is the number of groups of i tied values in the time series. If there is only one pair of equal values in the time series, then $i=2$ and $t_i=1$.

2.1.1 Effect of Serial Correlation on Trend Analysis

A trend analysis can be misleading if the long-term flow fluctuations are disregarded; for a reliable trend assessment several full time-series cycles are needed. Also, spatial correlation can create an additional problem, leading to a considerable reduction of data samples for trend assessment (Douglas et al. 2000). Khaliq et al. (2009) described several ways to remove serial correlation from hydrological time series, such as: (1) pre-whitening, (2) variance correction and (3) block bootstrap approach. Conversely, Yue and Wang (2004) dealt with the serial correlation problem by applying a modified Mann-Kendall test that uses the effective sample size in calculating the test statistic.

The variance correction approach (2) is selected here, which assumes that a correlated time series is comprised of N data, where N^* ($<N$) of them are uncorrelated. Hamed and Rao (1998) and Yue and Wang (2004) proposed variance correction of the Mann-Kendall S statistic using the effective size of the time series N^* by multiplying *Var* (*S*) with a correction factor CF:

$$\begin{aligned} Var^*(S) &= CF \cdot Var(S), \\ CF_1 &= 1 + \frac{2}{N(N-1)(N-2)} \sum_{\tau=1}^{N-1} (N-1)(N-1-\tau)^{(N-1-2)} r_\tau^R, \\ CF_2 &= 1 + 2\sum_{\tau=1}^{N-1} (1-N/\tau) r_\tau, \end{aligned} \tag{5}$$

where CF_1 is the variance correction factor according to Hamed and Rao (1998), CF_2 according to Yue and Wang (2004), and r_τ and r_τ^R are the autocorrelation coefficients for lag τ of time series Q and of the time series ranks, respectively. Khaliq et al. (2009) recommend the variance correction approach as it is applicable for autoregressive serial dependence not only of lag 1 (i.e. for the AR (1) process), but also for higher lags as well.

The Mann-Kendall test statistic z_s for the time series is calculated as:

$$z_s = \begin{cases} \frac{S-1}{\sigma}, & S > 0 \\ \frac{S+1}{\sigma}, & S < 0 \\ 0, & S = 0 \end{cases} \tag{6}$$

and follows the standard normal distribution (Kendall 1962). For z_s<1.96, which corresponds to a confidence level of 95 % or the significance level of 5 %, the hypothesis H_0 on the absence of a monotonic trend in mean flows is not rejected. Otherwise, for z_s>1.96 the alternative hypothesis H_1 is that there is a trend in the series.

2.1.2 Multi-Temporal Trend Analysis

Many trend analyses of hydrological time series involve trend assessment using all available data from the first to the last year of the record. The multi-temporal approach is an alternative method for trend assessment, which involves trend detection on a range of the sub-series within the available record. McCabe and Wolock (2002) discussed time series trend visualization by using the Kendall's tau non-parametric correlation statistic for trend assessment. This approach has been followed to analyze annual maximum flow trends in Germany (Petrow and Merz 2009) and Switzerland (Schmocker-Fackel and Naef 2010). Hannaford and Buys (2012) used the multi-temporal approach in which they introduced the length of the time window as a new parameter in the trend analysis. They applied this approach on long flow series (1932–2004) from northern and central Europe. Hannaford et al. (2013) also assessed trends with the Mann-Kendall test in mean and maximum annual flows by applying the multi-temporal approach to a large number of small basins in Europe. They grouped the flow time series according to the basins and regions, and then standardized the time series for each group. In addition, they applied the LOESS method to smooth the standardized series. This approach showed that the long-term fluctuations of annual flows have a considerable effect on the trend and its direction.

Starting from the above mentioned experiences, the stations considered in the present study are grouped according to the river for which the flow data is standardized. The standardized series Z is the average of a group of m stations and from the sample ($Q_1, \ldots, Q_N$) of size N:

$$Z_j = \frac{1}{m}\sum_{k=1}^{m}\frac{Q_{j,k}-\overline{Q}_k}{\sigma_{Q_k}}, \quad j = 1, 2, \ldots, N \tag{7}$$

where $Q_{j,k}$ is the mean annual flow at station k in the j-th year (j=1,2,…,N), $\overline{Q}_k$ is the long-term mean flow at station k and σ_{Qk} is the standard deviation of annual flows at station k.

Hannaford et al. (2013) applied the trend analysis to the standardized Z series using the moving window approach by including all possible start/end year combinations. In this study the time series is divided into 10 segments of equal length and the trends are calculated for the sub-series created by starting from a different segment and then by combining a different number of subsequent segments (Fig. 1). In the first step (i=1), the trend is first calculated for the sub-series comprised of the first segment (from year 1 to year N/10). The trend is then assessed for the sub-series combined from the first two, three, etc. segments (i.e. sub-series span from year 1 to year 2N/10, from year 1 to year 3N/10, etc. and finally from year 1 to year

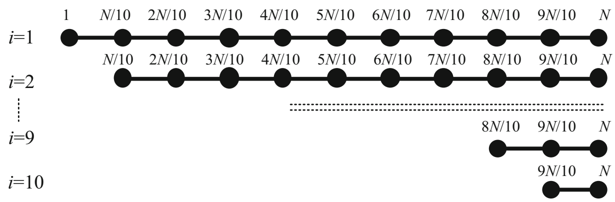

Fig. 1 Time series trend calculation scheme with the multi-temporal approach

N). In the second step (i=2), the trend analysis starts from the second segment, and the sub-series span from year N/10 to year 2N/10, from year N/10 to year 3N/10, etc. and finally from year N/10 to year N. The procedure is repeated until the tenth step (i=10), in which the last sub-series spanning from year 9N/10 to year N is assessed. In such a way, all combinations of the start/end years in the N/10 year increments are considered.

The Mann-Kendall test statistic is calculated for the standardized series Z of the Sava River mean annual flows for all sub-series from the start to the end of the period 1926–2005. The minimum sub-series length is 8 years and the maximum length is 80 years. Trends in all sub-series are considered, although the tests are generally less reliable for shorter periods (Hannaford et al. 2013).

2.2 Long-Term Periodicity

In addition to the multi-temporal trend analysis, there is a need to look into the long-term variability of the mean annual and seasonal flows. Many studies address the long-term oscillations in mean annual flows. Pekarova et al. (2003; 2006) have shown that there is a regular interchange of long-term dry and wet periods on major European rivers. They identified long-term cycles of 13.5 years and 28–29 years in the annual flows, and a shift in these periods of several years between northern and western/central Europe. Labat (2006) also focused on the long alternating dry and wet periods and found several such periods with lengths of 4–8 years, 14–16 years, 20–25 years and 30–40 years. Stojković et al. (2012) analyzed the long-term cycles in the Danube River basin and concluded that the length of cycles is between 16.4 and 42 years.

The long-term oscillations in time series are analysed by the Fourier transformation (Yevjevich 1972). This approach is the main technique for identifying significant harmonics of known cycle lengths and for testing the unknown cycle lengths.

The periodic component Z_P of a time series is represented as follows (Salas et al. 1980):

$$Z_P(j) = \sum_{i=1}^{q} \left[a_i \sin(2\pi f_i j) + b_i \cos(2\pi f_i j)\right], \tag{8}$$

where a_i and b_i are the Fourier coefficients (amplitudes of sine and cosine waves), f_i is frequency, j is time step, while q is the number of significant harmonics. The coefficients a_i and b_i are determined by Fourier transformation as:

$$a_i = \frac{2}{n}\sum_{j=1}^{n} Z_i \cos(2\pi f_i j),\; b_i = \frac{2}{n}\sum_{j=1}^{n} Z_i \sin(2\pi f_i j), \tag{9}$$

where n is the sample size of the time series Q_j (j=1,2…,n) and Z_j is the standardized series from Eq. (7). The Fourier coefficients derived from Eq. (9) are then used to compute the periodogram intensity I for frequencies f_i (Salas et al. 1980):

$$I(f_i) = \frac{n}{2}\left(a_i^2 + b_i^2\right),\; f_i = \frac{i}{n},\quad i = 1, 2, n/2 \text{ or } (n-1)/2 \tag{10}$$

Bartlett (1963) and Daniell (1946) identified three possibilities for a simpler periodogram interpretation: (1) smoothing the periodogram intensity I, (2) truncating and smoothing the autocorrelation function, and (3) smoothing the time series Z. The last alternative is chosen in this study with an aim to identify the long-term periodic component and remove the short-term periodicity and the random component from the series. For this purpose, the LOESS local regression technique is applied (Stojković et al. 2013).

2.3 Multiple non-Linear Regression

In this study, a multiple regression model is established between standardized annual flow series of the Sava River as the dependent variable, and annual precipitation sum *P*, mean annual air temperature *T*, mean annual atmospheric pressure *A*, *P* at meteorological station (m.s.) Ljubljana and the NAO index as the independent variables for the period from 1926 to 2005. The analysis is also performed for the four seasons, so that the model includes seasonal values of the parameters. The regression models are defined as (Prohaska 2006):

$$U(Q) = \alpha_1 \cdot U_1(P) + \alpha_2 \cdot U_2(T) + \alpha_3 \cdot U_3(AP) + \alpha_4 \cdot U_4(NAO) \tag{11}$$

where *U* (.) indicates a transformation performed to normalize the regression variables Prohaska (2006); *U* (*Q*) is the normalized Sava River annual or seasonal flow, U_1 (*P*) is the normalized annual or seasonal precipitation sum at m.s. Ljubljana, U_2 (*T*) is the normalized mean annual or seasonal air temperature at m.s. Ljubljana, U_3 (*AP*) is the normalized mean annual or seasonal atmospheric pressure at m.s. Ljubljana, and U_4 (NAO) is the normalized annual or seasonal NAO index. Since the regression uses the normalized variables, the multiple regression coefficients α_k (k=1 to 4) are equal to correlation coefficients between the normalized values of the dependent and independent variables. The regression coefficients are computed using the procedure described by Prohaska (2006).

3 Results

The mean seasonal and annual flows of the Sava River at hydrologic stations (h.s.) Zagreb and Sremska Mitrovica from 1926 to 2005 are analysed in this paper to demonstrate the proposed methodology. The normalized series *Z* (Eq. 7) derived from the flow time series are shown in Fig. 2 together with the smoothed series Z_{Loess} obtained by the LOESS method with the smoothing window of 16 time steps.

The smoothed series in Fig. 2 indicate presence of a long-term periodic component in annual and seasonal flows. Contribution of the smoothed series to the variance of the original time series is given with the fraction (Gudmundsson et al. 2011):

$$\Phi_Z = \frac{\sigma^2_{Z_{loess}}}{\sigma^2_Z}, \tag{12}$$

where $\sigma^2_{Z_{loess}}$ is the variance of the smoothed standardized flow series, while σ^2_Z is the variance of the observed standardized flow series. The variance fraction of smoothed annual flows *Z* (*Q*) is 36.2 %; for winter flows Z (Q_{I}) it is 35.2 % and 33.2 % for the summer flows Z (Q_{III}). The greatest variance fraction of smoothed flows of 37.8 % is noted for the spring flows Z (Q_{II}), and the smallest of 28.3 % for the autumn flows Z (Q_{IV}). Greater smoothed time series variance fraction corresponds to greater contribution of the deterministic components, i.e. trend and long-term periodicity. The remaining part of the time series represents a stationary stochastic component with a strong autocorrelation (Stojković et al. 2013). In this paper, we analyse the trend and long-term periodicity as the deterministic components of the annual and seasonal flows.

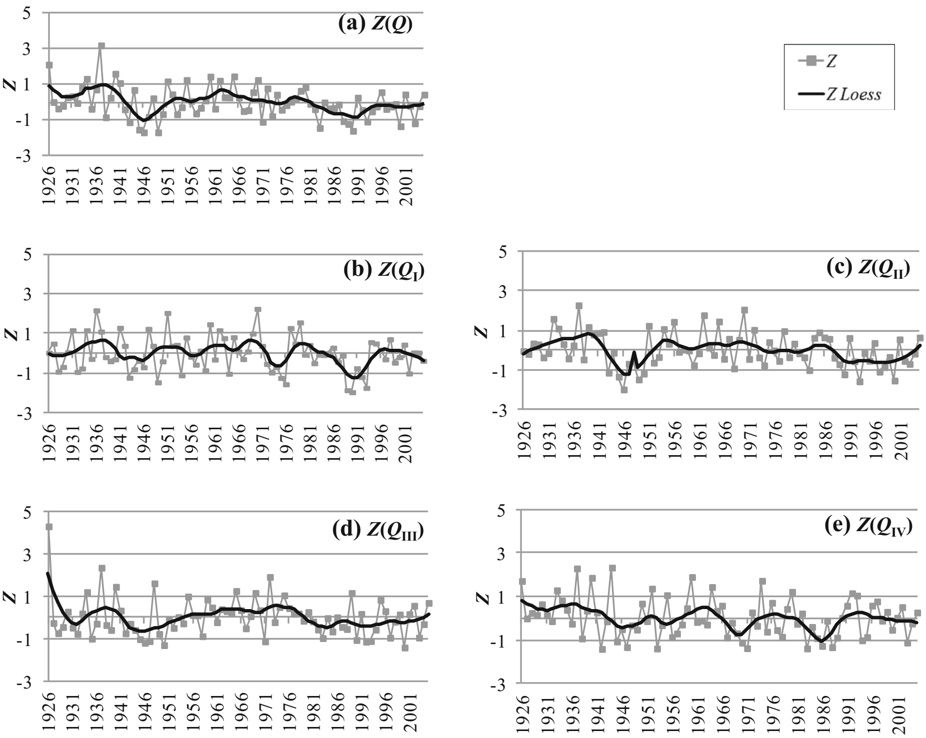

Fig. 2 The standardized series *Z* and the smoothed series Z_{Loess} of mean annual and seasonal flows of the Sava River: (**a**) annual flow *Z* (*Q*), (**b**) winter flow $Z\ (Q_{\mathrm{I}})$, (**c**) spring flow $Z\ (Q_{\mathrm{II}})$, (**d**) summer flow $Z\ (Q_{\mathrm{III}})$, and (**e**) autumn flow $Z\ (Q_{\mathrm{IV}})$

3.1 Trend in Annual and Seasonal Flows

The trend in the annual and seasonal flows is assessed with the Mann-Kendall test, first without taking the serial correlation effect into account and by calculating variance of the *S* statistic according to Eq. (4), and then by applying the serial correlation correction CF_2 in Eq. (5) according to Yue and Wang (2004). Table 1 shows the trend test results for the annual and seasonal flow time series.

The results shown in Table 1 indicate that the annual flow series exhibit a significant downward trend at the 5 % significance level since $z_s>1.96$. When the correction for serial correlation is included, the trend in annual flows is not significant. All seasonal flows have

Table 1 Trend in the standardized annual and seasonal flows of the Sava River: the standard Mann-Kendall test statistic z_s and statistic $z_{s,corr}$ with variance corrected for serial correlation

Season	z_s	$z_{s,corr}$
Annual	2.039	1.855
Winter	0.935	0.825
Spring	0.724	1.572
Summer	0.253	0.269
Autumn	1.433	1.431

positive values of z_s which correspond to downward trends, but these trends are not significant at the 5 % significance level.

Contrary to the standard trend analyses in which the complete available time series is assessed, the alternative multi-temporal approach uses the sub-series of different start/end combinations and different lengths. The timeline of the standardized annual and seasonal flows of the Sava River from 1926 to 2005 is divided into ten segments of 8 years each and combined into the sub-series as in Fig. 1. Figure 3 shows the results of the multi-temporal Mann-Kendall test; the shades of grey indicate values of the z_s test statistic for the sub-series starting from the segment specified on the x-axis and ending with the segment specified on the y-axis. Due to small sample sizes when combining just a few segments, the time series trend is analysed without the effect of serial correlation.

The graphical presentation of the z_s statistic in Fig. 3 for different sub-series suggests a periodic trend pattern. Significant trends in mean annual and seasonal flows are shown in Fig. 3 in framed areas where the H_1 hypothesis (trend is present) is adopted at the 5 % significance level. The significant downward trends of annual and seasonal flows are typical for the sub-series toward the end of the observation period, while the significant upward trends are noted at the middle of the period for annual and summer flow.

The multi-temporal trend analysis was also performed on meteorological parameters from the Ljubljana meteorological station in order to assess the effect of meteorological parameters on the Sava runoff. Annual precipitation sums, mean annual air temperatures, mean annual atmospheric pressure and NAO (North Atlantic Oscillation) index during the period 1926–2005 are analysed for trend and Fig. 4 shows the values of the z_s test statistic computed in the multi-temporal analysis for all meteorological variables.

It is evident that the annual flow trend (Fig. 4a) coincides with the annual precipitation trend (Fig. 4b). This is especially the case in the sub-series containing the last segment, which shows a pronounced downward trend. Annual air temperature trends (Fig. 4c) show the opposite

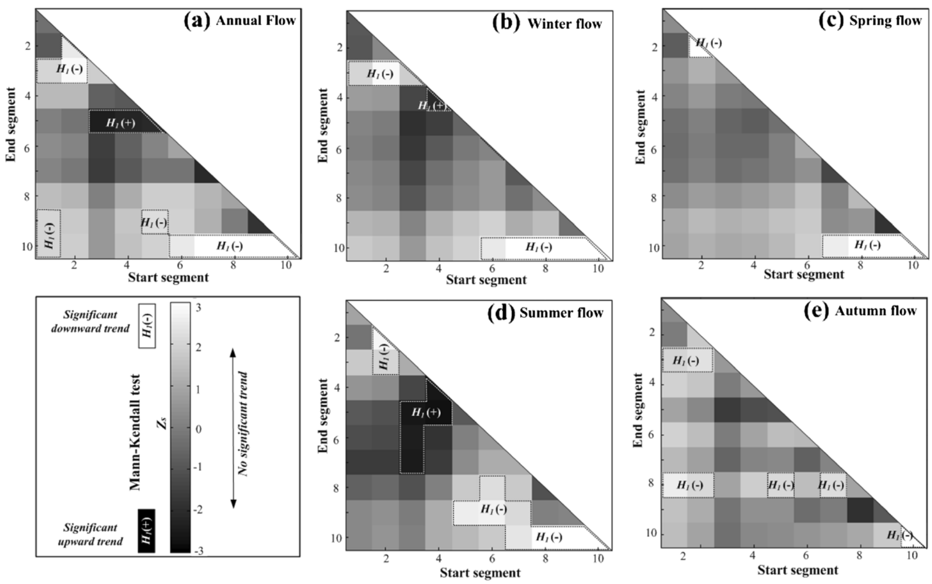

Fig. 3 Multi-temporal Mann-Kendall statistic z_s for the Sava River: (**a**) annual flow, (**b**) winter flow, (**c**) spring flow, (**d**) summer flow, and (**e**) autumn flow; greyscale coding for z_s is shown in lower left corner

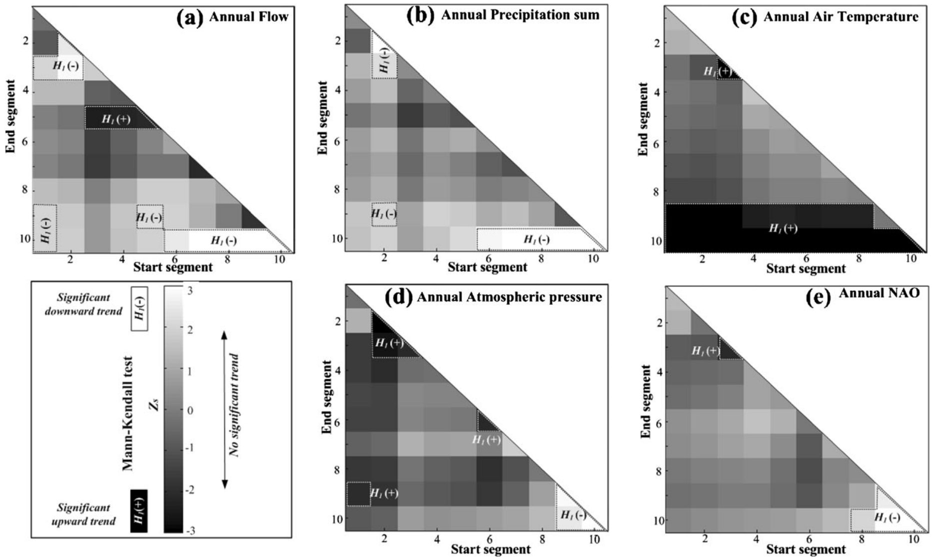

Fig. 4 The multi-temporal Mann-Kendall trend test results showing the values of the z_s statistics for: (**a**) annual flow, (**b**) annual precipitation sum, (**c**) annual air temperature, (**d**) annual atmospheric pressure, and (**e**) annual NAO index; greyscale coding for z_s is shown in lower left corner

direction compared to the annual flow trend. Strong upward temperature trend is seen in all sub-series which include the last two segments. The multi-temporal trends of the atmospheric pressure (Fig. 4d) and the NAO index (Fig. 4e) correspond to each other. The relation between the hydrological and the meteorological time series is also further analysed by using the multiple regression method.

3.2 Periodicity in Mean Annual and Seasonal Flows

From the results of the multi-temporal trend test it is evident that the trend direction and magnitude depend on the length of time series and the position of the sub-series within the whole series. Therefore, determination of the long-term periodicity in the time series is necessary in order to interpret the trends correctly. Figure 5 shows the periodograms of the original and smoothed annual and seasonal flow time series. The periodograms are determined with the Fourier transformation coefficients as given in Eq. 10. The smoothing of the time series removes the high-frequency component, so that the low-frequency component which characterizes the long-term periodicity would remain in the time series and could be detected with less difficulty.

According to Fig. 5, the annual flow time series has a significant low frequency of about 0.025 or a long-term periodicity of 40 years. A pronounced periodicity in the high frequency domain is 3.6 years. Typical long-term seasonal periodicity is 40, 16 and 8 years, while in the high-frequency domain it is from 2.4 to 5 years. It is clear that the long-term periodicity refers to long alternating wet and dry periods in the Sava River basin and that it largely determines the trend direction and magnitude in the multi-temporal analysis. The high-frequency (or short-term) component also contributes to the trend behaviour, and it was identified as a stationary stochastic component in annual and seasonal flows (Stojković et al. 2013).

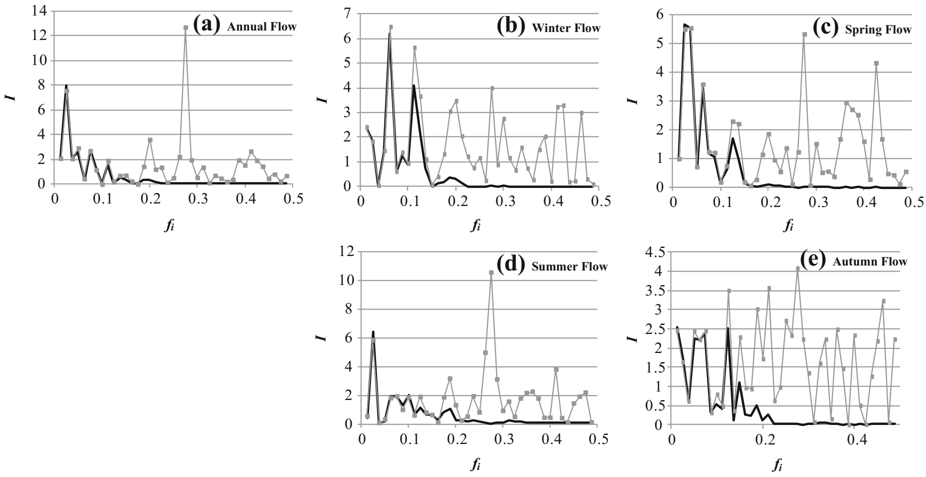

Fig. 5 Periodograms of the observed (*thin lines*) and smoothed (*thick lines*) time series of annual and seasonal standardized flows of the Sava River: (**a**) annual flow, (**b**) winter flow, (**c**) spring flow, (**d**) summer flow, and (**e**) autumn flow

3.3 Multiple non-Linear Regression of Annual and Seasonal Flows on Meteorological Parameters

In this study, the multiple non-linear regression is used in order to identify the cause-and-effect relationships between the meteorological and hydrologic parameters. A regression model is established between the standardized annual and seasonal flow time series *Z* (*Q*) of the Sava River and the corresponding meteorological parameters (*P*, *T*, *AP* and NAO) for the period from 1926 to 2005. Table 2 shows the correlation matrix between the meteorological and hydrologic parameters, the regression coefficients α and the variable weights δ which are defined as the fraction of variance explained by each variable in the regression model.

Based on the results shown in Table 2, the Sava River flow increases with an increase in precipitation and with a decrease in temperature (except in winter), atmospheric pressure, and NAO (except in spring). According to the variable weights, precipitation is the major driving force of the Sava River flows on the annual level and in summer and autumn. During the summer season, dependence of flows on air temperature is notable. Dependence of the atmospheric pressure and the flows is the strongest in the winter season. It is apparent from this table that each independent meteorological variable does affect runoff generation in at least one season. Some unexpected results can also be noticed, as is a strong negative correlation of flows with temperature in the spring season while a positive correlation would be expected during this snowmelt season. Positive correlation of the flows with the NAO index in the spring season causes is also not typical.

4 Discussion

The trends in the mean annual flows are explored in many studies and the methodology applied certainly has an impact on the final result. The results of the multi-temporal trend test demonstrate that the trend direction and magnitude depend on the length of time series and the

Table 2 Correlation coefficients, regression coefficients α and variable weights δ between the standardized annual/seasonal Sava flows $Z(Q)$ and the Ljubljana meteorological parameters; subscripts I, II, III and IV denote winter, spring, summer and autumn seasons

Correlation matrix						Regression coefficient α	Variable weight δ
	$Z(Q)$	P	T	AP	NAO		
$Z(Q)$	1.00	0.62	−0.38	−0.60	−0.40	–	–
P		1.00	−0.18	−0.48	−0.12	0.427	0.460
T			1.00	0.19	0.29	−0.208	0.138
AP				1.00	0.49	−0.289	0.304
NAO					1.00	−0.143	0.100
Correlation matrix						Regression coefficient α	Variable weight δ
	$Z(Q_I)$	P_I	T_I	AP_I	NAO_I		
$Z(Q_I)$	1.00	0.61	0.00	−0.69	−0.48	–	–
P_I		1.00	−0.01	−0.74	−0.45	0.200	0.237
T_I			1.00	0.15	0.48	0.133	0.000
AP_I				1.00	0.69	−0.480	0.648
NAO_I					1.00	−0.122	0.115
Correlation matrix						Regression coefficient α	Variable weightδ
	$Z(Q_{II})$	P_{II}	T_{II}	AP_{II}	NAO_{II}		
$Z(Q_{II})$	1.00	0.44	−0.56	−0.23	0.06	–	–
P_{II}		1.00	−0.40	−0.27	0.03	0.217	0.242
T_{II}			1.00	0.30	0.16	−0.474	0.675
AP_{II}				1.00	0.42	−0.101	0.058
NAO_{II}					1.00	0.171	0.025
Correlation matrix						Regression coefficient α	Variable weight δ
	$Z(Q)_{III}$	P_{III}	T_{III}	AP_{III}	NAO_{III}		
$Z(Q_{III})$	1.00	0.44	−0.41	−0.19	−0.09	–	–
P_{III}		1.00	−0.30	−0.38	−0.07	0.325	0.508
T_{III}			1.00	0.05	0.07	−0.309	0.456
AP_{III}				1.00	0.36	−0.036	0.024
NAO_{III}					1.00	−0.036	0.011
Correlation matrix						Regression coefficient α	Variable weight δ
	$Z(Q_{IV})$	P_{IV}	T_{IV}	AP_{IV}	NAO_{IV}		
$Z(Q_{IV})$	1.00	0.70	−0.02	−0.55	−0.18	–	–
P_{IV}		1.00	0.07	−0.51	−0.02	0.580	0.727
T_{IV}			1.00	−0.13	0.06	−0.087	0.003
AP_{IV}				1.00	0.30	−0.245	0.243
NAO_{IV}					1.00	−0.085	0.027

position of the sub-series within the whole series. Therefore, even for a seemingly long series such are the Sava River flows at h.s. Zagreb and Sremska Mitrovica, the trend test may provide misleading results. It has been shown that the trend in the annual flows specified as significant may actually not be significant if the effect of serial correlation is included in trend analysis.

The results also reveal that the trend magnitude and direction are heavily influenced by the long-term variability. It is found that the long-term periodicity of the Sava River flows involves dry and wet multi-year cycles of 40, 16 and 8 years. Significant upward flow trend is detected on both annual and seasonal level in the period 1926–1970, which represents one approximately 40-year long cycle (Fig. 2). The periodogram of the standardized flows also shows the short-term cycles in the range from 2.4 to 5 years. These short-term cycles are attributed to a stationary stochastic component of annual and seasonal flows.

The quality of the observed river flow data is also a limiting factor in trend analysis. Anthropogenic influence on river flows can also lead to the apparently significant flow trends. Moraes et al. (1998) conducted such an analysis in Brazil and showed that human activity can lead to incorrect conclusions. They found that a significant anthropogenic impact on river flow is a result of water export from the basin that led to a decreasing flow trend. Upon statistical analysis of precipitation, evapotranspiration and river flow, they also found significant increasing trends of meteorological parameters for the entire basin. Sanjay et al. (2008) demonstrated such an analysis at Harike Wetland in India and showed that exploitation of groundwater resulted in a 30 % reduction in river flows during 1990–2003.

The changing precipitation distribution over Europe is associated with the North Atlantic Oscillation, expressed by the NAO index (Bouwer et al. 2008). Many studies show that river flow variability is a result of atmospheric circulation, which affects precipitation distribution on the Earth (Hurrell 1995; Rodriguez-Puebla et al. 1998; Rimbu et al. 2002; Danilovich et al. 2007; Bouwer et al. 2008). This phenomenon potentially leads to the decreasing precipitation and mean annual flows in south-east Europe as it is shown for the Sava River through significant downward trends towards the end of the observation period. Seasonal flows of the Sava River also exhibit downward trend, but not significant at 5 % significance level. These results are in accordance with the detected downward trends in southern and eastern regions of Europe (Stahl et al. 2010). Stahl et al. (2010) determined in their analysis for the central northern European regions an opposite behaviour of the river flows in comparison to the south-east regions during 1962–2004.

The long-term periodicity of meteorological parameters is found to be an important contributor to the long-term variability of annual flows and consequently to their trends. Zhang et al. (2007) state that precipitation variations on the Earth cannot be attributed solely to atmospheric circulation; anthropogenic impacts over the past century have contributed to increased annual precipitation sums in the northern hemisphere, reduced precipitation in the tropics and elevated air humidity in the southern hemisphere. Labat et al. (2004) found correlation between global annual air temperature and runoff and suggested that an increase of 4 % in global runoff can be expected per 10C of the global temperature rise. They also warned that the global trend should be quantified on a regional scale, where they identified both upward and downward trends.

In the Sava River basin the downward trend of annual flows is accompanied with the downward trend of the annual precipitation sums and the upward trend of air temperature (Fig. 4). Such tendency is especially emphasized in the recent part of the observation period when a significant trend is detected. In addition to this, the multiple non-linear regression between the flows and the meteorological drivers showed that the process of annual and seasonal flow generation mostly depends on precipitation. The results of the regional climate models indicate that precipitation is expected decrease in southern Europe (ICPDR 2012). For the territory of Serbia, the results of the EBU-POM climate model with the A1B and A2 greenhouse gases emission scenarios show an increase in air temperatures of 2–4 °*C* and a decrease in annual precipitation sums of 13–16 *mm* up to 2100 (Djurdjević and Rajković 2010). Therefore, based on both trend assessments and climate projections, long-term downward trend of the Sava River discharge can be expected in the future. Based on the this study's results related to long-term periodicity, periodical alternations of dry and wet periods can also be expected in future that would in turn affect the trend magnitude and direction on a short-term time scale.

Estimation of the trend in hydrological time series is usually considered essential for water planning and management since it is expected to provide an outlook to future river flow tendencies. However, interpretation of the detected trends is even more important if realistic estimates of future river regime should be made. The long-term periodicity of the hydrometeorologic time series, which dictates the shifts of dry and wet multi-year periods in the basin, is seldom used as a tool for estimating tendencies of future river regimes. Importance of the long-term cycles in the Sava River basin may be illustrated by the fact that the deterministic component (annual and seasonal) explains 28.3–37.8 % of variance of the Sava River flow during the period 1926–2005. If the trend and the long-term periodic components are detected in the time series, they can be represented as a function of time and can be extrapolated into the future. This extrapolated deterministic component can then be used to prepare operational plans and strategies for water management.

5 Conclusions

A study on the long-term variability of the river flows in the Sava River basin, a tributary of the Danube River, is presented in this paper. Time series of the mean annual and seasonal flows at the hydrological stations Zagreb and Sremska Mitrovica during the period 1926–2005 are analysed for trends, long-term periodicity and dependence on major meteorological drivers and their variability. In order to avoid the effects of spatial dependence of the hydrologic data from different stations on the same river, a single time series is created by averaging the standardized flows from individual stations. The trend analysis is performed in the multi-temporal framework by means of the non-parametric Mann-Kendall test for trend detection. The standardized and unified annual and seasonal series are smoothed using the LOESS method for an easier separation of the long-term periodic component.

It has been shown that the deterministic component consisting of the trend and the long-term periodicity explains 28.3–37.8 % of the total variance of flows. The trends of mean annual and seasonal flows in the complete series are downward, but the only significant trend at the 5 % significance level is that in the annual flows. Furthermore, if the serial correlation is taken into account, even this trend is not significant. The multi-temporal trend analysis has shown that the trend direction and magnitude depend on the length of time series and the position of the sub-series within the whole series. The results indicate that the flow trends for sub-series in the period 1926–1970 are upward, and that the steepest downward trends appear for sub-series toward the end of the observation period. Therefore, the conclusions about the trend significance can be quite different depending on the period covered in the analysis. It has also been shown that the long-term periodicity affects the direction and the intensity of the trend. The multi-year wet and dry cycles of 40, 16 and 8 years are detected in the annual and seasonal flow time series.

The causal link between annual flows and meteorological parameters at the meteorological station Ljubljana within the headwater part of the basin has also been established. Comparative trend analysis in the multi-temporal framework has shown that significant downward trends of flows in the latter part of the record are accompanied by the downward trends in precipitation and significant upward trends in air temperature. Impact of the individual meteorological drivers on the Sava basin runoff via the multiple non-linear regression analysis has shown that precipitation has the greatest impact on runoff on both annual and seasonal level, while the strong impact of air temperature is seen in the spring and summer seasons. The influence of atmospheric pressure and the NAO index is significant during the winter season. Therefore, the reduction of the Sava River annual flows is attributed primarily to the precipitation reduction.

The results obtained in this study are in accordance with the projections coming from the climate modelling via global and regional climate models (GCM/RCM) under A1B and A2 greenhouse gases emission scenarios, which suggest further decrease in precipitation and an increase in air temperature in the south-east region of Europe. Inclusion of the future tendencies of river regimes into the management and planning in the water-related sectors is generally possible by application of the climate modelling outputs in combination with hydrologic models. However, by a careful analysis of the structure of the hydrometeorologic time series through trend, long-term variability and dependence of river flows of meteorological drivers, inclusion of the future tendencies into water management and planning is much more straightforward. If the trend and long-term periodicity of flows are known, it is possible to create the time-series models for the long-term projections of the deterministic component of flows. These projections can then be used to elaborate strategies for water resource management in terms of climate change.

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References

Bartlett MS (1963) Statistical estimation of density functions. Sankhya Ser A 25:245–254

Bates BC, Kundewicz ZW, Wu S, Palutikof JP (eds) (2008) Climate change and water, technical paper of the intergovernmental panel on climate change. IPCC Secretariat, Geneva

Becker A, Finger P, Meyer-Christoffer A, Rudolf B, Schamm K, Schneider U, Ziese M (2013) A description of the global land-surface precipitation data products of the global precipitation climatology centre with sample applications including centennial (trend) analysis from 1901–present. Earth Syst Sci Data 5:71–99. doi:10.5194/essd-5-71-2013

Birsan M-V, Molnar P, Burlando P, Pfaundler M (2005) Streamflow trends in Switzerland. J Hydrol 314(1–4): 312–329

Bouwer LM, Vermaat JE, Aerts JCJH (2008) Regional sensitivities of mean and peak river discharge to climate variability in Europe. J Geophys Res 113, D19103. doi:10.1029/2008JD010301

Bower D, Hannah DM, McGregor GR (2004) Techniques for assessing the climatic sensitivity of river flow regimes. Hydrol Process 18(13):2515–2543

Daniell PJ (1946) Discussion on the symposium on autocorrelation in the time series. JRoy Stat Soc 8:88–90

Danilovich I, Wrzesinski D, Nekrasova L (2007) Impact of the north Atlantic oscillation on river runoff in the Belarus part of the Baltic Sea basin. Nord Hydrol 38(4–5):413–423

Djurdjević V, Rajković B (2010) Development of the EBU-POM coupled regional climate model and results from climate change experiments. In: Mihajlovic TD, Lalic B (eds) Advances in environmental modeling and measurements. Nova Publishers, Hauppauge NY, pp 23–32. ISBN 978-1-60876-599-7

Douglas EM, Vogel RM, Kroll CN (2000) Trends in floods and low flows in the united states: impact of spatial correlation. J Hydrol 240(1–2):90–105

Gudmundsson L, Tallaksen LM, Stahl K, Fleig AK (2011) Low-frequency variability of european runoff. Hydrol Earth Syst Sci 15(9):2853–2869

Hamed KH, Rao AR (1998) A modified Mann-Kendall trend test for autocorrelated data. J Hydrol 204(1–4): 182–196

Hannaford J, Buys G (2012) Trends in seasonal river flow regimes in the UK. J Hydrol 475:158–174

Hannaford J, Buys G, Stahl K, Tallaksen LM (2013) The influence of decadal-scale variability on trends in long european streamflow records. Hydrol Earth Syst Sci 17(7):2717–2733

Hansen J, Sato M, Kharecha P, Schuckmann K (2011) Earth's energy imbalance and implications. Atmos Chem Phys 11:13421–13449

Hurrell JW (1995) Decadal trends in the north Atlantic oscillation and relationships to regional temperature and precipitation. Science 269(5224):676–679

ICPDR (2012) Danube Study – Climate Change Adaptation, Final Report. International Commission for the Protection of the Danube River, Vienna, Austria. http://www.icpdr.org/main/sites/default/files/nodes/documents/icpdr_climate-adaptation-strategy.pdf, accessed 8 July 2014

IPCC (2013) Fifth assessment report (AR5), intergovernmental panel on climate change, Geneva 2, Switzerland. http://www.ipcc.ch/report/ar5/index.shtml, accessed 8 July 2014

Jones PD, Lister DH, Osborn TJ, Harpham C, Salmon M, Morice CP (2012) Hemispheric and large-scale land-surface air temperature variations: an extensive revision and an update to 2010. J Geophys Res: Atmos 117, D05127. doi:10.1029/2011JD017139

Kendall MG (1962) Rank correlation methods, 3rd edn. Hafner Publishing Company, New York

Khaliq MN, Ouarda TBMJ, Gachon P, Sushama L, St-Hilaire A (2009) Identification of hydrological trends in the presence of serial and cross correlations: a review of selected methods and their application to annual flow regimes of Canadian rivers. J Hydrol 368(1–4):117–130

Krasovskaia I (1996) Sensitivity of the stability of river flow regimes to small fluctuations in temperature. Hydrol Sci J /J Sci Hydrol 41(2):251–264

Krasovskaia I, Sælthun NR (1997) Sensitivity of the stability of Scandinavian river flow regimes to a predicted temperature rise. Hydrol Sci J/J Sci Hydrol 42(5):693–711

Labat D (2006) Oscillations in land surface hydrological cycle. Earth Planet Sci Lett 242(1–2):143–154

Labat D, Godderis Y, Probst JL, Guyot JL (2004) Evidence for global runoff increase related to climate warming. Adv Water Resour 27(6):631–642

Loeb NG, Kato S, Su W, Wong T, Rose FG, Doelling DR, Norris JR, Huang X (2012) Advances in understanding Top-of-atmosphere radiation variability from satellite observations. Surv Geophys 33(3–4): 359–385

McCabe GJ, Wolock DM (2002) A step increase in streamflow in the conterminous united states. Geophys Res Lett 29(24):2185

Milly PCD, Dunne KA, Vecchia AV (2005) Global pattern of trends in streamflow and water availability in a changing climate. Nature 438(7066):347–350

Moraes JM, Pellegrino GQ, Ballester MV, Martinelli LA, Victoria RL, Krusche AV (1998) Trends in hydrological parameters of a southern Brazilian watershed and its relation to human induced changes. Water Resour Manag 12(4):295–311

Nakićenović N, Swart R (eds) (2000) Special report on emissions scenarios: a special report of working group III of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK

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(1–4):62–79

Pekarova P, Miklanek P, Pekar J (2006) Long-term trends and runoff fluctuations of european rivers. In: climate variability and change—hydrological impacts (proceedings of the fifth FRIEND world conference held at Havana, Cuba). IAHS Publ 308:520–525

Petrow T, Merz B (2009) Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002. J Hydrol 371(1–4):129–141

Prata F (2008) The climatological record of clear-sky longwave radiation at the Earth's surface: evidence for water vapour feedback? Int J Remote Sens 29(17–18):5247–5263

Prohaska S (2006) Hidrologija, II deo (Hydrology, Part II). Faculty of geology and mining, water resources development institute "Jaroslav Cerni", hydro-meteorological service of Serbia, Belgrade (in Serbian)

Renner M, Bernhofer C (2011) Long term variability of the annual hydrological regime and sensitivity to temperature phase shifts in Saxony/Germany. Hydrol Earth Syst Sci 15(6):1819–1833

Rimbu N, Boroneanț C, Buta C, Dima M (2002) Decadal variability of the Danube river flow in the lower basin and its relation with the north Atlantic oscillation. Int J Climatol 22(10):1169–1179

Rodriguez-Puebla C, Encinas AH, Nieto S, Garmendia J (1998) Spatial and temporal patterns of annual precipitation variability over the Iberian peninsula. Int J Climatol 18(3):299–316

Rohde R, Muller R, Jacobsen R, Perlmutter S, Rosenfeld A, Wurtele J, Curry J, Wickham C, Mosher S (2013) Berkeley earth temperature averaging process. Geoinfor Geostat: An Overview 1(2):1–13

Salas JD, Delleur JW, Yevjevich V, Lane WL (1980) Applied modeling of hydrologic time series. Water Resources Publications, Littleton, Colorado

Sanjay KJ, Sarkar A, Garg V (2008) Impact of declining trend of flow on harike wetland, India. Water Resour Manag 22(4):409–421

Schmocker-Fackel P, Naef F (2010) More frequent flooding? changes in flood frequency in Switzerland since 1850. J Hydrol 381(1–2):1–8

Smith TM, Arkin PA, Ren L, Shen SP (2012) Improved reconstruction of global precipitation since 1900. J Atmos Ocean Technol 29(10):1505–1517

Stahl K, Hisdal H, Hannaford J, Tallaksen LM, Van Lanen HAJ, Sauquet E, Demuth S, Fendekova M, Jodar J (2010) Streamflow trends in Europe: evidence from a dataset of near-natural catchments. Hydrol Earth Syst Sci 14(12):2367–2382

Stojković M, Prohaska S, Plavšić J (2012) Stohastička analiza serija godišnjih proticaja na stanicama na Dunavu (Stochastic analysis of mean annual flow series at stations on the Danube River), Proc. 16th conf. of the serbian association for hydraulic research and serbian association for hydrology, ISBN 978-86-7518-159-0, pp. 527–543 (in Serbian)

Stojković M, Prohaska S, Plavšić J (2013) Stochastic modelling of time series of mean annual discharge in the 21st century: ase study of the River Ibar. Proc. Int. conf. climate change impacts on water resources, Belgrade, Serbia, ISBN 978-86-82565-41-3, pp. 55–63

Wang K, Dickinson R, Liang S (2009) Clear Sky visibility Has decreased over land globally from 1973 to 2007. Science 323(5920):1468–1470

Wild M, Grieser J, Schär C (2008) Combined surface solar brightening and increasing greenhouse effect support recent intensification of the global land-based hydrological cycle. Geophys Res Lett 35(17), L17706. doi:10.1029/2008GL034842

Wong T, Wielicki BA, Lee RB III, Smith G, Bush KA, Willis JK (2006) Reexamination of the observed decadal variability of the earth radiation budget using altitude-corrected ERBE/ERBS nonscanner WFOV data. J Clim 19(16):4028–4040

Yevjevich V (1972) Stochastic processes in hydrology. Water Resources Publications, Fort Collins, Colorado

Yue S, Wang CY (2004) The Mann–Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Res Manag 18(3):201–218

Zhang X, Zwiers FW, Hegerl GC, Lambert FH, Gillett NP, Solomon S, Stott PA, Nozawa T (2007) Detection of human influence, on twentieth century precipitation trends. Nature 448(7152):461–465