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Trend analysis of mean and high flows in response to climate warming - Evidence from karstic catchments in Croatia

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Persistence and evolution of trends of mean and high river flows from six hydrological stations on watercourses of the Kupa River (Kupari, Kamanje), tributary Čabranka (Zamost 2), Dobra River (Stative donje, Trošmarija), Mrežnica River (Mrzlo polje) and annual precipitation on three meteorological stations (Parg, Ogulin and Karlovac) were analysed. The paper focuses on seven indicators: annual mean flow, seasonal mean flows (winter and summer mean flows), instantaneous annual maximum flow, annual and seasonal precipitation. Analysed time series range from 1951 to 2013, and the fixed period ranges from 1984 to 2013. Time series of each indicator was scaled to standardized flow anomaly and was analysed using the Mann-Kendall Z test for monotonic trend, after which it is smoothed using LOESS algorithm. The analysis was conducted for each indicator for full record, *e.g.* 1951–2013, then 1952–2013 and so on until 1984–2013. Thus, the sample size varies from 63 to 30 years. The smoothed standardized flow anomaly is easily comparable among different hydrologic stations. The standardized flow anomaly on all analysed stations for all analysed indicators shows lower mean value than long-time average after mid-1980's, when fixed period starts. Further analysis of summer and winter seasonal mean flows revealed different deviation from long-term annual flow average. Trend evolution of certain indicators was proven using Mann-Kendall Z test, by plotting Z values for each iteration of start year (1951 to 1984).

Keywords: Mann-Kendall, precipitation, river flows, trend evolution, trend persistence

1. Introduction

Change in annual runoff, frequency of extreme annual flows and regime of precipitation during a year are the evidence of human impact on the increase of greenhouse gases. These impacts that affects the global water cycle over the last 50 years have increased dramatically in the last few decades, in form of heavy precipitation, flooding and drought (Dai et al., 2004; Groisman et al., 2005; Milly et al., 2005; Gedney et al., 2006; Huntington, 2006; Barnett et al., 2008; IPCC, 2013; Murphy et al., 2013; Pavlić, 2016). Nevertheless, these evidence has not been accepted throughout the entire scientific community (Labat et al., 2004; Legates et al., 2005). However, unambiguous evidence of these events is present in the lower part of the karstic Kupa River catchment, at city Karlovac, where Kupa River floods at least one time and occasionally two times per year. These flood events occur in late summer and early winter period when heavy precipitation occur and in late winter and early summer period when together with heavy precipitation, snow starts to melt in upper part of the Kupa River catchment. Such occurrence of flood events has determined time scale of analysed parameters in this paper, such as winter and summer mean annual flows.

The fundamental step of this kind of analysis is trend analysis of flow and precipitation data and its significance (Ziegler et al., 2005; Wilby, 2006; Murphy et al., 2013). The climatological research of this and the wider area was carried out by Ugarković and Tikvić (2011), Mikuš et al. (2012), Sioutas et al. (2014) and Cindrić et al. (2015). Čanjevac and Orešić (2015) analysed trend of mean annual flows in time period from 1990 to 2009 at 53 gauging hydrological stations in Croatia, which include analysis of hydrological stations in karstic Kupa catchment. This paper focuses on narrower area in Croatia with specific hydrographical regime. Data from six hydrological and three meteorological stations from karstic Kupa catchment were considered: hydrological stations Kupari and Kamanje on Kupa River and Zamost 2 on tributary Čabranka, Stative Donje and Trošmarija on Dobra River, Mrzlo polje on Mrežnica River and meteorological stations Parg, Ogulin and Karlovac. Human impact, such as land-use, urbanization and water storage on the data from these stations is negligible.

Since there are plans to protect Karlovac City from flooding by building embankments and retention upstream of Karlovac on Korana and Kupa River, results of this paper would certainly justify this intervention

2. Research area

Research area is located in Gorski kotar, in the mountainous area of Croatian karst. The main river is Kupa River which flows downstream to Karlovac City in length of 160 km. The size of the Kupa River catchment area to the hydrological profile Kamanje is about 2,340 km^2 (Fig. 1). The whole catchment area, until hydrological profile Kamanje, is located in the karst. Downstream of the Karlovac City Kupa flows into alluvial part of its catchment which is not subject of this research. Kupa River has many tributaries of which the most important are: Čabranka, Dobra, Korana and Mrežnica. River Čabranka presents mountain river with great flow variations. River Dobra is divided into two different regions: Upper Dobra (Ogulinska Dobra) and Lower Dobra (Gojačka Dobra). It has approximate length of 105 km and catchment area of 1,010 km^2, until hydrological profile Stative Donje. Ogulinska Dobra is torrential river with fast flow changes. It was sinking in Đulin ponor until hydroelectric power plant Gojak was built in 1957. Downstream is Gojačka Dobra, which is flowing through deep canyons

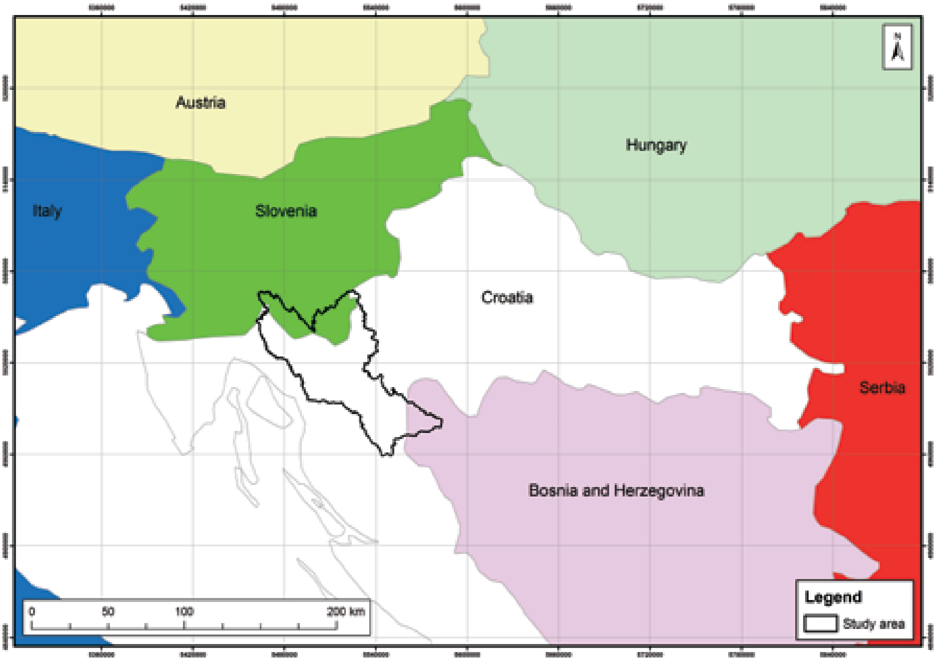


Figure 1. Study area.

with rugged river banks and high and steep hills. At the Gojačka dobra hydroelectric power plant Lešće was built in 2010. River Korana has catchment area of 1,100 km^2 up to hydrological profile Veljun. Length from its source to Kupa River is about 142 km. Mrežnica River is generally canyon river with approximate length of 71.4 km. In the Croatian karstic part of the Kupa River catchment there are 6 hydroelectric power plants (Ozalj, Gojak, Zeleni vir, Lešće, Čabranka and Kupica).

Kupa River catchment is made of Palaeozoic to Quaternary deposits. Palaeozoic rocks are generally presented by clay schists, sandstones, quartz conglomerates, shales and siltstones. Rarely, carbonates can be found. Impermeability of this rocks conditions surface runoff of precipitation and dense surface flow network. Mesozoic rocks are mostly carbonates. Due to their permeability, rivers in some areas sink and in other peak, what generates scarce hydrographic network. Triassic deposits are presented with clastites (marls, siltstones, conglomerates, shales, amphibole porphyries, tuffs and cherts) and carbonates, while Jurassic and Cretaceous are mostly carbonates. Paleogene and Neogene deposits are mostly clastites, *i.e.* marls, clays, silts, sandstones, conglomerates and breccias. In the valleys of the rivers and lakes unconsolidated sediments of Quaternary age can be found (Savić and Dozet, 1983).

Biondić (2005) has divided region of Gorski kotar into five main hydrogeological categories:

– Carbonate rocks with high permeability.
– Carbonate rocks with medium permeability.
– Carbonate rocks with low permeability.
– Impermeable clastic deposits.
– Quaternary deposits of variable permeability.

Carbonate rocks with high permeability are generally limestones, without or with small proportion of dolomite. This areas present typical karst region with very small number of surface flows and numerous karst phenomenon, *i.e.* sinkholes and caves. Increase and domination of dolomite component has generated carbonate rocks with medium permeability. Those rocks mostly have high permeability only in tectonised areas. Low permeability rocks are dolomites which have clastic component. Impermeable rocks are generally presented with Triassic and Palaeozoic clastites. In this area hydrographic network is developed, while infiltration and erosion is very limited. Quaternary deposits have intergranular porosity and their permeability depends on the granulometric composition and lithology. They generally have little thickness and are not hydrogeologically interesting. In the end, it can be seen that investigated area can be divided into two main units: high mountain area with specific karst regime and karst plateau (shallow karst).

According to Köppens climate classification, this area belongs to climate denoted as *Cfb* (maritime temperate climate). More precisely, the area of hydrological stations Kupari at Kupa and Zamost 2 at Čabranka belongs to climate denoted as *Cfsbx*. This particular area stands out with deviation of amount of precipitation (area of Kupari has large amount and area of Zamost 2 quite smaller amount of precipitation, Žugaj et al., 2011). The greatest amount of precipitation at station Parg is 1,849 mm. Downstream Kupa River to Kamanje hydrological station, climate is the same, *Cfb*, but with some different properties, *Cfwbx* (Zaninović et al., 2008).

3. Data and methods

Trend analysis was carried out on seven indicators: annual mean flow, seasonal mean flows (winter and summer mean flows), instantaneous annual maximum flow, annual and seasonal precipitation using time series from 1951 to 2013 from six hydrological stations and three meteorological stations. Figure 2 shows an example of a hydrograph and a hyetograph used in this analysis. Table 1 shows details of selected stations (Pavlić, 2016). Catchment area of considered hydrological stations varies from 106 km^2 to 2,337 km^2, with average value of 912 km^2. Available record length of hydrological and meteorological stations ranges from 57 years to 68 years, however, analysed record lengths range from 57 to 63 years with average value of 61.8 years. Analysed records are uninterrupted on all stations, except on hydrological station Kamanje at Kupa, where data from January 1996 and June 1997 are unavailable. However, this lack of daily one-month data is considered negligible, as the analysis is carried out with annual values, and missing mean annual data are interpolated using correlation with data from upstream hydrological station Metlika.

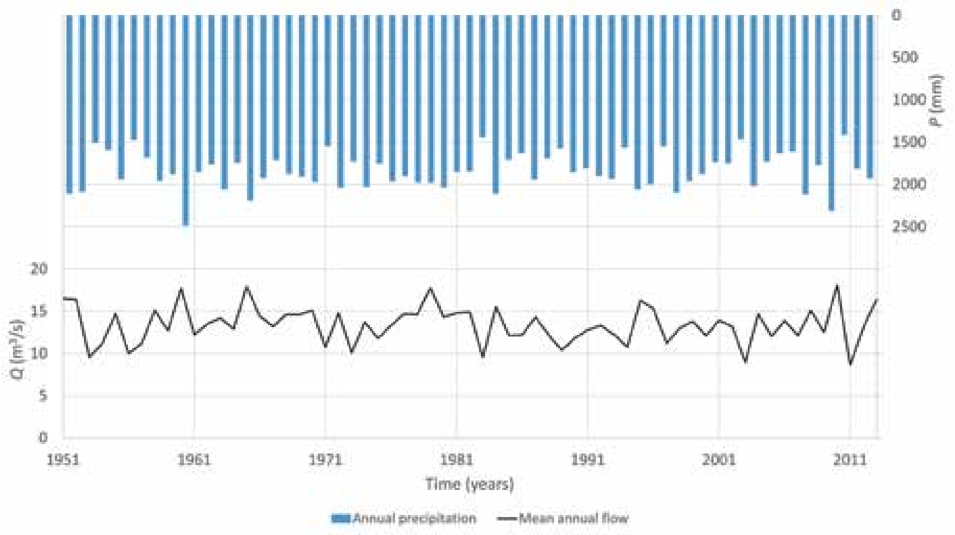


Figure 2. Hydrograph of mean annual flow at station Kupari at Kupa and hyetograph of annual precipitation at station Parg from 1951 to 2013.

Each indicator is transformed as standardized flow and precipitation anomaly (*SFA*) and smoothed using Local Polynomial Regression Fitting (*LOESS*) algorithm. Trend persistence and evolution is tested using Mann-Kendall *Z* test for each iteration of start year (1951 to 2013, 1952 to 2013 and so on until 1984 to 2013, which is fixed period of analysis).

Table 1. Hydrological and meteorological stations included in analysis.

Station name	River name	Type	Area (km^2)	Available record length (years)	Analysed record length (years)
Kupari	Kupa	HYD	205	63	63
Kamanje	Kupa	HYD	2,337	57	57
Zamost 2	Čabranka	HYD	106	64	63
Trošmarija	Donja Dobra	HYD	816	61	58
Stative donje	Donja Dobra	HYD	1,008	68	63
Mrzlo polje	Mrežnica	HYD	997	67	63
Station name	**River catchment**	**Type**		**Available record length (years)**	**Analysed record length (years)**
Parg	Kupa	MET		63	63
Ogulin	Dobra	MET		65	63
Karlovac	Kupa	MET		65	63

Type: HYD - hydrological station; MET - meteorological station

Trend analysis focuses on seven indicators that describes changes in high and mean flows:

- annual mean flow (Q_{mean}),
- seasonal mean flows (Q_{meanw}, Q_{means}),
- instantaneous annual maximum flow (Q_{max}),
- annual and seasonal precipitation (P, P_w, P_s).

Seasonal mean flows (Q_{meanw}, Q_{means}), as well as seasonal precipitation (P_w, P_s) that represent winter and summer seasons, are derived using monthly mean flow and monthly precipitation from April to September (for summer indicator) and from October to March (for winter indicator).

Tables 2 and 3 show statistical parameters of annual mean flow, instantaneous annual maximum flow and annual precipitation of analysed period. Homogeneity of time series was considered and results obtained by Pavlić (2016) for period 1951–2012 were adopted. Times series of fixed period (1984–2013) for mean annual flows are not homogenous at stations Kamanje at Kupa and Mrzlo polje at Mrežnica compared to full time series (1951–2013), but this inhomogeneity is very poorly pronounced and is similar to the upstream station Kupari at Kupa. Times series of fixed period (1984–2013) for annual maximum flows is not homogenous at station Zamost 2 at Čabranka compared to full time series (1951–2013). However, since only the evolution of the trend has been analyzed since 1951 and trends are compared in the fixed period (1984–2013), this inhomogeneity will not affect the obtained results.

North Atlantic Oscillation (NAO) phenomenon describes the varying strength of two atmospheric pressure systems lying over the subpolar region near Iceland and subtropical region near the Azores (Bachmann, 2007). In

Table 2. Statistical parameters of annual mean flow and instantaneous annual maximum flow of period (1951–2013).

Station name	Q_{mean} (m^3 s^{-1})	σ	c_v	c_s	Q_{max} (m^3 s^{-1})	σ	c_v	c_s
Kupari	13.4	2.22	0.17	0.02	195	23.4	0.17	0.27
Kamanje	72.1	14.0	0.19	–0.16	1,145	154	0.19	–0.43
Zamost 2	3.67	0.745	0.20	0.98	128	24.2	0.33	0.63
Trošmarija	26.2	7.12	0.27	–0.31	246	34.4	0.23	–0.03
Stative donje	33.9	7.79	0.23	0.20	405	57.6	0.24	0.63
Mrzlo polje	28.3	8.15	0.29	0.39	373	65.9	0.28	–0.76

Table 3. Statistical parameters of annual precipitation of period (1951–2013).

Station name	P (mm)	σ	c_v	c_s
Parg	1,843	216	0.12	0.15
Ogulin	1,558	233	0.15	0.14
Karlovac	1,101	162	0.15	–0.30

general, there is a high-pressure system over subtropical region, and low pressure over the subpolar region (Wanner et al., 2001). The North Atlantic Oscillation is one of the most prominent patterns of atmospheric circulation variability and can be observed during the whole year in the northern hemisphere (Hurrell et al., 2003). The strength of the pressure gradient between those two regions varies in time and measure for this variation is so called NAO Index. NAO Index defined by Hurrell (1995) uses weather data from Stykkisholmur/Reykjavik (Iceland) and Lisbon (Portugal). NAO Index is obtained by comparison of Icelandic and Portuguese normalized pressures. NAO Index gets positive in phases with a higher pressure gradient and negative in phases with a weaker pressure gradient (Brönnimann, 2005). The pressure difference between the Azores and Iceland is associated with westerly winds across the Atlantic, what has a high importance for weather and climate in the whole North Atlantic region (Bachmann, 2007; Hurrell and Dickson, 2004). Climatological elements which are exposed to change under the influence of the North Atlantic Oscillation are temperature, pressure, precipitation etc. The NAO is strongly related to the strength of the westerly winds (Hurrell, 1995). Figure 3 is showing an example of NAO Index variability for the period 1951–2015.

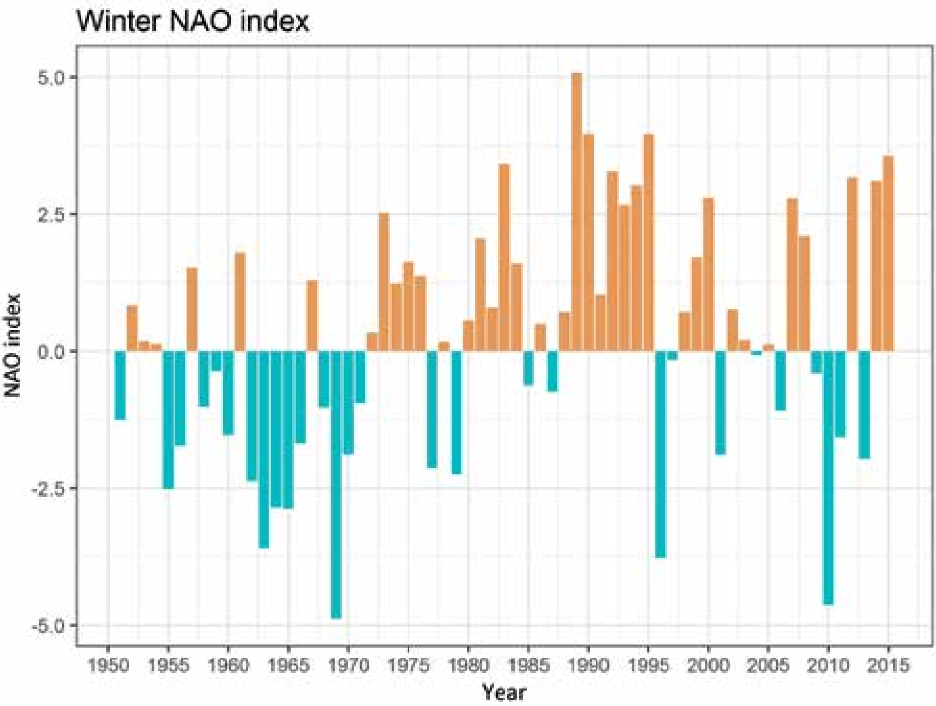


Figure 3. NAO wintertime Index from 1951 to 2015 with value of NAO Index on y-axis (Hurrell, 1995; new data available from *https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based*).

All flow indicators were calculated in m^3/s, while precipitation is in mm. Analysed time series ranges from 1951 to 2013 and selected fixed period ranges from 1984 to 2013.

Murphy et al. (2013) propose trend analysis and study approach procedure as follows. Time series of each indicator was scaled to standardized flow anomaly (*SFA*), proposed by Déry et al. (2005):

$$SFA = \left(\frac{X_i - \overline{X}}{\sigma_X} \right) \tag{1}$$

where X_i is river flow (m^3/s) or precipitation (mm) value for *i*-th year, $\overline{X}$ is the mean flow or mean precipitation for the selected time period and σ_X is standard deviation of *X* parameter. Sign of *SFA* represents higher or lower values of average value of considered indicator. Obtained *SFA* of each indicator were smoothed using *LOESS* algorithm with smoothing parameter set to 0.25. Detailed description of this method can be found in Déry et al. (2005) and Stahl et al. (2010).

Trend analysis of each indicator as *SFA* is then analysed using Mann-Kendall (MK) test for monotonic trend (Kendall, 1975). A two-tailed MK test is chosen with 5% significance level where null hypothesis of no trend is rejected if $|Z| > 1.96$.

Trend magnitudes were estimated using slope of the Theil-Sen Approach (*TSA*) (Theil, 1950; Sen, 1968), and slopes were calculated using time series of the *SFA*. Mann-Kendall test and slope of *TSA* were calculated using MAKESENS Microsoft© Excel template application (Salmi et al., 2002).

The analysis consists of two steps. First is related to the determination of the fixed period 1984–2013. This allows comparison of trend data between considered hydrological and meteorological stations. Second, the persistence of trends was inspected by systematically reducing the start year of analysis, starting from 1951 to 2013, then from 1952 to 2013 and so on until 1984 to 2013, which represents the fix period of 30 years (Wilby, 2006). For each iteration MK *Z* statistics test was calculated, for full record 1951–2013, then 1952–2013 and so on until 1984–2013, so the sampling size varies from 63 to 30 years. By plotting obtained *Z* values for each iteration of start years, trend persistence and evolution through a given period can be achieved (Murphy et al., 2013).

4. Results and discussion

Z values of Mann-Kendall test for trend significance for fixed period 1984–2013 shows that annual mean flows had mostly positive trends except on Zamost 2 at Čabranka, but that trend is not significant. Two significant positive trends are on Trošmarija and Stative donje at Dobra River. Winter mean flows showed positive trends on all stations, but significant only at Trošmarija and Stative donje at Dobra River and Mrzlo polje at Mrežnica River. On the other hand, summer mean flows showed mostly negative trends, but only one significant at Zamost 2 at Čabranka River. Maximum annual flows showed no significant trends for fixed period. Mann-Kendall *Z* values for trend significance for fixed period 1984–2013 are shown in Tab. 4.

Z values of Mann-Kendall test for trend significance for annual and seasonal precipitation are shown in Tab. 5. Only one positive significant trend is detected at Karlovac for annual precipitation, while trends on other stations for all indicators are not significant.

Table 4. Mann-Kendall Z values for fixed period of analysis 1984–2013 for Q_{mean}*,* Q_{meanw}*,* Q_{means} *and* Q_{max}*. Trend and significance is calculated using Mann-Kendall test with level of significance 5%.*

Hydrological station	Q_{mean}	Q_{meanw}	Q_{means}	Q_{max}
Kupari	0.839	1.855	–1.285	–0.125
Kamanje	0.000	1.267	–1.106	–0.856
Zamost 2	–0.821	0.607	***–2.355***	–0.963
Trošmarija	***2.172***	***2.113***	0.423	–1.285
Stative donje	***2.427***	***2.101***	–0.732	–0.214
Mrzlo polje	1.463	***1.970***	0.000	–0.143

Table 5. Mann-Kendall Z values for fixed period of analysis 1984–2013 for P, P_w *and* P_s*. Trend and significance is calculated using Mann-Kendall test with level of significance 5%.*

Meteorological station	P	P_w	P_s
Parg	–0.131	–0.257	–0.020
Ogulin	1.106	1.107	–0.356
Karlovac	***1.998***	0.882	0.657

Deeper insight into the behaviour of trend is clearer by inspecting trend evolution and persistence.

Figure 4 shows smoothed SFA values of annual, summer and winter mean flow and annual maximum flows for hydrological stations Zamost 2, Kupari, Kamanje, Trošmarija, Stative donje and Mrzlo polje. SFA of annual mean and maximum flows shows incoherence throughout the whole analysed period. This is most visible at the beginning of time series, in the mid-1950 where 5th and 95th percentile limits are widest. In the fixed period 1984–2013 incoherence is a little less developed. SFA of summer annual flow shows less incoherence, where more incoherence is developed by the late 1970's and in the mid 2000's. The second is due to the shorter time series of Trošmarija hydrological station. Best coherence is visible at the winter annual flows throughout the whole analysed period. Mean value of SFA of mean annual flows regularly oscillates from beginning of analysed period to mid-1990. After 1990's, mean value of SFA is constantly above long-time average. Mean values of SFA for summer mean flows and maximum annual flows are predominantly above long-time average, while SFA values of mean annual flows are predominantly around long-time average and tend to positive values.

Despite SFA of mean annual flows are around long-time average during fixed period 1984–2013, SFA of summer and winter mean flows show a deviation from the long-time mean values, with summer mean values lower than long-time average and winter mean values higher than long-time average.

Same approach was applied on annual precipitation data and is shown on Fig. 5. Annual, summer and winter precipitation shows fair coherence throughout whole analysed period 1951–2013, but winter precipitation has best coherence. In fixed period 1984–2013, mean value of SFA of annual precipitation oscillates around long-time average and in 2010's it tends to be greater than long-time average. SFA of summer precipitation is lower than long-time average in 2010's,

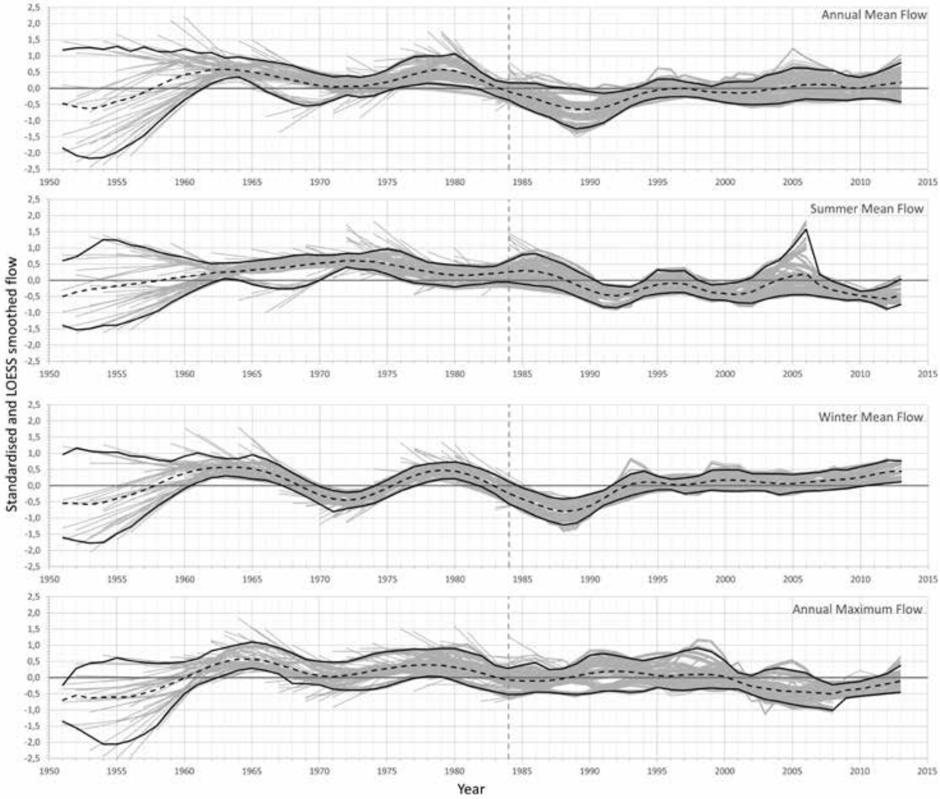


Figure 4. Standardised and LOESS smoothed annual mean flows and annual maximum flows for hydrological stations Zamost 2, Kupari, Kamanje, Trošmarija, Stative donje and Mrzlo polje. Light grey lines represent smoothed SFA of each time record, black solid lines are the 5th and 95th percentile of standardised and LOESS smoothed series and dashed black line is the mean of data set. Vertical dashed line represents the start of fixed period 1984–2013.

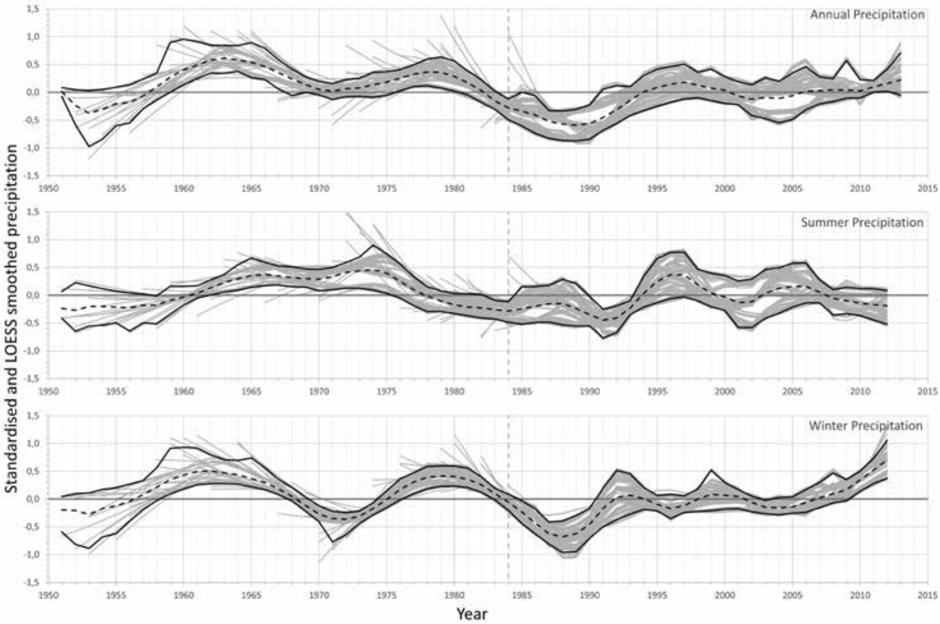
but winter precipitation is fairly greater than long-time average, and tends to even greater values.

Both SFA of annual and seasonal flows and precipitation and seasonal precipitation shows similar behaviour throughout fixed period 1984–2013.

Persistence and evolution of trends is shown on Fig. 6. Mann-Kendall *Z* test is conducted for mean annual and seasonal flows, maximum annual flows, annual and seasonal precipitation. Since trend analysis is sensitive to the length of the time series, persistence of trend ending in 2013 and in 2010 are analysed (Murphy et al., 2013). On the left-hand side persistence of trends ending in 2013 is shown, while on the right-hand side there is persistence of trends ending in 2010 (Fig. 6).

Majority of mean annual flow records for ending year 2013 have negative trend until mid-1970, however, only two records on Kupa have significant negative trend by the mid-1960 and one record on Mrežnica by the late-1950. Two records on Dobra have positive, but insignificant trend from beginning of 1950's by the mid-1950. Those trends then shift to negative values, but in the mid-1970's they are positive again, and in mid-1980, one record shows strong significant positive trend. Common feature of all records for mean annual flow is decrease of negative trend values and shifting towards positive values.

Winter mean annual flow records shows no significant trend throughout whole analysed period, but similar to mean annual flows, evolution of trend is



Annual Precipitation

Summer Precipitation

Winter Precipitation

Figure 5. Standardised and LOESS smoothed annual and seasonal precipitation on meteorological station Parg, Ogulin and Karlovac. Light grey lines represent smoothed SFA of each time record, black solid lines are the 5th and 95th percentile of standardised and LOESS smoothed series and dashed black line is the mean of data set. Vertical dashed line represents the start of fixed period 1984–2013.

from negative to positive values. Summer mean annual flow records show the same evolution, but there are negative significant trends on Kupa by the late-1970.

Maximum annual flow records show almost no evolution of trend throughout analysed period. Only one record on Kupa and one on Dobra shows significant negative trend through majority of analysed period.

Analysis of trend evolution with 2010 as the end year of analysis, showed on the right-hand side on Figure 6, does not have great effect on results. Trends for all analysed indicators are slightly shifted towards positive values, with one exception at maximum annual flows, where trend of one record at Kupa has more pronounced significant negative trend. Therefore, intertwined influence of precipitation and hydrogeological characteristics on trend of flow indicators can be distinguished, precipitation affects the trend evolution through analysed period,

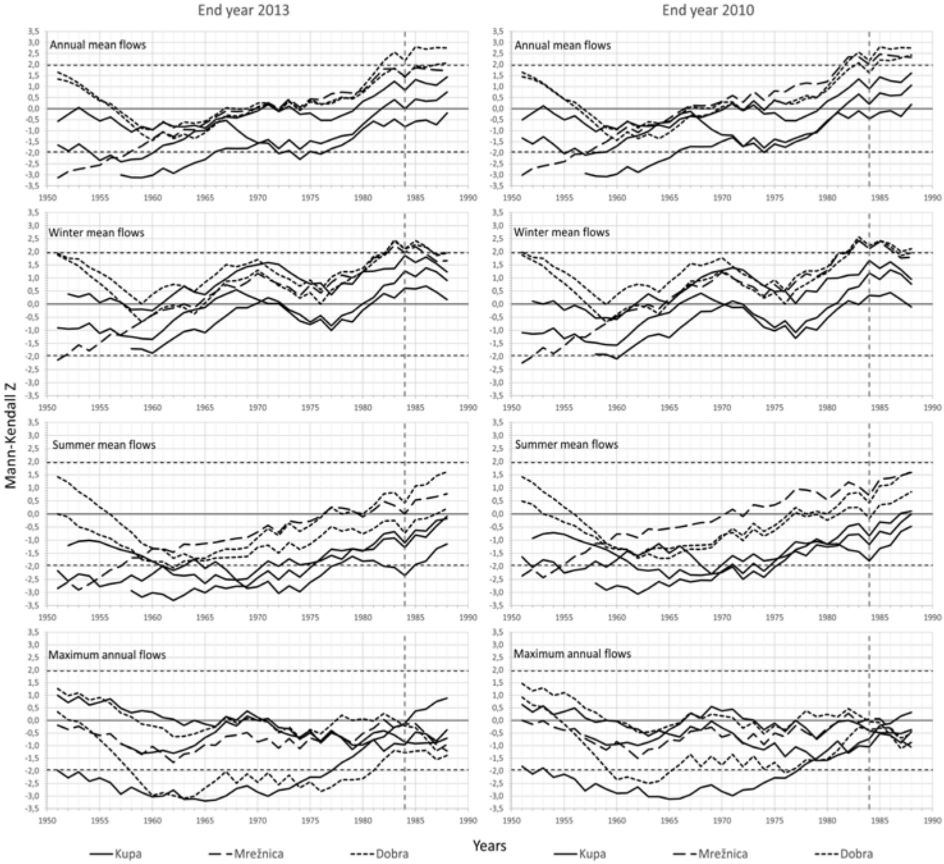


Figure 6. Persistence plots for mean annual, seasonal and maximum annual flows ending in 2013 on left-hand side and ending in 2010 on right-hand side. Dashed horizontal lines represents threshold for significant trends at 5% significance level. Vertical dashed line represents the start of fixed period 1984–2013.

while hydrogeological characteristics probably affect the difference between analysed trends at given time period.

Figure 7 shows trend persistence and evolution of annual and seasonal precipitation for three meteorological stations; Parg, Ogulin and Karlovac.

All three analysed indicators have mostly negative trend from beginning of 1950's until 1970's, when they shift to positive values but without significance. Only Karlovac station shows significant positive trend in mid-1980 for annual precipitation. Trend persistence and evolution for time series ending in 2010 on the right-hand side in Figure 7 shows similar trend evolution as one on left-hand side. Only difference is that trends are slightly shifted to positive values.

Increasing knowledge of large-scale variations of hydrological variables and water cycle parameters is becoming crucial (*e.g.* Massei et al., 2010). Several studies have established links between NAO and precipitation in western and southern Europe (Hurrell, 1995; Qian et al., 2000; Trigo et al., 2002) Also, links between NAO and streamflow have been studied (*e.g.* Bradbury et al., 2002; Kingston et al., 2007; Collins, 2009).

On Dobra, Mrežnica and Kupa river catchments, which are situated in central part of Croatia, a comparison was made between:

– SFA of annual and winter flows and NAO Index values and
– SFA of annual and winter flows and winter time NAO Index values.

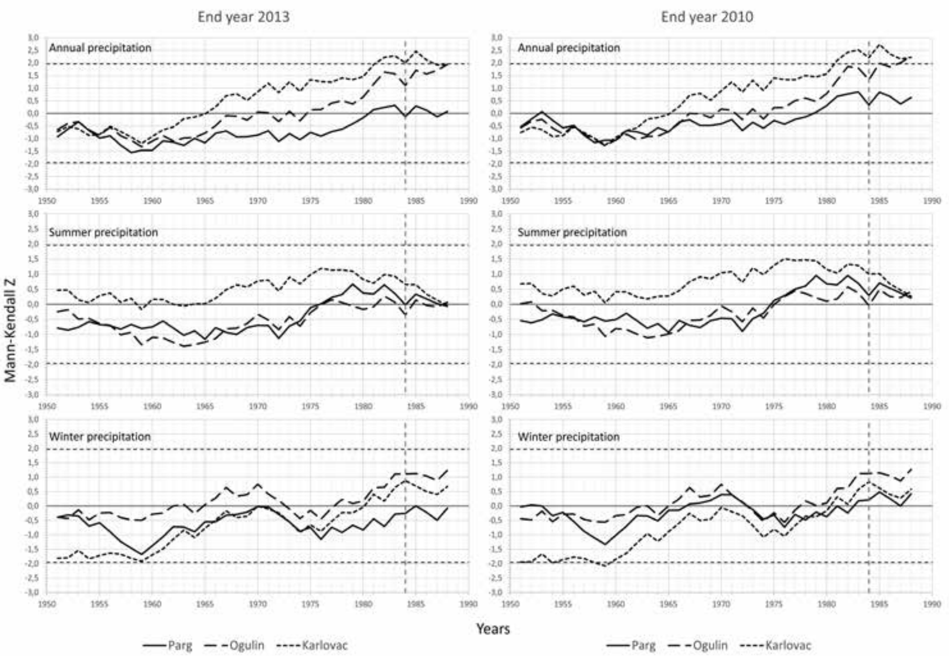


Figure 7. Persistence plots for annual, summer and winter precipitation ending in 2013 on left-hand side and ending in 2010 on right-hand side. Dashed horizontal lines represents threshold for significant trends at 5% significance level. Vertical dashed line represents the start of fixed period 1984–2013.

Resulting correlation coefficients for hydrological stations on these rivers indicate that there is a weak, mostly negative correlation between NAO and streamflow (Tab. 6).

Table 6. Pearson's and Spearman's correlation coefficients for Dobra, Mrežnica and Kupa Rivers catchments hydrological stations between SFA and NAO for annual and winter flow values.

Hydrological stations	*SFA* vs. *NAO* Pearson	*SFA* vs. *NAO* Spearman	SFA_{wi} vs. NAO_{wi} Pearson	SFA_{wi} vs. NAO_{wi} Spearman
Kupari	–0.445	–0.399	–0.356	–0.321
Kamanje	–0.358	–0.332	–0.420	–0.376
Zamost 2	–0.340	–0.324	–0.269	–0.229
Trošmarija	–0.215	–0.199	–0.115	–0.078
Stative Donje	–0.296	–0.244	0.016	0.025
Mrzlo Polje	–0.311	–0.287	–0.135	–0.102

SFA_{wi} – SFA winter (October, November, December, January, February, March) values; NAO_{wi} – NAO Index winter (December, January, February and March) values.

Table 7. Pearson's and Spearman's correlation coefficients for Kupa River catchment meteorological stations, between SFA and NAO for winter flow values; with and without one-month delay.

Meteorological stations	SFA_{JFMA} vs. NAO_{DJFM} Pearson	SFA_{JFMA} vs. NAO_{DJFM} Spearman	SFA_{DJFM} vs. NAO_{DJFM} Pearson	SFA_{DJFM} vs. NAO_{DJFM} Spearman
Parg	–0.398	–0.374	–0.468	–0.475
Ogulin	–0.463	–0.465	–0.487	–0.457
Karlovac	–0.462	–0.591	–0.445	–0.454
Catchment	–0.470	–0.491	–0.503	–0.508

DJFM – December, January, February and March; JFMA – January, February, March and April.

Table 7 shows comparison between SFA of winter precipitation from meteorological stations at Kupa catchment and NAO Index values. Comparison of two cases was made, with and without one-month delay between NAO Index values and SFA values. It is shown that there is no much difference in correlation coefficients in those two cases.

Comparing Tabs. 6 and 7, it is shown that weak correlation between winter time NAO and precipitation, is still greater than between winter time NAO and streamflow. That is expected due to the increase in uncertainty in the NAO-rainfall-runoff system. Positive NAO Index values leads to increased westerlies, consequently, cool summers and mild and wet winters in Central Europe. In contrast, for the negative NAO Index Values, westerlies are suppressed, northern Europe suffers cold dry winters and storms track southwards toward the Mediterranean Sea. This brings increased storm activity and rainfall to southern Europe and North Africa. With that in mind, the correlation coefficients from Table 6 and 7, have mostly negative values, what is expected for Mediterranean region. The possible reason for lower values of correlation coefficients is that the region of interest is situated at border area between Mediterranean Sea and Central Europe.

5. Conclusion

This analysis showed that there was equal amount of positive and negative trends for fix period 1984–2013, but with more significant positive trends. Two positive significant trends were detected for mean annual flows and three for winter mean flows. One negative significant trend is detected for summer mean flows. From this kind of trend distribution within a year it can be concluded that extremes during a wet period within a year are more pronounced than arid periods. This means that more floods than droughts can be expected in the future, which confirms the need to protect Karlovac City from possible floods in the future. Inspection of standardised flow anomaly for all considered indicators pointed that in the mid-1980's an arid period started. Mean value of SFA of all considered indicators was lower than long-time average at that time. Mean value of SFA of annual mean flow are predominantly slightly below long-time average in fixed period, but values of SFA of summer mean flow are much lower than long-time average and of winter mean flow are more than long-time average. This shows that intra-annual extremes that occur in summer and winter period during a year are more pronounced than in earlier period. The same conclusion can be drawn for SFA of precipitation and seasonal precipitation.

Trend analysis showed that all considered indicators had positive evolution of trend from early 1950's to mid-1980. Trend of annual mean flow is significantly negative for stations on Kupa until mid-1960 and on stations on Mrežnica by the late 1950's. In the mid-1980's all stations show positive trends except on Zamost 2 on Čabranka River. Winter mean flows have positive trend on all stations in mid-1980's while summer mean flows have mostly negative trends in mid-1980's. Maximum annual flows have mostly negative trends throughout the entire analysed period. Trend of annual precipitation showed significant positive trend only on Karlovac meteorological station. Annual and seasonal precipitation showed no significant trend change throughout analysed period, but trend evolution is positive, as in trend of flow indicators. Trend evolution of period ending in 2010 showed no significant change, except slight shift toward positive values. Since no satisfactory results were achieved concerning NAO index impact on flow indicators in karstic Kupa River catchment, further research should consider impact of parameters defined on near and smaller region.

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SAŽETAK

Analiza trendova srednjih i maksimalnih protoka u ovisnosti o klimatskim promjenama - Primjer na krškim slivovima Hrvatske

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U radu je analizirana ustrajnost i evolucija trendova srednjih i maksimalnih godišnjih protoka s hidroloških stanica na Kupi (Kupari, Kamanje), pritoku Čabranka (Zamost 2), Dobri (Stative donje, Trošmarija), Mrežnici (Mrzlo polje) i godišnjih oborina s tri meteorološke stanice (Parg, Ogulin i Karlovac). Rad je usredotočen na promatranje sedam veličina: srednji godišnji protok, srednji sezonski protok (srednji zimski i ljetni protok), trenutačni maksimalni godišnji protok, godišnja i sezonska količina oborine. Analizirani vremenski niz je od 1951. do 2013. godine, a fiksno razdoblje uzeto je od 1984. do 2013. godine. Vremenski niz svake razmatrane veličine je normiran na standardiziranu anomaliju toka, te je trend testiran Mann-Kendallovim Z testom, nakon čega je niz izglađen LOESS algoritmom. Analiza je izvedena za cijeli vremenski niz (primjerice, 1951.–2013., 1952.–2013. i tako dalje do 1984.–2013.). Time veličina uzorka varira od 63 do 30 godina. Standardizirana anomalija toka se tako lako može usporediti između različitih hidroloških stanica. Na svim analiziranim stanicama za sve analizirane veličine, nakon sredine 1980-ih godina kada počinje fiksno analizirano razdoblje, standardizirana anomalija toka ima niže vrijednosti od dugogodišnje srednje vrijednosti. Detaljnija analiza srednjih ljetnih i zimskih protoka pokazuje drukčije odstupanje od dugogodišnjeg prosjeka. Evolucija trenda razmatranih veličina je pokazana Mann-Kendallovim Z testom, prikazavši vrijednosti Z za početnu godinu svakog analiziranog vremenskog niza (od 1951. do 1984.).

Ključne riječi: Mann-Kendall, oborina, protok, evolucija trenda, ustrajnost trenda

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