TRENDS AND MULTI-ANNUAL VARIABILITY OF WATER TEMPERATURES IN
THE RIVER DANUBE, SERBIA

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ABSTRACT

The relationship between air (T_a) and water temperature (T_w) is very important because it shows how the temperature of a water body might respond to future changes in surface T_a . Mean monthly T_w records of three gauging stations (Bezdan, Bogojevo i Veliko Gradište) were analyzed alongside mean monthly discharge (Q) for the same stations. Additionally, T_a series from two meteorological stations (Sombor and Veliko Gradište) were correlated with T_w variations over the period 1950–2012. Locally weighted scatter point smoothing (LOWESS) was used to investigate long-term trends in the raw data, alongside the Mann–Kendall (MK) trend test. Trend significance was established using Yue-Pilon's pre-whitening approaches to determine trends in climate data. Also, the rescaled adjusted partial sums (RAPS) method was used to detect dates of possible changes in the time series. Statistically significant warming trends were observed for annual and seasonal minimum and maximum T_w at all investigated sites. The strongest warming was observed at Bogojevo gauging station for seasonal maximum T_w , with $+0.05^{\circ}\text{C}$ per year on average. RAPS established that the trend began in the 1980s. This behaviour is linked to climate patterns in the North and East Atlantic which determine the amount of heat advected onto mainland Europe. Statistically significant correlations were found for all T_w on an annual basis. Overall, the strongest correlations ($p < 0.01$) between T_w residuals and the North Atlantic Oscillation (NAO) were recorded for the winter period. These findings suggest possible predictability of T_w over seasonal time-scales.

Keywords: Danube; water temperature; air temperature; trends; variability; Serbia.

1. INTRODUCTION

Temperature is an important feature of flowing waters because it affects other physical properties and influences the chemical and biochemical reactions of lotic systems (Walling and Webb, 1992; Webb *et al.*, 2008). The life-cycles of lotic biota are regulated by river temperature variations (Gore, 1992; Everall *et al.*, 2015). Water temperature (T_w) also indirectly influences bulk density which causes thermal stratification in standing water bodies. In this way, temperature influences chemical and biochemical processes in the individual stratified layers (epilimnion and hypolimnion) (Pekarova *et al.*, 2011). Changes in the thermal regime of river systems may result in the disruption of established patterns of synchrony between the aquatic communities (Woodward *et al.*, 2010; Marković *et al.*, 2013).

Incoming solar radiation is commonly perceived as the major component of the heat budget of river systems. These effects are mostly modified by contributions from the river discharge, bed friction, riparian vegetation, groundwater-related heat transport and various anthropogenic perturbations such as thermal pollution, embankments and deforestation (Webb *et al.*, 2008; Olden and Naiman, 2010). According to Webb and Zhang (1997, 1999) who investigated 17 sites located mainly in South–West England, and in other parts of the UK, radiative fluxes accounted for more than 70% of heat inputs. Air temperature (T_a) is often used as a first approximation of T_w . However, while T_w and T_a can co-vary, the strength of the relationship varies between regions, through time, and can be highly site specific (Hannah *et al.*, 2008; Garner *et al.*, 2013; Johnson *et al.*, 2014; Wilby *et al.*, 2014), for example, due to the influence of river flow (Webb *et al.*, 2003; Pekarova *et al.*, 2008). The relationship between T_a and T_w is important as it could show how the temperature of a stream might respond to future climate variability and change (Morrill *et al.*, 2001, 2005). T_w is a dynamic parameter, which reflects the geophysical and climatic characteristics of the watershed as well as the locally dominant hydrological pathways. In this paper, we explore

the relationship between T_a and T_w . Since water has a higher specific heat capacity than air many studies regard T_w as a stable indicator of long-term trends (Pekarova *et al.*, 2008; Pedersen and Sand-Jensen, 2007). Moreover, increased stream T_w , as well as increased heat flow in a river, are probably indicative of warming of the aquatic environment (Pekarova *et al.*, 2008).

Past river T_w trends and variability have not been exhaustively investigated partly due to a lack of long, reliable and unbroken records (Webb and Nobilis, 2007). Most investigations are site specific (single station, e.g. Pekarova *et al.*, 2011) or consider only a small number of locations within a national station network (e.g. Webb and Nobilis, 2007; Bonacci *et al.*, 2008; Kaushal *et al.*, 2010; Langan *et al.*, 2001; Bartholow, 2005; Hari *et al.*, 2006; Moatar and Gailhard, 2006). Studies of long-term trends in large European and US rivers suggest that up to two thirds of warming during the 20th century may be attributed to human-induced changes in flow regime, discharges of treated wastewater, heated water and urbanization (Webb and Nobilis, 1994; Huguet *et al.*, 2008; Kaushal *et al.*, 2010). Significant changes in river T_w are also expected to occur in the 21st century as a consequence of climate change (e.g. Webb, 1996; Mohseni *et al.*, 2003; Webb and Walsh, 2004).

The impacts of large modes of climate variability such as the North Atlantic Oscillation (NAO) and East Atlantic Oscillation (EAO) on fluctuations in river T_w and discharge have been investigated (e.g. Kucuk *et al.*, 2009; Hosseinzadeh Talaei *et al.*, 2012; Cullen *et al.*, 2002; Trigo *et al.*, 2004; Rîmbu *et al.*, 2002; Webb and Nobilis, 2007; Tabari *et al.*, 2013). NAO is the dominant mode of atmospheric behaviour in the North Atlantic throughout the year, and is most prominent during winter. Unkašević and Tošić (2013) found that NAO influenced the Serbian extreme T_a variability during winter and summer but the effects of EAO were greater. The EAO pattern is seen as the second prominent mode of low-frequency variability over the North Atlantic, and appears as a leading mode in all months.

The EAO pattern consists of a north-south dipole of anomaly centres spanning the North Atlantic from east to west and it is structurally similar to the NAO. The anomaly centres of the EAO pattern are displaced south-eastward to the approximate nodal lines of the NAO pattern marking EAO pattern as southward shifted NAO (Barnston and Livezey, 1987).

The purpose of this article is to analyze long-term records of Tw and Ta, and to interpret recent changes in Tw records in the River Danube, Serbia. We also investigate the relationship between hydrological variables, Q and Tw, and Ta, so that the association between atmospheric conditions and river Tw can be better understood. We undertake detailed analysis on three gauging stations in the River Danube in order to explore the observed changes in Tw. Thus we address a series of questions:

- What is the behaviour of Tw in the Danube River over the period 1950 to 2012?
- What variations and trends exist in the data, what if any step changes have occurred, and how large are these relative to background variability?
- How do the changes in river flow affect Tw in the Danube, Serbia?
- How do the changes in Tw relate to changes in Ta in the Danube?
- What was the annual heat flow for three stations along the Danube from 1950 to 2012?
- How do changes in Tw on a seasonal and annual basis relate to the NAO and EAO?

River flow and water temperature are known to be fundamental controls of freshwater ecosystems. Thus, the results of this study represent a good potential reference point for the planning and management of Danube water resources in Serbia. The implications of the results could also be used to inform strategies to maintain the health of the river system, especially under future global climate change.

2. DATA AND METHODS

2.1 Study area and data

The Danube River flows across Europe from west to east. From the heights of the Schwarzwald Mountains to the Black Sea, it traverses 22 degrees of longitude and passes through 11 countries. The Danube is approximately 2850 km long with a basin area of 807 000 km² (Schiller *et al.*, 2010). The Danube in Serbia is approximately 588 km long.

Figure 1.

The 1961–2000 average discharge at the entrance of the Delta (Ceatal Izmail station, 45.22N, 28.73E) was ~6500 m³/s, (Global Runoff Data Centre, Germany, <http://grdc.bafg.de/>). Due to the large area of the Danube basin, the river encounters a range of climate and physiographic regimes. The highest annual average Ta (12°C) is experienced in the middle and lower Danube basin, whereas the coldest regions are in the Carpathians and the Alps at high altitudes. The lowest mean annual Ta (–6.2°C) is recorded in the Austrian Alps at the Sonnblick Observatory (Schiller *et al.*, 2010).

The study area is in the northern part of Serbia, in the Middle Danube Basin (Figure 1). To evaluate the temperature regime of the Danube River in Serbia, average values of daily Tw and discharge at three gauging stations Bezdan, Bogojewo and Veliko Gradište were analyzed (Figure 1). Table 1 presents the main characteristics (station name, datum plane (H), distance from mouth (L), period of available data and mean annual Tw and mean annual discharge in available period (Q)) at the monitoring stations used in this study.

Table 1.

Systematic measurements of T_w in Serbia began in 1949 at Bezdan (km 1426), at Bogojevo (km 1367) in 1948, and at Veliko Gradište (km 1060) in 1949. The Republic Hydrometeorological Service of Serbia (RHMZ) archived records of T_w obtained at regular daily intervals, at 7:00 a.m.

Data from meteorological stations in Sombor and Veliko Gradište for the period 1950-2012 are used to test the relationship between T_w and T_a . Sombor meteorological station is located in the vicinity of two gauging stations (Bezdan and Bogojevo) while Veliko Gradište is near to the river station with the same name. The datasets were obtained from the RHMZ.

2.2 Technique description

The RHtestsV4 software package was used to detect, and adjust for multiple shifts in a data series and that may have first order autoregressive errors (Wang *et al.*, 2007; Wang 2008a, 2008b). Seasonal values of T_w and Q were calculated for standard meteorological seasons (i.e. March to May for spring, June to August for summer, September to November for autumn, and December to February for winter). In order to investigate long-term trends, time series of annual and seasonal average values of Danube T_w and annual heat flow, Z_t , were calculated by two methods following Pekarova *et al.* (2008). The arithmetic mean water temperature (T_o) was calculated from measured daily and monthly values. Thus T_o was used to indicate intra and inter-annual variations of Danube T_w at three gauging stations. These values were also used for the calculation of T_{o_v} and Z_t . As the volume of warm and cold water flowing through the river varies throughout the year the weighted average of annual values (T_{o_v}) were calculated:

$$To_v = \frac{\sum_{i=1}^{365} To_i Q_i}{\sum_{i=1}^{365} Q_i} \quad \text{Eq. (1)}$$

where To_i is the average daily Tw for the i^{th} day ($^{\circ}\text{C}$), Q_i is the average daily discharge for the i^{th} day (m^3/s), and To_v is the weighted average annual Tw ($^{\circ}\text{C}$). To_v emphasizes the influence of Q on annual Tw. There is an apparent dependency of Tw on Q, meaning that higher Q is connected with lower Tw and vice versa. On the other hand, the To_v values show the influence of Q on volume of warm and cold water flowing through the river profile. In this case, higher Q is linked to higher To_v and vice versa.

The annual heat flow, Z_t , for every gauging station (referenced to 0°C) was also calculated using To :

$$Z_t = To_v \bar{Q} c \zeta \quad \text{Eq. (2)}$$

where Q is the average annual discharge (m^3/s), ζ is the density of water (1000 kg m^3), c is the specific heat capacity of water (4186.6 J/kgK), and Z_t is the annual heat flow (J/s). Z_t , by definition indicates the annual heat transfer in the river profile. An increased heat flow in a river, could be viewed as a signal that the water environment is warming (Pekarova *et al.*, 2008).

Locally weighted scatter point smoothing (LOWESS) was used to smooth variability in the raw data. LOWESS was applied in order to visually identify the presence of the trend. This nonparametric method relaxes the linearity assumptions of conventional regression methods. For this algorithm local linear polynomial fit was used. A similar approach was used by Webb and Nobilis (2007). The Mann–Kendall (MK) nonparametric test was used to evaluate the presence of long-term trends in the time series (Mann, 1945; Kendall, 1976). The

presence of a positive serial correlation in a data set can increase the expected number of false positive outcomes for the Mann–Kendall test (von Storch and Navarra, 1995). Therefore the Yue-Pilon (Yue *et al.*, 2002) pre-whitening approach was applied to the time series prior to application of the Mann-Kendall test. First, the slope of the trend in each time series was estimated using the Theil-Sen approach (TSA). If the slope was found to differ from zero, the identified trend was assumed to be linear and subtracted from the sample data. The resulting residual series is referred to as the detrended series. Next, the lag-1 serial correlation coefficient of the detrended series was computed and removed from the series. Finally, the identified trend and the modified residual series were combined, and the Mann–Kendall test was applied to this combined series to assess the significance of the trend (Yue *et al.*, 2002). We used *R* package “ZYP” (<http://www.r-project.org>).

The rescaled adjusted partial sums (RAPS) method (Garbrecht and Fernandez, 1994) was used for identifying dates of potential change in the time series. RAPS is a visualisation approach that highlights trends, shifts, data clustering, irregular variations and periodicities in the record (Garbrecht and Fernandez, 1994). Values of RAPS, for each observation in the time series are calculated by:

$$RAPS_k = \sum_{t=1}^n \frac{Y_t - Y}{S_y} \quad \text{Eq. (3)}$$

where Y is the sample mean; S_y is the variance; n is the number of values in the time series; and k is counter limit of the current summation that varies between 0 and n and Y_t is the time series being analyzed. Decreasing patterns in the RAPS are the consequence of generally below-average Y_t values, whereas increasing patterns are the result of periods mostly when Y_t is above-average values (Fiorillo *et al.*, 2014). The RAPS approach highlights shorter and systematic periods of increase or decrease within the record that might not be

visible in the time series itself. In contrast, the Mann-Kendall trend test looks for trends throughout the entire record.

The relationship between T_a and T_w was investigated using three regression models: linear, polynomial, and logistic. Linear regression is the simplest model and is widely used to model T_w from T_a (Eq 4) (e.g. Mackey and Berrie, 1991; Stefan and Preud'homme, 1993; Imholt *et al.*, 2012). However, this relationship is known to depart from linearity at extreme T_a (Johnson *et al.*, 2014). Translation from T_a to T_w is non-linear when polynomial regression models are used (Eq. 5).

$$T_{w_m} = a \cdot T_{a_m} + b \quad \text{Eq. (4),}$$

$$T_{w_m} = c \cdot T_{a_m}^2 + d \cdot T_{a_m} + f \quad \text{Eq. (5),}$$

where T_{w_m} is mean monthly T_w ; T_{a_m} is mean monthly T_a ; a , b , c , d and f are regression coefficients.

At low temperatures non-linearity becomes more pronounced because T_w is buffered by hyporheic and phreatic water and could freeze when T_a drops substantially below 0°C (Crisp and Howson, 1982; Johnson *et al.*, 2014). Thus, the relationship between T_a and T_w could be best described by a logistic function (Eq. 6) (Mohseni *et al.*, 1998):

$$T_w = \frac{\alpha}{1 + \beta^{-\gamma \cdot T_a}} \quad \text{Eq. (6),}$$

where α , β and γ are three logistic regression parameters, which are physically interpretable and have units in °C. The upper asymptote (α) of the model is the maximum T_w that the

model can predict. The inflection point of the curve (β) represents the region of T_a with the greatest rate of change of T_w . The gradient in the model at the inflection point (γ) gives the increase of T_w for a unit increase in T_a .

The accuracy of each model was assessed for each site by comparing model outputs to observed values. Two model error parameters were calculated. The mean absolute error (*MAE*) (Eq.7) and the root mean square error (*RMSE*) are defined as:

$$MAE = \frac{1}{n} \sum_{i=1}^n |T_{sim_i} - T_{obs_i}| \quad \text{Eq. (7)}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (T_{sim_i} - T_{obs_i})^2}{n}} \quad \text{Eq. (8)}$$

where T_{sim_i} is estimated mean monthly T_w at i month, T_{obs_i} is observed mean monthly T_w at the same time, and n is the number of pairs of mean monthly estimated and observed T_w at each monitoring station.

Correlations between climate indices (NAO and EAO) and mean monthly as well as seasonal T_w in the Danube were calculated using Spearman's rho test at 90 and 95% confidence levels. Spearman's rank correlation coefficient varies between ± 1 . A correlation of +1 or -1 occurs when each of the variables is a perfectly correlated to the other, and a correlation close to zero means there is a weak relationship between the variables.

3. RESULTS

3.1 Water and air temperature relations

Figure 2 shows mean annual T_w and T_a as well as discharge for the three stations. At Bezdan gauging station for the period between 1950 and 2012 long-term average annual T_w

was 12.1°C, for the Bogojevo station 11.7°C and for Veliko Gradište station 12.2°C. During the same period the long-term mean of Ta for meteorological stations Sombor and Veliko Gradište was 10.9°C and 11.0°C, respectively.

Figure 2.

Figure 3 shows annual time series of the long-term monthly average Tw at Bezdan and Ta at Sombor. The relationship between Tw and Ta averages for individual months are also shown. In the first half of the year the Ta and Tw rise together. During the first three months in the year Tw are on average 1.9°C higher than Ta. In the second half of the year when Ta decreases, Tw is approximately 2.6°C higher. The maximum long-term average Ta at Sombor is recorded in July (22.2°C), but the maximum long-term average Tw at Bezdan occurs in August (20.1°C). This delay is due to the specific heat capacity of water, which is the amount of energy required to raise the temperature of a mass by one degree. The lag is due to the difference between heat capacity of air and water. Owing to the greater heat capacity of water, during the summer months a water body will absorb large amounts of heat as it slowly warms up, while in the winter heat is slowly released from the water as it cools down. Also, this delay maybe be explained by spring snowmelt runoff that depresses Tw. Thus, river Tw can be seen as an indicator of long-term trends in river heat flow (Pekarova *et al.*, 2008).

Figure 3.

The relationship between Tw and Ta at the studied stations is strong with R^2 ranging between 0.94 for linear models to 0.96 for logistic models. Figure 4 shows the logistic regression models for mean monthly Tw in the Danube at the three stations Bezdan, Bogojevo and Veliko Gradište.

Figure 4.

Table 2.

The weakest linear regression model explains 94% of the variance (R^2) in monthly mean Tw at Bogojevo (Table 2). Linear models for mean monthly Ta-Tw relations have slightly higher MAE (ranging from 1.21 to 1.38) and RMSE (1.50-1.75) than MAE (1.09-1.30) and RMSE (1.41-1.70) for logistic regression. Similar results are obtained for polynomial regression (Table 2). Even though R^2 for logistic regression (0.95-0.96) is almost the same as for linear (0.94-0.96) and polynomial models (0.95-0.96) the MAE and RMSE are lower indicating that the logistic model was better at relating mean monthly Tw to Ta at all three sites.

3.2 Long-term trends and multi-annual variability of the annual Tw and Ta

Time series of annual mean values of Danube Tw (Figure 5) show considerable inter-annual variability. It is apparent from the LOWESS curves that Tw at all study sites rose from the start of the investigated period. RAPS helps to visualize and identify patterns in the time series. The expected value of the RAPS is a linear function of time given the magnitude and timing of the change. A shift in the time series is identified by the presence of a linear trend in the RAPS which reverses direction at the time at which the change occurs (Garbrecht and Fernandez, 1994). Even though the temperature time series and LOWESS curves generally show increasing trends the shift in the temperature time series and LOWESS curves is not visually apparent for all three station. However, the time series of RAPS for the mean annual Tw exhibit several smaller fluctuations (for Veliko Gradište Tw) and two major trends (for all three stations) (Figure 5). The first trend is defined by general decrease from the beginning of the investigated period until 1980 for Bezdan and Veliko Gradište, but for Bogojevo the decreasing trend ends in 1987 when the maximum departures occurred. The second trend is indicated by an increase from 1981 for Bezdan and Veliko Gradište, and from

1988 for Bogojevo. These results suggest that increases of Tw at the studied stations began during the 1980s.

Blue lines (Figure 5) show mean annual Q at the investigated stations. The RAPS series of the mean annual Q show sustained departures from the expected value of zero indicating that the change in mean annual Q occurs in the investigated period. The time series of RAPS for the annual mean Q (Figure 5) shows several smaller fluctuations and two major trends for all three stations. The first period of smaller fluctuations ends in 1964 when general increasing trend starts. This trend ends in 1970 for Bezdan, 1982 for Bogojevo (with a small breaks in 1969 and 1973), and in 1981 for Veliko Gradište (with breaks in 1969 and 1973). A general decreasing trend starts in 1974 and ends in 1994 for Bezdan, starts in 1983 and ends in 2008 for Bogojevo, and in 1982 until 1998 for Veliko Gradište. After those periods, the second period of smaller variations begins. The Mann–Kendall trend test indicates that statistically significant ($p < 0.05$) increases or decreases are not present in mean annual Q series.

Figure 5.

Figure 6.

Figure 6 presents time series of maximum annual Tw for investigated sites. At all stations fitted LOWESS curves show that there is a general increase in maximum annual Tw throughout the investigated period. The RAPS series show two major trends in maximum annual Tw. The decreasing RAPS lines indicate that maximum annual Tw for each year in the first period are below average maximum Tw for the entire period of investigation. A shift to higher than average values occurs in 1981 for Bezdan and Veliko Gradište, but for Bogojevo the change is observed in 1988. Thus, a larger increase in maximum annual Tw at the investigated stations is observed after the 1980s (Figure 6).

The blue lines in Figure 6 show maximum annual Q at the investigated stations. The time series of RAPS for the maximum annual Q at Bezdan (Figure 6a) suggests division of the data into several smaller periods. The first period is characterized by smaller variations and ends in 1964. The second period shows a general increase in maximum annual Q that lasts only five years between 1965 and 1970. A general decreasing trend starts in 1971 and ends in 1994 when an upward trend begins. RAPS lines for Bogojovo and Veliko Gradište (Figure 6b, c) exhibit different variability, consisting of two major trends. After smaller fluctuations the increasing trend starts and ends in 1981, with a general decreasing trend thereafter.

Figure 7.

Time series of minimum annual Tw as well as minimum annual Q are shown in Figure 7. Similar to maximum and mean annual Tw, fitted LOWESS curves of minimum Tw also exhibit an increase throughout the study period. According to RAPS, series of minimum annual Tw exhibit two major trends. The decreasing trend is evident from the beginning of the investigated period until 1981 for Bezdan and Veliko Gradište and for Bogojovo until 1987. The general increasing trends last from 1982 until the end of studied period for Bezdan and Veliko Gradište, but for Bogojovo the increase began after 1987.

Mann–Kendall trend tests of the minimum annual discharge showed that only at Bogojovo station there is a statistically significant decreasing trend which, according to RAPS time series, began at approximately the same time as the upward temperature trend.

The Mann–Kendall Trend test indicate that there is a statistically significant ($p < 0.05$) increase in mean annual values at Bezdan and maximum and minimum Tw at all investigated stations (Table 3). Sen's slope estimator indicates that mean annual Danube Tw at Bezdan was rising by 0.025°C per year, in line with minimum annual values, while maximum Tw

were increasing by 0.043°C per year. Winter Tw calculated using mean monthly values at Bezdan were increasing by 0.034°C per year, while the strongest increase was detected for summer Tw at 0.054°C per year. Even though, trends are not statistically significant for mean annual and seasonal values at Bogojevo and Veliko Gradište, all are positive (Figures 5, 6, 7).

Statistically significant increasing trends were observed for annual and seasonal minimum and maximum Tw at all sites. The strongest increase was observed at Bogojevo for seasonal maximum Tw, 0.05°C per year on average (Table 3). The application of RAPS in this study is used in a complementary way with standard non parametric Mann-Kendall trend test. The characteristics of RAPS are that it could lead to information about the magnitude, start and end dates of trends (Garbrecht and Fernandez, 1994). Based on the findings presented in Table 3 and Figures 5 to 7 the increasing trend began during the 1980s.

Table 3.

Mean monthly Q was used to calculate seasonal values. Similarly maximum and minimum annual and seasonal Q values were derived using maximum and minimum monthly values. The Mann–Kendall trend test was also applied on seasonal and annual Q series for the investigated gauging stations. The results show that statistically significant downward trends are present only for summer when Q decreased by $23.4\text{ m}^3/\text{s}$ at Bezdan, $43.5\text{ m}^3/\text{s}$ at Bogojevo and $80.7\text{ m}^3/\text{s}$ at Veliko Gradište per season.

Figure 8.

Figure 8 shows average annual Tw weighted by Q at all investigated stations. The long-term average annual Tw weighted by the discharge for Bezdan station was 13.2°C . For Bogojevo and Veliko Gradište, the long-term average annual Tw weighted by the discharge was 12.4°C and 11.9°C , respectively. A statistically significant increasing trend ($p<0.05$) for average annual Tw weighted by discharge was only found at Bogojevo gauging station.

Long-term trends in weighted T_w at Bezdan and Veliko Gradište did not exhibit any statistically significant changes. This indicates that the average heat load in the moving water has not changed over the study period. Similar results were found for Danube T_w at Bratislava gauging station (Pekarova *et al.*, 2008). The authors found that the intra annual monthly runoff of the Danube at Bratislava changed as a result of increased discharge during the winter half-year but declines in summer (Pekarova *et al.*, 2008).

The annual heat flow Z_t through Bezdan ranges between 91 and 200 GJ/s, through Bogojovo from 80 to 224 GJ/s and for Veliko Gradište from 169 to 389 GJ/s (Figure 9). The highest annual natural heat load of the Danube (in Serbia) was observed in 1970 at Veliko Gradište, whereas the lowest heat load was in 1971 at Bogojovo. The Mann–Kendall test showed that a statistically significant trend does not exist in the time series of annual natural heat load of the Danube.

Figure 9.

3.3 Correlations with NAO and EAO

Annual and seasonal river T_w series were correlated with the NAO and EAO indices. The resulting correlation coefficients of Danube T_w and NAO index are presented in Table 4.

Table 4.

Statistically significant values were found for all measures of T_w on an annual basis, except for the summer and autumn at Bezdan station, spring, summer and autumn period at Bogojovo station, and winter and summer for Veliko Gradište station (Table 4). On an annual basis, correlations are relatively similar across the sites, but the strongest association between T_w residuals and the NAO was recorded at Bezdan for the winter period.

Maximum Tw values for Bogojervo do not correlate with the NAO, although a modest but significant correlation in minimum Tw was present for winter and spring. Maximum Tw residuals were also modestly but significantly correlated with the NAO in winter and spring for the Bezdan station and in spring for the Veliko Gradište station. For minimum Tw, significant correlations were recorded for all stations, with the exception of summer and autumn periods.

Correlations between EAO and Tw are shown in Table 5. Correlations are positive and statistically significant ($p < 0.05$) for all sites and seasons except for spring at Bogojervo and summer at Veliko Gradište.

Table 5.

4. DISCUSSION

Over the past two decades there has been growing interest in river Tw has changed in the past (Webb, 1996). The studies suggest that changes in climate conditions are already affecting Tw in freshwater ecosystems worldwide (Wilby *et al.*, 2010). As the stream and river temperature is of great importance (Eaton and Scheller, 1996), it is of considerable interest to understand how and why the thermal regime changed in the past in order to better predict future modifications (Webb, 1996; Moatar and Gailhard, 2006). Variations in Tw could be attributed to changes in Ta and atmospheric circulation patterns. It has been shown that Ta is a very strong predictor of Tw in streams and rivers (Webb and Nobilis, 2007). It has been reported that mean monthly Tw lags behind monthly Ta (Webb 1996; Mohseni and Stephan 1999; Pekarova *et al.*, 2008, 2011). The strong relationship between mean monthly and annual ($R^2 \sim 0.95$ and $R^2 \sim 0.5$ respectively) Ta and Tw at investigated sites correspond to

previous findings. For example, Marković *et al.* (2013) found that T_a describes more than 80% of the variance in T_w .

Additionally, variations in stream flow can significantly affect T_w , mainly through changes in thermal capacity and travel time, and dilution capacity for thermal effluents (van Vliet *et al.*, 2012; Johnson and Wilby, 2015). At Bezdan, Bogojevo and Veliko Gradište it was found that when high monthly discharge and warm temperatures prevail, the monthly T_w is lower than in the case of low discharges. van Vliet *et al.* (2012) showed that a decrease in river runoff of 25% and 50% results in significantly lower minimum T_w during winter, but also in significantly higher maximum T_w during summer. This is probably due to the smaller thermal capacity and travel times which increase sensitivity to atmospheric warming and cooling. For the Danube station, a decrease in river runoff results in higher (rather than lower) minimum T_w , and strong increases in high T_w were found (van Vliet *et al.*, 2012). For the investigated stations the decreases in mean monthly Q and mean monthly T_a results, in most cases, in lower T_w comparing to T_a and vice versa.

Webb and Nobilis (2007) assert that correlations with the NAO index are generally present in T_a and T_w . Associations between the annual and seasonal T_w and the NAO index were found to be significant for most of the cases. Webb and Nobilis (2007) found evidence that inter-annual variations in T_w of the River Traub and Danube in Austria are influenced by the North Atlantic Oscillation, especially in the winter months. Others have shown that the NAO is strongly related to variations in midwinter stream temperatures (e.g. Elliott *et al.*, 2000). Based on the results of analysis of 25 alpine streams and rivers of Switzerland, Hari *et al.* (2006) concluded that substantial warming has occurred during the last quarter of the 20th century and suggested that an abrupt increase in 1987–1988 coincided with a shift in NAO to a highly positive phase. In this study the results of RAPS showed that an increase in Danube T_w occurred approximately at the same period.

Trends in Tw may be influenced by more than one climate pattern, which operate over different timescales (Enfield *et al.*, 2001). Changes in stream and river Tw and discharge during recent decades have been attributed to the North Atlantic Oscillation, Arctic Oscillation (AO) and East Atlantic Oscillation (Labat, 2010; Pekarova *et al.*, 2003; Kondrashov *et al.*, 2005; Robertson *et al.*, 2001). Recent studies concerning trends of climate indices based on the daily maximum and minimum Ta showed that NAO and EAO dominated extreme temperature variability in Serbia during summer and winter (Unkašević and Tošić, 2013; Knežević *et al.*, 2014). Correlations between Ta and EAO in Serbia showed that the extreme temperatures are dominated by EAO and NAO during the winter and summer (Unkašević and Tošić, 2013). When EAO was in a negative phase, the sea-level pressure was below-average over Europe, and the temperatures were below mean values for Europe and Serbia. When the EAO was in the positive phase, this depression moved towards the west of the UK and temperatures over Europe and Serbia were above normal. The results obtained in this study are in agreement with the Ta analysis for Serbia (Unkašević and Tošić, 2013; Knežević *et al.*, 2014; Bajat *et al.*, 2014). There is a statistically significant correlation between Tw and EAO for all gauging stations ($p < 0.05$) (Table 5). Generally, the highest correlations were found for Bezdan which is the most upstream station. This could be explained by lower flow volumes as well as negligible influence of tributaries. Upstream of Bezdan there are not many tributaries with discharges large enough to modify the natural temperature regime of the river Danube. Only downstream from Bezdan does the Danube receive water from Drava, Tisza, Sava and Velika Morava Rivers and hence additional influences on the thermal regime.

According Kržič *et al.* (2011), near surface Ta in Serbia could increase by 2 to 4°C and the seasonal precipitation decrease by between 13 and 6 mm under the SRES A1B and A2 scenarios for 2071–2100. This would be expected to increase Tw in the rivers of Serbia.

Along the Danube in Serbia, there are several protected areas such as Ramsar sites, Gornje Podunavlje, Kovilj-Petrovaradin Marshes and Labudovo Okno. Changes in Danube Tw could exert profound effects on aquatic ecology in these areas. Reduced ability of aquatic species to either cope with changing temperatures or to migrate to new habitats may leave rivers species poor, eutrophic, or toxic (Orr *et al.*, 2015). According to our results Tw is rising in the Danube River. This is crucial for aquatic species, ecosystem and human activities which could face serious deterioration, in the absence of management that is directly designed to address the multiple ways by which climate change affects aquatic ecosystems.

5. CONCLUSION

The present study represents the first high resolution trend analysis for Tw in the River Danube, Serbia. Ta has been linked to rising Tw in many previous studies (e.g. Pekarova *et al.*, 2011, 2008; Bonacci *et al.*, 2008) and is confirmed for the Danube. Over the long-term, Tw in the river approximates ambient Ta. However, inter-annual variations in Tw are influenced by natural climate variations operating in the North Atlantic region. These relationships warrant further investigation and could form the basis of a seasonal prediction system for Ta and Tw in Serbia.

Danube Tw in Serbia is measured daily at 7.00 a.m. A denser monitoring network is needed to identify Danube river water behaviour and reaches that are particularly sensitive to future warming. This would also provide better baseline data from which to make projections about changes and a reference point for prioritizing resources for interventions.

Using relationships between Ta and Tw in combination with the output of Regional Climate Models it would be possible to explore how Tw and natural heat loads of the Danube might vary in the future. With these results adaptation strategies could be presented in order

to buffer undesirable effects of river warming. It has been claimed that effective conservation of freshwater species under climate change requires protected zones and wilderness areas that encompass entire catchments, in addition to connective corridors between watersheds, to allow species migration and adaptation (Heino *et al.*, 2009). Along the Danube in Serbia there are several Ramsar sites which could be better connected thus ideally combining conservation goals for freshwater and terrestrial species and landscapes.

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Figure 1. Study area showing gauging stations (red dots) and meteorological stations (orange dots).

Figure 2. Average annual discharge Q of the Danube Bezdan (black line), Bogojevo (red line) (1950–2012) and Veliko Gradište (blue line) (1950–2007). Average annual T_w of Danube at Bezdan (black line), Bogojevo (red line) and Veliko Gradište (blue line) (1950–2012). Variation of the T_a at the Sombor station (black) and Veliko Gradište (blue) (1950–2012).

Figure 3. (a) Monthly mean T_w at the Bezdan station (T_w) and T_a at Sombor (T_a). (b) Relationship between T_w and T_a averages, showing hysteresis loop.

Figure 4. Logistic regression models for a) Bezdan, b) Bogojewo and c) Veliko Gradište showing local α (horizontal dashed line) and β parameters (vertical dashed line).

Figure 5. Time series of mean annual Tw at a) Bezdan, b) Bogojewo and c) Veliko Gradište with fitted LOWESS curves. Also shown are time data series of the rescaled adjusted partial sums (RAPS) for the mean annual Tw at three investigated sites. Blue lines represent minimum annual discharge as well as RAPS for the same stations.

Figure 6. Time series of maximum annual Tw at investigated stations a) Bezdan, b) Bogojevo and c) Veliko Gradište with fitted LOWESS curves. Also shown are time data series of the rescaled adjusted partial sums (RAPS) for the maximum annual Tw at three investigated sites. Blue lines represent maximum annual discharge rates as well as RAPS for the same stations.

Figure 7. Time series of minimum annual Tw (black lines) at investigated stations stations a) Bezdan, b) Bogojewo and c) Veliko Gradište with fitted LOWESS curves. Also shown are time data series of the rescaled adjusted partial sums (RAPS) for the minimum annual Tw (black lines) at three investigated sites. Blue lines represent minimum annual discharge rates as well as RAPS for the same stations.

Figure 8. Weighted average of the annual Danube water temperatures T_w at a) Bezdan b) Bogojewo and c) Veliko Gradište during 1950–2012, with the long-term trend shown.

Figure 9. Annual heat flows, Z_t , at a) Bezdan, b) Bogojewo and c) Veliko Gradište for the period 1950–2012.

Table 1. Description of mean annual discharge rates and water temperature at three gauging stations during the period 1950–2012.

Station name	Elevation H (m a.s.l.)	Basin area A (km ²)	Distance from mouth L (km)	Period of available data	Mean annual discharge Q (m ³ /s)	Mean annual Temperature T (°C)
Bezdan	80.64	210250	1425.6	1950-2012	2282.259	12.08
Bogojevo	77.46	251593	1367.3	1950-2012	2801.034	11.70
Veliko Gradište*	62.17	570375	1059.8	1950-2012	5492.105	12.24

*Data for maximum and minimum Danube water temperatures are obtained for period 1953–2012.

Table 2. Statistical error parameters for linear, polynomial, and logistic regression models fit to mean monthly Tw and mean monthly Ta at the investigated sites. Also shown is the amount of explained variance (R^2).

Bezdan			
	Linear	Polynomial	Logistic
MAE (°C)	1.27	1.23	1.17
RMSQ (°C)	1.59	1.52	1.49
R²	0.95	0.95	0.96
Bogojevo			
	Linear	Polynomial	Logistic
MAE (°C)	1.38	1.31	1.30
RMSQ (°C)	1.75	1.66	1.70
R²	0.94	0.95	0.95
Veliko Gradište			
	Linear	Polynomial	Logistic
MAE (°C)	1.21	1.17	1.09
RMSQ (°C)	1.50	1.44	1.41
R²	0.96	0.96	0.96

Table 3. Annual and seasonal trend coefficients of Danube water temperatures, red and italic correspond to $p < 0.01$ and only red to $p < 0.05$.

Mean Danube water temperature									
	Bezdan			Bogojevo			Veliko Gradište		
	tau	Sen's slope	Start	tau	Sen's slope	Start	tau	Sen's slope	Start
annual	<i>0.46</i>	<i>0.025</i>	1980	0.03	0.000	-	0.11	0.005	-
winter	<i>0.40</i>	<i>0.034</i>	1970	0.00	0.002	-	0.014	0.003	-
spring	<i>0.45</i>	<i>0.045</i>	1997	0.03	0.000	-	0.074	0.003	-
summer	<i>0.51</i>	<i>0.054</i>	1988	0.04	0.002	-	0.081	0.003	-
autumn	<i>0.56</i>	<i>0.043</i>	1996	0.03	0.003	-	0.016	0.003	-

Max Danube water temperature									
	Bezdan			Bogojevo			Veliko Gradište		
	tau	Sen's slope	Start	tau	Sen's slope	Start	tau	Sen's slope	Start
annual	<i>0.57</i>	0.043	1981	<i>0.32</i>	0.025	1987	<i>0.45</i>	0.024	1985
winter	<i>0.46</i>	0.040	1986	<i>0.52</i>	0.050	1986	<i>0.25</i>	0.027	1986
spring	<i>0.39</i>	0.046	1988	<i>0.53</i>	0.050	1988	0.20	0.016	1988
summer	<i>0.49</i>	0.046	1988	<i>0.38</i>	0.050	1989	<i>0.28</i>	0.023	1990
autumn	<i>0.39</i>	0.038	1987	<i>0.48</i>	0.053	1988	<i>0.24</i>	0.022	1980

Min Danube water temperature									
	Bezdan			Bogojevo			Veliko Gradište		
	tau	Sen's slope	Start	tau	Sen's slope	Start	tau	Sen's slope	Start
annual	<i>0.44</i>	0.025	1980	<i>0.54</i>	0.038	1986	<i>0.48</i>	0.035	1991
winter	0.03	0.004	1970	<i>0.32</i>	0.025	1987	<i>0.33</i>	0.027	1993
spring	<i>0.30</i>	0.030	1988	<i>0.40</i>	0.050	1987	<i>0.33</i>	0.035	1987
summer	<i>0.40</i>	0.041	1986	<i>0.39</i>	0.050	1989	<i>0.34</i>	0.037	1991
autumn	<i>0.36</i>	0.029	1979	<i>0.40</i>	0.037	1983	<i>0.31</i>	0.031	1980

Table 4. Correlation coefficients between the NAO index and Danube Tw at Bezdan, Bogojevo and Veliko Gradište

Mean Danube water temperature						
	Bezdan		Bogojevo		Veliko Gradište	
	Spearman's rho	p-value	Spearman's rho	p-value	Spearman's rho	p-value
annual	0.35	0.00	0.31	0.00	0.34	0.00
winter	0.39	0.00	0.25	0.03	0.13	0.15
spring	0.34	0.00	0.15	0.11	0.28	0.01
summer	-0.11	0.79	0.11	0.20	-0.03	0.58
autumn	0.11	0.20	0.20	0.05	0.32	0.00

Max Danube water temperature						
	Bezdan		Bogojevo		Veliko Gradište	
	Spearman's rho	p-value	Spearman's rho	p-value	Spearman's rho	p-value
annual	0.31	0.01	0.20	0.06	0.28	0.01
winter	0.23	0.04	0.20	0.06	0.10	0.21
spring	0.25	0.02	0.17	0.09	0.25	0.03
summer	-0.04	0.62	-0.16	0.89	-0.05	0.66
autumn	0.13	0.16	0.00	0.49	0.17	0.09

Min Danube water temperature						
	Bezdan		Bogojevo		Veliko Gradište	
	Spearman's rho	p-value	Spearman's rho	p-value	Spearman's rho	p-value
annual	0.45	0.00	0.33	0.00	0.19	0.07
winter	0.35	0.00	0.39	0.00	0.16	0.11
spring	0.38	0.00	0.22	0.04	0.29	0.01
summer	-0.07	0.71	-0.05	0.66	-0.12	0.83
autumn	0.18	0.07	0.12	0.17	0.16	0.10

Table 5. Correlation between EAO and Danube Tw at Bezdan, Bogojevo and Veliko Gradište

Mean Danube water temperature						
	Bezdan		Bogojevo		Veliko Gradište	
	Spearman's rho	<i>p</i> -value	Spearman's rho	<i>p</i> -value	Spearman's rho	<i>p</i> -value
annual	0.59	0.000	0.29	0.011	0.32	0.007
winter	0.50	0.000	0.25	0.025	0.30	0.010
spring	0.33	0.004	0.20	0.061	0.30	0.021
summer	0.52	0.000	0.27	0.018	0.20	0.077
autumn	0.47	0.000	0.23	0.033	0.30	0.012

Max Danube water temperature						
	Bezdan		Bogojevo		Veliko Gradište	
	Spearman's rho	<i>p</i> -value	Spearman's rho	<i>p</i> -value	Spearman's rho	<i>p</i> -value
annual	0.65	0.000	0.61	0.000	0.70	0.000
winter	0.60	0.000	0.58	0.000	0.50	0.000
spring	0.39	0.001	0.33	0.004	0.30	0.016
summer	0.49	0.000	0.50	0.000	0.40	0.002
autumn	0.33	0.004	0.30	0.010	0.34	0.004

Min Danube water temperature						
	Bezdan		Bogojevo		Veliko Gradište	
	Spearman's rho	<i>p</i> -value	Spearman's rho	<i>p</i> -value	Spearman's rho	<i>p</i> -value
annual	0.56	0.000	0.64	0.000	0.74	0.000
winter	0.23	0.034	0.44	0.000	0.42	0.000
spring	0.21	0.046	0.30	0.013	0.44	0.000
summer	0.44	0.000	0.50	0.000	0.53	0.000
autumn	0.57	0.000	0.50	0.000	0.55	0.000