Spatial and temporal variability of precipitation in Serbia for the period 1961–2010

Article *in* Theoretical and Applied Climatology · October 2017

DOI: 10.1007/s00704-017-2118-5

Theor Appl Climatol
DOI 10.1007/s00704-017-2118-5

ORIGINAL PAPER

Spatial and temporal variability of precipitation in Serbia for the period 1961–2010

Boško Milovanović[1] · Phillip Schuster[2] · Milan Radovanović[1,3] · Vesna Ristić Vakanjac[4] · Christoph Schneider[2]

Received: 10 June 2016 / Accepted: 5 April 2017

Abstract Monthly, seasonal and annual sums of precipitation in Serbia were analysed in this paper for the period 1961–2010. Latitude, longitude and altitude of 421 precipitation stations and terrain features in their close environment (slope and aspect of terrain within a radius of 10 km around the station) were used to develop a regression model on which spatial distribution of precipitation was calculated. The spatial distribution of annual, June (maximum values for almost all of the stations) and February (minimum values for almost all of the stations) precipitation is presented. Annual precipitation amounts ranged from 500 to 600 mm to over 1100 mm. June precipitation ranged from 60 to 140 mm and February precipitation from 30 to 100 mm. The validation results expressed as root mean square error (RMSE) for monthly sums ranged from 3.9 mm in October (7.5% of the average precipitation for this month) to 6.2 mm in April (10.4%). For seasonal sums, RMSE ranged from 10.4 mm during autumn (6.1% of the average precipitation for this season) to 20.5 mm during winter (13.4%). On the annual scale, RMSE was 68 mm (9.5% of the average amount of precipitation). We further analysed precipitation trends using Sen's estimation, while the Mann-Kendall test was used for testing the statistical significance of the trends. For most parts of Serbia, the mean annual precipitation trends fell between −5 and +5 and +5 and +15 mm/decade. June precipitation trends were mainly between −8 and +8 mm/decade. February precipitation trends generally ranged from −3 to +3 mm/decade.

✉ Boško Milovanović
b.milovanovic@gi.sanu.ac.rs

[1] Geographical Institute "Jovan Cvijić" of the Serbian Academy of Sciences and Arts, Djure Jakšića 9, Belgrade 11000, Serbia

[2] Geographisches Institut, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany

[3] Perm National Research Polytechnic University, Perm, Russia

[4] Department of Hydrogeology, Faculty of Mining and Geology, University of Belgrade, Djušina 7, Belgrade 11000, Serbia

1 Introduction

Due to their importance for impact on the environment and many spheres of human activity (water resources, ecosystems, agriculture, economic planning, etc.), climate and climate change are crucial fields of contemporary scientific research. In this paper, the focus will be on the spatial variance of precipitation and precipitation trends in Serbia for the period 1961 to 2010.

Since the characterization of climate for a given area is based on data obtained from a limited number of often irregularly distributed weather stations, the climate of areas where no meteorological observations are performed remains insufficiently known. Therefore, it is necessary to interpolate the values of climatic elements (knowing the impacts of various climate factors) for areas where no measurements have been performed. Chilès and Delfiner (1999) suggest that the reconstruction of a phenomenon over a domain on the basis of values sampled at a limited number of points is the central problem in corresponding studies. When interpolating values of climatic elements, the lack of observations from a sufficiently large number of weather stations can be compensated for by using indirect data (e.g. data about areas where there are data from weather stations regarding altitude, latitude, longitude and distance from the sea) and by determining the functional dependence of the values of climatic elements from these data. For this purpose, a large number of interpolation

Published online: 10 April 2017

techniques, e.g. various types of kriging (Burrough and McDonell 1998), have been devised. However, after interpolation, there is still a need to verify and evaluate the obtained results and the used methods. In this regard, a particularly important study for Serbia is a study by Bajat et al. (2013), in which the authors performed the interpolation of precipitation data for Serbia based on data obtained from 1014 precipitation stations using regression kriging and multiple regression analysis and ran an accuracy assessment by comparing the results obtained by the two methods. It should be pointed out that the authors performed the interpolation of precipitation data and an assessment of various interpolation techniques for an earlier period (1961–1990), while Prohaska et al. (2012) performed the interpolation of precipitation in the period 1946–2006 using elevation data for 437 precipitation stations. Štrbac (2014) presented an indirect method for modelling the spatial distribution of precipitation. By introducing a coefficient defined as the ratio between precipitation and altitude, he obtained an annual precipitation for Serbia in the period 1961–2010.

Another important segment of acquiring information on climate and climate change in a particular area is the time series analysis of the observed climatic elements. There are a number of papers dealing with the trend analysis of air temperature or precipitation of Serbia which generally cover a fairly small number of weather-observing stations (e.g. Bajat et al. (2014) for temperature; Luković et al. (2014) for precipitation; Milovanović (2014) for urban temperature; Savić et al. (2014) for extreme temperature in relation to atmospheric circulation), and there is only one study discussing the cyclic component of precipitation based on data obtained from more than one weather observation station (Tošić 2004). To the best of our knowledge, there are only two contributions (Pandžić et al. 2013; Prohaska et al. 2012) which deal with the stochastic time series analysis of precipitation in Serbia. Along with the lack of studies dealing with deterministic and stochastic components of the time series of precipitation amounts obtained from a large number of weather observation stations in the recent period (until 2010), there is also an evident lack of spatially consistent information on climate elements. In particular, the last Climate Atlas of the Socialist Federal Republic of Yugoslavia (1985) presented data analyses for the period 1931–1960. Other more recent station-based datasets that include the study area such as the Climate Research Unit dataset of the University of East Anglia (Harris et al. 2014) or daily precipitation products of the Global Precipitation Climatology Centre (GPCC) at the German Weather Service (Schamm et al. 2013) are provided at much lower spatial resolution only than the one aimed at in this study.

Bearing in mind the aforementioned information, the main objective of this study is to achieve more detailed and accurate knowledge about the spatial distribution of precipitation and precipitation trends in Serbia for the period 1961–2010 while approaching the following key questions:

1. What are the temporal and spatial variations of precipitation amounts in Serbia in the period 1961 to 2010?
2. What would be the optimal approach to interpolate the values of precipitation on the basis of indirect data (spatial data: altitude, latitude, longitude, slopes and exposition of the terrain near precipitation stations)?
3. How accurate are the interpolated values?

In this study, we limit the set of methods to the statistical analysis and spatial interpolation using as predictors only temporally invariant predictors. This allows processing of data within a geographical information system (GIS) without extensive computational costs. Since this approach is not building on atmospheric numerical modelling but only on observations and statistical approaches, the results can be used to compare with and benchmark against more advanced numerical weather modelling products or dynamically downscaled products from global weather or climate models. All spatial data produced in this study can be downloaded as geo-coded GIS raster data from a website hosted at Humboldt University, Berlin (https://www.geographie.hu-berlin.de/en/professorships/climate_geography/climate_serbia/).

2 Data and methods

Serbia is located in the southeast of Europe (Fig. 1) covering a topographically diversified area of over 88,000 km^2. In the north, there is a plain (Pannonian Plain), while hilly and mountainous terrain prevails in the rest of the country. The altitude varies from 28 m (northeastern part of the country) to 2656 m on Peak Djeravica (southwestern area). There are three main types of climate in Serbia: continental (in the north), moderate continental (in the central, western, eastern and southern parts of the country), and modified Mediterranean climate (in the southwest). Precipitation ranges from 500 to 600 mm in the northern part of Serbia to more than 1100 mm in the western mountains. In almost the whole study area, the precipitation regime is continental with two maxima (the primary in May or June and the secondary in November or December) and two minima (the primary in January or February and the secondary in September or October) except for the southwestern part of the country (Metohija), where influences of Mediterranean climate with a precipitation maximum during winter months and a minimum in August can be observed (Ducić and Radovanović 2005).

The data of Republic Hydrometeorological Service of Serbia obtained from 421 precipitation stations in the period 1961–2010 were used to create a spatial model of precipitation

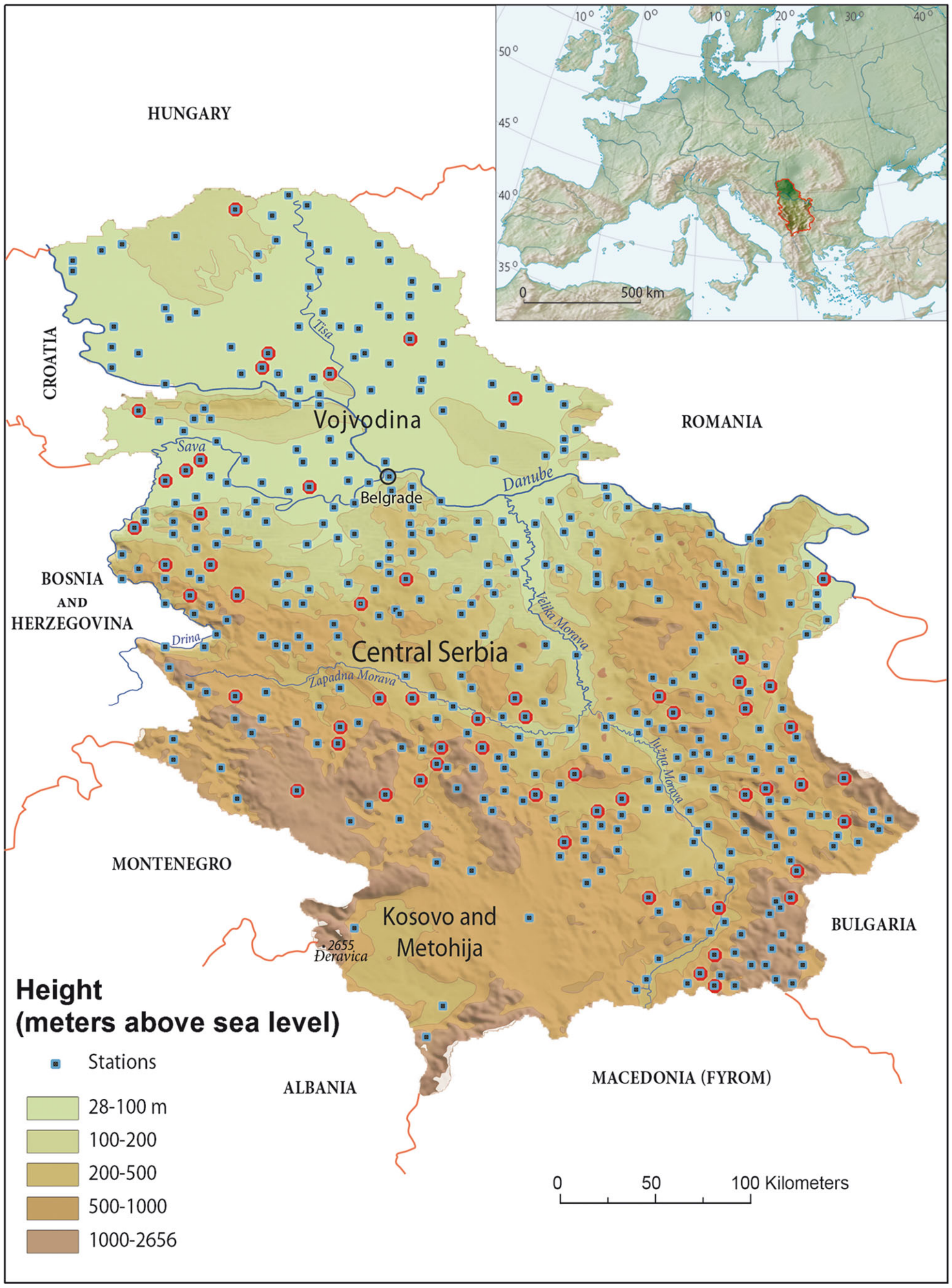


Fig. 1 Relief of Serbia and position of precipitation stations. Stations marked with *red circles* show statistically significant trends of precipitation on annual scale; *inset*: position of Serbia in Europe

in Serbia (Fig. 1). Except for Kosovo and Metohija, for which we have had data for seven stations only, the remaining part of Serbia is relatively well and uniformly represented by weather stations. However, in mountainous terrains, with increasing altitude, the number of stations decreases significantly (Table 1).

In the process of filling in missing data, we first sought to determine the correlation coefficient between spatially close pairs of stations. Correlation coefficients were not established at the level of annual values, but for each pair of stations, the correlation coefficient was determined separately for each month. For missing data, a combination of methods was then used in order to fill in the missing values based on pairs of stations with maximum correlations in the specific month of consideration. The method of data reduction with the same number of years was used in the first place: At station A for which there is a lack of data of the amount of rainfall for a specific month in a given year Y_t, the mean value of precipitation R_a for the particular month in all other months is calculated. Then the mean value of R_b is calculated over the same

Table 1 Distribution of precipitation stations by altitude ranges

Altitude range (m a.s.l.)	Number of stations	Surface area (km^2) (Ćalić et al. 2017)	Percentage of Serbia
28–100	104	20,897.61	23.6
101–200	79	11,592.39	13.1
201–300	56	8180.55	9.2
301–400	41	6839.39	7.7
401–500	41	6660.39	7.5
501–600	25	6746.58	7.6
601–700	24	5790.80	6.5
701–800	9	4743.75	5.4
801–900	12	3873.98	4.4
901–1000	11	3170.70	3.6
1001–1100	10	2619.72	3.0
1101–2656	9	7327.53	8.2

months at station B, where there is a measured amount of rainfall in the particular year Y_t ($R_{b(Y_t)}$) as well. Then a proportion is set to derive rainfall in month i at station A in the year Y_t ($R_{a(Y_t)}$) according to

$$R_{a(Y_t)} = \frac{R_a R_{b(Y_t)}}{R_b} \quad (1)$$

Secondly, we interpolated missing data using a matrix-based approach. For this purpose, we used a matrix with eight elements.

Basically, the method of interpolation using the matrix approach consists of the following steps: if at a station A there is a lack of information on the amount of rainfall for a certain month M_t in a certain year Y_t, then the sum of precipitation in M_{t-1}, M_t and M_{t+1} is calculated in the years Y_{t-1}, Y_t and Y_{t+1} (so we obtain a matrix of eight data). Here we set M_t for Y_t at station A to 0. The same procedure is applied to a station B in which there is a measured value of rainfall M_t for Y_t and which has a high correlation in this month with a station A. Then the quotient of the two sums of stations A and B (Q) is calculated. Subsequently, M_t for Y_t of station B is multiplied with Q. The result is entered in the place of M_t for Y_t at station A (Vujević 1956).

The third method used was an extrapolation based on the assumption of constant statistical relation of shorter and longer series (Radovanović and Milovanović 2003).

Extrapolation of precipitation for a station A at which there are no data for a particular month i in one or more years is performed by the calculation of the monthly mean of precipitation at station A in month i (R_{ai}). Then for station B that has all the information for the same month, the mean value of the entire series (R_{bc}) and the mean value (R_{bi}) of the incomplete series are calculated, that is, only for those years for which data are available at station A. The calculation of the mean rainfall to complete the record at station A for a particular

Table 2 Statistics of multiple linear regression model

Dependent variable (precipitation amount)	Predictor significance (t value / p level)			Coefficient of determination (R^2)
	Longitude	Altitude	Slope	
January	−6.10 / 0.01	3.97 / 0.01	7.47 / 0.01	0.34
February	−3.48 / 0.01	4.80 / 0.01	8.47 / 0.01	0.41
March	−5.60/ 0.01	4.75 / 0.01	9.08 / 0.01	0.43
April	−2.73 / 0.01	5.11 / 0.01	9.58 / 0.01	0.47
May	−9.34 / 0.01	6.92 / 0.01	12.01 / 0.01	*0.59*
June	−15.81 / 0.01	2.41 / 0.02	6.31 / 0.01	0.41
July	−20.27 / 0.01	2.95 / 0.01	8.30 / 0.01	*0.53*
August	−21.19 / 0.01	3.09 / 0.01	7.90 / 0.01	*0.55*
September	−17.64 / 0.01	6.30 / 0.01	9.19 / 0.01	*0.56*
October	−10.91 / 0.01	5.46 / 0.01	8.35 / 0.01	0.48
November	−7.76 / 0.01	7.26 / 0.01	8.76 / 0.01	*0.50*
December	−5.34 / 0.01	3.55 / 0.01	7.43 / 0.01	0.32
Annual	−12.77 / 0.01	5.45 / 0.01	10.03 / 0.01	*0.51*
Spring	−6.59 / 0.01	6.11 / 0.01	11.13 / 0.01	*0.54*
Summer	−19.17 / 0.01	2.92 / 0.01	7.79 / 0.01	*0.52*
Autumn	−13.23 / 0.01	7.01 / 0.01	9.64 / 0.01	*0.54*
Winter	−5.12 / 0.01	4.20 / 0.01	8.01 / 0.01	0.37

Statistically significant values of R^2 is shown in italic

Table 3 Root mean square error (RMSE) and the mean absolute error (MAE) of the modelled values for precipitation in Serbia

	RMSE (mm)	MAE (mm)	Average (mm)	RMSE (%)	MAE (%)
I	4.9	3.5	48.5	10.1	7.2
II	4.0	3.2	46.3	8.6	6.9
III	5.3	3.7	50.3	10.5	7.4
IV	6.2	4.4	59.4	10.4	7.4
V	4.3	3.2	72.9	5.9	4.4
VI	5.8	4.6	85.9	6.8	5.4
VII	5.2	4.1	65.6	7.9	6.3
VIII	5.4	3.6	56.2	9.6	6.4
IX	4.5	3.5	56.2	8.0	6.2
X	3.9	2.9	51.7	7.5	5.6
XI	5.6	4.1	61.7	9.1	6.6
XII	5.9	4.3	60.8	9.7	7.1
Annual	68.0	46.6	715.5	9.5	6.5
Winter	20.5	13.1	152.5	13.4	8.6
Spring	16.9	12.7	182.4	9.3	7.0
Summer	18.3	11.1	207.5	8.8	5.3
Fall	10.4	7.9	169.5	6.1	4.7

month (R_{ac}) of all years for which data are available at station B is made according to

$$R_{ac} = \frac{R_{ai} R_{bc}}{R_{bi}} \quad (2)$$

Given the expectation to be justified that the use of a large number of predictors will result in more accurate information on the criterion variable, in our case on precipitation, such an approach is selected in this paper.

To obtain more information on altitude, slope and aspect, data of the SRTM (Shuttle Radar Topography Mission) digital elevation model (DEM) were used at a resolution of 30 × 30 m. Additionally, two extra rasters were formed for testing the impact of longitude and latitude on precipitation.

In order to get information on the local factors (slope and aspect of the terrain around the station), circular 'buffer' zones with a radius of 10 km around each precipitation station were selected. The mean values and standard deviations of the variables were calculated for each station's buffer from the DEM. This created a set of seven predictor variables (latitude, longitude, altitude of station, mean values and standard deviations of the slope and aspect of the buffer zones around precipitation stations).

The variables were selected as predictors due to their explaining power for the spatial distribution of precipitation according to direct linear correlations. Masson and Frei (2014) have shown that the consideration of topography effects is important for spatial interpolation of precipitation. Guan et al. (2005) suggest that the exposure of the terrain in relation to sources of moisture plays an important role in the spatial variability of rainfall but that this is often not captured by precipitation products with low spatial resolution. Gao et al. (2006), using data of extreme and mean rainfall from a regional model (RegCM3), revealed that there are substantial and seasonally dependent fine-scale topographically induced structures in the climate change signal over a number of regions of the Mediterranean area (i.e. the Alpine and Balkan regions, the Iberian, Italian and Hellenic peninsulas, and the Northern African coastal regions). Serbia is characterized by highly dissected relief. It is separated by a mountain range from the Mediterranean Sea as a source of moisture. Therefore, with increasing latitude and longitude, i.e. with distancing from the sea, precipitation decreases and the degree of continentality increases. Rakićević (1979) states that comparing pluviometric gradients, it was found that the places at the same altitudes and approximately the same parallels receive annually 1.11 mm less rainfall at every kilometer distance when moving from west to east. This is supported by the fact that the maritime pluviometric regime is recorded only in the extreme southwest of the country, which is connected to the Adriatic Sea by the Beli Drim river valley.

The Mann-Kendall test was applied to detect and evaluate the statistical significance of precipitation trends. According to Salmi et al. (2002), this test is useful in cases where there is a monotonic trend (excluding seasonal and cyclical variations) while Sen's method is suitable for assessing slope trends. In the application of these methods, the series can also be used in case of missing values. Further, these tests are independent of the type of distribution. Given the fact that Sen's slope rating trend represents the median value of the successive changes per unit of time, this method is insensitive to individual errors and outliers (Ahmad et al. 2015). According to Sutapa and Galib (2016), Sen's slope estimation can be calculated if there is a linear trend in the form

$$f_t = Q_t + B \tag{3}$$

where Q is the slope and B is a constant. To obtain slope Q in Eq. (3), it is necessary to calculate the slope for all data with the equation

$$Q_i = \frac{X_j - X_k}{j - k} \tag{4}$$

with $j > k$. If there are 'n' values of 'X_j' in a time series, Q is obtained as $N = n(n-1) / 2$ slope estimation Q_i. Sen's slope estimate is the median of N values of Q_i. N values of Q_i are ranked from small to large, with an estimated Sen's slope:

$$Q = Q_{\left[\frac{N+1}{2}\right]} \text{ if } N \text{ is odd}$$

or

$$Q = 0.5\left(Q_{\left(\frac{N}{2}\right)} + Q_{\left(\frac{N+2}{2}\right)}\right) \text{ if } N \text{ is even}$$

To obtain estimates of B in Eq. (3), the values of n data from the difference $(Xi - Q_{ti})$ are calculated. The median value is the estimate for B.

For interpolation of Sen's slope estimation of trends, the method of radial basis functions was used whereby (at this stage) their possible dependence on the characteristics of the terrain (position and altitude of the stations, slope and orientation of the terrain in their environment) was not investigated.

All data preprocessing and statistical computing concerning multiple linear regression and trend analysis have been done using R (R Development Core Team 2008); for interpolation, spatial analysis and mapping, ArcGIS by Esri (Esri 2011) and open-source QGIS (QGIS Development Team 2015) were used.

3 Results and discussion

Using the data and procedures described above, 34 maps were produced (17 maps of the spatial distribution of precipitation and 17 maps of the precipitation trends for the period 1961–2010). The combined influence of the predictors according to

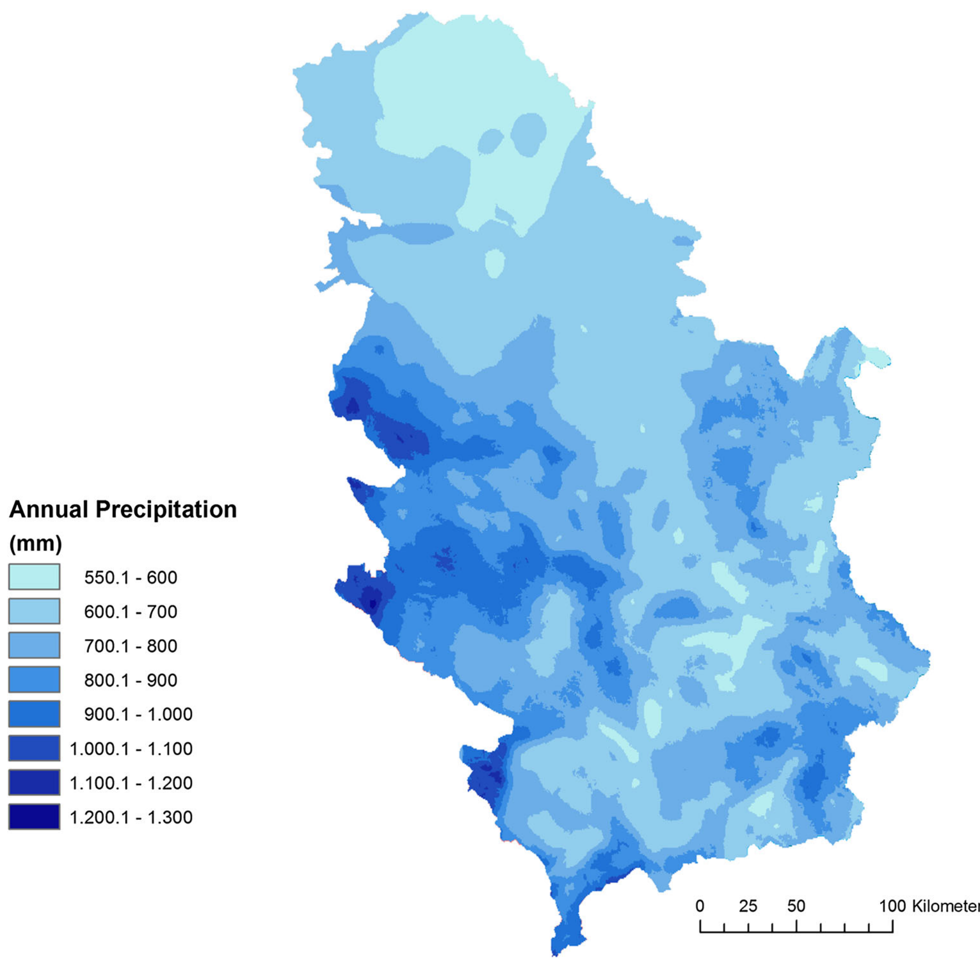


Fig. 2 Spatial distribution of annual amounts of precipitation in Serbia in the period 1961–2010

the best fitting statistical model was subtracted from the observations. Residuals were interpolated using simple kriging. Using the inverse of this procedure, a raster of the values of precipitation at each grid point was created. In other words, by adding the interpolated residual at each grid point to the modelled influence of altitude, longitude and slope, precipitation was obtained for any grid point of the study area. To avoid overfitting and visualization of unrealistic micro-scale details, the final computation of spatial precipitation products was carried out at a raster size of 500 m. Due to the fact that they cannot be all presented here, a description of the results will be given using six selected maps (mean annual precipitation, mean precipitation in June as the rainiest month and in February as the month with the lowest rainfall at most stations, and trends of mean annual, June and February precipitation). Further, the variability of annual precipitation sums in the period of observations is presented.

3.1 Model accuracy

As it is already mentioned, a set of seven predictor variables was created. A regression model drawing the greatest proportion of the precipitation variances was chosen. It turned out that in all cases (at the level of monthly, seasonal and annual precipitation), the most statistically significant were the predictors of altitude, longitude and mean value of slope. The value of the coefficient of determination in the regression models from these three predictors ranged from $R^2 = 0.32$ in December to $R^2 = 0.59$ in May (Table 2). The effect of other predictors was not statistically significant or marginally contributing to the involvement of the variance of precipitation (<1%). In the next step, the set of data was divided into a subset of test data (10% of all stations, that is, 42 randomly selected stations) and a subset for modelling (the remaining 90% or 379 stations).

The accuracy of the model was validated by calculating the root mean square error (RMSE) and the mean absolute error (MAE) between the modelled values for precipitation and the observed precipitation from the test data (Table 3). Regarding the seasonal precipitation values, the greatest errors of the model occurred during winter (13.5% of the average precipitation at all stations), while the lowest were found in autumn (6.1% of the average precipitation at all stations). For monthly values, the lowest errors were detected for May and June (5.9 and 6.8%, respectively), which are the rainiest months in most parts of Serbia, while the highest errors occurred in January,

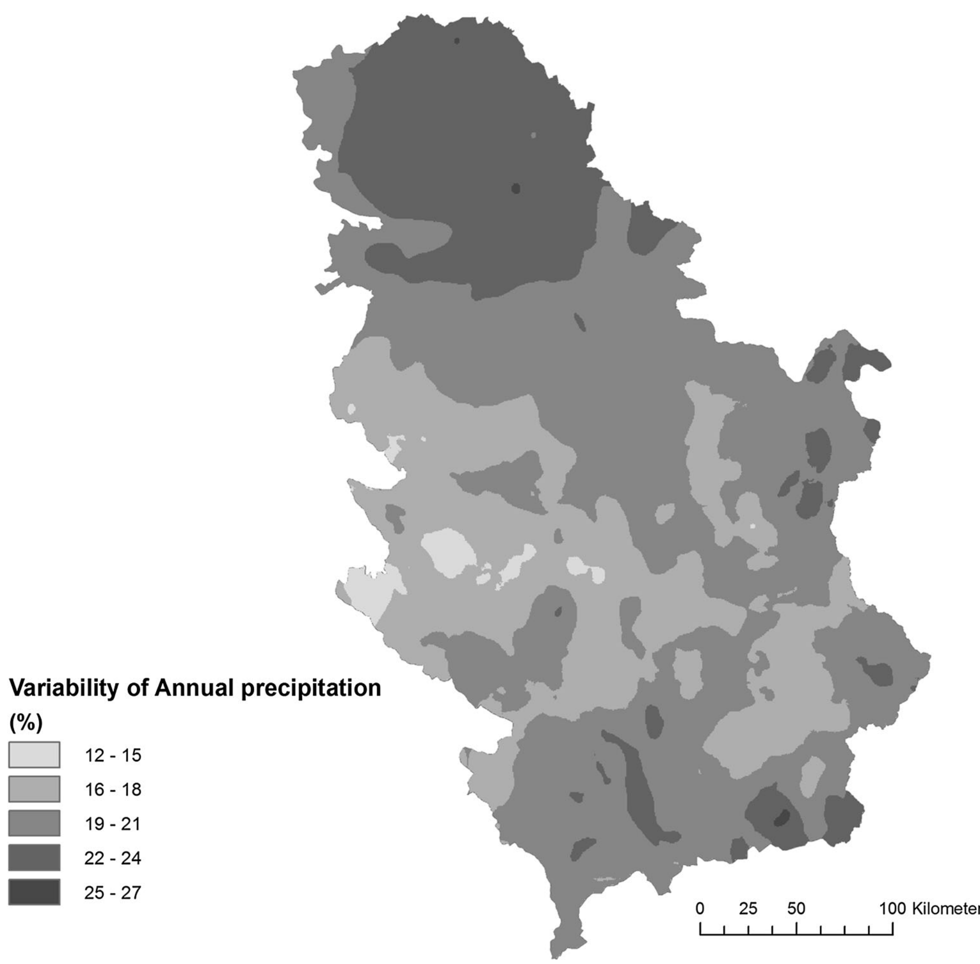


Fig. 3 Spatial distribution of the variability of annual precipitation in Serbia in the period 1961–2010

March and April, ranging from 10.1 to 10.5%. Generally, the errors of the model are less than 10% (Table 3). MAE of monthly values fell between 2.9 mm in October (5.6% of the average amount of precipitation for this month) and 4.6 mm in June (5.4% of the average amount of precipitation for this month). For seasonal sums, MAE ranged from 7.9 mm during autumn (4.7% of the average amount of precipitation during this season) to 13.1 mm during winter (8.6% of the average amount of precipitation during this season). On the annual scale MAE was 46.6 mm (6.5% of the average amount of precipitation).

3.2 Spatial distribution of precipitation

The average annual precipitation of 500–600 mm is characteristic of the eastern part of Vojvodina (the northern province of Serbia) and smaller parts of the Južna and the Velika Morava valleys (Fig. 2). In the western part of Vojvodina, central parts of Serbia at the lower terrains and the largest part of Kosovo and Metohija, precipitation ranges between 600 and 700 mm. In the mountainous areas of central Serbia, rainfall reaches 700–800 mm. This amount of precipitation is also characteristic of parts of southwestern Serbia, parts of Metohija and the north of Kosovo and the parts of the lower mountain terrains of eastern and southern and southeastern Serbia. The average annual precipitation of 800–900 mm is characteristic of the mountainous terrains of eastern and southern Serbia, as well as the hilly and mountainous areas of central Serbia, while the mean annual precipitation of 900–1000 mm is found only at the highest terrains in the central part of Serbia. The average annual amount of 1000–1100 mm mainly characterizes the westernmost and the furthest southwestern parts of the country, while precipitation above 1100 mm can only be found in the highest terrains in this part of Serbia. The computation of spatial variability of annual precipitation (Fig. 3) was carried out in the same way as outlined above for the precipitation sums using primarily altitude (r = 0.26) and subsequently on residuals longitude (r = 0.2) and slope (r = 0.11) as predictors. Residuals were interpolated using simple kriging in the same way as for precipitation sums and precipitation trends. Variability at each station or grid point is defined as the percentage of calculated as the ration of mean standard deviation and annual precipitation sum. An obvious spatial pattern occurs with larger variabilities of up to 27% in the north of the study area and lowest variabilities of between 12 and 15% in the central western

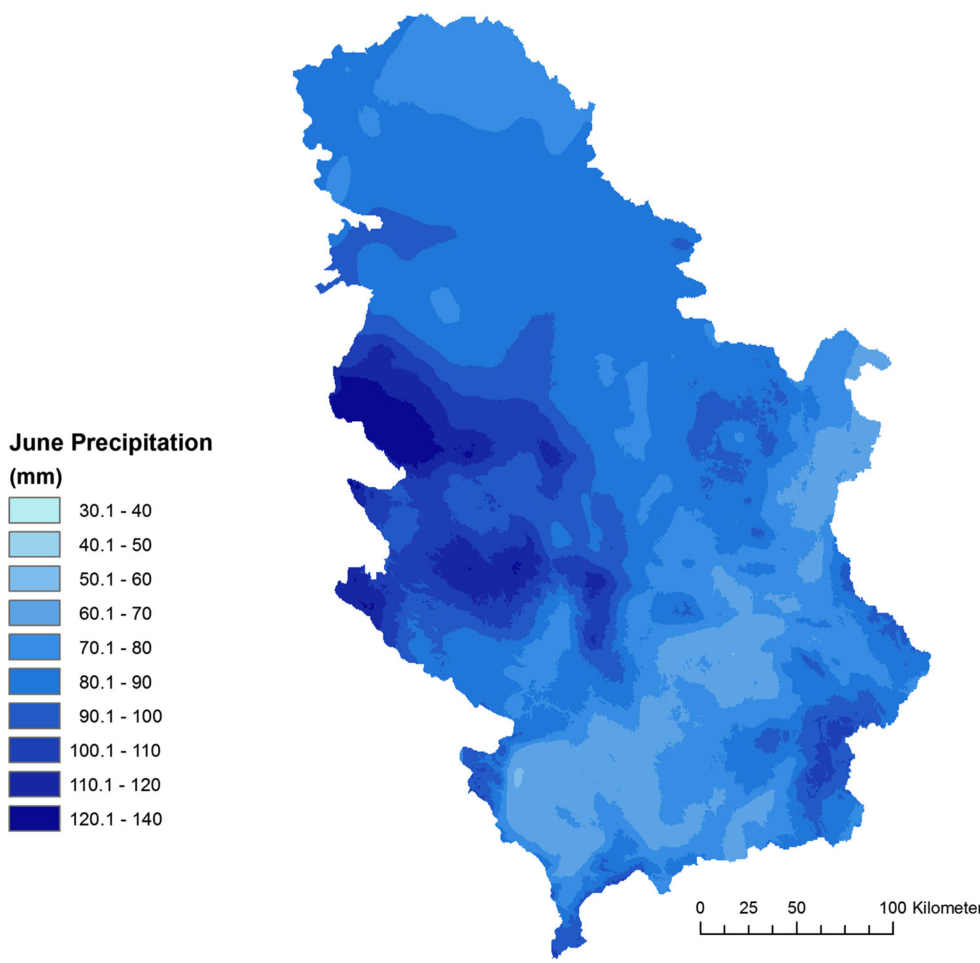


Fig. 4 Spatial distribution of the June amounts of precipitation in Serbia in the period 1961–2010

parts of Serbia. The RMSE of the statistical spatial model for the standard deviation amounts to 19.5 mm, which overall is 14% of the mean standard deviation or 3% of the average precipitation sum. The spatial distribution of precipitation in June and February as the rainiest and driest months, respectively, of the year is very similar to the annual spatial distribution. The precipitation ranges from 60 to 140 mm in June and from 30 to 100 mm in February for the largest part of Serbia (Figs. 4 and 5).

3.3 Precipitation trends

According to the EEA (2017), in the period 1960–2015, there are very large regional differences in changes in annual precipitation in Europe. Great Britain, Scandinavia and the Baltic countries have recorded an increase, while the most prominent decrease is on the Iberian Peninsula. The area of southeastern and central Europe recorded either decreases in precipitation from −20 to 0 mm/decade or an increase in precipitation from 0 to 20 mm/decade, whereby the boundary of change from the negative to the positive trend passes through Serbia to around 22° eastern longitude. However, it seems that this is still a largely generalized survey. Regional studies provide a more precise insight into the changes in precipitation in this part of Europe. According to Gajić-Čapka et al. (2015), in the eastern part of Croatia (northwest of Serbia) in the period 1961–2010, there is a slight positive trend of annual rainfall. Hungary (which is located north of Serbia) in the period 1961–2009 did not record changes in annual precipitation (Klapwijk et al. 2013) while in western Romania (to the northeast of Serbia) in the period 1961–2013, some stations recorded a statistically significant increase in the mean annual precipitation while the stations in the southwest of Romania (to the east of Serbia) recorded a statistically significant decrease in the mean annual precipitation (Croitoru et al. 2016). Bulgaria (east, i.e. southeast of Serbia) recorded a decrease in precipitation but without statistical significance in the period 1961–2005 (Bocheva et al. 2009). Southwest of Serbia, in northern Montenegro, there has been an increase in the annual precipitation in the period 1951–2010 (Burić et al. 2015). All these changes in precipitation are in accordance with the trends shown in Serbia in this study.

For most parts of Serbia, the mean annual precipitation trend for the period 1961 to 2010 falls in between −5 and +5 and +5 and +15 mm/decade (Fig. 6). A decrease in annual precipitation is more dominant in the eastern part of the

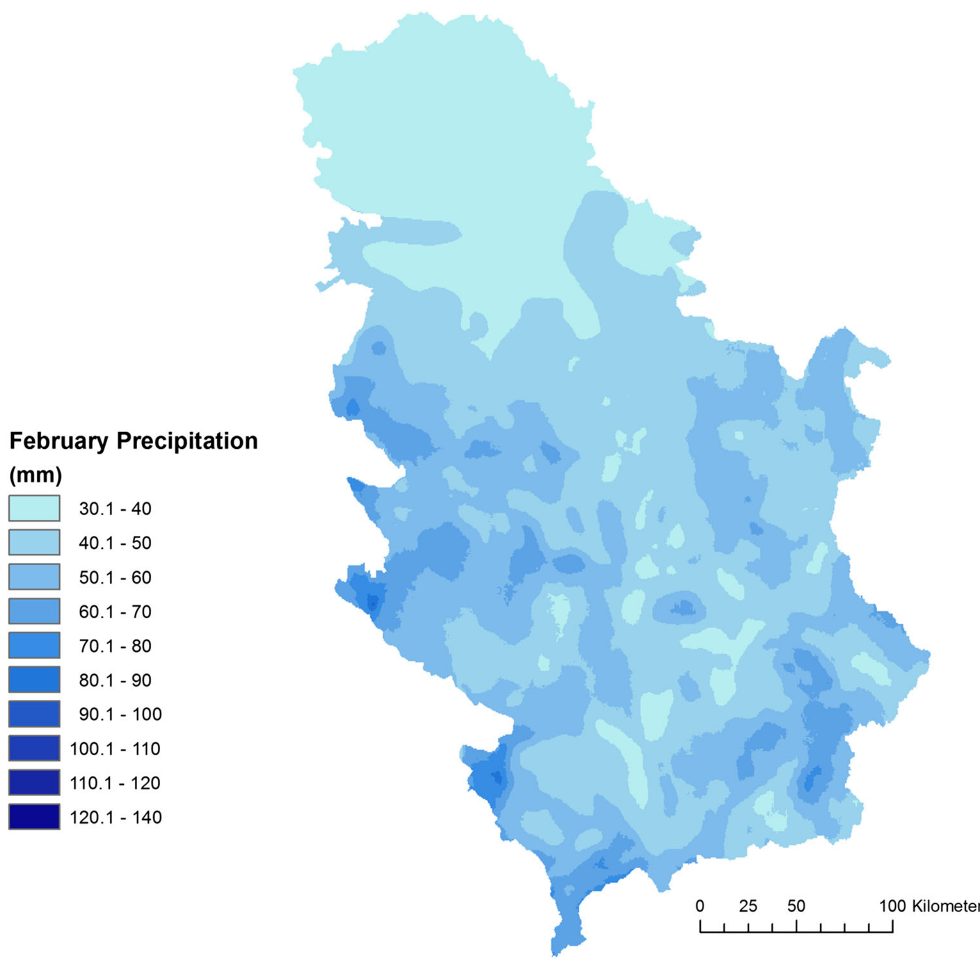


Fig. 5 Spatial distribution of the February amounts of precipitation in Serbia in the period 1961–2010

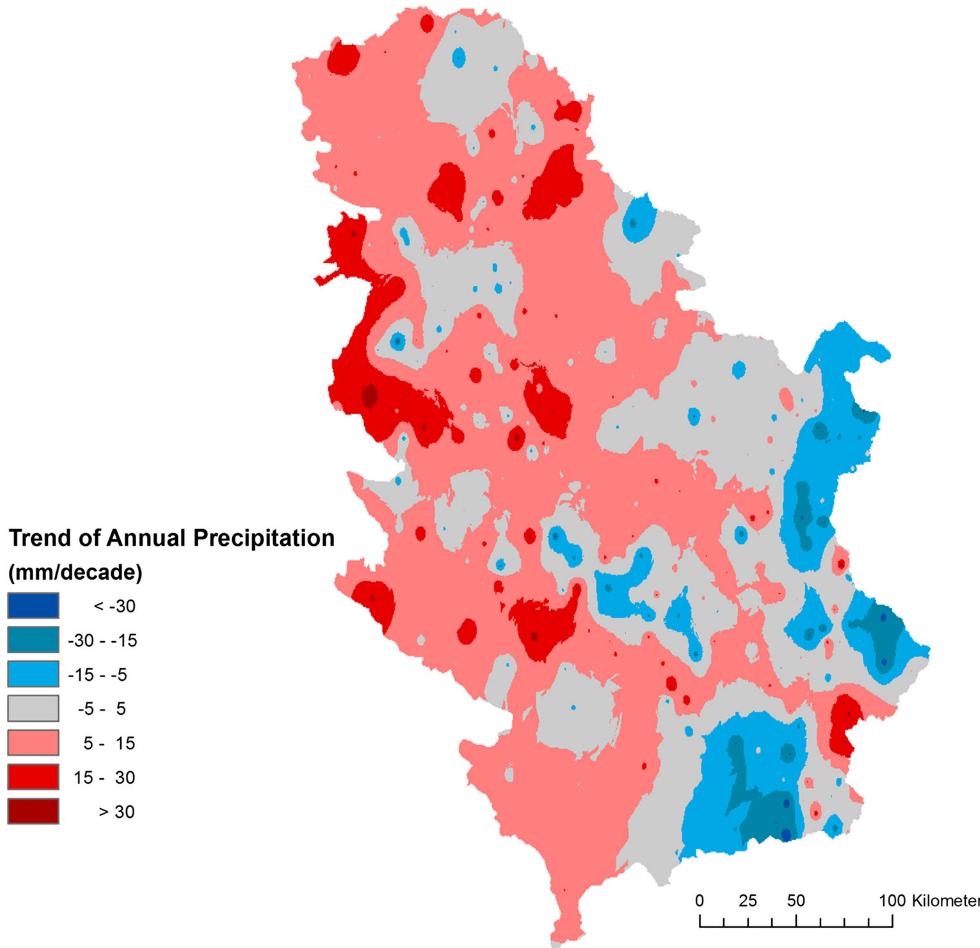


Fig. 6 Trends in the annual amounts of precipitation in Serbia in the period 1961–2010

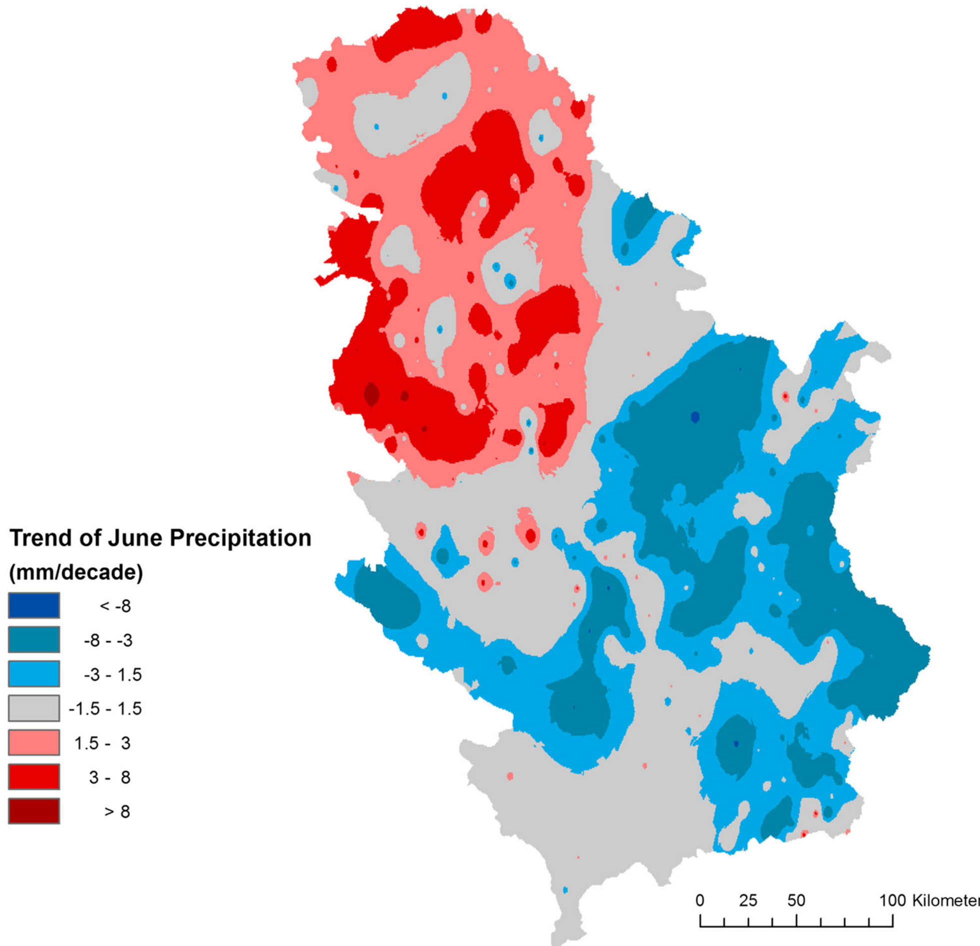
country (up to −15 mm/decade), while the area towards the borders with Bulgaria and Macedonia recorded an appreciable reduction in rainfall (less than −15 mm/decade). In some parts of western Serbia, there was an increase in precipitation sums of up to +30 mm/decade. Only a few stations recorded a greater increase. About 15% of the stations recorded a statistically significant (significance level of $p = 0.05$) increase/decrease in annual precipitation (marked with red circles in Fig. 1). June precipitation (Fig. 7) increased in the northern and northwestern parts of Serbia. Increases in June precipitation amounts reach up to 3 mm/decade (with small zones where growth goes up to 8 mm/decade), while the rest of Serbia records a decrease in the amount of precipitation of up to −3 mm/decade (with smaller zones where reduced precipitation goes up to −8 mm/decade). Only at few stations this decrease is statistically significant. Trends in February precipitation range from −1.5 to +1.5 mm/decade in practically the entire study area (Fig. 8). A more pronounced reduction in the amount of precipitation is in the furthest east and southeast of the country (up to −3 mm/decade), while only stations in the westernmost and southwestern parts recorded a slightly higher increase than the rest of the country in the amount of precipitation. As in the case of the June precipitation, a statistically significant increase or decrease in the February precipitation was recorded at only a few stations.

3.4 Discussion

Serbia is under the influence of the quasi-permanent action centres of the Icelandic Low and the Azores High over the North Atlantic Ocean in the warmer part of the year and under the influence of the Siberian anticyclone and the Mediterranean cyclones in the colder part of the year (Milovanović 2005; Milovanović 2013; Milovanović et al. 2009; Savić et al. 2014).

In late spring and early summer, cyclones are frequently passing Serbia coming from the northern Adriatic Sea or the Atlantic. Air flow often is constrained in its direction along the large valleys of the rivers Sava and Danube. These systems bring the maximum precipitation in May or June. During the summer, the Azores anticyclone ridge is extending across southern Europe to the east, which causes dry, stable and

Fig. 7 Trends in the June amounts of precipitation in Serbia in the period 1961–2010



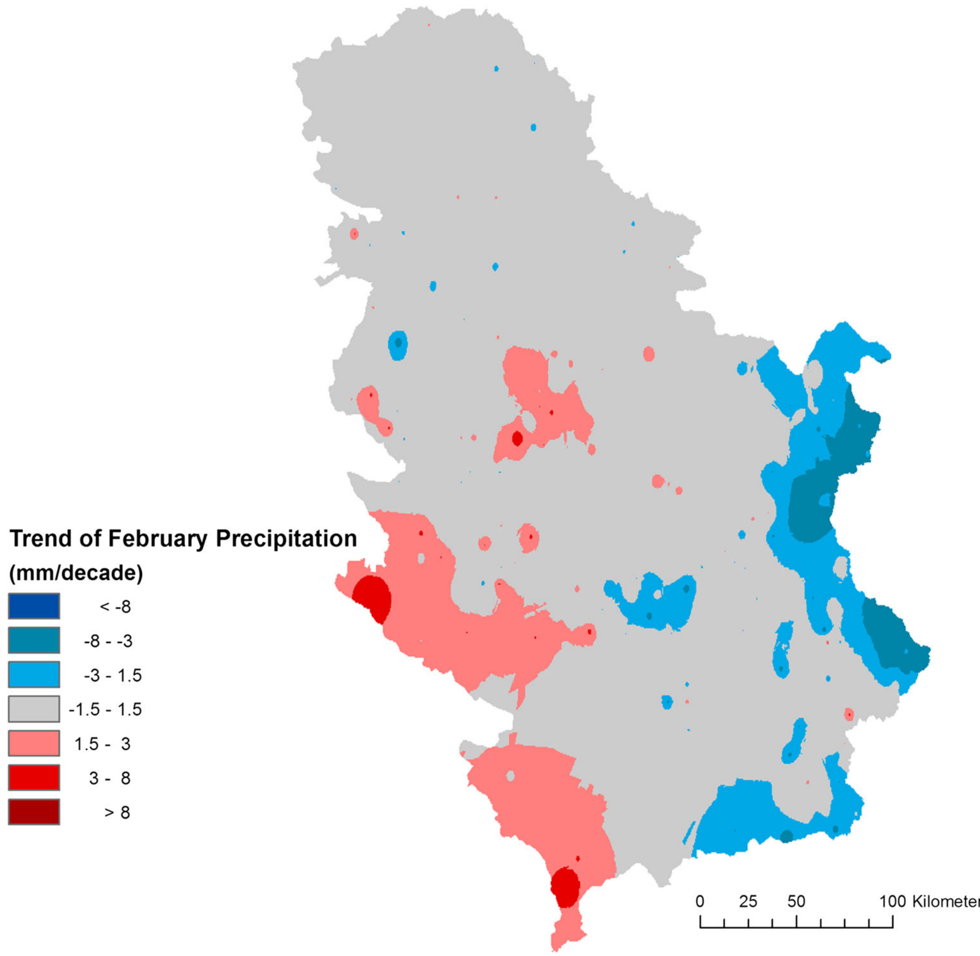
warm weather (Milovanović et al. 2017). Regularly, a high-pressure field is formed in the east of Eurasia (Siberian anticyclone) during the colder part of the year. A related high-pressure ridge extending from the east sometimes reaches central Europe. With these systems, cold and dry air is moving towards the south and the prevailing winds from the northern quadrant are prevalent in southern, southwestern and southeastern Europe (Ducić and Radovanović 2005). In this part of the year, the Mediterranean Sea in general is an area of low air pressure whereby particularly expressed cyclogenesis areas are the Gulf of Genoa in the Ligurian Sea and the northern and southern Adriatic occasionally affect precipitation in Serbia through frontal precipitation advected towards northeast from the Adriatic Sea across the mountains (Šegota 1976).

The dominant directions of arrival of cyclonic and humid air masses are northwest and southwest. Therefore, the spatial distribution of precipitation is a direct consequence of the prevailing air masses both in summer and winter. The configuration of the terrain in which the western part of Serbia is dominated by high mountain ranges intensifies this pattern, so that a reduction in precipitation from west to east (i.e. with a change of longitude) is evident and consistent with the presented reasoning. A similar pattern can be noticed in precipitation trends where the most pronounced increase is located in the western parts and the most intense decrease of precipitation is found in the eastern parts of Serbia. The observed trends indicate an overall intensification of the westerlies both in summer and in winter during the period of observations.

A similar spatial distribution of precipitation and its trends can also be observed in the studies of the aforementioned authors who have dealt with this issue (Bajat et al. 2013; Luković et al. 2014; Prohaska et al. 2012; Štrbac 2014). However, the data on the spatial distribution of annual precipitation are directly comparable only to the results presented by Štrbac (2014) because they were collected during the same observation period at the same number of precipitation stations, whereas the calculated trends are only comparable to the results presented in Luković et al. (2014). The methodology used in this paper is identical to the methodology used in our study. The observation period is very similar, 1961–2009, but the data originated from a much smaller number of precipitation stations than that in our study: 63 stations in Luković et al. (2014) compared to 421 stations in this study.

As far as the spatial distribution of annual precipitation is concerned, we obtained practically identical results to those

Fig. 8 Trends in the February amounts of precipitation in Serbia in the period 1961–2010



presented in Štrbac (2014), although different methodologies were used for precipitation modelling. On the other hand, in our study, model errors, calculated based on a set of test data collected at 42 randomly selected precipitation stations (approximately 10% of the total number of precipitation stations) and expressed as a root mean square error (RMSE) and the mean absolute error (MAE), account for less than 10% of the average value of the annual precipitation of Serbia, while Štrbac (2014) measured the deviation of the modelled precipitation from the observed precipitation at each station, where the error of the modelled precipitation values was less than 5% at about 90% of the observation stations. As far as the precipitation trends are concerned, in Luković et al. (2014), the obtained values were not interpolated, but it was rather examined whether there was a specific spatial clustering of the obtained results. On the other hand, in our study, we have calculated precipitation trends based on data from a significantly greater number of precipitation stations and we have performed the interpolation of the obtained values, thereby acquiring detailed information on precipitation changes in Serbia.

4 Conclusion

The main conclusions of this study are related to the methodology of calculating the spatial and temporal distribution of precipitation in Serbia and the analysis of results. It has been shown that the model, in which the functional link between precipitation and the position of stations (altitude and longitude) as well as elements of the relief (slope) is calculated, provides satisfactory results given that errors of modelled values generally remain below 10%. We limit our approach to purely statistical measures that allow for spatial interpolation within a GIS. By these means, we derive spatial patterns of mean precipitation and precipitation trends that are based only on direct observations and temporally invariant parameters. Therefore, our product can be used as a benchmark or at the least comparison product to more advanced approaches such as dynamical downscaling of reanalysis data or the upcoming ERA 5 meso-scale reanalysis product of the European Centre for Medium-Range Weather Forecasts (ECMWF) (https://climate.copernicus.eu/climate-reanalysis). Finally, our GIS-based mean precipitation and precipitation trend data may be used to compare spatial and seasonal patterns as well as trends, with data from control runs of the Coordinated Regional Climate Downscaling Experiment (CORDEX, http://www.cordex.org/) for this part of southeast Europe.

Bearing in mind that precipitation is largely dependent on atmospheric circulation, these indicators should be included in future research, e.g. the frequency of synoptic weather patterns and the frequency of storm tracks impacting Serbia. Based on the results, it can be concluded that the north of Serbia receives the least annual amount of precipitation (500–600 mm in a large part of Vojvodina as well as the Velika Morava and the Južna Morava valleys). High mountainous terrains in the western and southwestern parts of Serbia receive the highest amount of precipitation (over 1100 mm), while in the eastern part of Serbia, terrains with the same altitude rarely receive over 1000 mm. In terms of changes in annual precipitation in the period 1961–2010, it can be concluded that in most of Serbia, there was a slight increase in the amount of precipitation but without any statistical significance. However, some regional differences still exist. In the eastern and southeastern part of Serbia, there is a reduction in annual precipitation, which is especially pronounced towards the borders with Bulgaria and Macedonia, while in western Serbia, there are few zones with an appreciable increase in annual precipitation. It is shown that regional and subregional studies using methods based on GIS and observed weather station data are capable to provide fine-resolution information on the mean precipitation and precipitation trends in the second half of the twentieth and early twenty-first centuries—for Serbia in the case of this study. An overview of trends in precipitation in the countries that surround Serbia is discussed, and it has been shown that precipitation trends in Serbia are in accordance with those reported from the neighboring countries.

All spatial data produced in this study can be downloaded as geo-coded GIS raster data from a website hosted at Humboldt University, Berlin (https://www.geographie.hu-berlin.de/en/professorships/climate_geography/climate_serbia/).

Acknowledgements This paper presents the results of research on Project III 47007 funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia and German Academic Exchange Service (DAAD—funding programme 50015559), Germany.

References

Ahmad I, Tang Deshan F, Wang T, Wang M, Wagan B (2015) Precipitation trends over time using Mann-Kendall and Spearman's rho tests in Swat River basin, Pakistan. Adv Meteorol 2015:1–15. doi:10.1155/2015/431860

Bajat B, Pejović M, Luković J, Manojlović P, Ducić V, Mustafić S (2013) Mapping average annual precipitation in Serbia (1961–1990) by using regression kriging. Theoretical and Applied Climatology 112:1–13

Bajat B, Blagojević D, Kilibarda M, Luković J, Tošić I (2014) Spatial analysis of the temperature trends in Serbia during the period 1961–2010. Theoretical and Applied Climatology 121:289–301. doi:10.1007/s00704-014-1243-7

Bocheva L, Marinova T, Simeonov P, Gospodinov I (2009) Variability and trends of extreme precipitation events over Bulgaria (1961–2005). Atmos Res 93(1):490–497

Burić D, Luković J, Bajat B, Kilibarda M, Živković N (2015) Recent trends in daily rainfall extremes over Montenegro (1951–2010). Nat Hazards Earth Syst Sci 15:2069–2077. doi:10.5194/nhess-15-2069-2015

Burrough PA, McDonell RA (1998) Principles of geographical information systems—spatial information systems and geostatistics. Oxford University Press

Ćalić J, Milošević M, Milivojević M, Gaudenyi T (2017) Reljef Srbije. Geografija Srbije (in Serbian). Ed. Milan Radovanović, Geografski Institut "Jovan Cvijić" SANU (in press)

Chilès JP, Delfiner P (1999) Geostatistics: modeling spatial uncertainty. Wiley, New York

Croitoru AE, Piticar A, Burada DC (2016) Changes in precipitation extremes in Romania. Quat Int 415:325–335

Ducić V, Radovanović M (2005) Klima Srbije (Climate of Serbia, in Serbian) Zavod za udzbenike i nastavna sredstva, Beograd

EEA report No 1 (2017) Climate change, impacts and vulnerability in Europe 2016. An indicator-based report. European Environmental Agency (http://www.eea.europa.eu/publications/climate-change-impacts-and-vulnerability-2016 Accessed 4 February 2017)

ESRI (2011) ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute. ArcGIS® and ArcMap™ are the intellectual property of Esri and are used herein under license. Copyright © Esri. All rights reserved

Gajić-Čapka M, Cindrić K, Pasarić Z (2015) Trends in precipitation indices in Croatia, 1961–2010. Theor Appl Climatol 121:167–177. doi:10.1007/s00704-014-1217-9

Gao X, Pal JS, Giorgi F (2006) Projected changes in mean and extreme precipitation over the Mediterranean region from a high resolution double nested RCM simulation. Geophys Res Lett 33:L03706. doi:10.1029/2005GL024954

Guan H, Wilson JL, Makhnin O (2005) Geostatistical mapping of mountain precipitation incorporating autosearched effects of terrain and climatic characteristics. J Hydrometeorol 6(6):1018–1031

Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations—the CRU TS3.10 Dataset. Int J Climatol 34:623–642. doi:10.1002/joc.3711

Klapwijk M, Csóka G, Hirka A, Björkman C (2013) Forest insects and climate change: long-term trends in herbivore damage. Ecol Evol 3 (12):4183–4196. doi:10.1002/ece3.717

Luković J, Bajat B, Blagojević D, Kilibarda M (2014) Spatial pattern of recent rainfall trends in Serbia (1961–2009). Reg Environ Chang 14: 1789–1799

Masson D, Frei C (2014) Spatial analysis of precipitation in a high-mountain region: exploring methods with multi-scale topographic predictors and circulation types. Hydrol Earth Syst Sci 18:4543–4563

Milovanović B (2005) Statistical procedure application and results of research of precipitation on mountain Stara Planina. J. Geogr. Inst. Cvijic. 54:33–45

Milovanović B (2013) About hidden influence of predictor variables—suppressor and mediator variables. JGeogr InstCvijic 63:1–10

Milovanović B (2014) Air temperature changes in Serbia and Belgrade heat island. J. Geogr. Inst. Cvijic. 65:33–42

Milovanović B, Radovanović M, Ducić V (2009) Ocean and atmosphere coupling, connection between sub-polar Atlantic temperature, Icelandic minimum and temperature in Serbia. Glasnik Srpskog Geografskog Društva (Bull Serbian GeogrSoc) 89:165–176 (in Serbian; summary on English)

Milovanović B, Radovanović M, Stanojević M, Pecelj M, Nikolić J (2017) Klima Srbije. Geografija Srbije (in Serbian). Ed. Milan Radovanović, Geografski Institut "Jovan Cvijić" SANU (in press)

Pandžić J, Bajat B, Luković J (2013) Mapping probabilities of precipitation occurrence on the territory of the Republic of Serbia by the indicator kriging. Bulletin of the Serbian Geographical Society 93: 23–33

Prohaska S, Koprivica A, Bartos Divac V, Majkic-Dursun B, Ilic A, Catovic A, Djukic D, Kapor B (2012) GIS presentation of latest results of climate parameter processing in the Republic of Serbia. BALWOIS 2012 - Ohrid, Republic of Macedonia - 28 May, 2 June 2012

QGIS Development Team (2015) QGIS geographic information system. Open Source Geospatial Foundation Project. http://www.qgis.org/

R Development Core Team (2008) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3–900051–07-0, URL http://www.R-project.org

Radovanović M, Milovanović B (2003) Methods to complete the missing data on precipitation in the mountains of Serbia—testing and application. Studia Geograficzne 75, No 2542, International conference "Man and climate in the 20th Century", Wroclaw, 13–15 June 2002. – Institute of Geography, University of Wroclaw and Polish Geophisycal Society of Marshall of the Voivod of Lower Silesia, Wroclaw, Poland

Rakićević T (1979) Osnovne zakonitosti u geografskom rasporedu padavina na teritoriji SR Srbije. Zbornik radova Geografskog instituta PMF 26:5–18 (In Serbian)

Salmi T, Määttä A, Anttila P, Airola T, Amnell T (2002) Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates—the Excel template application MAKESENSE. Finish Meteorological Institute, Helsinki, Finland http://www.ilmanlaatu.fi/ilmansaasteet/julkaisu/pdf/MAKESENS-Manual_2002.pdf. 03.05.2016

Savić S, Milovanović B, Lužanin Z, Lazić L, Dolinaj D (2014) The variability of extreme temperatures and their relationship with atmospheric circulation: the contribution of applying linear and quadratic models. Theor Appl Climatol 121:591–604. doi:10.1007/s00704-014-1263-3

Schamm, Kirstin; Ziese, Markus; Becker, Andreas; Finger, Peter; Meyer-Christoffer, Anja; Rudolf, Bruno; Schneider, Udo (2013): GPCC first guess daily product at 1.0°: near real-time first guess daily land-surface precipitation from rain-gauges based on SYNOP data. DOI: 10.5676/DWD_GPCC/FG_D_100

Šegota T (1976) Klimatologija za geografe (in Croatian). Školska knjiga, Zagreb

Štrbac D (2014) Quantification and spatial distribution of the precipitation on the territory of Serbia. J Geogr Inst Cvijic 64:267–277

Sutapa W, Galib I (2016) Application of non-parametric test to detect trend rainfall in Palu Watershed, Central Sulawesi, Indonesia. International Journal of Hydrology Science and Technology 6(3): 238–253

Tošić I (2004) Spatial and temporal variability of winter and summer precipitation over Serbia and Montenegro. Theor Appl Climatol 77:47–56

Vujević P (1956) Klimatološka statistika (in Serbian). Naučna knjiga, Beograd

Yugoslavia (1985) Atlas klime Socijalističke Federativne Republike Jugoslavije. Hidrometeorološka služba SFRJ (in Serbian)