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Parameterization of the rainfall-runoff model in changing climate

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Pollack Periodica • An International Journal for Engineering and Information Sciences

16 (2021) 3, 64–69

DOI:
10.1556/606.2021.00340

Received: December 28, 2020 • Revised manuscript received: March 9, 2021 • Accepted: April 4, 2021

ORIGINAL RESEARCH PAPER

ABSTRACT

A conceptual rainfall-runoff model was used for estimating the impact of climate change on the runoff regime in the Myjava River basin. Changes in climatic characteristics for future decades were expressed by a regional climate model using the A1B emission scenario. The model was calibrated for 1981–1990, 1991–2000, 2001–2010, 2011–2019. The best set of model parameters selected from the recent calibration period was used to simulate runoff for three periods, which should reflect the level of future climate change. The results show that the runoff should increase in the winter months (December and January) and decrease in the summer months (June to August). An evaluation of the long-term mean monthly runoff for the future climate scenario indicates that the highest runoff will occur in March.

KEYWORDS

climate change, conceptual rainfall-runoff model, Myjava River basin

1. INTRODUCTION

The understanding of modeling is that this process is a complex accumulation of all processes in nature, transferred into the system, which can be simulated virtually. Making a model that could be reproduced repeatedly is common practice, for example, in developed rainfall-runoff models for hydrological variability [1] or the simulation of the groundwater flow [2]. Rainfall-runoff models are often used as tools to estimate the impact of climate change on runoff. For hydrologists, this topic is still at the forefront. The formation of the runoff is a complex process in which several mechanisms are involved. Therefore, it is essential to estimate the possible impact of climate change on water resources and propose some strategic measures, e.g., [3–8]. In this area, the conceptual rainfall-runoff models are in focus. An example of this model is a conceptual rainfall-runoff model named the “Technische Universität Wien” (TUW) model [9].

In this study, it was tested how the model works in different periods. Therefore, the calibration of the hydrologic model was made in periods 1981–1990, 1991–2000, 2001–2010, 2011–2019 that are different in terms of climate. For further analysis, parameters were chosen from the recent calibration period (i.e., 2011–2019) because of the assumption that this period would be similar to the recent/warmer climate in terms of the average daily air temperatures. Finally, parameterization of the rainfall-runoff model lies in further creating hydrological scenarios for hydrological regime development. The scenarios will thus be contributing to climate and environmental protection in the future. The paper focuses on doing the TUW model's parameterization in the Myjava River basin in Slovakia and estimating the impact of climate change on runoff in the future. The modeling process was completed in the open-source software R. More on various hydrological models and changes in hydrological processes in the Carpathian Basin can be found in [10].

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2. MATERIALS AND METHODS

2.1. Study area and data

The Myjava River catchment, with an outlet at the Jablonica gauging station, was selected as a pilot catchment for this study. The catchment area is 238.45 km^2. Elevation of the catchment varies from 206 to 792 m a.s.l. The mean annual precipitation varies from 650 to 700 mm/year. The mean annual air temperature varies in a range from 7 to 11 °C. This area can be classified as a small to medium-sized river basin. The river basin location and locations of the nearest water gauging, rainfall, and climatic stations are shown in Fig. 1.

2.2. TUW model

A lumped conceptual rainfall-runoff model (the TUW model) was used to simulate the catchment hydrological regime. The model follows the structure of a widely used Swedish Hydrologiska Byråns Vattenbalansavdelning (HBV) model and working in a daily time step. To some extent, the rainfall-runoff models imitate the process of creating water runoff from a river basin using mathematical equations, which is often a demanding process. The "lumped" version implies that all the input and output data or the model parameters are constant for the river basin's total area. The model involves three main routines (i.e., snow, soil moisture, and runoff routine) [11], representing changes in snow, soil, and groundwater storages. The snow routine consists of five parameters: the Degree-Day Factor (DDF), the Snow Correction Factor (SCF), and the threshold temperatures (*Tr*, *Ts*, and *Tm*). The soil moisture routine involves three parameters: the Field Capacity (FC), the parameter of runoff generation (BETA), and the limit for potential evapotranspiration (*Lprat*). The runoff routine consists of seven parameters: the storage coefficients responsible for surface and subsurface runoff (*k*0, *k*1, and *k*2), the threshold storage state (*lsuz*), the percolation rate (*cperc*), the maximum base at flows (*b*max), the scaling parameter (*croute*).

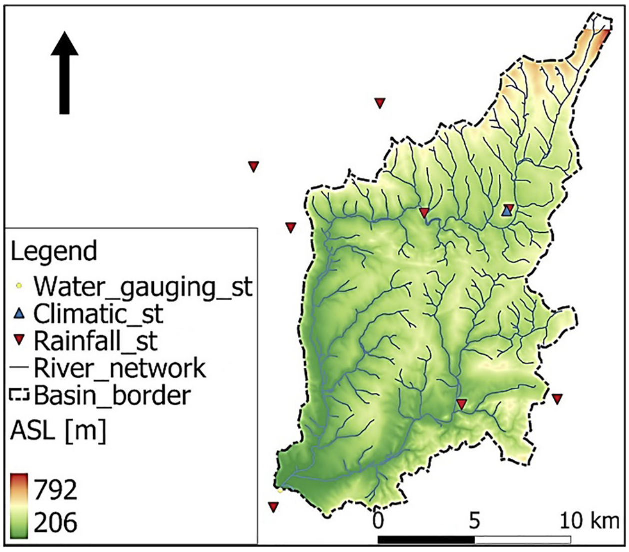

Fig. 1. The position of the Myjava River basin and the location of the stations

For the rainfall-runoff modeling, the hydro-meteorological and the data from water gauge stations were used. Inputs into the model include daily catchment data, i.e., daily precipitation totals (*P*), mean daily air temperature (*T*), and mean daily Potential EvapoTranspiration (PET). Mean daily flows observed at the outlet of the selected catchment were used to compare with simulated values. Daily precipitation totals were calculated using the Inverse Distance Weighting (IDW) method. Mean daily air temperatures were obtained by the temperature gradient method. PET values were estimated by a Blaney-Criddle method using daily air temperature and glare index obtained from the Digital Elevation Model (DEM).

The calibration of the model requires identifying a set of global parameters, which will provide the best possible agreement between the hydrological model's measured and simulated parameters per selected criteria [12]. Generally, calibration and validation could be used in a variety of fields of science. For example, calibration is used to determine deforestation's effect on drainage processes from a river basin [13]. The calibration and validation procedures were performed for the period 1.1,1981 to 12.31, 2019. This period was divided into four sub-periods: three ten-year periods and one nine-year period: 1.1,1981–12.31,1990, 1.1,1991–12.31,2000, 1.1,2001–12.31,2010, and 1.1,2011–12.31,2019. Cross-calibration and validation of the TUW hydrological model were performed for a specific period. The optimization algorithm searches for the optimal set of model parameters, and with founded parameters, this model could be run (validated) for further periods. The Calibration (C) and Validation (V) strategies are shown in Table 1.

The objective function used in calibration is selected based on prior analyses performed in different calibration studies (see, e.g., [14]). While the Nash-Sutcliffe efficiency (NSE) [15] gets a greater weight on high flows, the logarithmic Nash-Sutcliffe efficiency (log NSE) gets a great weight on low flows. Both metrics were used to achieve a more balanced evaluation of flows. Individual components of Optimization Function (OF) are written using the following equations:

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(Q_{sim,\,i} - Q_{obs,\,i}\right)^2}{\sum_{i=1}^{n} \left(Q_{obs,\,i} - \overline{Q}_{obs}\right)^2}, \tag{1}$$

$$\log NSE = 1 - \frac{\sum_{i=1}^{n} \left(\log(Q_{sim,\,i}) - \log(Q_{obs,\,i})\right)^2}{\sum_{i=1}^{n} \left(\log(Q_{obs,\,i}) - \log\left(\overline{Q}_{obs}\right)\right)^2}, \tag{2}$$

Table 1. The strategies of calibration and validation

1981–1990	1991–2000	2001–2010	2011–2019
C	V	V	V
V	C	V	V
V	V	C	V
V	V	V	C

where $Q_{sim,i}$, and $Q_{obs,i}$ represent the simulated and observed mean daily flows on day i, $\overline{Q}_{obs}$ and represent the average values of flows observed. OF was calculated using the following equation:

$$OF = \frac{NSE + \log NSE}{2}\,. \tag{3}$$

Parameter calibration was performed using the Differential Evolutionary algorithm (DEoptim) [16], which includes optimization functions mentioned above. DEoptim imitates evolutionary processes (i.e., mutation, natural selection), searching for the best results and optimal set of parameters [17]. The number of iterations used is 600. After calibration, the process of validation of other periods is started.

2.3. Climate change model

Computer models are used as a tool in the creation of climate scenarios. Climate change models are divided into global and regional. Global models are used for modeling climate change for the whole planet in divided grid cells. In pursuance of making global models, the regional models were started to develop more. This kind of regional model is Koninklijk Nederland Meteorological Institute, (KNMI) [18]. The KNMI model is divided into grid cells with a spatial resolution of 25 × 25 km. To gain characteristic data and to forecast future climate change, simulations were being made. KNMI uses a medium pessimistic scenario [19]. Output for the KNMI model for the region was downscaled to climatic stations and interpolated using the IDW method based on basin data. Values of temperature (T) and precipitation (P) are used as daily time series input basin's data for the period from 1981–2100. There were made scenarios for stream-flows in the Myjava River basin for four thirty-year periods: 1.1,1981–12.31,2010, 1.1,2011–12.31,2040, 1.1,2041–12.31,2070, and 1.1,2071–12.31,2100. The KNMI model was also used to model future climatologic components scenarios similar to air temperature and precipitation.

3. RESULTS AND DISCUSSION

This chapter presents the achieved results of parameterization of the rainfall-runoff TUW model in changing climate. Firstly, the time series from 1.1,1981 to 12.31,2019 was chosen. This period was divided into four sub-periods. The calibration was processed in one period, and then the validation was processed onto the rest of the sub-periods.

3.1. Climate development in calibration periods

The most exciting development is seen in the temperature values. The highest values in temperature are noticed in the period 2011–2019. Average T increased by approximately 1.2 °C. This period is most similar to the future climate. P values are between 620 and 730 mm. Q values do not change much in the 2011–2019 study period.

Figure 2 shows the hydroclimatic characteristics. The line shows the mean value of the hydroclimatic characteristics in a particular period. The colored area indicates the range of 75 and 25 percentiles.

3.2. Assessment of model performance and selection of parameters

Model performance was evaluated by the result of a combination of the optimization functions, the Nash-Sutcliffe coefficient and the logarithmic Nash-Sutcliffe coefficient after this referred to as OF, together with the Volume Error (VE) values. The combination of the first two optimization functions was calculated as the arithmetic mean. As the value of the OF approaches 1 indicates a better correspondence between the observed and simulated water flows [20]. Volume error values, which are less than 0, express underestimating the stream-flow volume, while VE values, which are greater than 0 express an overestimation of the stream-flow volume. The ideal case is if the volume error's value was equal to 0, indicating no change between the observed and simulated stream-flows. Tables 2 and 3 show the resulting

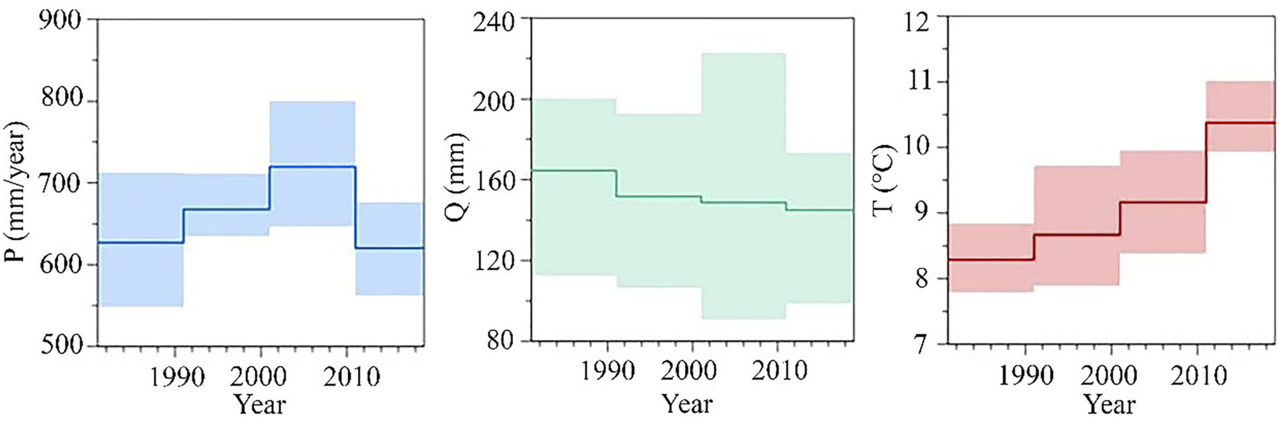

Fig. 2. The hydroclimatic characteristics annual precipitation (P), mean annual air temperatures (T) and annual flow graph (Q) over four specific periods; the line shows the mean value of the hydroclimatic characteristics in a particular period; the colored area indicates the range of 75 and 25 percentiles

Table 2. Results of OF coefficients for all periods in the Myjava River basin

OF [-]			
1981–1990	1991–2000	2001–2010	2011–2019
0.72	0.52	0.49	0.58
0.59	**0.68**	0.58	0.58
0.43	0.61	**0.70**	0.57
0.53	0.48	0.46	**0.77**

Table 3. Volume error values for all periods in the Myjava River basin

VE [%]			
1981–1990	1991–2000	2001–2010	2011–2019
−**2.86**	16.96	28.74	−9.88
−15.09	**4.24**	14.07	−16.93
−30.46	−9.12	−**2.00**	−33.03
0.25	24.44	36.06	−**3.09**

values of the OF and VE values. The calibration periods are the same, as it is shown in Table 1.

The qualitative calibration indicators, the OF, and VE values showed the best agreement between the observed and measured flows in the calibration periods from 1.1,1981 to 12.31,1990 and from 1.1,2011 to 12.31,2019. The obtained values of a combination of optimization functions were 0.72 and 0.77. The smallest overestimation of the flow volume occurred in the period from 1.1,1981 to 12.31,1990, where the volume error had the smallest plus value of 0.25%. The smallest underestimation of the flow volume occurred in the period from 1.1,2001 to 12.31,2010 with the value of the volume error -2.00%.

A graph for the period from 1.1,2011 to 12.31,2019 for the comparison of long-term average monthly discharge values (Q) is shown in Fig. 3.

Even though the calibration was performed in the whole period from 1981–2019 divided into four parts, only the last period from 2011–2019 is shown for comparison of flows and considering. For further analysis parameters from the recent calibration period (i.e., 2011–2019) were chosen because of the assumption that this period would be similar to the recent/warmer climate in terms of the average daily air temperatures. Fig. 3 presents observed and simulated discharge values. Based on the comparison of observed and simulated daily discharge values in the entire Myjava River basin, it is possible to evaluate the calibration in the "lumped" version of the TUW model. There are significant differences between the observed and simulated values of flows in February. The difference reaches 0.16 mm/day. Further, the model captures reality relatively well.

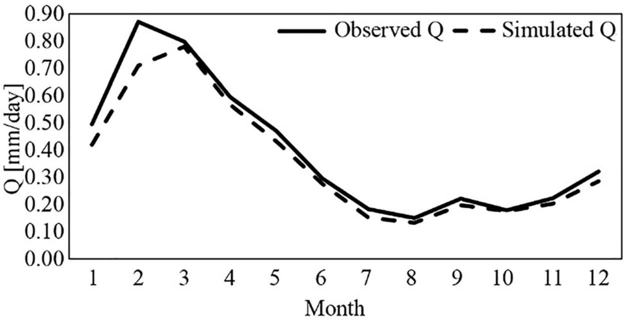

Fig. 3. Average monthly flow values for the period from 1.1,2011 to 12.31,2019

3.3. Climate change impact on hydrological regime

One of the leading climate change indicators is air temperature. Using the KNMI model, the course of the changing temperature in the long-term average monthly values for periods 1981–2010, 2011–2040, 2041–2070, 2071–2100 are shown in Fig. 4.

The parameters were selected from the calibration process from 2011–2019. Based on the same set of parameters, the modeling scenario was performed. The modeled scenario temperature graph shows the most significant rise in temperature in the winter months (January and February) by 3 °C, in the summer months by 3.6 and 3.9 °C (June and July). The mentioned rise is between the reference period 1981–2010 and the farthest scenario period 2071–2100. In Fig. 5, the scenario stream-flow results using model KNMI are shown.

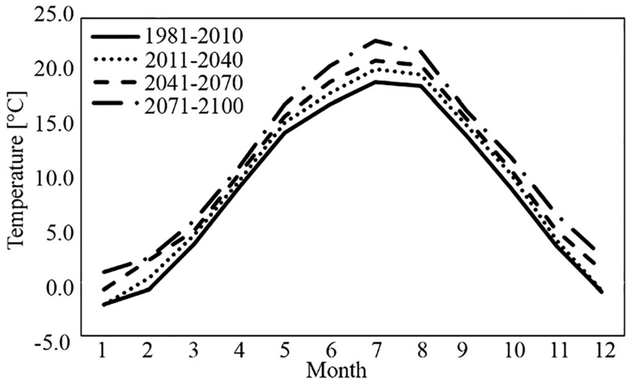

Fig. 4. Long-term average monthly values of air temperature [°C]

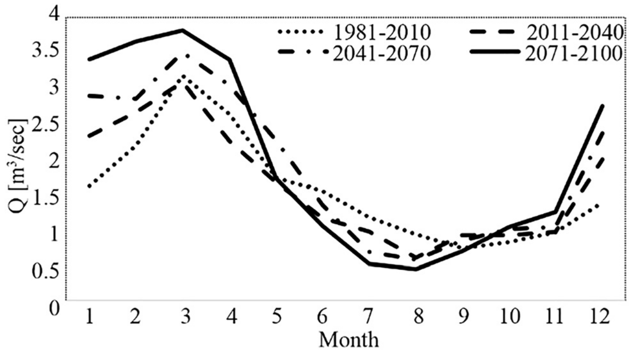

Fig. 5. Long-term average monthly values of scenario stream-flow in the period 1981–2100

Table 4. Percentage evaluation of the deviation of the stream-flow ref. period 1981–2010 from other scenarios 2011–2040, 2041–2070, and 2071–2100

	1	2	3	4	5	6	7	8	9	10	11	12
$Q_{1981–2010}$ [m^3/sec]	1.618	2.192	3.176	2.636	1.732	1.544	1.175	0.930	0.737	0.824	0.964	1.384
$Q_{2011–2040}$ [%]	44	21	−3	−15	−4	−25	−17	−35	25	12	0	44
$Q_{2041–2070}$ [%]	79	30	10	15	31	−13	−42	−38	15	22	7	71
$Q_{2071–2100}$ [%]	111	67	20	29	0	−32	−56	−52	−6	26	30	99

The long-term course of the flows from 1981–2100 as average monthly values can be seen. Table 4 shows the percentage deviation of the average monthly flow scenarios from the reference period 1981–2010.

The model simulates stream-flow using mm as units. For better clarity, the stream-flow in the graph is shown in m^3/sec.

Comparing the long-term mean monthly runoff for the KNMI scenario in three time periods indicates that the highest runoff value will occur in March. On the other hand in August, the runoff will have the lowest value point. The monthly flow will gradually increase in the winter months (December and January) up to 111%. However, the monthly flow values are expected to decrease to 56% from June to August. These results are in general agreement with the findings presented, e.g., by [4], [6–9]. For example, [9] their study looked at the impact of climate change on extreme runoff regimes in two Slovak catchments (i.e., Váh and Laborec). Their results showed an increase in average monthly runoff, especially in the winter months. A similar pattern was also observed by the authors in [7]. The authors used a distributed model WetSpa for estimating the impact of forest changes on the hydrological regime in the Hron and Topla catchment. Similar results have been reported by authors in paper [8], who evaluated the impact of climate change on catchment runoff in five selected catchments of Slovakia. They observed an increase in runoff in the winter period and a decrease during the summer/autumn periods.

4. CONCLUSION

This study shows the parameterization of the rainfall-runoff model and the modeling of climate change impact on runoff in the periods from 1981–2019 (respectively 2100). The evaluation of observed values in air temperature from 1981–2019 showed an increase. This course of value movement is expected as the global temperature is on the rise. Although the precipitation in this period has lowered, the course of stream-flow has been decreased. Based on the dominance in air temperature, this is also expected development in these climate indicators. According to the stream-flow modeled scenarios, the stream-flow's extreme values are gaining higher values in the first two months of the year and the period between the seventh and eight months, where the stream-flows are the lowest. Due to the internal annual breakdown in the year, the seasonal distribution of runoff will be changed. It can be concluded that based on the parameterization of the TUW model and based on the modeling scenarios of the KNMI model, the further the future goes with modeling, the more significant the increase in temperature and extreme precipitation will be. It is expected that the flow deficit in the summer will be challenging. Based on processed calibration and validation of model parameters, it is possible to assess and select a specific set of model parameters that would be best transferable for modeling the hydrological regime and flows in the future, assuming changed climatic conditions. The modeling results depend on the input data, the hydrological model used; therefore, the results' interpretation must be approached carefully. In the future, the plan is to extend this kind of analysis to other Slovak catchments.

ACKNOWLEDGEMENTS

This work was supported by the Slovak Research and Development Agency under the contracts No. APVV-19–0340; and VEGA 2/0065/19 and VEGA 1/0632/19. At the same time, we would like to acknowledge the support from the Stefan Schwarz grant of the Slovak Academy of Sciences.

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