Comparison of daily flows simulated for the year 2060 on the Kaczawa River for various scenarios of climate change by simple time series analysis

Leszek Kuchar[1,*], *Ewa* Broszkiewicz-Suwaj[1], *Slawomir* Iwanski[1], and *Leszek* Jelonek[2]

[1]Wroclaw University of Environmental and Life Sciences, Department of Mathematics, ul. Grunwaldzka 55, 50-357 Wroclaw, Poland
[2]Institute of Meteorology and Water Management, ul. Parkowa 30, 51-616 Wroclaw, Poland

Abstract. In this paper a time series analysis for daily flow simulations according three climate change scenario for Kaczawa River a left side tributary of the Odra River in south-west Poland is presented. The flow sequences were simulated using the hydrological model MIKE SHE and the spatial SWGEN meteorological data generator. Meteorological data for the hydrological model were generated based on data from 24 meteorological stations and 35-year daily data from the Institute of Meteorology and Water Management of the National Research Institute (IMGW). Data were generated for future climate condition for 2060 according GISS Model E, HadCM3, and GFDL R15 scenarios as well for the present conditions. The year 2000 was used as a reference year. The results obtained on the basis of a simple time series analysis point to small changes in flows for current and simulated conditions for 2060 for the Kaczawa River.

1 Introduction

This work is a continuation of earlier studies on changes in the Kaczawa River flows simulated for various scenarios of climate change [14−17]. The following studies compared the time series of daily flows in a period of the year in contrast to previous studies on the probability distributions of flows, e.g. maximum and minimum flows. The aim of this work is to answer the question whether in simulated flows for the year 2060 there are significant changes in the periodicity of the phenomenon, amplitude, time shift or others resulting from the analysis of the time series [2, 9, 21, 26]. For example, floods in Poland, which are accompanied by high flows, appeared mainly in the summer. However, in the last 20 years, as a results of changes in the course of winters, mainly higher temperatures, meltwater thaw floods began to appear more frequently and on a much larger scale [15, 19, 23]. In the studies, flows were simulated for the year 2060 according to the three most likely scenarios GISS Model E, HadCM3, and GFDL R15 which are considered to comply with the new scenarios of Representative Concentration Routes (RCPs) 4.5 and 6.0. Three selected SRES scenarios were adopted in the present study due to the extensive experience in generating meteorological data for these scenarios for the condition of Poland, as well as due to their high convergence with the RCP4.5 and RCP6.0 scenarios [7, 8, 15]. It has been assumed that
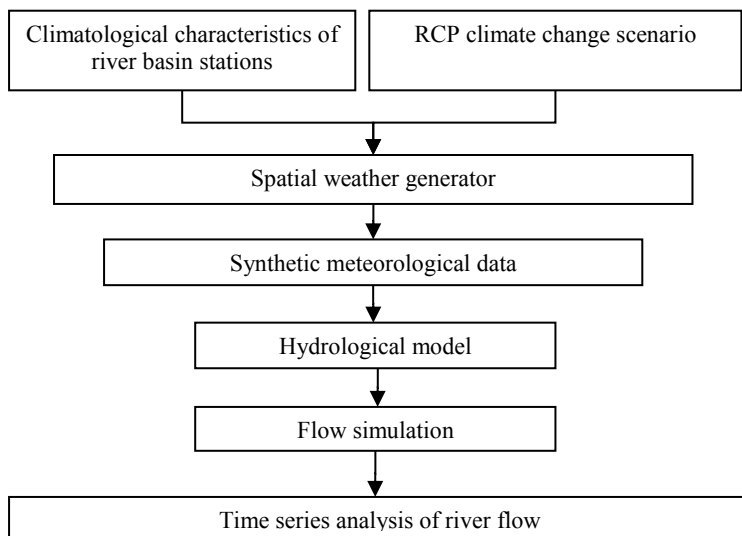
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* Corresponding author: leszek.kuchar@upwr.edu.pl

the background in the research, i.e. the reference period, are the years at the turn of the 20th and 21st centuries. Similarly to previous studies, the spatial SWGEN meteorological data generator was used, the MIKE SHE rainfall-outflow hydrological model and the operating scheme were consistent with earlier studies and described in [10, 13, 20, 16, 17]. Simulations were performed for the small tributary of the Odra (south-west region of Poland) due to the high quality of observational data and previous experience in hydrological modelling [17, 18, 25, 31].

2 River flow simulation procedure

As in previous studies, the simulation of river flows for the future climate is carried out in three stages [14−17]. Climate description of all meteorological stations are prepared using an observed data. Above characteristics are modified according to climate change scenario and it is required for the weather generator producing synthetic data [3, 12, 13, 16]. In the next step, synthetic meteorological data are generated for all stations by the SWGEN weather generator. These data are used as an input for the hydrological   rainfall-runoff model MIKE SHE to simulate river flows. This is step 3. The described procedure is presented in Figure 1 originally described in the papers [16, 17] and has been used many times to simulate processes in river catchment [14−17]. The daily flows sequences obtained are the basis for analysis illustrating the hydrological effect of climate changes in rivers [5, 16, 17, 22, 24].

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│ Climatological characteristics of │   │  RCP climate change scenario  │
│      river basin stations      │   │                               │
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              │                                   │
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              ┌─────────────────────────────┐
              │    Spatial weather generator    │
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              │       Hydrological model        │
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              │        Flow simulation          │
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        │   Time series analysis of river flow    │
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Fig. 1. Diagram of river flow simulation for future climate using synthetic meteorological data and climate change scenario.

3 Catchment and data

Our research has been conducted for many years in south-western Poland in the Kaczawa river basin (Fig. 2) [16, 17]. This choice is related to recommendation of the Institute of Meteorology and Water Management National Research Institute (IMGW) due to the first order meteorological and hydrological data. A 35-year dataset (1981−2015 series) for daily solar radiation, maximum and minimum air temperature and total rainfall were obtained for 24 stations from the Institute network and used for presented research [13, 16].
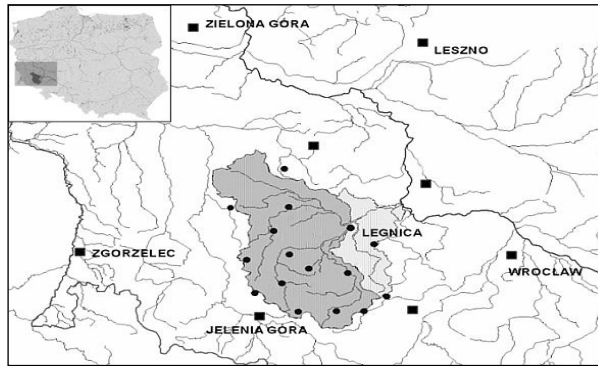
Fig. 2. The Kaczawa River catchment (left, area of 1807 km2, main sit: Legnica 51°13'N, 16°14'E) with meteorological (●) and first order (■) meteorological stations.

An information about climate change, required for the simulation were derived from the Special Report on Emissions Scenarios (SRES) as well from the Representative Concentration Routes (RCP) scenarios [7, 8]. Used from 2014 new RCP scenarios are considered for simulations, but due to the extensive experience in generating meteorological data for SRES scenarios for the condition of Poland, SRES A1B scenarios finally were selected.

For the study three typical SRES A1B scenarios (GISS Model E, HadCM3, and GFDL R15) were used, which correspond to the RCP 4.5 and 6.0 scenarios assumes a changes in CO_2 concentrations in Poland, amounting to 538 ppm and 670 ppm respectively up to 2100 (with additional consideration of changes in CH_4 and N_2O emissions, the total concentration would be equivalent to CO_2 values of 630 ppm and 800 ppm) [7, 8, 15].

4 Spatial weather generator and rainfall runoff model

The weather generator SWGEN is used to generate daily data for n years and for k stations as described in earlier papers [10, 11, 29, 30]. The model generates total precipitation by means of the first-order Markov chain to determine the occurrence of wet/dry days, and then for the amount of precipitation the multidimensional two-parameter gamma distribution is used [4, 16]:

$$\left(\Gamma_m(\alpha_1, \beta_1), \dots, \Gamma_m(\alpha_k, \beta_k)\right) \tag{1}$$

where m is the month number ($m = 1, \dots, 12$, i.e. January = 1, February = 2, ..., December = 12) and k is the location number. Daily values of solar radiation (SR), temperature maximum (T_{max}) and minimum (T_{min}) are treated as a multidimensional time series AR(1) in the following form:

$$X_t = \Phi_m \cdot X_{t-1} + \varepsilon_t \tag{2}$$

where X_t and X_{t-1} are vectors ($3k \times 1$) of standardized values for all three variables for day t and t-1, ε_t is a vector ($3k \times 1$) of independent random components normally distributed with vector of means equal to zero and matrix of covariance Σ_m, and Φ_m (for m = 1, …, 12) is a matrix of parameters [10, 18, 27]. For this study, the SWGEN was used to produce long series of 400 years of synthetic data for 24 stations as an input for the rainfall runoff model. Generated data are applied to the MIKE SHE hydrological model [6, 14, 28] to simulate daily flows for closing water-gauges. In these studies, 2000 was selected as the reference year to identify potential changes in river flows [1, 16, 17].

5 Results

As in our previous papers [14, 15, 16, 17] the simulations of daily runoff in the Kaczawa River catchment were done at discharge point in Piatnica. The simulations were done for the time horizon 2060 with 2000 as a reference year. Three typical scenarios (GISS Model E, HadCM3, and GFDL R15) were considered. The number of generated years (400) for each case, with total of 1200 simulations for the flow. The rainfall-runoff MIKE SHE model was used in each year for the simulation a daily flow at discharge point (basic information about the average daily flows are included in table 1).

Table 1. Means, standard deviations, maximum and minimum of daily flow over 400 simulated flows, and different scenarios.

Time horizon	Scenario	Mean, m^3/s	Std Dev	Maximum, m^3/s	Minimum, m^3/s
2000	Present	7.07	1.76	12.94	3.10
2060	GISS Model E	8.47	1.80	14.83	3.78
	HadCM3	6.85	1.55	13.17	3.52
	GFDL R15	7.87	1.73	14.48	3.48

　The first step of data analysis is the investigation of yearly mean and standard deviation shape for all scenarios. All plots are given in the Figure 3.
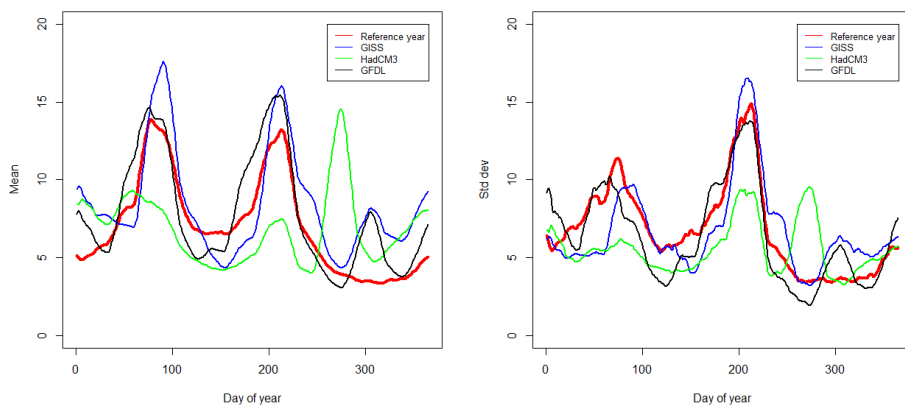

Fig. 3. Plot of yearly smoothed (moving average with window size of 15 days) mean and standard deviation for four scenarios.

For all data types based on the yearly mean shape we can distinguish the regularity of flows within the year. For the present conditions two periods with high flows are identified during March–April and second during July–August. Simulated flows for the GISS Model E and GFDL R15 scenarios for the years 2060 show a high compliance with flows for 2000, however, in the period October-November, the third larger flow appears clearly (on a much smaller scale). In the case of simulated flows for the HadCM3 scenario there are also three periods with larger flows, however, with significantly different values. In the March–April and July–August periods, these are small values, while in the autumn period they are on a level comparable to those simulated for the GISS Model E and GFDL R15 scenarios for the spring and summer. Additionally, in the case of the HadCM3 scenario, high flows appear at the turn of September and October. It should also be noted that for the scenarios considered, the maximum flows may increase by up to 25% and the minimum flows may be reduced by 20% (mainly in May) compared to the current conditions. Already these simulated changes in flows are important information not only in the context of flood safety, but also proper water management. The variance of simulated flows (expressed by standard deviation) does not indicate large changes, in particular their increase in periods of high or low flows. Only in the case of the GISS Model E scenario, an increase in the standard deviation by about 10% along with higher flows by 20% in the July-August period may determine a higher flood risk.

Simulated flows over the year were compared to the reference period (2000), assessing the periodicity of time series. As a standard tool for periodicity detection the periodogram was applied as an asymptotically unbiased estimator of the spectral density. On the Figure 4 the plots of periodograms of flows for reference year and for climate scenarios are presented. Peaks at points d, 2d, 3d etc. indicate periodicity with period of length $T = N/d$ where N is the length of given time series. The analysed data have length $N=400\cdot365$. For all scenarios we observe peaks (Fig. 4) in points $d = 400$, $2d = 800$ and $3d = 1200$ which means that periodogram detected the yearly periodicity. From the above computations, it can be concluded that in the simulated flows for the climate scenarios considered, the periodicity in relation to the reference period (year 2000) will be at a similar level.

In the next step the structure of autocorrelation functions of given flow series were compared. On the graph (Fig. 5), there are vertical lines (a "spikes") corresponding to each lag. The height of each spike shows the value of the autocorrelation function for the lag. Each spike that rises above the dashed line is considered to be statistically significant. In all scenarios, the spikes are statistically significant for lags up to 20. This means that the daily flows are highly correlated with each other. In other words, when the flow rises, it tends to continue rising. When the flow falls, it tends to continue falling. However, the most important issue is that the presented autocorrelation functions for flows simulated for given climate change scenarios do not differ from the autocorrelation function for the reference period. This suggests that flows for the reference period and for three simulations consistent with the adopted climate change scenarios maintain similar relationships and may confirm the absence of major changes in the flows of the Kaczawa River for 2060.
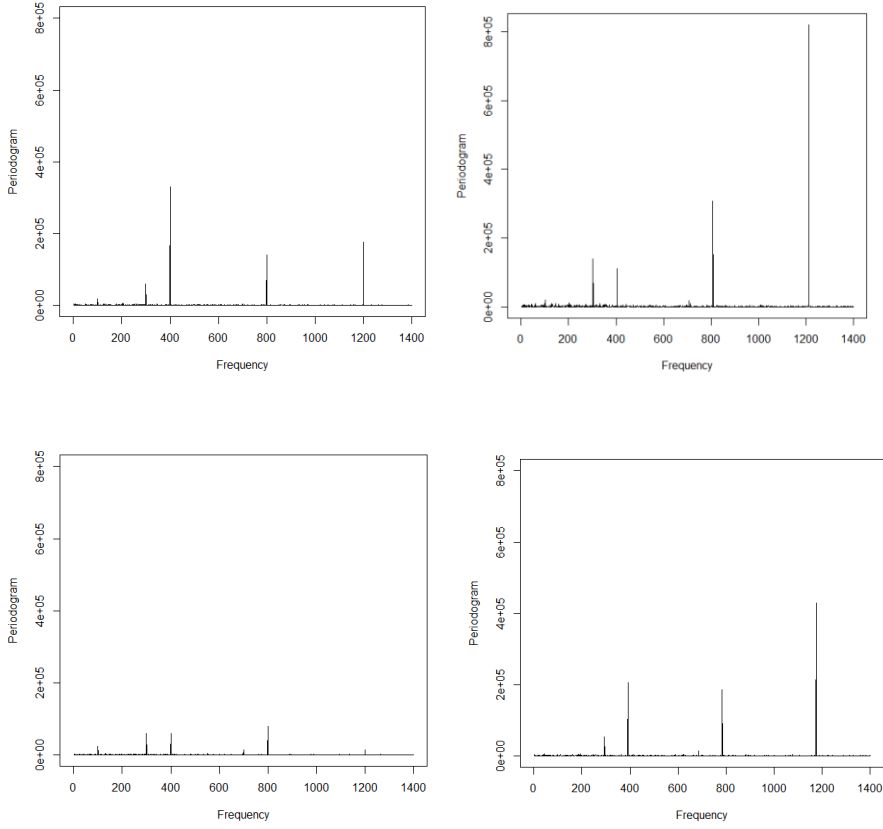
Fig. 4. Plot of periodogram for reference year (left top panel), GISS scenario (right top panel), HadCM3(left bottom panel), GFDL (right bottom panel).
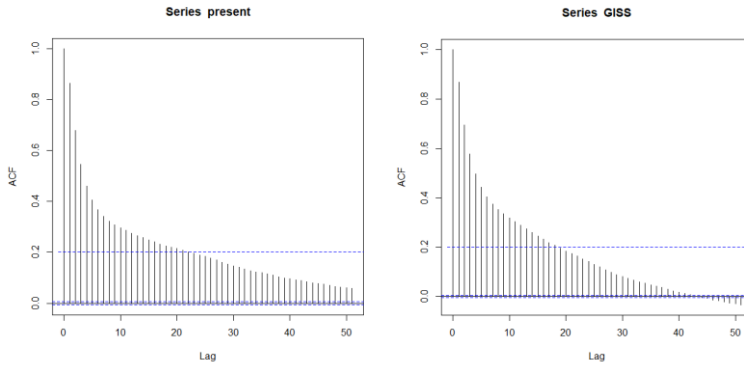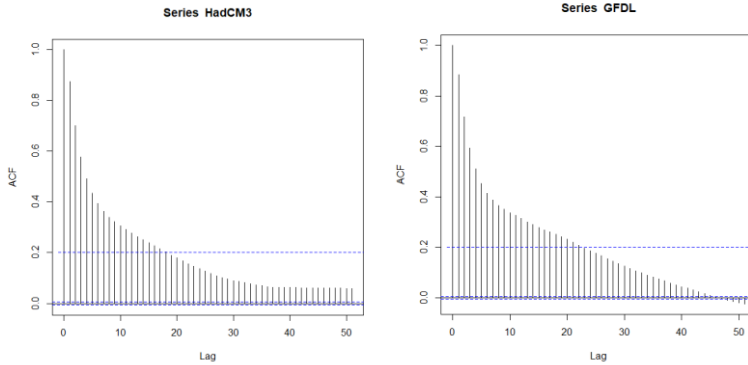
Fig. 5. Plot of autocorrelation function for reference year (left top panel), GISS scenario (right top panel), HadCM3(left bottom panel), GFDL (right bottom panel).

6 Conclusions

The maximum daily flow during the March-April and July-August periods simulated for the GISS scenarios Model E and GFDL R15 increase by 20–25% in relation to the reference period.

In the case of the HadCM3 scenario, only one period of higher flows was detected shifted for the period October–November but with similar values in relation to the reference period.

The course of flow variances in the year for the GISS Model E and GFDL R15 scenarios shows compliance with the reference period. In the case of the HadCM3 scenario, the values of flow variances show a significant drop except for the period October–November.

No changes were detected in long-term flows as well as in the structure of the autocorrelation function.

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