LESZEK KUCHAR, SŁAWOMIR IWAŃSKI, LESZEK JELONEK,
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APPLICATION OF SPATIAL WEATHER GENERATOR FOR THE ASSESSMENT OF CLIMATE CHANGE IMPACTS ON A RIVER RUNOFF

KUCHAR, L., IWAŃSKI, S., JELONEK, L., SZALIŃSKA, W. (2014): Application of spatial weather generator for the assessment of climate change impacts on a river runoff. Geografie, 119, No. 1, pp. 1–25. – In this study, the impacts of climate change on streamflow are investigated. The ensemble of outputs from three different Global Circulation Models models: GISS, CCCM, GFDL developed for the emission scenario A1B were analyzed to infer projected changes in climatological conditions for the region of the Upper and Middle Odra basin. Obtaining hydrological scenarios of future changes for the scale of subcatchment required simulating short-term and fine scaled weather patterns for this area. SWGEN model (Spatial Weather GENerator) was applied to downscale projected changes of climatological conditions to the ones required by hydrological model temporal and spatial resolution. Daily time series of solar radiation, temperature and precipitation were generated for the reference period 1981–2000 and for the time horizon 2030 and 2050. The generated data from SWGEN model were integrated in the hydrological model NAM to simulate streamflow under changed conditions with daily time step. The results show considerable changes in annual and seasonal runoff daily distributions for selected study catchment in the future time horizons of 2030 and 2050.
KEY WORDS: climate change – spatial weather generator – regional hydrology – runoff distribution.

1. Introduction

The projected changes in climate may have a potential significant impact on the hydrological cycle and water resources (IPCC 2007; Bates et al. 2008, Sivakumar 2011). A warmer climate can trigger an increase in evaporation, intensity of water cycling, and greater amounts of moisture in the air. In the recent year, the hydrological risk has been recognized and studied by various authors (Gates 1985; Rind, Goldberg, Ruedy 1989; Grotch, MacCracen 1991; Gleick 1993; Katz 1996; Wilby et al. 2000; Prudhomme, Reynard, Crooks 2002; Barnett et al. 2004; Sulivan, Meigh 2005; Wilby, Harris 2006). There were many attempts to quantitatively assess the impact of climate hazards on

water resources (Müller-Wohlfeil, Bürger, Lahmer 2000; Bergstrom et al. 2001; Burlando, Rosso 2002; Chiew, McMahon 2002; Arnell 2003; Christensen et al. 2004; Wood et al. 2004; Dibike, Coulibaly 2005; Merritt et al. 2006; Leander, Buishand 2007; Kilsby et al. 2007; Bavay et al. 2009; Hagg et al. 2010; Vano et al. 2010). This assessment is crucial in formulating and implementing adaptation strategies to mitigate the effects of climate change. The challenge is that the coarse spatial and temporal resolution of climate system simulations may neither accurately reproduce short-term weather patterns nor explicitly capture the fine-scale climatic structures needed for climate change impact studies and policy planning at the catchment or basin scale (Teutschbein, Wetterhall, Seibert 2011). Therefore, there is an obvious need for research that focuses on developing methods for coupling results of climate models with hydrological modeling to enhance regional detail and introduce fine-scale structures in climate data that force the hydrological model.

The use of regional, high-resolution climate models (RCMs) is a promising approach (Teutschbein, Seibert 2010) though the shortcomings such as bias problem inherent to the parent GCM, calculation costs, simulations of extreme precipitation or specifying consistent estimates on the local and site-specific scale still limit their hydrological use (Chen, Brissette, Leconte 2011; Sharma, Coulibaly, Dibike 2011; Varis, Kajander, Lemmelä 2004). Developed in parallel to RCMs, statistical downscaling methods have been used to overcome these challenges (Wetterhall et al. 2009). Weather Generators fall into category of statistical downscaling techniques. With the use of them, it is possible to rapidly produce sets of climate scenarios for studying impacts of rare climate events and investigating natural variability (Wilks 1992; Kilsby et al. 2007; Wilby 2007; Qian et al. 2010; Wilks 2010, Chen, Brissette, Leconte 2011; Fatichi, Ivanov, Caporali 2011).

In this paper, a SWGEN model (Spatial Weather GENerator) was applied as a downscaling interface between the global circulation model outputs and the hydrological model for the purpose of assessing the impact of climate change on a river runoff. SWGEN model is modification of Richardson and Wright (1984) and Richardson (1985) weather generator to provide multi-site information on meteorological parameters. It accounts for correlations in time and space between the available hydrometeorological observational records from the stations located within the investigated river basin. A set of climate change scenarios, obtained from selected circulation and emission models (GCMs), were introduced to SWGEN model in order to generate daily values of the set of meteorological parameters required to run hydrological model. The output of the SWGEN model was adjusted to the spatial and temporal resolution of the applied hydrological model. The application of weather generator allowed to replicate the statistical attributes (i.e. probability distribution) of current and future hydrological regimes. Studying the changes in probability distributions of the daily outflows allowed to infer climate change impacts on water resources. Research was carried out for the Kaczawa catchment – one of the main left bank tributaries of the Odra River located in the Lower Silesia region. The paper presents the results for two time horizons year 2030 and 2050. Application of SWGEN model allowed to assess regional patterns of climate projections and obtain quantitative assessment of climate change impacts on the selected river streamflow.

2. The study system

2.1. Study area

Basin scale scenarios of future changes in climate on hydrological regime were developed for the Kaczawa catchment. Kaczawa is the left bank tributary of the Odra River with the catchment area of 1,807 km^2 located in the south-west part of Poland. Due to its location – the Sudeten foothills, the Kaczawa catchment has very differentiated landscape with a specific climate typical for mountain and mountain-foot regions. The average annual air temperature is lower than 7 °C. The average annual precipitation varies from 500 to 800 mm. Snow cover remains for about 40–45 days a year. In the Kaczawa catchment there are small post-glacial lakes, three dry reservoirs used for flood protection and one multipurpose reservoir with total capacity of 41 million m^3. At the closing water gauge, the maximum discharge (418 m^3/s) was recorded in July 1997.

2.2. Hydro-climatic data

Daily weather series were used to estimate climatological characteristics from the set of monitoring stations operated by the Institute of Meteorology and Water Management, State Research Institute and located within or in a close
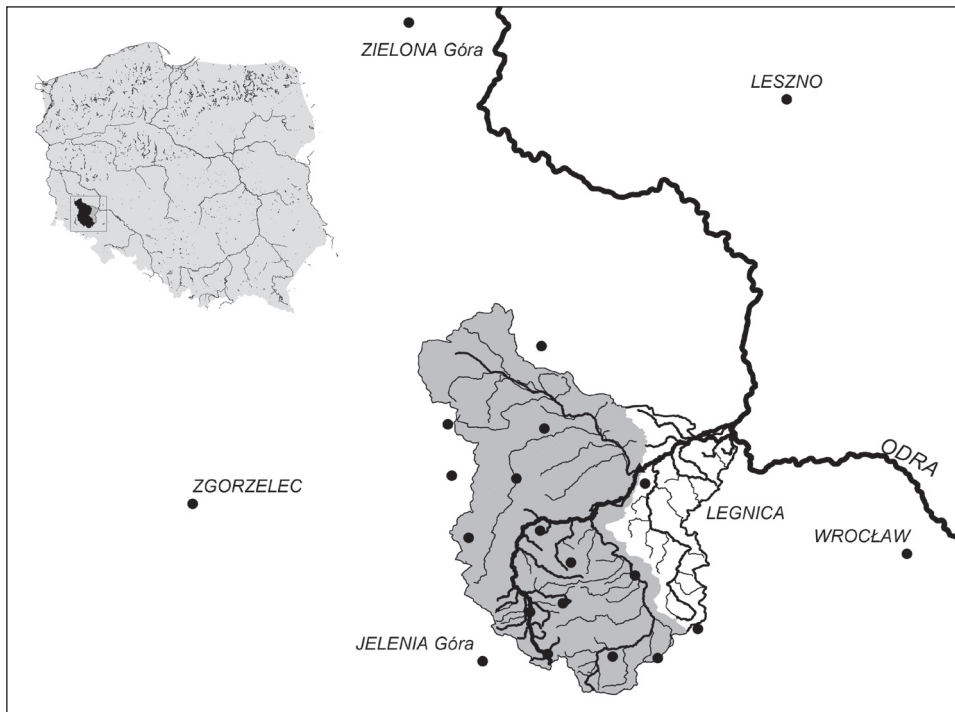

Fig. 1 – The Kaczawa river catchment and location of weather stations used in the study

Table 1 – Weather stations and measurements used in the study (P – precipitation, SR – solar radiation, IS – isolation, t – temperature)

No	Station	Location			Data
		Long.	Lat.	Alt.	
1.	Bolków	16°06'E	50°55'N	361	P
2.	Chocianów	15°55'E	51°25'N	146	P
3.	Chojnów	15°56'E	51°17'N	162	P
4.	Dobromierz	16°15'E	50°55'N	278	P
5.	Iwiny	15°42'E	51°12'N	211	P
6.	Jawor	16°11'E	51°03'N	178	P
7.	Kaczorów	15°58'E	50°55'N	487	P
8.	Legnica	16°12'E	51°12'N	107	SR, IS, t, P
9.	Lubin	16°12'E	51°24'N	127	P
10.	Stanisławów	16°01'E	51°04'N	373	P
11.	Strzegom	16°21'E	50°58'N	227	P
12.	Tomaszów Bolesławiecki	15°41'E	51°17'N	186	t, P
13.	Twardocice	15°45'E	51°06'N	258	P
14.	Wojcieszów Dolny	15°55'E	50°59'N	397	P
15.	Zagrodno	15°52'E	51°12'N	193	P
16.	Złotoryja	15°56'E	51°07'N	223	P
17.	Chwałkowie	16°37'E	51°27'N	159	t
18.	Jelenia Góra	15°48'E	50°54'N	345	IS, t
19.	Leszno	16°32'E	51°50'N	87	IS, t
20.	Polkowice Dolne	16°03'E	51°30'N	150	t
21.	Pszenno	16°33'E	50°51'N	205	t
22.	Wrocław	16°53'E	51°06'N	110	IS, t
23.	Zgorzelec	15°02'E	51°08'N	198	t
24.	Zielona Góra	15°32'E	51°56'N	169	IS, t

vicinity of the analyzed catchment (Fig. 1). The baseline climate conditions were developed from the period of 1981–2000 and were used as a reference to assess future changes. A basic set of 16 meteorological stations within the catchment area plus 8 additional stations in the region used in the study are listed in Table 1 along with the available data of the selected meteorological parameters.

With the aim of weather generator model calibration, the characteristics of required meteorological parameters: SR (solar radiation), t_{min} and t_{max} (minimum and maximum temperature) and P (precipitation total) were estimated for each station of the Kaczawa catchment. Solar radiation values were obtained from insolation (IS) measurements according to Black formula (Black, Bonython, Prescott 1954). The characteristic of each analyzed meteorological parameter was represented by its monthly mean value and standard deviation. For the stations with lack of measurements of a given meteorological parameter, these characteristics were obtained with the use of interpolation techniques: ordinary kriging and inverse distance weighing method. The selection of better interpolation techniques was performed with the use of cross-validation method with the criteria based on the value of RMSE (root mean square error).

2.2. Projections of climate change

Global Circulation Models (GCMs) are mathematical representations of numerous atmosphere, ocean, and land surface processes based on the laws of physics. Such models consider a wide range of physical processes that characterize the climate system and have been used to examine the impact of increased greenhouse gas concentrations on global climate. The approved set of emission scenarios is described in the IPCC Special Report on Emission Scenarios (SRES). The study focus on scenario A1B that assumes balance across all sources of energy for a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies (IPCC SRES SPM 2000). The results from a set of three GCM models: GISS2 model (Russell, Miller, Rind 1995; Russell, Rind 1999; Yao, Del Genio 1999) developed at Goddard Institute for Space Studies (GISS), CGCM1 model (Boer et al. 1992, 2000a, 2000b) of Canadian Climate Centre Modeling and Analysis (CCCma), GFDL_R15_a model (Manabe et al.1991; Stouffer, Manabe 1999) of Geophysical Fluid Dynamics Laboratory (GFDL). In the study the selected models were labeled by their institution of origin. The selected models satisfy the following criteria and constitute rationale for their selection: i) consistent with widely accepted global estimates of climate change, ii) physically plausible and internally consistent and iii) able to estimate a sufficient number of variables and iv) reflect a regional range of potential climate change in Europe (Smith, Pitts 1997).

Table 2 – Assumed changes of climate elements for the time horizons 2030 and 2050 according to adopted GCM models for the analyzed area

| Institution of origin	Applied model and reference	P*	Time horizon					
			2030			2050		
			winter MEAN	summer MEAN	year STD	winter MEAN	summer MEAN	year STD
Goddard Institute for Space Studies *(GISS),* USA	GISS2 (Russell et al., 1995; 1999; Yao and Del Genio, 1999)	T	+0.9 °C	+0.7 °C	+3%	+2.8 °C	+2.0 °C	+9%
		P	+4%	0%	+4%	+12%	0%	+12%
Canadian Climate Centre Modeling and Analysis *(CCCma),* Canada	CGCM1 model (Boer et al., 1992; 2000a; 2000b)	T	+0.8 °C	+0.6 °C	+2%	+2.4 °C	+1.9 °C	+6%
		P	+5%	−3%	+2%	+14%	−9%	+6%
Geophysical Fluid Dynamics Laboratory, *(GFDL)*, USA	GFDL_R15_a model (Manabe et al., 1991; Stouffer et al., 1999)	T	+0.9 °C	+0.6 °C	+2%	+2.6 °C	+2.3 °C	+6%
		P	+10%	−8%	+10%	+30%	−24%	+30%

Note: P* = parameters
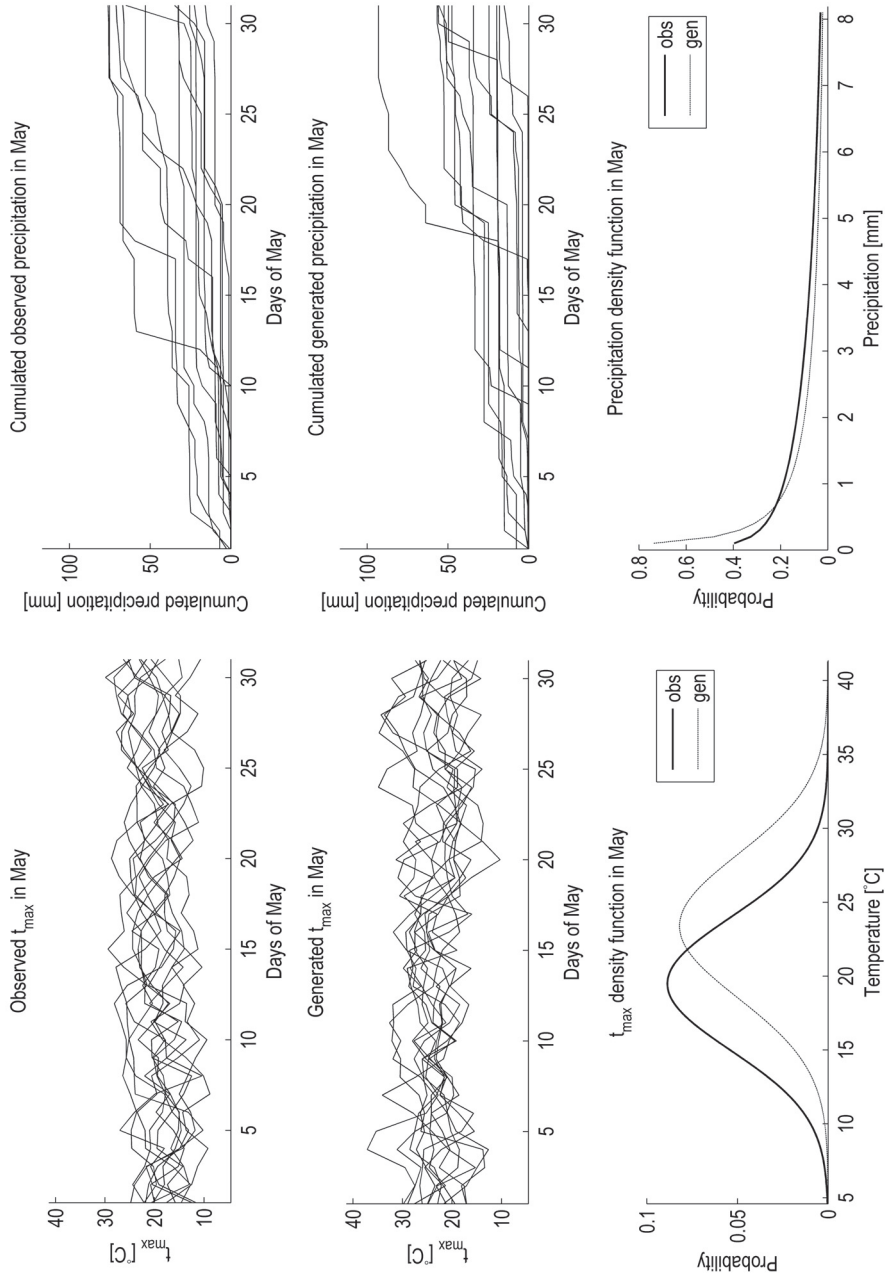
Fig. 2 – Estimated impact of climate change on the temperature (left panel) and precipitation (right panel) patterns in June along with the probability distribution functions developed for current and changed conditions.

These models were used in order to provide raw information on the climate change scenarios for the time horizon 2030 and 2050 for the territory of Poland. Particular values summarizing the changes in mean values and standard deviations of temperature and precipitation were developed by approximating selected model results to the area of interests (Southwest part of Poland – see Table 2).

Each of the daily value of the analyzed meteorological parameters (SR, t_{min}, t_{max} and P) was construed as realization of the stochastic process that is characterized by the mean value, standard deviation and probability distribution function (pdf). Primarily these characteristics were developed for individual locations and months for the control period from 1981 to 2000 and then were modified according to projected changes summarized in Table 2 for the time horizon 2030 and 2050. Analyzed climate change scenarios do not specify the solar radiation behavior and therefore these characteristics were assumed to remain unchanged. An example of the potential impact of projected climate change on temperature and precipitation patterns in May for the time horizon 2050 are presented in Figure 2.

2.3. Geographical context

The region of Sudety mountains is characterized with the highest after Carpathian mountains annual precipitation totals in Poland. Simultaneously, the area is marked by a large precipitation variation due complex orography causing the increase in the amount of precipitation with the altitude and rain shadows. According to the Polish National Department of Safety and Crisis Management the biggest risk of flooding is recognized for the areas of five southern provinces of Poland including province of Lower Silesia. In the province of Lower Silesia the highest flood hazard come from the following rivers: Mala Panew, Olza, Nysa Kłodzka, Bystrzyca and Kaczawa. Kaczawa catchment river network is well developed and is reinforced mainly from the rain in summer period and from snow in winter time. The pluvial foods are caused by both convective and frontal rainfalls. In the years 1950–2002 the significant flood were observed in 1965, 1977, 1981 and 1997. Floods in the Kaczawa catchment have direct impacts on the regional economy and society due to high degree of industry and agriculture in the region. The agricultural activity in the region is exposed to water deficit hazard. Within the period 1966–2003 Kaczawa was found to the note highest number (54–41) of low flow periods within the whole province.

According to climate change projections the frequency of extreme meteorological event is likely to increase causing higher frequency of floods and droughts (Kundzewicz 2011). Development of the tools dedicated to the basins that are particularly prone to these risks are the basis for building mitigation strategies and adaptation plans.

3. Methodology

The fundamental idea of application of Spatial Weather GENerator for the assessment of climate change impacts on a river runoff can be streamlined into 5 steps: i) estimation of the characteristics of meteorological parameters, ii) spatial weather generator calibration, iii) synthetic meteorological data replication, iv) hydrological modeling and runoff simulations, v) evaluation of statistical attributes of hydrological regime.

These steps are performed for 3 options: for the baseline year 2000 (control period of current meteorological conditions), for the time horizon 2030, for the time horizon 2050. For the baseline period, the characteristics of meteorological parameters were obtained from available daily data and with the use of interpolation techniques described above. For year 2030 and 2050 these characteristics were modified accordingly to the projected changes. Calibration phase of spatial weather generator was done with the use of observed data within the period 1981–2000 in order to estimate model parameters accounting for spatial correlation among the collocated stations within the analyzed river catchment. In the next step, 300 replications of annual pattern of analyzed meteorological parameters were performed to produce synthetic data for three benchmarking years: 2000, 2030 and 2050. Then, these data were introduced to hydrological model to simulate river runoff. The obtained results were evaluated in terms of statistical distribution functions representing current and projected hydrological regimes.

3.1. Spatial Weather Generation model SWGEN

Standard measurements of meteorological parameters are performed on the meteorological and precipitation stations. It provides point information of varying representativeness that depends *inter alia* on the analyzed parameters, adopted scale and temporal resolution. Spatial interpolation techniques allowed to obtain areal information from a set of stations. In order to improve quality of this assessment it is highly profitable to include information on the spatial correlation between stations. Applied weather generator model is aimed to account for this information. Weather generation model SWGEN is based on a point WGEN model (Richardson, Wright 1984; Richardson 1985) with modifications introduced by Kuchar (2004) and with extension to a spatial domain (Iwanski, Kuchar 2003). There were several efforts to develop multi-site weather generators for precipitation data generation (Bardossy, Plate 1992; Wilks 1998; Bellone, Hughes, Guttorp 2000; Hughes, Guttorp 1994; Hughes, Guttorp, Charles 1999; Brissette, Khalili, Leconte 2007; Tae-woong, Hosung, Gunhui 2007; Khalili, Leconte, Brissette 2007; Khalili, Brissette, Leconte 2009). Multi-site generation of precipitation and non-precipitation data were developed by Wilks (1998) and Buishand and Brandsma (2001), Beersma and Buishand (2003) and most recently by Khalili, Brissette, Leconte (2009).

SWGEN provides daily values for precipitation (P), insolation (IS), maximum temperature (t_{max}), minimum temperature (t_{min}), and solar radiation (SR) simultaneously for the set of collocated stations. The model accounts for

the persistence of each variable, the spatial dependence among the variables, dependence in time and the seasonal characteristics of each variable. SWGEN accounts for seasonal variation for data simulation and generates all the analyzed meteorological parameters for each month m (m = 1, 2, …, 12) and for each station k (k = 1, 2, …, K), where K is the total number of stations. As an input the generator requires daily measured values in order to calculate the monthly statistics, which then are used to generate synthetic daily data. Model is containing two main components: 1. precipitation generator, 2. temperature and solar radiation generator.

Precipitation simulation is done with two-step procedure. First, the occurrence of wet (W) and dry (D) days is determined by a first order Markov chain with two-states S = {0,1}. 0 corresponds to dry day (D) with precipitation total < 0,1 mm and 1 is denoting wet day (W). Transition probabilities: $P_m^k(W/W)$, $P_m^k(W/D)$, $P_m^k(D/W)$, $P_m^k(D/D)$ define occurrence of wet (W) and dry (D) days that is conditioned on the state in the previous day for the particular station k. A covariance matrix CS_m is identifying the spatial relationship between states occurring on different stations. In order to generate the ultimate state for a given day and station $S_t(k)$, values of transition probabilities are compared with the values from distribution simulating random process: $\Omega_k^m(w_t(k))$, where w_t is generated from normal distribution with mean 0 and covariance matrix CS_m: $N(0, CS_m)$. Marginal distributions of $\Omega_k^m(.)$ follow $N(0, \omega_k^m)$ with w_k^m being a standard deviation of states developed for station k and month m. The state for time t is set to 1 (wet), once the value $w_t(k)$ is smaller or equal to transition probability $P_m^k(W/W)$ or $P_m^k(W/D)$ pending on the state in time step $t–1$.

The next step is to model the amount of precipitation for a given day and location $P_t(k)$. 2-parameter gamma distribution $\Gamma_m^k(a_m^k, b_m^k)$, was fitted individually for each month and for each station during the model calibration phase. Similarly a covariance matrix CP_m was used to define the correlations between amounts of precipitation in different stations. Simulation was done through the generation of random process u_t from normal distribution $N(0, CP_m)$ with marginal distributions $\Psi_k^m(.)$ following $N(0, y_k^m)$ with y_k^m denoting standard deviation of daily precipitation totals developed for station k and month m. Precipitation totals for a given wet day was found from formula:

$$P_t(k) = S_t(k) \cdot \Gamma^{-1}{}_k^m (\Psi_k^m(u_t(k))) \qquad \text{(Eq. 1)}$$

In contrary to other weather generation models, SWGEN allows for simulations of insolation values. It is done with the similar procedures as the ones applied for precipitation simulations. Two states of insolation were recognized: 0 with cloudiness during the daylight and 1 for the other cases. Simulation of state for a day was done with the use of two-state, first-order Markov chain. The adopted procedure differs from the one of precipitation simulation only with the adopted function to simulate the amount of insolation for a non-cloudy day. In this case a 2-parameter Weibull distribution was used. The values of Weibull distribution parameters were developed for each month with the separation of wet and dry days in order to account for their substantial difference of insolation values.

Maximum temperature, minimum temperature and solar radiation is generated through second component of SWGEN model. Priori to this long term daily

data series of minimum and maximum temperature and solar radiation used for model calibration were standardized on a monthly basis. Standardization was done separately for wet and dry days with the use of monthly mean value and standard deviation estimated from wet days observations and the ones from dry days. Then a first-order multivariate stochastic process AR(1) was used to simulate simultaneously for all K stations, random residuals of analyzed parameters:

$$X_t = \Phi_m X_{t-1} + \varepsilon_t \qquad\qquad\qquad\text{(Eq. 2)}$$

where X_t is a matrix containing current daily standardized value of t_{max}, t_{min} and SR and X_{t-1} matrix containing previous daily standardized values of t_{max}, t_{min} and R. $\varepsilon_t = (\varepsilon_{t1}, \varepsilon_{t2}, \dots, \varepsilon_{tL})'$ is matrix of independent vectors of errors of normal distribution with mean 0 and covariance matrix $\Sigma_m = E(\varepsilon_t \varepsilon_t') N(0, \Sigma_m)$. Φ_m is a $L{\times}L$ matrix of parameters developed for each month. Because t_{max}, t_{min} and SR are simulated simultaneously $L = 3 \times K$.

After estimation of parameters, developed monthly multiple regression models were combined together by introducing the values obtained from the last day from previous month as the starting value to generate first value in next month from AR(1) model. In this way a construction of unique stochastic model adaptive to monthly variation of parameters was achieved. After generation of residual destandardization procedure was performed in order to obtain simulated data.

3.2. Hydrological model

NAM is a deterministic, conceptual model developed by Danish Hydrological Institute. Its name – NAM – comes from the abbreviation of the Danish "Nedbør-Afstrømnings-Model" meaning rainfall-runoff-model. NAM's objective is to simulate the rainfall-runoff process in catchments (Havnø, Madsen, Dørge 1995). The model is a set of linked mathematical statements describing, in a simplified quantitative form, the behaviour of the land phase of the hydrological cycle. It operates by continuously counting moisture content in four different and mutually interrelated storages (snow storage, surface storage, root zone storage, groundwater storage) which represent physical elements of the catchment (Madsen 2000, MIKE 11 User Guide 2003). It simulates overland-, inter- and baseflow components of a catchment runoff. It calculates sub-catchment inflow to river model (hydrodynamic model). The input data requirements are meteorological data as rainfall, temperature and potential evaporation. The latter was estimated by modified Turc formula (Nilsen, Hansen 1973).

4. Results

4.1. Calibration and validation of Spatial Weather Generator

Model calibration phase consisted of calculating the relevant statistical parameters of the spatial weather generator corresponding to the current climate.

Parameters were calculated on the historical data sets observed in the period of 1981–2000. In the first stage, observed daily precipitation time series were used to calculate transition probabilities of wet/dry days and estimate parameters of gamma distributions for each station and each month. Next, daily mean, maximum and minimum temperatures together with total solar radiation data sets were used to estimate the parameters of the multidimensional matrix describing temporal and spatial interdependencies among these variables. For the purpose of model validation, the obtained statistical parameters were then used to generate stochastically realistic climate data corresponding to the current conditions.

Spatial weather generator validation was done in a different way for solar radiation and temperature variables and differently for precipitation. Validation of spatial weather generator for SR, t_{max}, t_{min} was performed by assessing the difference between correlations, mean values and standard deviation obtained respectively for the observed and synthetic (generated from the model) monthly sets of daily data. The correlations were analyzed in terms of cross correlations: between different parameters and/or different stations and cross-lag correlations: autocorrelation and cross correlation with time lag. Then, the cross and cross-lag correlations were compared pairwise: correlation obtained for simulated data with the correlation obtained for the observed ones. The same was done with the mean values and standard deviations. Selection of the resulting plots is presented in Figure 3. and in Figure 4 which visualize the ability of spatial weather generator to replicate current climatological conditions according to the adopted criteria.

The resulting graphs (Fig. 3) show satisfactory agreement between cross and cross-lag correlations obtained for generated versus observed data. The highest values of the difference in correlations were noted for the cross correlation and cross-lag correlations of t_{max} versus SR and t_{min} versus SR. The highest difference reached however only 0.09. The plots indicate a slight bias of generated temperature values with the respect to the observed ones. The generated temperature values were more cross correlated then the observed ones. However, the maximum difference in correlations did not exceed 0.05.

Spatial Weather Generator reproduced satisfactorily the statistical properties of the generated meteorological variables including mean values and standard deviations (Fig. 4). Mean values of simulated SR, t_{min} and t_{max} variables corresponded to the observed ones. For the higher values of t_{min} temperature simulated data had higher standard deviation then the observed ones. Also standard deviation of simulated t_{max} was slightly higher than the one of the observed t_{max} values, however, despite its range. The observed bias was not exceeding 5% for standard deviation of t_{min} values and 7% of standard deviation of t_{max} ones.

Validation of Spatial Weather Generator in terms of its ability to reproduce precipitation patterns was done by analyzing correlations between generated and observed daily precipitation totals for the same station and collocated stations, number of wet days, transition probability from wet day to dry one and from wet to wet (Fig. 5).

Correlations of simulated daily precipitation totals were underestimated comparing to the ones for the observed data. The difference varied from 0.08
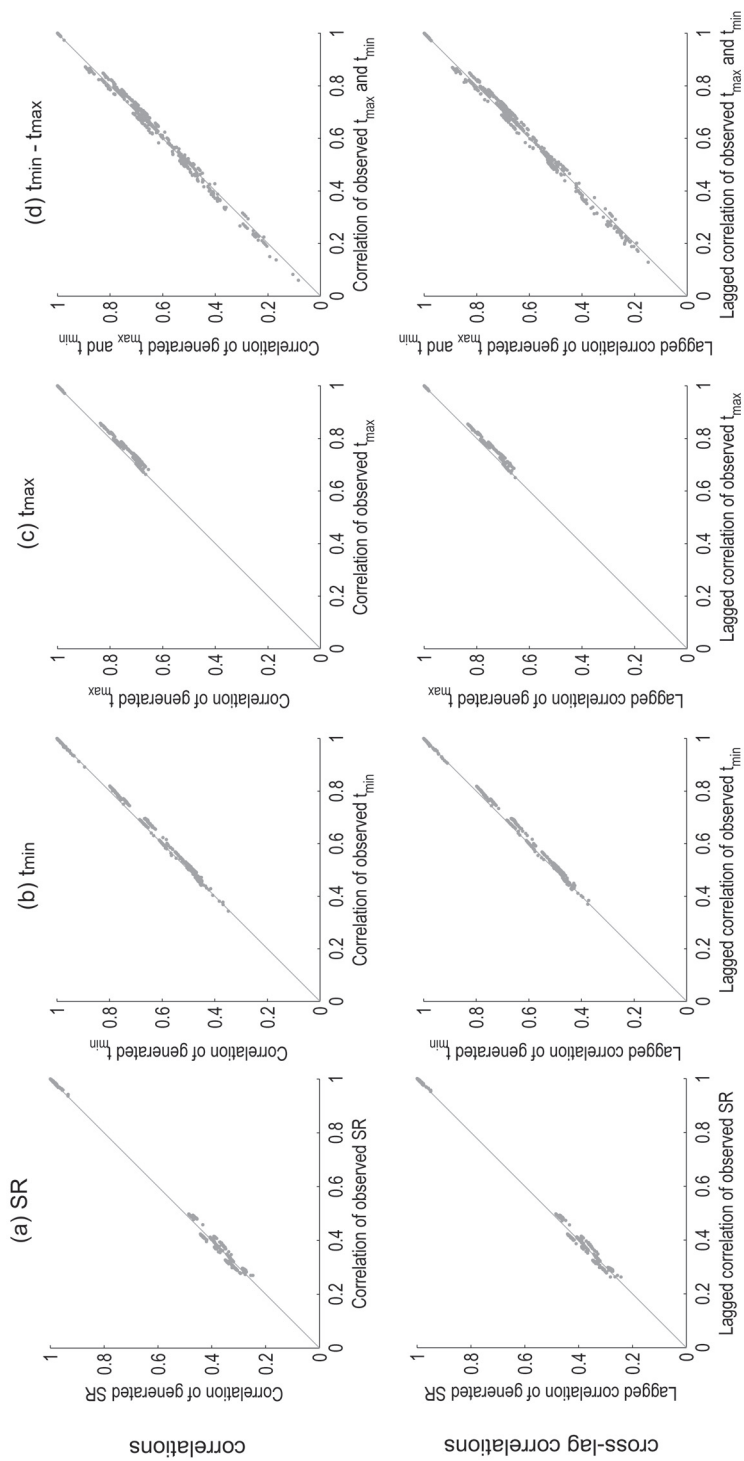
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Fig. 3 – Cross and cross-lag correlations for the observed versus simulated monthly sets of daily data of SR(a), t_{min} (b), t_{max} (c) and t_{min} and t_{max}(d).
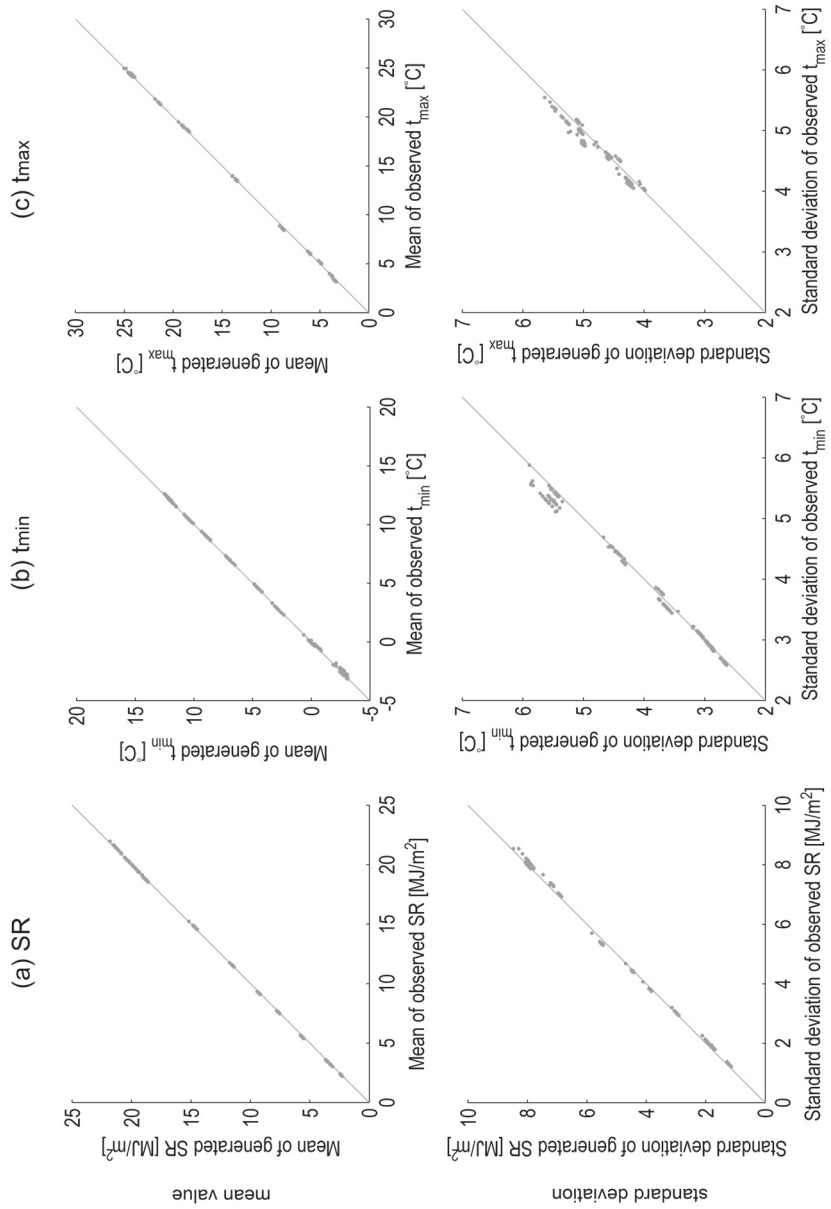
Fig. 4 – Mean values and standard deviations for the observed versus simulated monthly sets of daily data of SR (a), t_{min} (b) and t_{max}(c).
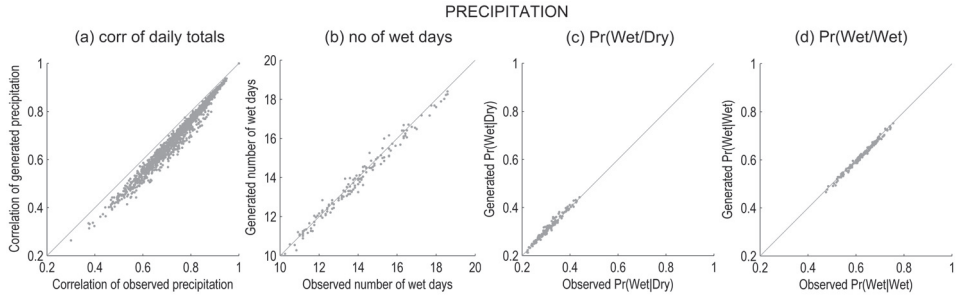
PRECIPITATION

Fig. 5 – Correspondence plots between generated and observed: daily precipitation totals correlations (a), number of wet days (b), transition probability from wet day to dry one (c) and from wet to wet (d).

obtained for October to 0.23 in May. A proper correlation was found in the simulated versus observed number of wet days as well as in the transition probabilities from wet to dry day and from wet to wet.

4.2. Calibration and validation of hydrological model

The initial step for hydrological model calibration and validation consisted in preparing precipitation basin-averaged, temperature and potential evapo-transpiration data input. Potential evaporation daily totals were calculated with the use of modified Turc formula from the Legnica synoptic station that is representative for the analyzed catchment. Mean daily precipitation totals were calculated by Thiessen polygon method (or inverse distance method weighting method) from the set of 16 stations within the catchment area. Daily discharge data observed at 6 closing gauge stations in the Kaczawa catchment, were used for hydrological model calibration. The calibration of the Kaczawa NAM model

Table 3 – Resulting values of parameters of hydrological model obtained with the automatic optimalization routine

Parameter		Value
Maximum water content in surface storage	$Umax$	10
Maximum water content in root zone storage	$Lmax$	125
Overland flow runoff coefficient	$CQOF$	0.9
Time constant for interflow	$CKIF$	256.3
Time constant for routing interflow and overland flow	$CK1.2$	44
Root zone threshold value for overland flow	TOF	0.54
Root zone threshold value for interflow	TIF	0.14
Root zone threshold value for groundwater recharge	TG	0.811
Baseflow time constant	$CKBF$	3955
Root zone threshold value for groundwater recharge	$CK2$	10
Recharge to lower groundwater storage	$CQLOW$	50
Time constant for routing lower baseflow	$CKLOW$	1.00E+04

was done with the use of the automatic optimization routine with the use of data from the control period 1981–2000. This automatic calibration routine is based on a multi-objective optimization strategy. With this routine, nine parameters of the model were estimated (Tab. 3).

The results of Kaczawa NAM model calibration allowed for obtaining good agreement between observed and modelled values of water balance, shape of the hydrograph and good agreement of the peak flows with respect to the peaks' timing, rate and volume. On the other hand, the performance of hydrological model calibration was worse in case of low flows agreement. This is due to the fact that for Kaczawa river low flows are strongly influenced by water management. Also the evapotranspiration is calculated by the model on the basis of available water in the upper model storage. However, it does not take into account the vegetation and land use. The uncertainty linked to model calibration in future climate was not considered in this study.

4.3. River runoff simulations

Simulations of daily values of total runoff volume from hydrological model were performed for the closing gauge station Piatnica of Kaczawa catchment. The resulting hydrographs were computed using synthetic data from spatial weather generator for both the baseline year 2000 and for the investigated time horizons: year 2030 and 2050. Representing results for control period by synthetic data not real observed ones was done to ensure that any systematic error introduced by hydrological model is not taken into account when comparing the future to baseline conditions. The baseline year 2000 was replicated 300 times, as well as the year 2030 and 2050 for three analyzed climate change scenarios. This gave a total number of synthetic meteorological data sets of 2,200 ($300 + 2 \times 300 \times 3$). Synthetic data sets were then repeatedly introduced to hydrological model NAM and daily totals of runoff volumes were estimated. The obtained discharge values were used to calculate mean values for individual months and for the selected periods: from June to August (summer period), from May to October (warm season) and from November to April (cold season). For each of these periods the ensemble average obtained from 300 replications were fitted to probability distribution function (Fig. 6). 3-parameter gamma distribution was found as the best fitting monthly, seasonal and annual distributions of daily runoff basing on K-S and Chi-Square tests.

4.4. Hydrological responses to climate change

Fitting results to PDFs allow reducing the uncertainty of daily time series of each variable and examining the general tendencies for river runoff. Information on statistical properties of the obtained PDFs was the basis to infer climate change impacts on water resources.

The resulting graphs indicate the tendencies of discharge values over the analyzed periods for investigated time horizons according to different climate change scenarios. With the analysis of the properties of obtained PDFs, it
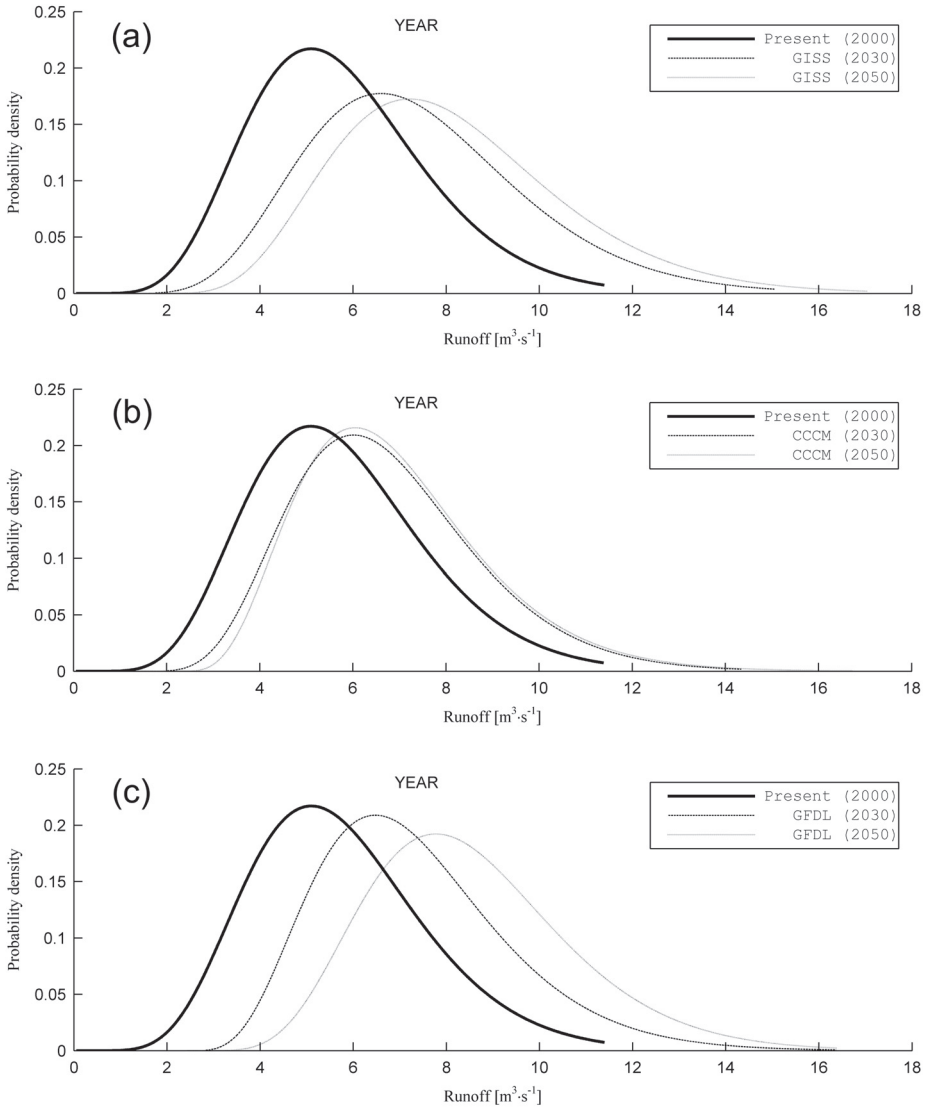
Fig. 6 – Seasonal distribution of daily runoff at gauge Piątnica of the Kaczawa river for the period of November–April (a), May–October (b) and June–August (c) developed for the baseline year 2000 and for the year 2030 (left panel) and for the baseline year 2000 and for the year 2050 (right panel). GISS – model of Goddard Institute for Space Studies; CCCM – model of Canadian Climate Centre Modeling and Analysis; GFDL – model of Geophysical Fluid Dynamics Laboratory.

is possible to identify the changes in the value of mean runoff, coefficient of variation and runoff quintile values. The predicted future runoff conditions in the Kaczawa catchment clearly depend on the general development of both temperature and precipitation assumed in the analyzed GCM scenarios. Annual average streamflow tends to increase gradually with time under all
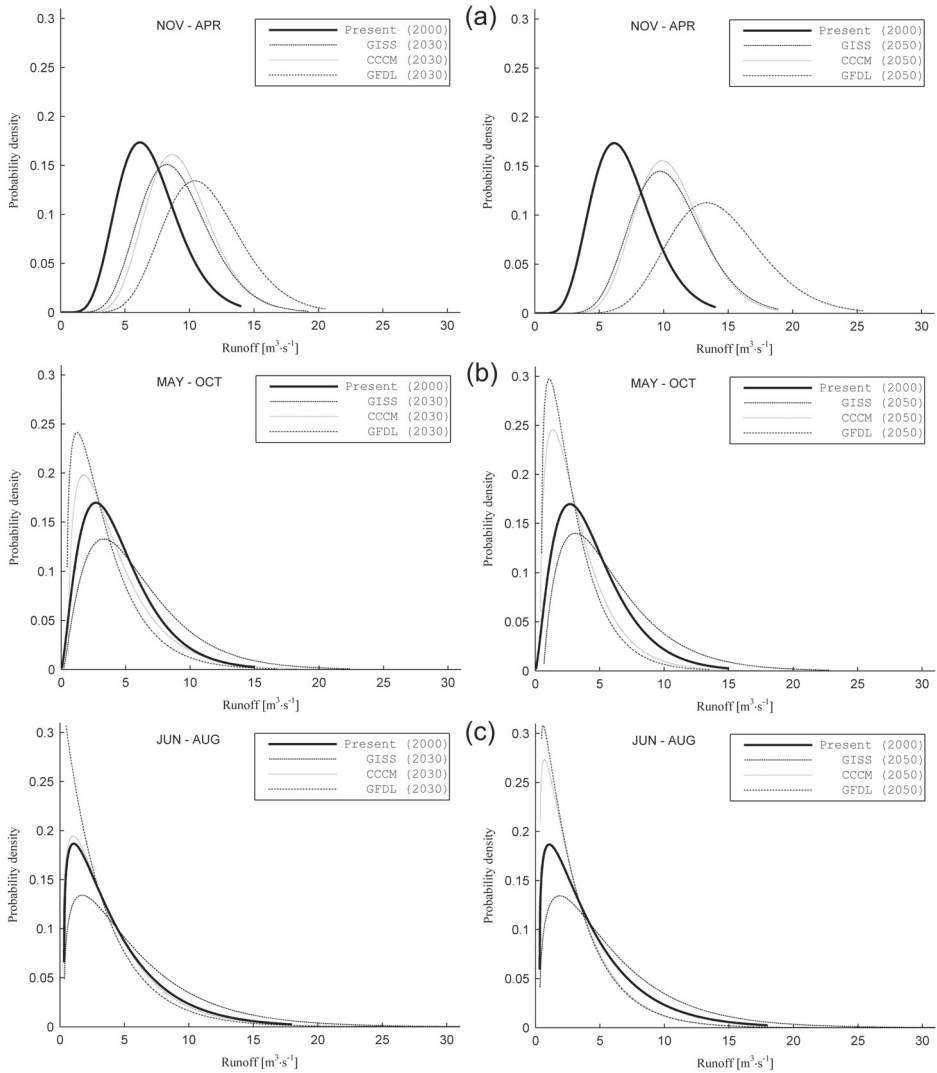
Fig. 7 – Annual distribution of daily runoff at gauge Piątnica of the Kaczawa river for the baseline year 2000, for the year 2030 and 2050 according to different climate change scenarios according to (a): model of Goddard Institute for Space Studies – GISS, (b) – model of Canadian Climate Centre Modeling and Analysis – CCCM, (c) – model of Geophysical Fluid Dynamics Laboratory (GFDL).

analyzed scenarios relative to the current runoff (4.9 m³/sec) and except from CCCma scenario is expected to exceed 7 m³/sec in 2050 (Fig. 6). For the year 2050 the predicted increase of mean runoff value for the cold season varies from 30% for GISS and CCCma scenarios to 60% for GFDL scenario. For the warm season according to GISS scenario, 20% increase in mean runoff value is expected while basing on CCCma and GFDL scenarios, mean runoff value can decrease by 10% to 25%. For the summer period the expected change in

mean runoff value is relatively small ±15% for GFDL and GISS scenarios respectively (Fig. 7).

The results obtained for all three scenarios show significant increase in coefficient of runoff variation for all analyzed periods. The increase was the most strongly pronounced for GISS scenario and summer period exceeding 100% and for warm season exceeding 80%. The value of 95th percentile of runoff is estimated to increase by 50% for most of the analyzed periods.

5. Conclusions

Weather generators can reproduce time series of meteorological variables that are statistically similar to observations. The combination of the applied methods – the coupling of the several of GCM outputs with the Spatial Weather Generator and the subsequent hydrological simulation of the river runoff has been demonstrated as a useful tool for climate impact studies. The results from Spatial Weather Generator replicated successfully the current climatological conditions. This was the foundation for future climate simulations. Climatological data were generated with the temporal and spatial resolution adjusted to the applied hydrological model. Each replication of the potential realization of climate condition for the baseline 2000, year 2030 and 2050 was introduced to hydrological model to estimate the series of daily runoff values from Kaczawa catchment at the closing gauge. Fitting the obtained runoff results to probability distribution functions allowed to infer the statistical properties and summarize the impact of climate change on the hydrological regime of Kaczawa catchment. The achieved results characterize the whole spectrum of hydrological characteristics of the river – i.e. mean daily runoff, extreme values as well as their confidence levels – within the time horizon of 30–50 years.

The obtained results of runoff change scenarios show significant changes in the annual and seasonal runoff distribution. The most significant change in runoff was found for cold season according to all the three climate change scenarios. Further study is needed to quantify the effect of model uncertainties on such predictions. Nevertheless, the application of spatial weather generator allows for explicit incorporation of uncertainty by simulating a wider range of possible climate change scenario realizations.

Identifying trends and tendencies of changes in discharge characteristics triggered by climate change is required for optimal management of water resources to reduce potential social, economical and environmental losses.

6. Discussion

Within the period 1951–2008 the mean annual temperature in Poland has increase from 1 °C up to locally almost 2 °C in the seaside (Miętus et. al 2012). For the south-west part of Poland the gradient of observed changes in temperature was relatively high and varied from 1.2 °C to 1.6 °C. The biggest changes were observed in winter varying in the analyzed region from 1.6 °C up to 2.2 °C. The summer period was characterized with the smaller and more uniform changes

around 1.2 °C. According to most of the emission scenarios these trends will be continued although with different rates pending to the region and the season (Kundzewicz 2011). This will lead to increase of thermal contrasts between different regions. Observed and projected climate change in the past decades are not only limited to the temperature rise (Wibig, Jakusik, eds. 2012). A change in many meteorological elements can lead to major structural changes in the water balance (Majewski, Walczykiewicz, red. 2012). The value and variability of rainfall in the catchment affect in a decisive way the water recourses. The climate change studies confirm a distinct seasonal and spatial variability of precipitation trends direction and significance (Łupikasza, Hansel, Matschullat 2011; Niedzwiedź, Twardosz, Walanus 2009). In recent years the most comprehensive analysis of the projected climate changes and their potential effects including the impacts on water recourses were developed within the framework of the KLIMAT project (The effects of climate change on the environment, the economy and the society – changes, their effects and the ways to mitigate them, conclusions for science, engineering and economic planning) carried out at the Institute of Meteorology and Water Management – National Research Institute in Poland in the years 2008–2012. The results of the KLIMAT project concerning water resources are presented as the percentage of potential changes in unit runoff for the period 2011–2030 in comparison to the reference period 1971–1990 according to 3 climate change scenarios:A2, A1B, B1. The results did not show a significant change of surface water resources in the period 2011–2030 for the analyzed region of Kaczawa catchment. The projected changes were however found in the temporal distribution of the runoff value. For the A1B emission scenario in the summer period the mean runoff value in Kaczawa catchment is likely to decrease by max 15%. In winter period the runoff will increase by max 5%. That is consistent with the tendencies obtained with the use of SWGEN model.

Projections and climate change models are based on many assumptions and simplifications, and therefore the results are subject to varying degrees of uncertainty. There are two major sources of uncertainties in the assessment of hydrological impact of climate change: uncertainties in the future greenhouse emission scenarios and uncertainties in representing rainfall-runoff processes. The further research will concentrate on quantification of the uncertainty of the future scenarios derived from ensemble of GCM models (Thompson et al. 2012). Uncertainty in hydrological modeling will be reduced by an attempt to use fully distributed hydrologic models (Ludwig et al. 2009).

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S h r n u t í

VYUŽITÍ PROSTOROVÉHO GENERÁTORU POČASÍ PRO HODNOCENÍ DOPADŮ KLIMATICKÉ ZMĚNY NA ŘÍČNÍ ODTOK

Předpokládané změny klimatu mají potenciálně významné dopady na fungování hydrologických cyklů a stav vodních zdrojů. Již bylo učiněno mnoho pokusů o kvantitativní zhodnocení dopadů klimatických rizik na vodní zdroje. Takové zhodnocení je klíčové pro úspěšnou formulaci a implementaci adaptačních strategií zaměřených na zmírňování dopadů klimatické změny. Problémem ovšem zůstává, že prostorové a časové rozlišení faktorů pro simulaci počasí je příliš hrubé, než aby dokázalo poskytnout přesný model krátkodobých projevů počasí, popřípadě zachytit jemné klimatické struktury, jejichž znalost je nezbytná pro výzkum klimatické změny a politickou iniciativu na úrovni povodí. Vyvstává tak zřejmá potřeba rozvoje metod, které by dokázaly sloučit výsledky klimatických modelů s hydrologickým modelováním. To umožní větší regionální detailnost studií a pomůže zahrnout jemné struktury klimatických dat používané v hydrologických modelech.

Scénáře dopadů budoucí klimatické změny na hydrologické režimy byly vytvořeny pro povodí řeky Kaczawa, levého přítoku řeky Odry, které zabírá celkovou rozlohu 1807 km^2. Průměrná celoroční teplota vzduchu v této oblasti je nižší než 7 °C. Průměrný roční úhrn srážek se pohybuje mezi 500 až 800 mm. Sněhový pokryv se objevuje po dobu 40–45 dní v roce. V povodí Kaczawy můžeme nalézt malá glaciální jezera, tři poldry používané pro ochranu před povodněmi a jednu víceúčelovou nádrž s celkovou kapacitou 41 milónů m^3. Na přehradě Piatnica dosáhl maximální průtok vody 418 m^3/s, a to v červenci 1997.

Tvorba hydrologických scénářů možných budoucích změn vyžadovala simulaci detailních a krátkodobých meteorologických jevů v dané oblasti. SWGEN model (Spatial Weather GENerator) byl využit ke měřítkovému zmenšení předpokládaných klimatických změn na úroveň vyžadovanou prostorovým a časovým rozlišením hydrologického modelu. Generátory počasí mohou reprodukovat časové série meteorologických proměnných, které se statisticky podobají pozorovaným měřením.

Soubor výsledků ze třech různých modelů globální cirkulace (Global Circulation Models): GISS, CCCM, GFDL vytvořeným pro scénář emisí A1B byl zanalyzován za účelem projekce změn v klimatických podmínkách v oblasti horního a středního povodí Odry. Časové série dat o slunečním záření, teplotě vzduchu a úhrnu srážek byly pořízeny pro zkoumané období 1981–2000 a časové horizonty 2030 a 2050.

Každá replikace potenciálního stavu klimatických podmínek byla vložena do hydrologického modelu NAM kvůli simulaci hodnot denního odtoku vody v povodí Kaczavy a jejího průtoku na poslední přehradě v takto pozměněných podmínkách. NAM je výpočetní koncepční model pro kalkulaci srážek a odtoku vytvořený Dánským hydrologickým institutem. Model je souborem propojených matematických výroků, popisujících ve zjednodušené kvantitativní formě chování povrchové a podpovrchové části hydrologického cyklu. Funguje pomocí soustavného počítání vlhkosti ve čtyřech separátních, ale propojených vrstvách (sněhová zásoba, povrchová zásoba, podpovrchová zásoba, podzemní zásoba), které představují fyzické prvky daného povodí. Model simuluje nadzemní, zemní a podzemní komponenty odtoku vody v povodí. Propočítává tak přítok do řek uvnitř povodí (hydrodynamický model). Vstupními daty do tohoto modelu jsou meteorologické údaje o srážkách, teplotě a potenciálním výparu.

Vložení získaných výsledků o odtoku do funkcí distribuce pravděpodobnosti umožnilo odvození statistických charakteristik a shrnutí dopadů změny klimatu na hydrologický režim povodí Kaczavy. Získané výsledky popisují celé spektrum hydrologických charakteristik sledované řeky, např. průměrný denní odtok, standardní deviaci, extrémní hodnoty a úroveň spolehlivosti pro horizonty 30–50 let.

Získané výsledky odtokových scénářů vykazují významné rozdíly v ročním i sezónním objemu odtoku vody. Největší změna v objemu odtoku se podle všech tří scénářů objevuje u chladných sezón. Další výzkum by se měl zaměřit na kvantifikaci modelových odchylek na tyto predikce. Využití prostorového generátoru počasí každopádně umožnilo explicitní zahrnutí možných nejistot prostřednictvím simulace většího souboru scénářů možných klimatických změn. Identifikace trendů ve změnách průtokových charakteristik způsobených klimatickými změnami je nezbytná pro dobrou správu vodních zdrojů a prevenci případných sociálních, ekonomických nebo environmentálních ztrát.

Obr. 1 – Povodí Kaczawy a umístění meteorologických stanic použitých v rámci výzkumu.

Obr. 2 – Odhadovaný dopad změny klimatu na teplotu (vlevo) a srážky (vpravo) v období července spolu s funkcemi distribuce pravděpodobnosti vytvořenými pro současný i odhadovaný stav.

Obr. 3 – Korelace „cross" a „cross-lag" pro vysledované a simulované měsíční soubory dat SR (a), t_{min} (b), t_{max} (c) a t_{min} a t_{max} (d).

Obr. 4 – Průměrné hodnoty a standardní odchylky u sledovaných a simulovaných dat SR (a), t_{min} (b) a t_{max}(c).

Obr. 5 – Korespondenční analýza mezi pozorovanými a vygenerovanými hodnotami: korelace denních úhrnů srážek (a), počet dní se srážkami (b), pravděpodobnost přechodu mezi dnem se srážkami a dnem beze srážek (c) a mezi dnem se srážkami a následujícím dnem se srážkami.

Obr. 6 – Sezónní distribuce denního odtoku na přehradě Piatnica za období (a) listopad–duben, (b) květen–říjen, a (c) červen–srpen pro rok 2000 a srovnání s odhadem pro rok 2030 (vlevo) a 2050 (vpravo). GISS – model Goddard Institute for Space Studies; CCCM – model Canadian Climate Centre Modeling and Analysis; GFDL – model Geophysical Fluid Dynamics Laboratory.

Obr. 7 – Roční odtok řeky Kaczawa měřený na přehradě Piatnica pro rok 2000, rok 2030 a rok 2050, vzhledem k rozdílným scénářům změny klimatu podle (a) modelu Goddard Institute for Space Studies – GISS; (b) modelu Canadian Climate Centre Modeling and Analysis – CCCM; (c) modelu Geophysical Fluid Dynamics Laboratory (GFDL).

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