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MODELLING FLOW CHANGES IN POTENTIAL CLIMATE CHANGE CONDITIONS – AN EXAMPLE OF THE KACZAWA BASIN

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Abstract: Climate change, regardless of the causes shaping its rate and direction, can have far-reaching environmental, economic and social impact. A major aspect that might be transformed as a result of climate change are water resources of a catchment. The article presents a possible method of predicting water resource changes by using a meteorological data generator and classical hydrological models. The assessment of water resources in a catchment for a time horizon of 30–50 years is based on an analysis of changes in annual runoff that might occur in changing meteorological conditions. The model used for runoff analysis was the hydrological rainfall-runoff NAM model. Daily meteorological data essential for running the hydrological model were generated by means of SWGEN model. Meteorological data generated for selected climate change scenarios (GISS, CCCM and GFDL) for the years 2030 and 2050 enabled analysing different variants of climate change and their potential effects. The presented results refer to potential changes in water resources of the Kaczawa catchment. It should be emphasized that the obtained results do not say which of the climate change scenarios is more likely, but they present the consequences of climate change described by these scenarios.

1. INTRODUCTION

The development and improvement of modern methods of forecasting global climate change has become a fact and has provided numerous arguments for the necessity of analysing its consequences (Barrow et al. [2], Katz [9], Kidson and Thompson [10], Lall and Sharma [15], Wilby [19]). It has also become an impulse to further studies of the effects of climate change on a regional and local scale. Global change forecasts cannot give explicit answers about their effects on a local scale. One of the major effects of climate change may be changes in accessible water resources and in the hydrological regime of rivers resulting from extended precipitation-free periods or an increased number of extremely high precipitation events. However, the analysis of changes in hydrological characteristics of local catchments requires access to information about local meteorological conditions, their patterns and seasonal changes on a particular catchment scale. In order to obtain satisfactory results of water resource analysis for small and medium-size catchments, daily discharge values are required. Obtaining such data is possible with the use of precipitation-runoff hydrological models, provided similar meteorological data are available for the forecasting period. A tool which has proved to be helpful here is meteorological data generators. At the initial stage, point data generators were used alongside spatial models which enable creating data sequences of precipitation and temperature for many stations simultaneously, while retaining relationships between meteorological variables from different stations (Kuchar and Iwański [12], [14]).

The article presents the idea and selected results of research into potential runoff changes in the Kaczawa catchment in the summer half-year for the period 2030–2050 conducted with the use of a spatial weather data generator, interpolation methods, selected climate change scenarios and a hydrologic precipitation-runoff model.

2. THE RESEARCH AREA AND THE AIMS

The research was conducted for the area of the Kaczawa river catchment. The Kaczawa is one of the left-bank tributaries of the middle reach of the Odra. The river is 84 km long and has a catchment area of 2261 km^2. The source area of the river is in the southern part of the catchment, in the Kaczawa Mountains. The major tributaries of the Kaczawa are the Nysa Szalona (443.1 km^2) with a multi-purpose storage reservoir Słup and the river Wierzbiak on the right bank, and the left-bank Czarna Woda (986.0 km^2) with the Skora. The Kaczawa flows northward through the Kaczawa Mountains and Foothills and then to the north-east across the Silesian Lowland. In its upper course, the character of the river is that of a highland-upland stream. Near Legnica it gradually acquires a lowland character and flows into the Odra near the town of Prochowice. The Kaczawa Mountains, which are also the spring area for the Nysa Szalona and the Skora rivers, are low mountains; the elevation of the highest peak, Skopiec, is 724 m a.s.l. The geology of the Kaczawa Mountains is very varied. They

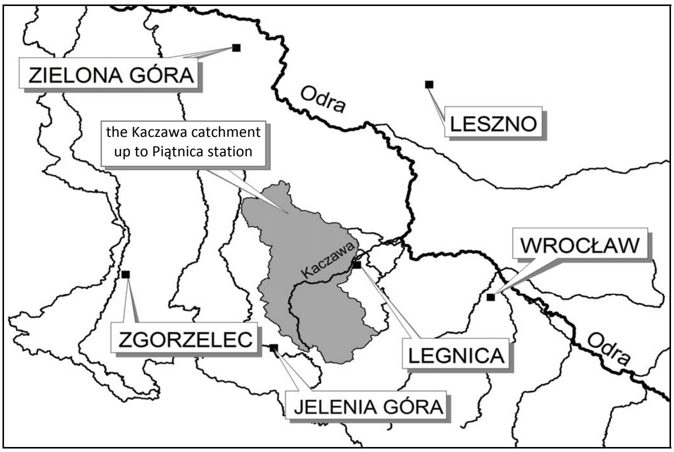

Fig. 1. Location of the Kaczawa catchment

Table 1

List of stations with 24-hour observations of meteorological variables

Location	Station type	Geographical location		Available data					
		Longitude	Latitude	*SR*	U_s	$T_{\min}$	T_{sr}	$T_{\max}$	*P*
Bolków	O	16°06'E	50°55'N						x
Chocianów	O	15°55'E	51°25'N						x
Chojnów	O	15°56'E	51°17'N						x
Chwałkowie	O	16°37'E	51°27'N			x	x	x	
Dobromierz	O	16°15'E	50°55'N						x
Iwiny	O	15°42'E	51°12'N						x
Jawor	O	16°11'E	51°03'N						x
Jelenia Góra	S	15°48'E	50°54'N		x	x	x	x	
Kaczorów	O	15°58'E	50°55'N						x
Legnica	S	16°12'E	51°12'N	x	x	x	x	x	x
Leszno	S	16°32'E	51°50'N		x	x	x	x	
Lubin	O	16°12'E	51°24'N						x
Polkowice Dolne	O	16°03'E	51°30'N			x	x	x	
Pszenno	K	16°33'E	50°51'N			x	x	x	
Stanisławów	O	16°01'E	51°04'N						x
Strzegom	O	16°21'E	50°58'N						x
Tomaszów Górny	K	15°41'E	51°17'N			x	x	x	x
Twardocice	O	15°45'E	51°06'N						x
Wojcieszów Dl.	O	15°55'E	50°59'N						x
Wrocław	S	16°53'E	51°06'N		x	x	x	x	
Zagrodno	O	15°52'E	51°12'N						x
Zgorzelec	K	15°02'E	51°08'N			x	x	x	
Zielona Góra	S	15°32'E	51°56'N		x	x	x	x	
Złotoryja	O	15°56'E	51°07'N						x

Key: K – weather station, O – precipitation station, S – synoptic station; *SR* – solar radiation, U_s – sunshine duration, $T_{\max}$ – maximum 24-hour temperature, $T_{\min}$ – minimum 24-hour temperature, T_{sr} – mean 24-hour temperature, *P* – 24-hour precipitation sum

are built of Pre-Cambrian Radzimowice schists, Cambrian limestones, greenschists, Permian porphyries, melaphyres and sandstones and Upper-Cretaceous jointed sandstones. All the Kaczawa Foothills are built of Tertiary basalts. The Czarna Woda, except for its right-bank tributary, the Skora, flows south-east across the Silesian Lowland and has a lowland character. Arable land occupies 50.2% of the catchment area, meadows and pasture – 11.5% and forest – 26.4%, mostly in the southern part of the catchment, in the Kaczawa Mountains and their foothills. The remaining areas account for 11.9% of the catchment. The Kaczawa catchment lies in the mountain climate zone with oceanic influence. The mean air temperature is lower than 7 °C and the mean annual precipitation varies from 500 to 800 mm. Snow cover lasts for 40–45 days per year. In terms of meteorological regime, the Kaczawa catchment has diverse character.

The upper Kaczawa, as far as Świerzawa gauge, the Nysa Szalona and the Skora are dominated by highland river regime with numerous rain-induced floods characterized by rapid flow rises and large discharge amplitudes. The middle and lower parts of the Kaczawa catchment and the Czarna Woda catchment are characterised by a regime typical of a lowland river. The time of precipitation concentration is much longer and discharge amplitude – lower. Besides the above-mentioned Słup reservoir, the catchment has two flood-control reservoirs: Świerzawa on the Kamiennik and Bolków on the Rachowicka Woda. They have local importance due to reducing flood wave crests, but they do not affect significantly the water balance of the whole catchment.

Stations chosen for the research are part of the measurement-observation network run by the National Hydrological and Meteorological Service of the Institute of Meteorology and Water Management (IMGW) operating in the catchment area and around it, comprising meteorological and hydrological stations. In the Kaczawa catchment, there is a hydrological station in Piątnica, covering most of the catchment area, which has a sequence of many years of verified hydrological observations.

The set of weather data employed, consisting of 24-hour values obtained from weather station networks, included: precipitation for the years 1981–2000, observations of maximum, minimum and mean temperatures and sunshine duration for two stations (Legnica and Tomaszów Górny) and the amount of solar radiation for Legnica. For those stations where measurements of total radiation and temperature had not been conducted, these quantities were interpolated from the data from Legnica, Tomaszów Górny and other additional stations located in this part of Poland, outside the Kaczawa catchment. As no data on total radiation was available for four synoptic stations – Jelenia Góra, Leszno, Wrocław and Zielona Góra, these values were estimated from sunshine duration by means of Black‘s formula (Angström [1], Bac and Rojek [3]):

$$SR = SR_0\left(0.18 + 0.62\frac{US}{US_0}\right)$$

where:

SR – the amount of total radiation,
SR_0 – solar radiation at the upper boundary of the atmosphere,
US – actual sunshine duration
US_0 – possible sunshine duration.

3. RESEARCH METHODOLOGY

The idea of estimating catchment water resources in climate change conditions was to conduct a simulation of the hydrological process occurring in a catchment in changeable weather conditions in a hydrological year caused by climate change. The first stage was to generate spatial weather data for the conditions of predicted climate change based on measurement data and results of climate change scenarios for the Kaczawa catchment. The obtained 24-hour weather data were used as input data for a precipitation-runoff hydrological model. Simulation of the precipitation-runoff transformation process produced discharge hydrographs for the catchment outlet. 24-hour discharges for Piątnica gauging station were a basis for preparing hydrological characteristics of runoff from the Kaczawa catchment in climate change conditions (Fig. 2).

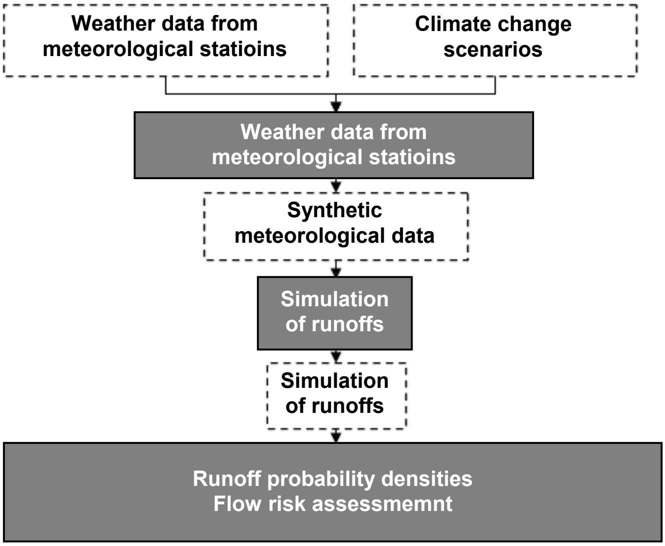

Fig. 2. Simulation of catchment runoff with the use of generated weather data and climate change scenarios

The weather data for the Kaczawa catchment were generated from meteorological characteristics based on 20-year long measurement sequences and climate characteristics modified with information from three climate change scenarios: GISS, GFDL and CCCM (Mearns et al. [16]). Changes in climate characteristics for the prognostic period, i.e., the years 2030 and 2050, based on selected climate change scenarios, are shown in Table 2. The overall weather characteristics essential for calibrating the spatial model generating 24-hour weather data were supplemented by using interpolation methods. The missing temperature values (mean value and standard deviations for particular months) for 14 stations were estimated from data obtained from 10 stations located in and around the catchment area. As for solar radiation, parameter values for 15 stations were estimated from data coming from 5 synoptic stations situated in south-western Poland.

Table 2

Climate change characteristics for 2030 and 2050 according to selected models

Variable	Parameter	Period	Change according to model		
			GISS	CCCM	GFDL
for 2030					
Temperature	Mean value	Winter	+0.9 °C	+0.8 °C	+0.9 °C
		Summer	+0.7 °C	+0.6 °C	+0.6 °C
	Standard deviation	Year	+3%	+2%	+2%
Precipitation	Mean value	Winter	+4%	+5%	+10%
		Summer	0%	–3%	–8%
	Standard deviation	Year	+4%	+2%	+10%
for 2050					
Temperature	Mean value	Winter	+2.8 °C	+2.4 °C	+2.6 °C
		Summer	+2.0 °C	+1.9 °C	+2.3 °C
	Standard deviation	Year	+9%	+6%	+6%
Precipitation	Mean value	Winter	+12%	+14%	+30%
		Summer	0%	–9%	–24%
	Standard deviation	Year	+12%	+6%	+30%

The volume of potential evaporation, required by the hydrological model, was estimated with the use of modified Turc's formula, whose constants were variabilized and a constant term was added (Bac and Kuchar [4], [5], Kuchar and Bac [13]),

$$E_p = a_0 + a_1 T_{\mathrm{sr}} \frac{a_2 SR + a_3}{T_{\mathrm{sr}} + a_4}$$

where:

a_i – model parameters,
E_{p} – potential evaporation,
T_{sr} – mean air temperature,
SR – sum of total radiation.

All the characteristics refer to monthly values.

3.1. SWGEN MODEL

Spatial 24-hour weather data were generated by means of SWGEN model (Iwański and Kuchar [6]), based on a one-point WGEN model (Richardson [18]) with further modifications (Kuchar [11]). In the selected model, data are generated in two stages.

At first, 24-hour precipitation amounts are simulated in the following way: a day state (a day with or without precipitation) is defined by using a two-state first-order Markov chain. For each weather station and each month m = 1, 2, ..., 12 transition probabilities $P_m(W|W)$, $P_m(W|D)$, $P_m(D|W)$, $P_m(D|D)$ are estimated, where W and D stand for a day with precipitation and a precipitation-free day, respectively.

Next, precipitation value is generated by means of gamma distribution ($\Gamma_m(\alpha_1, \beta_1)$, ..., $\Gamma_m(\alpha_k, \beta_k)$), $m = 1, ..., 12$, and k is the number of stations. In the case when a precipitation-free day is obtained for the i-th station, it is assumed that $\Gamma_m(\alpha_i, \beta_i) = 0$. Transition probabilities and distribution parameters are estimated for each station and each month.

In the next stage, the minimum, maximum and mean temperatures, as well as the amount of total radiation are generated by means of a multi-dimensional time sequence AR(1)

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

where:

X_t and X_{t-1} – column vectors of standardized maximum, minimum and mean temperature as well as total radiation values for all the stations on days t and $t-1$, respectively,

ε_t – errors whose expected values are equal to zero and covariance matrix Σ_m,

Φ_m – parameter matrix, where $m = 1, ..., 12$.

3.2. NAM MODEL

NAM is a hydrological model representing the precipitation-runoff transformation process for a particular catchment. It is a module of a hydrological modelling system Mike11. NAM model may be used in a single river catchment or a group of catchments. However, for more complex and complicated hydrological systems, one should apply an integrated model composed of the catchment and river reaches whose flow is modelled by means of a hydrodynamic model. NAM is a deterministic conceptual model with concentrated parameters, which points to the absence of a direct relationship between the model parameters and the physical characteristics of the river catchment.

This model, in a simplified quantitative form, describes the basic processes of the hydrological cycle in a catchment. The precipitation-runoff simulation takes into account the following factors: mean precipitation, evaporation from free water surface and from soil layer, water retention on the surface and in soil, infiltration to groundwaters and surface runoff, retention in groundwater layer and recharge with groundwaters. The model also allows for the process of snow accumulation in the period of negative temperatures and the process of snow cover thawing. The latter two processes can take into account variations in elevation zones and vertical temperature gradient in the catchment area, which has a significant influence on the pattern of snow thawing simulation.

NAM model can be used for modelling runoff from the catchment both for long periods – a full year's hydrological cycle (or many years) and short flood events as individual episodes like rain or thawing-induced floods (Nielsen and Hansen [17]).

Simulation of precipitation-runoff transformation for a single catchment is based on an single time sequence of weighted means of precipitation, temperature and potential evaporation at measurement stations.

Mean 24-hour precipitation values for the Kaczawa catchment required for model calibration were determined with Thiessen's method from data from 16 precipitation stations located in the Kaczawa catchment and its immediate neighbourhood. Likewise, temperatures and potential evaporation were determined from measurement data from meteorological stations situated in the analysed catchment. The hydrological data were 24-hour discharges based on observation data from Piątnica gauge.

In total, a 20-year-long sequence of observations was used for model calibration (1991–2000) and validation (1981–1990). The basic criterion adopted for the assessment of model parameter adjustment was the determination coefficient (R^2). In the calibration process, an automatic procedure of selecting model coefficient values was employed. In total, 9 model parameters were involved in the optimization of the Kaczawa catchment model. Bearing in mind future applications of the model, i.e. assessment of the Kaczawa catchment water resources, it was assumed that the basic objective of calibration was obtaining the possibly fullest agreement of the catchment water balance, and secondly – the agreement of maximum discharges. The obtained results were satisfactory enough. However, it should be remembered that the Kaczawa is considerably influenced by anthropogenic factors, especially with regard to modification of low flows by water withdrawal and high flows by reservoir storage. The extent of this influence is not well documented or information is very scattered, which practically prevents collecting it and using in the modelling process. The simulation process for the period of predicted climate change was based on weather data generated for the model parameters defined. Therefore, it should be remembered that the results obtained in this way will be appropriate with the assumption that there are no significant changes in water management in the catchment.

4. RESEARCH RESULTS

As a result of flow simulations conducted by means of the hydrological model, predicted 24-hour discharges were obtained for potential climate changes for a time horizon of the years 2030 and 2050, for each of the analysed climate change scenarios. In each case, simulations were conducted for 500 hydrological years, regarding each year as an autonomous series of 24-hour data. The results obtained were used to assess runoff variations in the Kaczawa catchment for the adopted scenarios. In the examples discussed, gamma distribution was applied and the estimation of distribution parameters was performed with the maximum likelihood method.

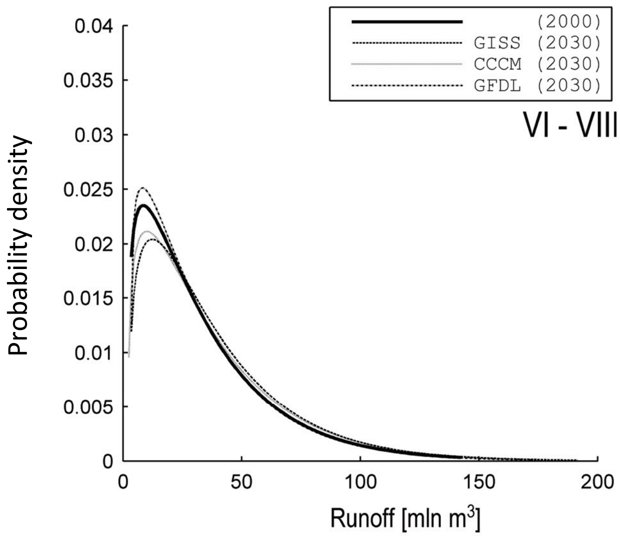

Fig. 3. Changes in probability density for runoff from the Kaczawa catchment for the 2030 summer season against the probability density for the starting year 2000

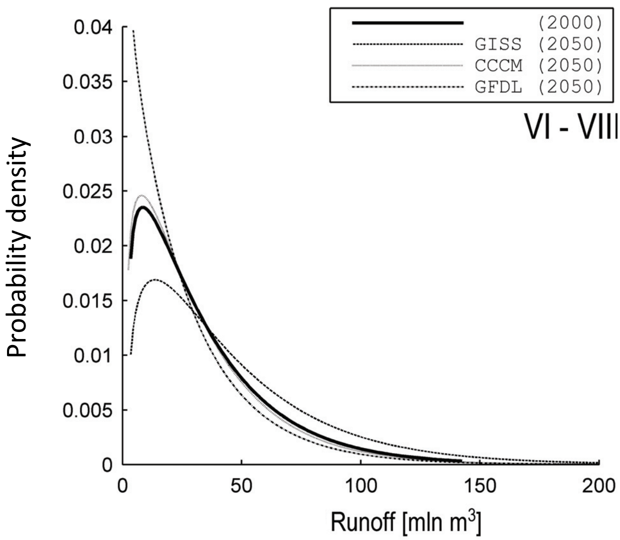

Fig. 4. Changes in probability density for runoff from the Kaczawa catchment for the 2050 summer season against the probability density for the starting year 2000

Examples of probability density for annual runoff for the years 2030 and 2050 against the year 2000 are shown in Figs. 3 and 4. The densities presented reflect changes in river catchment runoffs caused by changing weather conditions. All the scenarios being analysed assume a rise in precipitation variability with unchanging precipitation volume (GISS scenario) or a drop (CCCM and GFDL scenarios) both in the period until 2030 and until 2050. This will cause a rise in extreme flows in the case of all the analysed scenarios for both periods. This is particularly evident with regard to high flows. However, in view of temperature rise and precipitation decrease in the summer season for scenarios CCCM and GFDL, a fall in the volume of water resources is predicted for the 2050 time horizon.

5. CONCLUSIONS

Strategic water management planning in a catchment system requires taking into account the influence of potential climate change on water resources in the catchment. Information about potential changes in climatic conditions seems to be insufficient. Applying a spatial weather data generator SWGEN, combined with a hydrological precipitation-runoff NAM model and climate change scenarios provides a possibility of obtaining data useful for decision-making processes concerning investments in water management for a time horizon of 20–40 years. The obtained runoff probability densities provide full information about moment characteristics, confidence intervals and critical values, which are a significant source of information used in decision support systems. Change trends in catchment water resources, which can result from climate changes, combined with demographic forecasts and economic plans, should be an impulse to rational actions. The information comprised in discharge probability densities could also be a starting point for the assessment of potential threats triggered by dangerous hydrological phenomena and for determining a strategy of security system development.

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