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Impact of Climate Change on a Runoff Formation in Seaside Catchment Area on the Example of the Babica River Catchment

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***Abstract*—The paper presents the impact of taking into account climate change in the perspective of 2050 on the results of hydrological calculations of characteristic flows in the hydrographically diverse seaside catchment area on the example of the Babica river catchment. A mathematical model of the Babica river catchment was made in the HEC-HMS program. The SCS method was used. The outflow from the basin was analysed for waters with a specified probability of exceedance for the adopted synthetic hietogram for rainfall with a probability of exceeding p = 10 %, p = 1 % and p = 0.2 %. To determine the maximum amount of rainfall in the assumed calculation time, formula of Institute of Meteorology and Water Management for the analysed area was used. The calculations took into account the impact of climate change on the amount of precipitation in the perspective of 2050 - A1B scenario was used.**

***Keywords*—hydrology; rivers; geospatial analysis; computer simulation; geophysics computing; global warming.**

I. INTRODUCTION

The progressing process of urbanization causes changes in the coverage and development of urban and sea coastal areas [1 – 4]. This process entails the development of scientific research on the use of modern measurement techniques and tools based on the GIS technique [5 – 14]. This problem particularly affects coastal zones and the Baltic Sea [15 – 19]. This has a significant impact on the process of forming outflow from particular catchment areas, both as to the size of this outflow and its variability in time. This applies to such investments as the construction of new housing estates and the development of industrial areas. It also involves the development of rainwater drainage systems and the accompanying hydrotechnical constructions (e.g. retention reservoirs [20]). The transformation process of natural areas is associated with the coverage of significant spaces with impermeable materials. As a result, the water entering the basin together with the atmospheric precipitation, instead of feeding the ground water, changes into surface runoff and threatens with flooding of areas adjacent to the watercourses.

The second factor influencing the increase in the outflow from the catchment are climate changes affecting the variability of precipitation in the perspective of several decades. Numerous model studies are conducted to determine the impact of climate change on various weather indicators, and thus also on the amount of precipitation. Scenarios are created in the perspective of climate change until 2100 [21]. Considering the urbanization plans of the catchment area, usually within 20-30 years, it seems that hydrological analysis should be performed in the perspective of 2050.

The aim of this work is to show the impact of climate change in the perspective of 2050 on the size and variability of the outflow on the example of one of the coastal catchments. For the analysis, due to its diverse nature, the catchment of the Babica River carrying water from part of the city of Elbląg was selected. In the case of climate change the moderate A1B scenario was used, as the most likely scenario for this area [21].

II. CHARACTERISTICS OF THE CATCHMENT

Babica river is located in the north of Poland and flows down from the Elbląg Upland towards the south-west, falling into the Elbląg River (Fig. 1). The Babica's catchment has an elongated, arched shape, its length is 9.5 km, area is 8.25 km^2.

Terrains elevation range is from + 2 m above sea level at the mouth to 165 m above sea level in the source part. This is partly urbanized catchment (approx. 30 % of the area), and partly an agricultural and forestry catchment. The calculations in the perspective of 2050 take into account the areas of designed residential development in accordance with local spatial development plans (highlighted on maps).

III. Materials and Methods

As part of this work, a mathematical model of the Babica river catchment from its sources to its outlet to the Elbląg River was made. The SCS (Soil Conservation Service) method was used [22, 23]. The construction of the model required the prior determination of a number of catchment parameters, including, among others, the basic geomorphological characteristics of the catchment, data on watercourses and data on the catchment cover and development. For the designated catchment boundaries and its division into sub-basins, the division of partial catchment areas into homogeneous areas was carried out in terms of soil permeability, land cover and land use (Fig. 2). The network-centric maps and digital elevation model (DEM) of this area prepared in the QGIS environment were used for this purpose. The values of parameters characterizing the catchments in terms of retention capabilities were determined. The boundaries of the basins were determined on the basis of water divisions resulting from the topographic map. This division was verified on the basis of a hydrographic map and DEM for the analysed area. The basic geomorphological parameters were also determined on the basis of the topographical map and DEM analysis. Based on the soil coverage map, areas with uniform characteristics in terms of permeability have been designated. Information on land development was obtained from the Topographic Objects Database (polish acronym: BDOT10k - a spatial database with details corresponding to a 1:10 000 topographical map), which is the official system of sharing high-quality spatial data (GIS) in Poland.

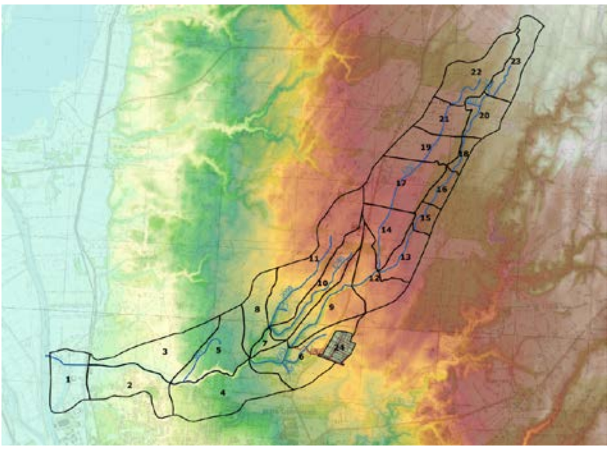

Fig. 1. Height differences in the catchment area - hypsometric map on the topographic map background with separated sub-basins (source: Web Map Service in QGIS – http://mapy.geoportal.gov.pl).

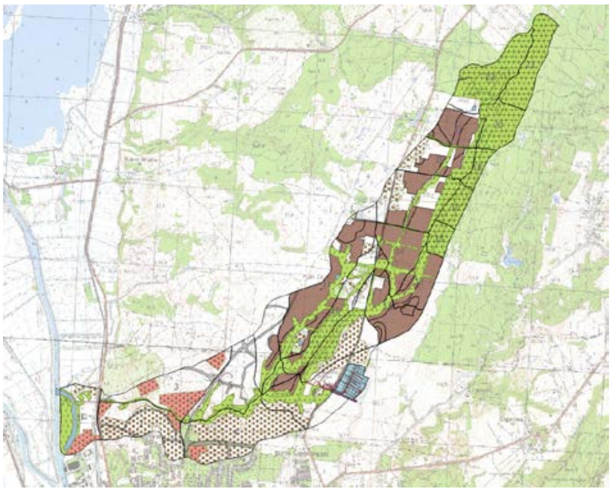

Fig. 2. Homogeneous areas in terms of soil permeability, land cover and land use (source: Web Map Service in QGIS – http://mapy.geoportal.gov.pl).

IV. Metorological Data

A. The Amount of Precipitation

To determine the maximum amount of rainfall in the assumed calculation time, formula of Institute of Meteorology and Water Management for the analysed area was used in following form:

$$P_{pD} = \varepsilon(D) + \alpha(R,D)\cdot(-\ln p)^{0.584} \quad (1)$$

where: $\varepsilon(D)$ – the scale parameter of the equation [mm] calculated from the dependence:

$$\varepsilon(D) = 1.42\cdot D^{0.33} \quad (2)$$

where $\alpha(R, D)$ – position and scale parameter [mm] determined on the basis of the location of the considered object (R – region) and duration of rainfall D [min] – Table I.

B. The Distribution of Precipitation in Time

The study adopts the distribution of precipitation in time $I(t)$ according to German Standardisation and Derivation of Dimensioning Values for Wastewater Facilities (german DVWK). It assumes the highest intensity of rainfall in the middle of its duration. In this distribution, we distinguish three periods of rain duration:

- first period – 30 % of rain duration D - drops 20 % of the total amount of rainfall;
- second period – 20 % of rain duration D - drops 50 % of the total amount of rainfall;
- third period – 50 % of rain duration D - drops 30 % of the total amount of rainfall.

Fig. 3 graphically depicts the DVWK distribution for the sum of precipitation, while the corresponding precipitation intensity diagram in a given time interval I [mm] in relation to the maximum value of I_{max} [mm] is shown in Fig. 4.

TABLE I. THE EQUATIONS FOR ALPHA PARAMETER

<table>
<tr><th rowspan="2">Time D</th><th colspan="3">$\alpha(R,D)$ [mm]</th></tr>
<tr><th>north-western area</th><th>central area</th><th>south and coastal area</th></tr>
<tr><td>5 min < $D \leq$ 30 min</td><td>$3.92 \cdot \ln(D+1) - 1.662$</td><td colspan="2" rowspan="3">$4.693 \cdot \ln(D+1) - 1.249$</td></tr>
<tr><td>30 min < $D \leq$ 1 h</td><td>$8.944 \cdot \ln(D+1) - 18.6$</td></tr>
<tr><td>1 h < $D \leq$ 2 h</td><td></td></tr>
<tr><td>2 h < $D \leq$ 12 h</td><td colspan="2" rowspan="2">$2.223 \cdot \ln(D+1) + 10.64$</td><td></td></tr>
<tr><td>12 h < $D \leq$ 18 h</td><td rowspan="2">$9.472 \cdot \ln(D+1) - 37.03$</td></tr>
<tr><td>18 h < $D \leq$ 72 h</td><td colspan="2">$3.01 \cdot \ln(D+1) + 5.173$</td></tr>
</table>

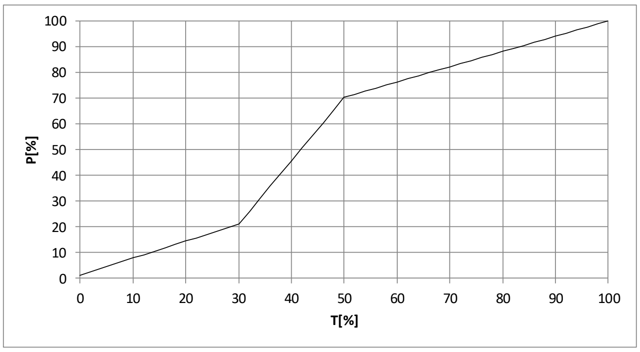

Fig. 3. The distribution of the sum of rainfall with the maximum intensity in the middle according to DVWK.

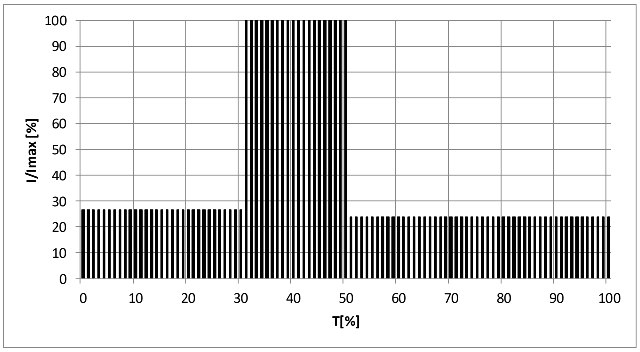

Fig. 4. The distribution of rainfall intensity I [mm] in relation to I_{max} [mm] according to DVWK.

C. Impact of Climate Change on the Amount of Precipitation in the Perspective of 2050

In the model studies taking into account climate changes, the GHGs (greenhouse gases) emission scenario is most often used. This was developed by the Intergovernmental Panel on Climate Change (IPCC) and described in the Special Report on Emissions Scenarios (SRES) [21]. These scenarios assume different pace of economic development and economic growth, different ecological priorities and differentiated intensification of activities mitigating climate pressure. They are divided into four groups: A1, A2, B1, B2. Group A1 assumes a very rapid economic development of the world, the population reaches a maximum in the middle of the century, rapid implementation of new and very efficient technologies. Leveling the level of civilization and the level of profitability between regions through increased economic cooperation and migration of people. The scenario distinguishes three ways of energy development: intensive use of fossil fuels (A1FI), use of alternative (non-fossil) energy resources (A1T) and sustainable use of all sources (A1B). In this work, the A1B scenario was considered the most probable.

Table II lists the calculated according to (1) total precipitation amounts for current conditions and taking into account climate change in the perspective of 2050 according to scenario A1B.

TABLE II. LISTING OF MAXIMUM PRECIPITATION SUMS FOR SELECTED PROBABILITIES AND DURATION OF RAIN

Time	**PpD [mm]**					
	p = 0.2 %		***p = 1 %***		***p = 10 %***	
[min]	***now***	***2050***	***now***	***2050***	***now***	***2050***
5	18.01	19.81	15.51	17.06	11.15	12.27
10	25.55	28.11	21.94	24.13	15.65	17.22
15	30.26	33.29	25.96	28.56	18.49	20.34
30	38.71	42.58	33.20	36.52	23.62	25.98
60	57.93	63.72	49.52	54.47	34.89	38.38
120	68.79	75.67	58.87	64.76	41.60	45.76
360	79.07	86.98	68.00	74.80	48.72	53.59
720	86.17	94.79	74.37	81.81	53.85	59.24
1440	108.63	119.49	93.76	103.14	67.89	74.68

D. Time Duration of Rain

An analysis of different rain durations was performed in relation to the maximum flow value in the hydrograph in closing cross-section of catchment area. The duration of rain was 5, 10, 15, 30 min and 1, 2, 6, 12 and 24 hours with an asymmetrical distribution of rainfall intensity with maximum intensity in the middle. The highest flow value was obtained for 2 hours, and this was assumed and further analyses.

V. HYDROLOGICAL MODEL

A. Construction of the Model

In the process of hydrological modeling of outflow from the catchment area, caused by rainfall, one of the basic problems is the determination of effective precipitation. In this work, the SCS-CN method was used to determine the effective precipitation [22 – 24]. The effect of applying this method is to assign the number of the curve to each sub-basin (CN – Curve Number), representing the potential retention of each catchment. To determine the curve number, it is necessary to analyze the type of soil occurring on the catchment surface, as well as to recognize the land cover and the catchment development.

The division of the individual catchment areas into homogeneous areas in accordance with the SCS-CN methodology allowed to develop curve numbers (for suitable soil classes), the values of which are presented in Table III. Marks used in the Table III are shown in Fig. 6. They correspond to the adopted designations in the HEC-HMS program.

TABLE III. LIST OF GEOMORPHOLOGICAL PARAMETERS OF SUB-BASINS

No.	F	L	I	CN	Tlag
	[km^2]	[*km*]	[*%*]	[-]	[*min*]
J17	0.3927	0.54	0.13	67.68	119.52
J16	0.4919	1.41	1.72	59.00	88.07
J15	0.5380	1.93	2.63	79.29	52.55
J14	0.7241	1.66	2.65	81.50	43.34
J13	0.4964	1.46	2.22	78.61	46.74
J12	0.5695	1.82	4.01	81.18	38.28
J11	0.0662	0.58	7.77	78.59	11.93
J10	0.3015	1.38	4.44	82.77	27.69
J9	0.4447	1.77	1.58	75.78	70.26
J8	0.3869	2.23	1.72	72.99	87.87
J7	0.7971	2.39	1.67	80.73	74.90
J6	0.3778	0.89	1.56	79.84	36.07
J5	0.2658	0.92	3.25	74.49	30.18
J4	0.3470	0.93	2.15	76.33	35.53
J3	0.1103	0.54	2.76	60.46	31.23
J2	0.1274	0.56	1.95	56.07	42.72
J1	0.5907	1.06	2.49	79.12	33.75

B. Calculation of Effective Rainfall and Outflow Hydrograph from the Catchment

Using the SCS-CN method, effective hyetographs were calculated for the amount of precipitation in each of the analyzed sub-basins and the corresponding for them hydrographs (SCS UH method [23]) in closing cross-sections. The results for the exemplary sub-basin No. 6 for precipitation with a probability of exceeding p = 1 % and rain duration 24 h are shown in Fig. 5. The same was done by preparing synthetic hyetograph for the perspective of 2050, taking into account climate changes according to the A1B scenario.

C. Calculation of Outflow Hydrographs from the Catchment

Then, calculations of hydrographs were made in the characteristic cross-sections of the Babica River basin for precipitation with a proper probability of exceeding (p = 0.2 %, p = 1 % and p = 10 %). As previously described, the calculations were performed using the HEC-HMS program, which was developed by the Hydrological Engineering Corps of the United States Army [24, 25].

First, the numerical model of the analyzed catchment was made. A structure of connections was established, linking the outflow from each sub-basin, sections of the Babica River up to the place where the river flows into the Elbląg River.

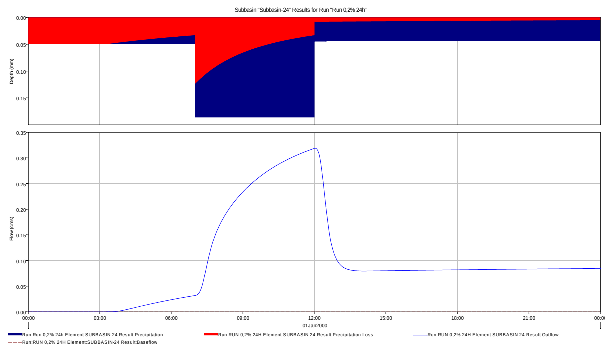

Fig. 5. The effective hyetographs for the exemplary sub-basin No. 6 for precipitation with a probability of exceeding p = 1 % and rain duration 24 h (source: HEC-HMS).

The scheme of the structure of the adopted calculation model is presented in Fig. 6. The results of maximum flow in individual calculation nodes are presented in Table IV.

Analyzing the results obtained in Table IV, it can be concluded that taking into account climate change (in accordance with the adopted scenario A1B) may result in an increase in outflow from individual sub-basins from 20 to even over 40 %.

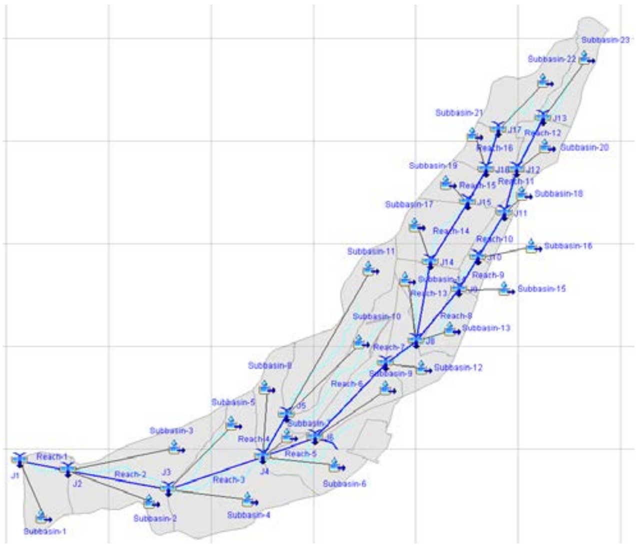

Fig. 6. The structure scheme of the adopted hydrological model of the Babica River.

TABLE IV. THE RESULTS OF MAXIMUM FLOW IN INDIVIDUAL CALCULATION NODES

No.	Table Column Head								
	now	*2050 (A1B)*	*Δ %*	*now*	*2050 (A1B)*	*Δ %*	*now*	*2050 (A1B)*	*Δ %*
J17	0.2	0.3	42.1	0.6	0.8	31.7	0.9	1.2	26.1
J16	0.3	0.5	40.6	1.0	1.2	29.5	1.4	1.8	25.4
J15	0.7	1.0	30.1	1.8	2.3	27.9	2.7	3.3	25.3
J14	1.6	2.0	26.9	3.6	4.5	24.6	5.1	6.2	22.4
J13	0.4	0.5	25.6	0.9	1.1	22.7	1.2	1.5	20.5
J12	0.5	0.7	31.5	1.3	1.6	23.7	1.8	2.2	21.2

No.	Table Column Head								
	now	*2050 (A1B)*	*Δ %*	*now*	*2050 (A1B)*	*Δ %*	*now*	*2050 (A1B)*	*Δ %*
J11	0.5	0.7	32.7	1.3	1.6	24.8	1.8	2.3	22.3
J10	0.5	0.7	31.4	1.3	1.6	26.4	1.9	2.3	23.0
J9	0.5	0.7	32.0	1.3	1.6	26.4	1.9	2.3	23.4
J8	2.3	2.9	29.5	5.4	6.6	23.1	7.5	9.1	21.0
J7	2.7	3.5	28.7	6.3	7.7	22.8	8.7	10.5	20.6
J6	2.8	3.7	29.6	6.7	8.2	22.9	9.3	11.3	20.8
J5	1.3	1.6	26.2	2.8	3.3	21.0	3.8	4.5	19.2
J4	4.7	5.9	27.7	10.5	12.8	22.0	14.5	17.4	20.2
J3	5.5	7.0	25.9	12.0	14.5	20.9	16.2	19.4	19.2
J2	5.7	7.2	26.1	12.4	15.0	21.2	16.9	20.2	19.5
J1	5.7	7.2	26.6	12.6	15.3	21.5	17.2	20.6	19.7

VI. SUMMARY AND CONCLUSION

The hydrologically diversified seaside catchment up to a size of 10 km^2 was selected for the analysis. The amount of precipitation for various probabilities was calculated and its distribution over time was assumed. Next, the calculations of hydrographs in characteristic cross-sections in the catchment of the Babica River were made for the actual state and after taking into account changes in land development and taking into account climate changes in accordance with the adopted scenario A1B. In this scenario, the total amount of rainfall increases for these areas by around 10%. An increase in outflow from individual sub-basins was obtained from 20 to over 40%. It allows us to formulate the conclusion that in the case of hydrological calculations in the perspective of several decades, an important element in addition to changes resulting from Local Spatial Development Plans is also to take into account the climate change.

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