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FLOOD FLOW FORECAST FOR A IN SMALL LOWLAND CATCHMENT FOR DIFFERENT SCENARIOS OF URBANIZATION

Katarzyna Krężałek✉

Department of Water Engineering and Management, Institute of Technology and Life Sciences, Falenty,
Al. Hrabska 3, 05-090 Raszyn

ABSTRACT

The purpose of the work was to present the results of simulation studies of river runoff carried out with the use of a conceptual model specially developed for this purpose. Different variants of forecasts were developed for the impact of introducing various forms of urbanization on the formation of river runoff progression during flood flows in the small, lowland catchment of upper Mławka river, covering the area of 66 km^2. For the needs of the research, classification of urbanized areas was made based on their location within the catchment, and the method of discharging rainfall runoff. Particular variants differed from one another as to the location of sealed areas, the degree of urbanization of the catchment, the initial waterlogging of the catchment, as well as the model rainfall assumed for calculations. They provided the foundations for the assessment of the impact of various forms of urbanization of the catchment area on the formation of flood flows, taking into account the catchment's natural properties, such as the occurrence of variable source areas. The subject of the analysis was not only the total runoff volume, but also its components – surface, subsurface and groundwater runoff. The analysis of the results of river runoff simulation, taking into account the components of this runoff, leads to the conclusion that the total increase of direct runoff volume and its peak value are caused not only by direct supply from sealed surfaces, but also from indirect impact, causing changes in the runoff regime in non-urbanized areas. Sealed and channelled areas located beyond the maximum range of active (variable source) areas, on which direct runoff does not occur in natural conditions, increase the runoff area in the scale of the catchment area as a whole. To compare, the peak flood flow values for variants associated with urbanization and channelling outside the variable source areas are between 20% and 40% higher than in the case of analogous conditions and the sealing of the same area in the area of direct runoff.

Keywords: urbanization, variable source areas (VSA), hydrograph, conceptual model.

INTRODUCTION

Urbanization of agricultural areas is a phenomenon observed especially in the vicinity of large cities. It causes changes to the formation of river runoff, and it is manifested by the occurrence of increasingly frequent flooding, with simultaneously larger and increasing ranges. The issuing of building permits usually takes place without a thorough examination of their consequences for the changes in the water regimes on a local scale, and throughout the catchment in which the given investment project is located. One of the reasons is the lack of appropriate methods that would make it possible to perform hydrological analyses in a reliable way, and without involving excessive financial resources. Therefore, it is necessary and justified to conduct research, the results of which could be helpful in making rational decisions, and in undertaking activities aimed at minimizing the negative effects related to transformations of land use in agricultural areas.

✉e-mail: k.krezalek@itp.edu.pl

Considering the above justification, a new method was developed and applied to determine the impact of urbanization of a small agricultural catchment on the parameters of rainwater flood flows, based on simulation tests performed using a hydrological model developed and adjusted specifically for this purpose. The applied model has been verified based on hydro-meteorological data from the research catchment used by the Institute of Technology and Life Sciences, namely the upper Mławka river catchment situated within the Wkra river catchment (Krężałek 2017). Based on the analysis of the results of the simulation, conclusions were drawn regarding the impact of the degree and type of urbanization on the parameters of flood flows, and practical recommendations were derived, regarding the principles of planning the development of urbanization in rural areas.

METHODOLOGY

Simulation studies were used to forecast changes in the behaviour of the complex natural system of river catchment, occurring as a result of modifications to the latter, including both parameter values and the internal structure diagram. The modifications were aimed at reflecting different rates of growth in the share of sealed areas, and different ways of implementing the catchment's development, and rainwater discharge. The basis for calculations was a conceptual model, designed specifically for this purpose, and then verified, of the total river runoff and its components (Szymczak and Krężałek 2018). The river runoff model was developed for the upper Mławka river catchment area, with the surface area of 66.17 km^2, where measurements and observations of hydrological processes have been conducted since 1976. Based on the results of these observations (e.g. Szymczak and Szelenbaum 2003), coupled with studies of subject literature (Horton 1933; Betson 1964; Cappus 1960; Dunne and Black 1970; Hewlett and Hibbert 1967; Weyman 1970, 1973), it was decided that the model for making predictions should be developed in accordance with the variable source areas concept, proposed by Hewlett and Hibbert (1967).

The upper Mławka river catchment area is well instrumented, and long-term data on precipitation and flood flows are available. There are 5 pluviographic stations within the catchment area, namely: in Mławka, Piekiełko, Uniszki Gumowskie, Białuty, and Kuklin. The area in question is a lowland catchment, used mainly for agriculture, therefore, for the purposes of forecasting, it was possible to imagine various scenarios of changes to its use.

It was assumed that 5 basic cases of urbanization of the river catchment can be distinguished. The basic distinction among various types of urbanized areas was based on the criterion of their location according to the catchment division into two zones: the maximum extent area of *Sb* variable source areas, in where the direct runoff is formed, and the *Sinf* infiltration zone, where the surplus of precipitation, after deducting the losses on interception and evaporation can only infiltrate (see: Fig. 1).

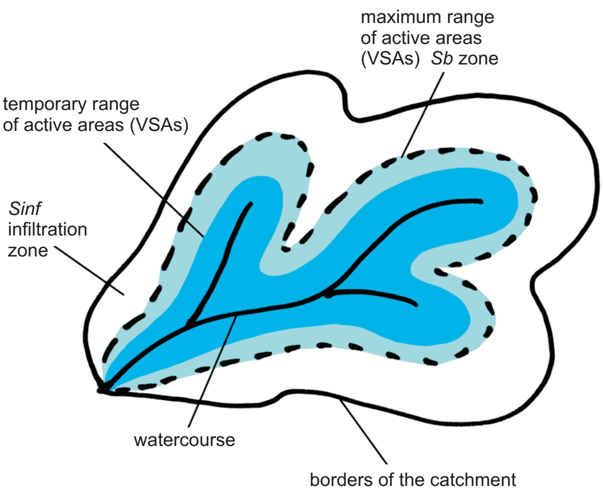

Fig. 1. Maximum and temporary range of active areas (VSAs) within the river catchment

Source: own study

Type A areas are distinguished, which will be located in the zone of direct runoff (*Sb*) and B type areas, which will be located in the areas of the infiltration zone (*Sinf*).

A more detailed breakdown referred to the way rainwater was discharged from urbanized areas. In the areas located within the *Sb* zone, that is, the maximum extent of variable source areas, the following are distinguished:

A1 – urbanized areas with water removal by drainage system, or those without channelling, where water flows directly to the riverbed;

A2 – urbanized areas, not channelled, where waters flow to unsealed areas and additionally supply surface runoff.

In the *Sinf* infiltration zone, the following areas were distinguished:

B1 – urbanized areas with water drainage via rainwater channels directly to the river network;

B2.1 – urbanized areas without channelling, located so close to the *Sb* area that the flow from these areas constitutes an additional supply of that zone;

B2.2 – urbanized areas, not channelled, with the management of rainwater near the occurrence of precipitation (including reservoirs and absorbing wells, or infiltration equipment).

In all variants it has been assumed that 60% the urbanized area is sealed. Unsealed areas in these locations have such properties as prior to urbanization, that is, they are characterized by very high permeability.

Simulation research was aimed to illustrate how the urbanization of the catchment affects the formation of river runoff during the occurrence of flood flows. The study included 45 different variants, which differed in the degree of urbanization, the location of sealed areas, the way of discharging rainwater, the initial waterlogging of the catchment, and the parameters of the reference precipitation model hyetograph.

Detailed analysis of selected simulation results was conducted using a specially developed model (Szymczak and Krężałek 2018). The identification of model parameters was carried out in the natural catchment area of the Mławka river.

Input data consisted of time series of hourly sums of total precipitation averaged for the catchment and evaporation area. The maximum daily sums of rainfall were used for the years 1966–2010, with the exceedance probability equal to: for p = 1% – 106.80 mm; for p = 10% – 68.1 mm; and for p = 50% – 37.8 mm (Krężałek and others 2013). It was assumed that with the increase of probability, the duration of rainfall also increased. The maximum daily precipitation values with the exceedance probability equal to: p = 1%, p = 10%, and p = 50% were assigned to the total rainfall durations, D = 6 h, D = 12 h and D = 24 h, respectively.

In the next step, the area reduction of the point precipitation was carried out. The method described by Banasik (2009) was used for this purpose. The reduction for the time D = 6 h was 5%, resulting in an area precipitation volume of $P_{max,10\%}$ equal to 101.46 mm. In the case of rainfall duration D = 12 h, the point precipitation was reduced by 4% and area precipitation of $P_{max,10\%}$ was obtained equal to 65.38 mm, and for D = 24 h and a reduction of 3%, area precipitation of $P_{max,10\%}$ was obtained, equal to 36.67 mm. Distributions of the intensity of precipitation in time were determined using the standard hyetograph method according to the recommendations of DVWK 9 (Banasik 2009).

The calculations of the Penman's reference evapotranspiraton were made on the basis of meteorological data obtained from the IMGW PIB weather station (level one) located in Mława. A simplifying assumption was made that only two evapotranspiration values will be determined: an hourly total representative of the periods in which precipitation occurs, and the hourly total characteristic for rainless periods. The input data defining the evapotranspiration volume consisted of time series with elements that assumed the value of either 0.05 or 0.15 mm · h^{-1}, depending on whether there was a rainfall or not in the given hour.

The basis for the analysis of changes in the formation of the total runoff and its components consisted in the comparisons between the relevant hydrographs obtained as a result of simulation for an urban catchment and for a natural catchment.

RESEARCH RESULTS

The description of the results of the performed simulations consists of two parts – the first, concerning the impact of urbanization on the total runoff in individual variants, and the second, concerning the impact of catchment urbanization on the runoff components. In the first, the results showing the impact of the degree of catchment urbanization (including all types of the considered areas, that is A1, A2, B1, B2.1 and B2.2, and separately at the level of 5%, 10% and 20% share in the total surface of the catchment) were presented for high state of the initial waterlogging of the catchment (*Zwys*), and three probability levels of rainfall exceedance, namely 1%, 10% and 50% (See: Table 1). It was assumed that the high waterlogging of the catchment takes place at the initial flow rate in the riverbed at the level of WSQ = 0.554 $m^3 \cdot s^{-1}$, determined on the basis of data from the years 1966–2014. The impact of the catchment urbanization on the runoff volume was assessed, among others, on the basis of the C_{Qmax} parameter – the coefficient of increasing the maximum total runoff flow rate increase understood as the ratio of the peak runoff from the urbanized catchment to the peak runoff flow rate from the natural catchment: $C_{Qmax} = Q_{Cmax\_U} / Q_{Cmax\_N}$. In addition, the acceleration of the occurrence of the flood wave peak in comparison with natural conditions was analysed.

Table 1. Summary of basic parameters of the simulated hydrographs of total runoff for a partially urbanized catchment

Number of variant	Name of variant	Assumptions for the calculation: Location of urbanized areas within the given area type:	Increment of urbanized areas in %	Waterlogging of the catchment	Exceedance probability p, %	Parameters describing the results of the total runoff simulation: Maximum flow Q_{cmax}	Time until peak t_k	Decrease in the time until peak compared to t_k for the natural catchment $\Delta(t_k)$	Peak flow increment index C_{Qmax}
						$m^3 \cdot s^{-1}$	h	h	–
1	2	3	4	5	6	7	8	9	10
1	nat_*Zwys*_p1	none	0	high	1	3.743	30	–	–
2	nat_*Zwys*_p10				10	2.734	30	–	–
3	nat_*Zwys*_p50				50	1.753	34	–	–
4	u5_*Zwys*_p1	Evenly over the areas of A1, A2, B1, B2.1, and B2.2	5		1	4.519	16	–14	1.208
5	u5_*Zwys*_p10				10	3.068	22	–8	1.122
6	u5_*Zwys*_p50				50	1.899	31	–3	1.083
7	u10_*Zwys*_p1		10		1	5.649	13	–17	1.510
8	u10_*Zwys*_p10				10	3.628	17	–13	1.327
9	u10_*Zwys*_p50				50	2.094	27	–7	1.195
10	u20_*Zwys*_p1		20		1	7.867	10	–20	2.102
11	u20_*Zwys*_p10				10	4.900	14	–16	1.792
12	u20_*Zwys*_p50				50	2.569	25	–9	1.465
13	A1_u5_*Zwys*_p1	A1	5		1	4.804	10	–20	1.284
14	A1_u5_*Zwys*_p10				10	3.093	14	–16	1.131
15	A1_u5_*Zwys*_p50				50	1.786	25	–9	1.019
16	A1_u10_*Zwys*_p1		10		1	6.804	7	–23	1.818
17	A1_u10_*Zwys*_p10				10	4.003	13	–17	1.464
18	A1_u10_*Zwys*_p50				50	1.979	24	–10	1.129

Table 1. cd.

1	2	3	4	5	6	7	8	9	10
19	A2_u5_*Zwys*_p1	A2	5	high	1	4.111	18	–12	1.098
20	A2_u5_*Zwys*_p10				10	2.881	22	–8	1.054
21	A2_u5_*Zwys*_p50				50	1.793	30	–4	1.023
22	A2_u10_*Zwys*_p1		10		1	4.804	15	–15	1.284
23	A2_u10_*Zwys*_p10				10	3.214	19	–11	1.176
24	A2_u10_*Zwys*_p50				50	1.878	28	–6	1.071
25	B1_u5_*Zwys*_p1	B1	5		1	6.023	12	–18	1.609
26	B1_u5_*Zwys*_p10				10	3.824	17	–13	1.399
27	B1_u5_*Zwys*_p50				50	2.181	26	–8	1.244
28	B1_u10_*Zwys*_p1		10		1	8.753	9	–21	2.339
29	B1_u10_*Zwys*_p10				10	5.402	14	–16	1.976
30	B1_u10_*Zwys*_p50				50	2.766	25	–9	1.578
31	B1_u20_*Zwys*_p1		20		1	14.408	7	–23	3.850
32	B1_u20_*Zwys*_p10				10	8.582	13	–17	3.139
33	B1_u20_*Zwys*_p50				50	3.933	24	–10	2.243
34	B2.1_u5_*Zwys*_p1	B2.1	5		1	4.628	30	0	1.237
35	B2.1_u5_*Zwys*_p10				10	3.373	31	1	1.234
36	B2.1_u5_*Zwys*_p50				50	2.139	35	1	1.220
37	B2.1_u10_*Zwys*_p1		10		1	5.500	26	–4	1.470
38	B2.1_u10_*Zwys*_p10				10	3.999	30	0	1.463
39	B2.1_u10_*Zwys*_p50				50	2.512	35	1	1.433
40	B2.1_u20_*Zwys*_p1		20		1	7.597	19	–11	2.030
41	B2.1_u20_*Zwys*_p10				10	5.299	26	–4	1.938
42	B2.1_u20_*Zwys*_p50				50	3.238	35	1	1.847
43	B2.2_u20_*Zwys*_p1	B2.2	20		1	3.742	30	0	1.000
44	B2.2_u20_*Zwys*_p10				10	2.734	30	0	1.000
45	B2.2_u20_*Zwys*_p50				50	1.753	34	0	1.000

Source: own study

Figure 2 presents the results of a simulation of total runoff hydrographs from the catchment, the area of which was 10% urbanized in various ways. The course of these hydrographs varies greatly depending on the adopted variant of urbanization, with the exception of hydrographs generated for urbanization areas of B2.2 type, which coincide with the hydrographs obtained for the natural catchment. The differences are most pronounced in the case of simulations performed for basic precipitation with exceedance probability equalling p = 1%. In order to explain them, later in the present work, the hydrographs for this case were subjected to a more detailed analysis taking into account the components of the total runoff.

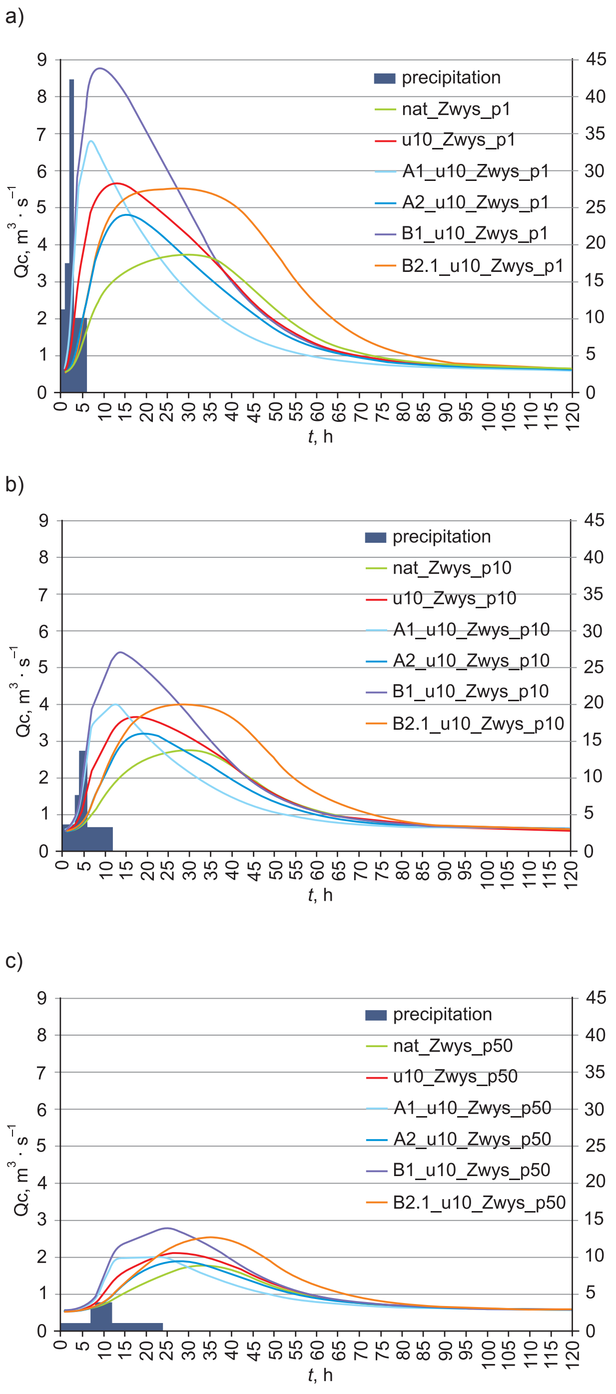

Fig. 2. Formation of total runoff from catchment urbanized in 10% with various types of areas, in the conditions of high waterlogging, and precipitation with the probability of overrun amounting to a) 1%, b) 10%, c) 50%; symbols as in table 1

Source: own study

The changes in the catchment area caused by the introduction of urbanized areas type B1 have the greatest impact on the parameters of total runoff during rainfall flood flows. Increasing the sealing with areas of this type causes a significant reduction of time until the peak of the flood flow, and a significant increase in the maximum flow rate. Acceleration of the peak is by up to 23 hours, and the maximum flow rate increases by 385% (see: Table 1, item 31). The other case of such a significant reduction of time to peak occurred only once in the calculation variant No. 16. Simulation of the hydrograph was performed for the variant of 10% degree of catchment urbanization involving only A1 type areas, in the conditions of average waterlogging of the catchment, and for precipitation with exceedance probability equalling 1%. This is related to the fact that both urbanized areas of type A1 and B1 are drained by rainwater sewage system.

The second part of the work presents simulation results that form the basis for inference about the influence of river catchment's urbanization on individual components of river runoff. One variant was selected for component analysis: 10% degree of urbanization, and precipitation with the exceedance probability of 1%. The illustrations showing hydrographs of direct runoff components for each of the adopted types of urbanized areas are presented. One example is the figure showing the progression of the direct runoff hydrograph for areas of B1 category, which differs most from hydrographs obtained in natural conditions in terms of the maximum runoff H_{max} reported in mm · h^{-1} (see: Fig. 3).

The overrun of H_{max} is over 8-fold for the catchment of urbanized areas of B1 type. In other cases, an increase by 3.6 times was recorded for evenly urbanized areas, by 7.3 times for the urbanized catchment of the A1 type, by 1.7 times for the urban catchment with A2 type areas, and almost two-fold for the urbanized catchment of the B2.1 type.

The forecasts also concerned the impact of rainwater discharge by means of rainwater sewage system on various components of the runoff. The progression of hydrographs of total runoff and its components for different location variants of urbanized areas was compared. Due to the fact that urban areas of B1 type generate the most forceful response of the catchment to precipitation, the paper presents in detail how the

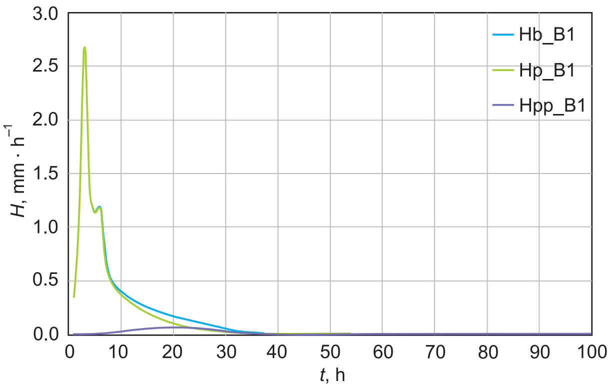

Fig. 3. Hydrograph of feeding the river channel with direct runoff, and its components, simulated for urbanized catchments in areas of B1 type

Source: own study

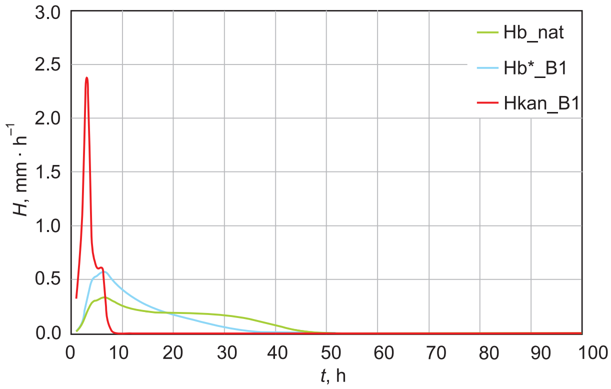

Fig. 4. Change of the hydrograph of direct runoff component as a result of additional feeding of the riverbed with the runoff of rainwater sewage B1 type areas – *Hkan*_B1

Source: own study

runoff discharged by the sewage system from these areas is shaped as compared to direct runoff, subsurface runoff, and surface runoff. It was found that the dominant component of the runoff during the formation of flood flows from the catchment, on which the urbanized areas of B1 type had been created, is the runoff from the stormwater sewer system (see: Fig. 4). The latter is about four times larger than the direct runoff from the unmodified catchment area. As a result, the natural direct runoff is also increased. The resulting change of the river regime consists in expanding variable source areas, thereby generating saturation excess surface runoff caused by the water level rise in the riverbeds network as a result of their additional supply with runoff from sealed areas. The increase in water levels causes a slowdown of subsurface and groundwater runoff and, as a consequence, an increase in the water level in the soil. This phenomenon is taken into account in the developed model in a conceptual way (Szymczak, Krężałek 2018).

During the tests, a comparison between hydrographs of individual components for different types of land sealing was conducted. Examples include figures 5, 6, and 7, presenting the total, subsurface and ground runoff.

In Figure 6, we can clearly see how the A1 and B1 type areas, associated with sealing and channelling of the land, cause a rapid increase in the dynamics of the flood water runoff. Hydrographs have high peaks and a short times of rise. In turn, flood flows from the

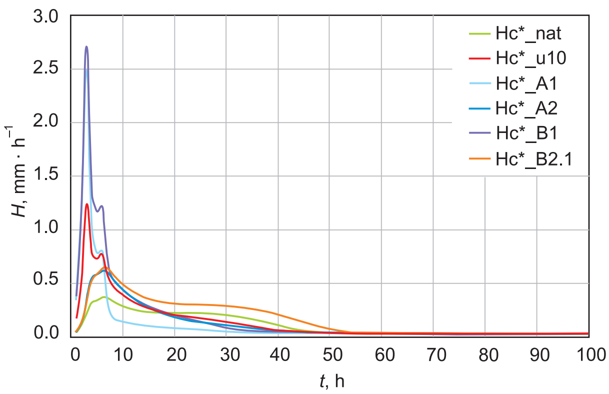

Fig. 5. Comparison between hydrographs of the component describing total feed into the riverbed *Hc** simulated in the model for different location variants of urbanized areas

Source: own study

urbanized catchment areas of the B2.1 type are similar to those in natural areas, however, they have a larger volume and higher peak. This is related to the fact that the runoff from B2.1 type areas supplies the unsealed areas of the *Sb* zone, where surface and subsurface runoff is generated in natural conditions.

Therefore, we observe an increase of subsurface runoff for these areas (see: Fig. 6).

Urbanization of areas located within the maximum reach of variable source areas does not reduce the groundwater runoff (see: Fig. 7). The main impact on the limitation of this component comes from the intro-

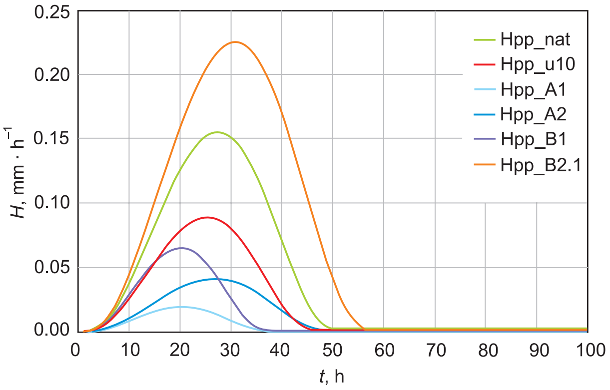

Fig. 6. Comparison between hydrographs of the component of subsurface feed *Hpp* simulated in the model for different location variants of urbanized areas

Source: own study

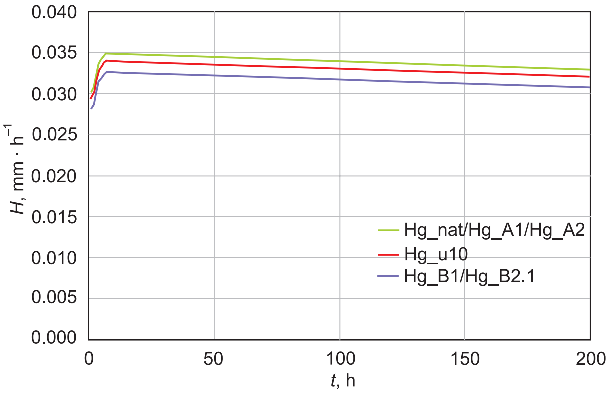

Fig. 7. Comparison between hydrographs of the component of groundwater feed *Hg* simulated in the model for different location variants of urbanized areas

Source: own study

duction of sealing in the areas of infiltration zone (B1 and B2.1 type) with the discharge of rainwater away from the place of precipitation. A slightly smaller reduction in groundwater runoff is observed when the catchment is evenly urbanized, also including categories B1 and B2.1.

While analysing the test results for the components of the runoff, it was found that the highest, over 8-fold increase in the maximum runoff was recorded for direct runoff in areas of B1 type, shortening the period of the rise by 3 hours. The biggest reduction in the duration of the rise was by 7 h, and it was observed for subsurface runoff while reducing the peak of the wave in the A1 and B1 type areas.

In the present work, we have also analysed the changes in the volume of direct runoff from a catchment, where urbanized areas of various types occupy 10% of its total surface. Research results have shown a significant increase in the volume of direct runoff from the partially urbanized catchments containing areas of B1 or B2.1 type as well as all other types of the analysed areas simultaneously, compared to the volume of direct runoff from the natural catchment. In the case of only A1 and A2 type areas, the direct runoff volume increments were small, and they amounted to $21 \cdot 10^3$ m^3 and $18 \cdot 10^3$ m^3 respectively. For the urbanized catchment of B2.2 type, no change in the volume of runoff water has been observed. The presented values of direct runoff volume increments may be useful for determining the necessary capacity of retention devices or rainwater sewage system.

CONCLUSIONS

Performing the forecasts being the subject of the present work was made possible by mapping the progression of the total runoff (and its main components) from a small lowland river catchment with a predominantly agricultural use, using a simple conceptual model. The description of the river runoff progression should take into account the variable source areas concept, especially in the case of a small lowland drainage catchment with high infiltration capacity. In this particular case, the model structure distinguishes two types of areas: areas where only direct runoff (*Sb*) is created, and areas where water coming from precipitation after taking into account evaporation losses completely infiltrates and feeds groundwater runoff (*Sinf*). Taking into account the variable source areas concept in the description of river runoff is important in forecasting the impact of urbanization of the catchment on the formation of flood flows. Sealing and channelling such areas results in a greater increase in total surface runoff across the whole catchment than it would appear from calculations made with models consistent with the Horton theory (Horton 1933).

The results of simulation studies covering 45 calculation variants confirmed the hypothesis that the increase in urbanized areas within the agricultural catchment influences the change in the structure of its individual runoff components, the increase in the volume of direct runoff, and the intensity of maximum flow rates. These changes depend not only on the extent of urbanization, but also on the location of the urbanized areas in relation to the two types of catchment zones, *Sb* and *Sinf* that are distinguished and described above, performing different hydrological functions in the catchment, as well as on the manner of draining the rainwater.

The changes in the catchment area caused by the introduction of urbanized areas of B1 type have the greatest impact on the parameters of total runoff during rainfall flood flows. They are located in the infiltration zone of *Sinf*, and the rainwater sewage from their surface is discharged by rainwater sewage system directly to the river network.

Sealed and channelled areas located beyond the maximum range of active areas (variable source areas) on which direct runoff does not occur in natural conditions, increase the size of the runoff zone in the scale of the entire catchment area. For comparison, the flood flow peaks for the variants related to urbanization of B1 type are between 20% and 40% higher than in the case of analogous conditions and the sealing of the same surface area in the zone of direct runoff *Sb* (urbanized areas of A1 type).

In the *Sinf* infiltration zone, therefore, it is particularly important to limit surface runoff and to retain the rainwater on the site, that is, to convert B1 type areas to B2.2 type areas, in which case the infiltration discharge of rainwater is assumed.

Considering only the increase in the volume of direct runoff, the area of the catchment that is most appropriate for development, according to the obtained results, is the zone of direct runoff formation, where surface runoff also occurs under natural conditions. Practically complete urbanization of this zone (areas of A1 or A2 type) results in an increase in the volume of direct runoff by only about 4% compared to the runoff arising in natural conditions. However, such areas occupy only a little more than 8% of the total catchment area, and a significant part of these can be found in the flood hazard zone.

Based on the analysis of the research results, taking into account the components of the runoff for the variant with the category of urbanized areas of B1 type, it can be concluded that the sealing and channelling of the area radically changes the shape and values of hydrograph parameters of runoff components from the entire catchment, such as direct runoff, surface runoff, and subsurface runoff. The urbanization of the catchment with only A1 type areas, and with equal shares of all the discussed urbanization area types, has a slightly smaller impact.

Analysis of simulation results of river runoff from a natural catchment and from an urban catchment, taking into account the runoff components, leads to the conclusion that the total increase of the direct runoff volume and its peak value are caused not only by direct supply from sealed surfaces, but also by the changes in runoff formation in non-urbanized areas.

Urbanization of land within the maximum range of variable source areas does not reduce groundwater runoff. The limitation of this component is mainly influenced by the introduction of sealing in the infiltration zone of the *Sinf* catchment with rainwater drainage away from the precipitation site (urban areas of B1 and B2.1 types).

Avoiding the most unfavourable locations for surface sealing, and quick discharge of rainwater into the surface waters facilitate limiting the increase in the intensity of extreme hydrological phenomena associated with the gradual urbanization of rural areas.

In order to reduce the maximum runoff rates, when introducing urbanization into agricultural land, it is recommended that technical solutions are applied that would facilitate the management of rainfall sewage in situ, for instance, in the form of balanced, sustainable drainage systems (Kozłowska 2008, Krężałek 2011, 2012, 2014). One example might be replacing impermeable surfaces with partially permeable surfaces, for instance in the construction of car parks, “eco” (environmentally friendly) type slabs should be used instead of asphalt or paving slabs. We should remember about the option of implementing small-scale retention solutions. In the case of an increase in the share of sealed areas, it is crucial to introduce solutions such as filtering beds, retention reservoirs, filtration-retention reservoirs, ponds, and green roofs. Furthermore, all solutions enabling infiltration and underground retention such as wells, drainage chambers and boxes are beneficial. We should also remember to maintain the so-called biologically active area on plots intended for housing development. Ensuring adequate share of lawns and green areas on private properties and in public spaces alike helps limit the runoff by rainwater sewage system.

Simulation studies similar to those presented in this paper should be considered in the scope of work related to the preparation of a hydrological study included in the zoning plan of every municipality. Taking them into account at the stage of spatial planning is an opportunity, which will help reduce flood risks in a given area, related to its urbanization.

Through research into the urbanization process by way of modelling, it is possible to determine how the sealing of land affects the formation of flood flows in the given area. Adopting different variants of land cover and percentage share and different locations of sealed areas in the catchment, at the stage of simulation research, allows us to predict changes in hydrological conditions of agricultural areas after urbanization. Furthermore, it should be added that variant simulation research, using a mathematical model, is low cost and requires relatively short research time, simultaneously allowing the analysis of non-existent systems as well as simulation of systems behaviour under different conditions, which is its unquestionable advantage. In addition, it ensures repeatability of the experiment, versatility of the analysis, and full control over the system by eliminating interference. The disadvantages of simulation testing include simplification of the reality, problem of estimating the reliability of results, as well as the fact that the result obtained in a short time is approximate only and may be less accurate. The problem of the credibility of results in the case of the research performed will be minimized, thanks to the verification of the model using the actual measurement data from the upper Mława research catchment.

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PROGNOZA KSZTAŁTOWANIA SIĘ WEZBRAŃ OPADOWYCH W MAŁEJ ZLEWNI NIZINNEJ DLA RÓŻNYCH WARIANTÓW JEJ URBANIZACJI

ABSTRAKT

Celem pracy było przedstawienie wyników badań symulacyjnych odpływu rzecznego przeprowadzonych za pomocą specjalnie w tym celu opracowanego modelu konceptualnego dla nizinnej zlewni częściowo zurbanizowanej.

Wykonano wariantowe prognozy wpływu wprowadzania różnych form urbanizowania terenu na kształtowanie się odpływu rzecznego w czasie wezbrań opadowych w małej nizinnej zlewni górnej Mławki o powierzchni 66 km^2. Na potrzeby badań dokonano klasyfikacji obszarów zurbanizowanych na podstawie ich lokalizacji na terenie zlewni i sposobu odprowadzania ścieków opadowych.

Warianty zróżnicowane były między sobą lokalizacją terenów uszczelnionych, stopniem zurbanizowania zlewni, stanem początkowego uwilgotnienia zlewni, a także przyjętym opadem obliczeniowym. Stanowiły podstawę do oceny wpływu różnych form urbanizacji zlewni na kształtowanie się wezbrań opadowych z uwzględnieniem jej naturalnych właściwości, takich jak występowanie obszarów czynnych.

Przedmiotem analiz był nie tylko odpływ całkowity, ale również jego składowe – odpływ powierzchniowy, podpowierzchniowy oraz gruntowy.

Analiza wyników symulacji odpływu rzecznego z uwzględnieniem składowych tego odpływu prowadzi do wniosku, że sumaryczne zwiększenie objętości odpływu bezpośredniego i wartości jego kulminacji jest spowodowanie nie tylko bezpośrednim zasilaniem z powierzchni uszczelnionych, ale oddziaływaniem pośrednim powodującym zmiany w reżimie odpływu na obszarach nieobjętych urbanizacją.

Obszary uszczelnione i skanalizowane położone poza maksymalnym zasięgiem występowania obszarów czynnych, na których w warunkach naturalnych nie powstaje odpływ bezpośredni zwiększają powierzchnię spływu w skali całej zlewni. Dla porównania wartości kulminacji wezbrania dla wariantów związanych z urbanizacją i kanalizacją poza obszarami czynnymi są od ok. 20 do 40% wyższe niż w przypadku analogicznych warunków i uszczelnienia takiej samej powierzchni na obszarze formowania się odpływu bezpośredniego

Słowa kluczowe: urbanizacja, obszary czynne, hydrogram, model konceptualny