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RAINFALL MODELS IN SMALL CATCHMENTS IN THE CONTEXT OF HYDROLOGIC AND HYDRAULIC ASSESSMENT OF WATERCOURSES

MODELE OPADÓW W MAŁYCH ZLEWNIACH W ASPEKCIE OCENY HYDROLOGICZNO-HYDRAULICZNEJ CIEKÓW

Abstract: This paper presents a proposed application of methods for determining heavy rainfall in small ungauged agricultural catchments in lowland areas. Moreover, we discuss the methodology for a comprehensive hydrological and hydraulic analysis of the functioning of a small lowland watercourse. In order to properly (correctly) use the methods for determining heavy rainfall, a comprehensive workflow had to be created for the dimensioning of structures designed to evacuate rainfall water (i.e. drainage, irrigation and sewer systems), that could be used by designers and would account for the small water retention solutions. In the paper we propose methods for determining heavy rainfall that allow the management of rainfall water in small ungauged agricultural catchments in lowland areas. The calculations of the rainfall intensity with assumed duration times are proposed using three precipitation models: the Bogdanowicz and Stachy formula, the Lambor formula and the Woloszyn formula. The models of Lambor and Woloszyn are advantageous because they are local. On the other hand, the Bogdanowicz and Stachy formula is the recommended model for the dimensioning of structures intended to evacuate rainfall water; this formula makes use of the intensity of design storm in rural areas (p = 10 %). As an example of calculations, we present the initial rainfall intensity results and the values of runoff for a rainfall with the exceedance probability p = 10 % and the duration time 15, 30, 60 and 120 minutes, for the micro-catchment of the watercourse R-4 located in the Dobrzen Wielki commune, south-west of Poland. In the calculations each of the three formulae was used, but the highest values were obtained for the Bogdanowicz and Stachy formula. An analysis of the runoff values for each duration time reveals that the longer the duration time of rainfall, the lower the rainfall intensity. The runoff of precipitation water from the catchment was determined using *the European standard* EN 752:2008. Moreover, in order to properly select and dimension the retention reservoir for precipitation water the authors used the ATV-A117 guidelines and a study about this standard. The proposed methodology for the determination of heavy rainfall in small ungauged agricultural catchments in lowland areas for the purpose of rainfall water management could be of interest in practical water management applications.

Keywords: small lowland watercourse, rainfall intensity, small agricultural catchment, water retention, stochastic model, probabilistic model, precipitation model

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Introduction

The extreme natural phenomena like floods and droughts in climatic zone of Poland can cause significant loss in economy (especially agriculture) and natural environment [1]. In recent years, an increasingly violent weather anomaly has been observed and more frequent, recurring extreme natural phenomena, including long-lasting drought [2–3]. In order to limit the negative impact of these phenomena, it should be pay special attention to irrigation and drainage systems [1], including hydrotechnical constructions [4].

The rational management of water should aim to improve the natural water resources in places where they are formed [5]. The largest water user in Poland is agriculture. Consequently, the aspect of water balance in rural areas should be considered together with the issue of climate change observed in recent years. In addition, agriculture has a significant impact on the availability and quality of water [6]. Therefore, the principles of dimensioning of soil drainage systems, i.e. drainage, irrigation and sewer systems should be constantly developed [7]. In water management, hydrological models may be used to evaluate the risks and to design the water infrastructure [8]. In order to model hydrological processes, a synthetic information on the rainfall with a given duration time and exceedance probability is required. The increasing frequency of heavy rains in recent years both in Poland and more generally in Europe [9] requires a thorough analysis using a probabilistic approach [10]. The quantitative description of the amount of rainfall is based on mathematical models which prove a relationship between the amount of rainfall or the intensity of rainfall and its duration time and exceedance probability [11–16]. The rainfall intensity measurements may be determined by processing the observation data from a meteorological gauging station [17]. If there is no such station in the vicinity of the catchment, the parameters are calculated from empirical formulae [18]. Moreover, the authors of [7] recommend the use of this model in the design of structures intended to evacuate rainfall water from ungauged catchment in order to comply with the requirements of EN 752:2008 [19] in terms of the design frequencies of rainfall c = 2, 5 and 10 years.

This paper aims to propose methods for determining heavy rainfall that would allow the management of rainfall water in small ungauged agricultural catchments in lowland areas. Based on the experience and results to date, we present the calculation of rainfall intensity with assumed duration times using three precipitation models: the Bogdanowicz and Stachy formula, the Lambor formula and the Woloszyn formula. In order to determine the runoff of precipitation water from the catchment, a European standard [19] is used. In order to properly select and dimension the retention reservoir for precipitation water we used the guidelines of ATV-A117 [20] and the explanations provided in [21].

Methods

The methodology of work includes the following actions: determining the catchment area (the surface area of the drainage basin), analysing the structure of land use in the catchment, hydraulic field measurements of the watercourse and of the structures located on it, determining the flow capacity of the watercourse channel, calculating the discharge of the communication structures built on the watercourse, calculating the intensity of design storm with a given exceedance probability p [%] and a given duration time (t [min]), determining the runoff of precipitation from the catchment under study, selection and dimensioning of the small retention reservoir, intended to reduce the flood risk in the catchment by holding the excess of rainfall or meltwater.

Determining the drainage basin area and of its structure of land use

The principle of determining the catchment is discussed in [22, 23]. The catchment areas based on topographic maps can be determined using either analogue maps (sheets of paper maps) or digital (in GIS applications). Lowland catchments are characterized by small slopes and a difference in altitude, so the determined catchment limits must be validated by analysing the topographic profile in a digital model of the terrain and by field measurements of the altitude. The development of the watercourse valley is determined based on maps, orthophotomaps and field work.

Hydraulic field measurements of the watercourse and of the structures located on it

The length of a watercourse can be measured in several ways. The easiest is to measure it in the streamline on an orthophotomap. Since the cartographic data may not always be up to date, it is recommended to verify the obtained results through field measurements. When determining the cross sections of a watercourse channel, the measurements of longitudinal slope of the watercourse are performed. The measurements are carried out using the sequence levelling method. The measurements of the longitudinal slope are shown in [24]. Parameters of the watercourse channel such as its width and the height and slope of embankments are also recorded.

Flow capacity of the watercourse channel

In the calculations of flow capacity of the channel we used the cross sections for the low and high water level of the communication structures. The discharge values at the cross sections were determined according to the Manning formula [19, 24].

Discharge of the communication structures built on the watercourse

The discharge values for the communication structures (culverts and pipelines) were determined according to the Chezy formula [25]. The velocity coefficient C was calculated from the Kutter relationship [26].

Determining the characteristics of rainfall

In catchments with no rainfall measurement stations the characteristics of rainfall can be determined using several models. In order to determine the intensity of rainfall for the assumed duration times (15, 30, 60 and 120 minutes), we used three precipitation models of Bogdanowicz and Stachy, Lambor and Woloszyn. While the first model is based on data collected all over Poland, the two others are based on local data and are used by the designers in the city of Wrocław and its surroundings [27, 7]. The probabilistic model of Bogdanowicz and Stachy [7] is described by the following relationship:

$$h_{\max} = 1.24t^{0.33} + \alpha(R,t)\cdot(-\ln p)^{0.584} \tag{1}$$

where: $h_{\max}$ – maximum rainfall [mm];
t – the rainfall duration [min];
p – the exceedance probability: $p \in (0;1)$;
α – parameter (of scale) which depends on the region of Poland and the parameter t, the assumed value is that for central Poland (R1).

The use of this model is recommended for the design frequencies c = 2, 5 and 10 years [7].

The rainfall intensity was determined based on the formula of Woloszyn. The relationship is as follows [27, 7]:

$$I = \frac{a_p}{(t+4)} + c_p \tag{2}$$

with:

$$a_p = \frac{4.326(5-p)}{p^{0.6051}} + 28.056 \tag{3}$$

$$c_p = 0.0427 - 0.00025p \tag{4}$$

where: I – rainfall intensity [mm · min^{-1}];
p – exceedance probability [%];
a_p and c_p – coefficients [-] [7].

The empirical model of Lambor for the city of Wroclaw and its surroundings was used for the calculation of rainfall intensity. The formula is as follows [7]:

$$I = \frac{43.7 - 15\log p}{(t+0.03)^{0.7}} \tag{5}$$

where: I – rainfall intensity [mm · h^{-1}], which is equivalent to the number of occurrences in 10 years [%];
t – rainfall duration [h].

Designers rarely use this model, despite its applicability up to the altitude of 1500 m ASL and the duration time of one month [27, 7].

Determining the precipitation runoff from the catchment under study

In order to determine the runoff of precipitation water from the catchment under study, a European standard [19] was used. According to this standard, the recommended frequency of design storm to be used in the design of systems intended for evacuation of rainwater in rural areas should be once every 10 years.

The precipitation runoff from the catchment under study Q [$m^3 \cdot s^{-1}$] was determined according to the rational equation [19, 27, 28], after the rainfall characteristics had been obtained:

$$Q = k \psi_z IA \tag{6}$$

where: k – unit conversion factor;
ψ_z – substitute surface flow coefficient [-];
A – area receiving rainfall [km^2].

Selection and dimensioning of the precipitation water reservoir

Amongst the many methods of selection and dimensioning of a reservoir we used the guidelines of a German standard [20] and the guidelines provided in [21]. The key advantage of this method is its high efficiency of retention during heavy rainfall and the delayed runoff and controlled water inflow to other structures. The designed rainfall reservoir will have a restricted outflow capable of holding an appropriate amount of water. The dimensioning is performed according to ATV-A117. The goal of this dimensioning is to determine the allowed flow (outflow from the reservoir) and the reservoir volume [21]. We suggest that a two chamber reservoir might be considered, in which the first chamber (at the entry to the reservoir) will be the pre-dam reservoir, aimed to improve water quality.

The main goal of the proposed small reservoir is flood protection. As confirmed in the literature [29, 30], any reservoir, regardless of its type and size, contributes to curbing the flood risk, simply by accumulating the excess of rainfall or meltwater.

Results and discussion

As an example of hydrological calculations an ungauged agricultural micro-catchment was investigated. This catchment is located in the south-west of Poland, in the Upper Odra basin. The catchment under study is that of the watercourse R-4 with a surface area of 82.9 ha. The catchment is located in the villages of Dobrzen Wielki and Brzezie, in the Dobrzen Wielki commune. The hydrological calculations of rainfall intensity carried out using the three precipitation models allowed us to obtain the maximum catchment runoff value for the rainfall duration time t = 15, 30, 60 and 120 minutes and the exceedance probability p = 10 % (Fig. 1).

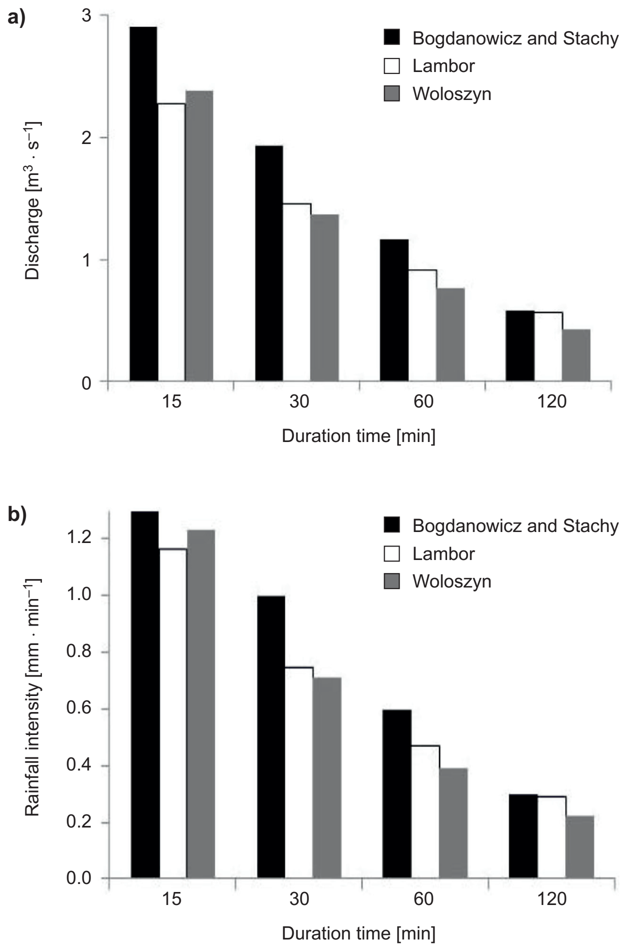

Fig. 1. Hydrological characteristics a) rainfall intensity and b) runoff calculated using three models for given rainfall duration times

The highest rainfall intensity with the exceedance probability p = 10 % and the rainfall duration time t = 15, 30, 60 and 120 minutes was obtained from the Bogdanowicz and Stachy formula. The smallest rainfall intensity was obtained from the Lambor formula for t = 15 min and from the Woloszyn formula for all other duration times (t = 30, 60 and 120 min).

The hydrological calculations performed using the Bogdanowicz and Stachy formula show that the runoff from the catchment at the mouth cross section would be 2.9 $m^3 \cdot s^{-1}$ for a heavy rainfall lasting 15 minutes and 0.580 $m^3 \cdot s^{-1}$ for a rainfall lasting 120 minutes. This indicates that the longer the duration of rainfall, the smaller its intensity.

Conclusions

This paper presented the methodology for solving heavy rainfall problems and for the management of such rainfall and – in relation to that – for the determination of heavy rainfall in small lowland ungauged agricultural catchments for the purpose of rainfall water management.

The methods proposed in the paper, which include:

a) the calculation of rainfall intensity for assumed rainfall durations for three precipitation models: Bogdanowicz and Stachy, Lambor and Woloszyn, and

b) the calculation of precipitation runoff from the catchment, as well as

c) the methods for appropriate selection and dimensioning of the retention reservoir for precipitation water, provide the information required for rainfall water management. The models of Lambor and Woloszyn are advantageous because they are local. On the other hand, the Bogdanowicz and Stachy formula is the model that is recommended for the dimensioning of structures intended to evacuate rainfall water; this formula makes use of the intensity of design storm in rural areas (p = 10 %). The sample initial hydrological calculations for the micro-catchment of a lowland watercourse in the south west of Poland indicate that in the case of rainfall with the probability p = 10 % and any of the duration times under study the highest rainfall intensities are obtained when using the Bogdanowicz and Stachy method. Moreover, the results reveal that the longer the duration of rainfall, the lower its intensity.

A comprehensive workflow is proposed for the dimensioning of structures designed to evacuate rainfall water, i.e. drainage, irrigation and sewer systems. This workflow that could be used by designers and would account for the existing small water retention solutions. The methodology proposed in this paper may be of interest in practical water management applications.

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MODELE OPADÓW W MAŁYCH ZLEWNIACH W ASPEKCIE OCENY HYDROLOGICZNO-HYDRAULICZNEJ CIEKÓW

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Abstrakt: W niniejszej pracy przedstawiono propozycje zastosowania metod wyznaczania opadów nawalnych w małych niekontrolowanych zlewniach użytkowanych rolniczo, na terenach nizinnych. Ponadto w pracy przedstawiono metodykę wykonania kompleksowej analizy hydrologiczno-hydraulicznej funkcjonowania małego cieku nizinnego. Dla właściwego (poprawnego) stosowania metod wyznaczania opadów nawalnych konieczne było stworzenie kompleksowego schematu postępowania dla wymiarowania urządzeń odprowadzających wody opadowe, tj. systemów melioracyjnych i kanalizacyjnych, który może być stosowany przez projektantów uwzględniając zastosowanie rozwiązania małej retencji wodnej. W pracy zaproponowano metody wyznaczania opadów nawalnych umożliwiających zagospodarowanie wód opadowych w małych niekontrolowanych zlewniach nizinnych na terenach rolniczych. Zaproponowano obliczenia natężenia deszczy przy założonych czasach ich trwania przy zastosowaniu 3 modeli opadów: wg Bogdanowicza i Stachego, Lambora oraz Wołoszyna. Zaletą stosowania modeli Lambora i Wołoszyna jest fakt, że są modelami lokalnymi. Natomiast zalecanym modelem w wymiarowaniu urządzeń odprowadzających wody opadowe, który wykorzystuje natężenie deszczu miarodajnego na terenach wiejskich (p = 10 %) jest model Bogdanowicza i Stachego. Jako przykład obliczeń przedstawiono wstępne wyniki natężenia deszczu i wartości odpływów dla deszczu o prawdopodobieństwie przewyższenia p = 10% i czasie trwania 15, 30, 60,120 minut dla mikrozlewni cieku R-4 zlokalizowanej w południowo – zachodniej Polsce w Gminie Dobrzeń Wielki. W obliczeniach zastosowano wszystkie wymienione modele, jednak najwyższe wartości uzyskano modelem Bogdanowicza i Stachego. Analiza wartości odpływów wskazuje, że im czas trwania deszczu jest dłuższy, tym mniejsze jest jego natężenie. Ustalono wartości odpływu wód opadowych ze zlewni przy zastosowaniu *normy* europejskiej EN 752:2008. Ponadto dla właściwego doboru i wymiarowania zbiornika do retencji wód opadowych autorzy zastosowali wytyczne normy ATV-A117 oraz opracowania poświęcone tej normie Zaproponowana w niniejszej pracy metodologia wyznaczania opadów nawalnych w małych niekontrolowanych zlewniach użytkowanych rolniczo, na terenach nizinnych, na potrzeby zagospodarowania wód opadowych, stanowi interesującą propozycję do wykorzystania w praktyce gospodarki wodnej.

Słowa kluczowe: mały ciek nizinny, natężenie deszczu, mała zlewnia rolnicza, retencja, model stochastyczny, model probabilistyczny, model opadów