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DETERMINING HYPOTHETICAL FLOODS IN THE ODRA BASIN BY MEANS OF THE CRACOW METHOD AND THE VOLUME FORMULA

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Summary

Methods of hypothetical flood waves determining with the Cracow method developed for the Upper Vistula area are unlikely to be implemented by the common engineering practice in case when their verification was conducted only for one region. One of the methods is the Cracow method which is used for determining the flood waves in gauged catchments, whereas the other called the volume formula, is meant for ungauged catchments. In this method the wave volume is calculated by a formula, whereas its wave course is determined on the basis of a unit flood wave by means of SCS UHG method.

An attempt was made in the paper to apply both methods for the catchment in the Odra river basin. The Nysa Kłodzka river was selected as a pilot catchment, in which 12 gauging stations were identified, for which the assessment of results was conducted using the criterion of hypothetical flood wave volume. Additionally these results were compared with the results obtained using the Hydroproject method.

Conducted assessment allows to state that the Cracow method and the volume formula of hypothetical flood waves determining may be applied in the Odra basin. Verification of the methods and satisfactory results obtained in geographical region, other than the one for which they were developed allows to put forward a thesis that neither of methods has a regional character, so they may be applied in various catchments. Also the volume formula may be used for a catchment up to 1000 km^2, like for the Upper Vistula catchment. However, the spatial range of both methods applicability should be verified on a wider material, i.e. for catchments of various morphological character, management and hydrological regime.

Keywords: design flood hydrograph, volume formula, Cracow formula, Hydroproject method

INTRODUCTION

A hypothetical flood wave denotes a flow hydrograph which presents a potential flood wave course, which may occur under specific conditions in a specific place, for a given value of maximum flow. The value of the peak flood discharge is assumed as the annual maximum flow $Q_{max,p\%}$ with determined probability of exceedance at a given watercourse cross section.

Currently, application of hypothetical flood waves is still increasing due to a much wider range of supplied information, in comparison with the methods which allow only to determine the values of design. Application of the methods for developing hypothetical flood waves makes possible providing the data and characteristics which enable the presentation of the flows course in time and state their total duration, as well as the time of flood rising and falling (O'Connor *et al*. 2014). Moreover, they may be used to determine the flood volume for the needs of hydraulic objects e.g. small water reservoirs, their operation and management (Mioduszewski 2012). Hypothetical waves became the basic data resources used for determining flood hazard areas, estimating loss of life and property (Jonkman *et al*. 2008), and risk estimation (Büchele *et al*. 2006; Ernst *et al*. 2010). A wide variety of their potential applications caused that they are often used in contemporary water management (Linsley *et al*. 1975; Pilgrim 2001), including the papers on urbanized catchments (Hattermann and Kundzewicz 2010; Kurczyński 2012; Kriščiukaitienė *et al*. 2015; Wałęga and Grzebinoga 2014; Zevenbergen *et al*. 2011).

Determining hypothetical flood waves in gauged cross sections is relatively simple and commonly used due to availability of information about historical hydrographs. The problem appears when we want to use similar solutions in ungauged catchments. Determining the flow course is difficult, not only because of a lack of registered data but also the lack of tools verified for individual regions.

In case of gauged cross-sections, graphic and analytical methods are used, in which the shape and course of a hypothetical flood wave may be determined on the basis of a single or several observed maximum flood waves. The methods which use a single historical flood include the Reitz-Kreps method (Ciepielowski and Dąbkowski 2006; Gądek and Środula 2014a) and the Hydroprojekt method (Gądek and Środula 2014b). The methods, in which hypothetical fllod waves are elaborated on the basis of several selected observed floods, much better show the river character; these comprise: the Warsaw University of Technology method and the Cracow method. Both base on developing a unified hydrograph. The Warsaw University of Technology method (Gądek 2012a) requires 6 historical floods, whereas the Cracow method requires 8 (Gądek 2010). Another group comprises methods which describe floods as mathematical equations using probability density functions (Strupczewki 1964; McEnroe 1992).

Hydrological modelling is used to estimate flow hydrographs for rainfall episodes in ungauged catchments (Banasik 2009; Gądek *et al*. 2012; Wałęga 2013). Some of the works are realized on the assumption of the equality of probabilities of the maximum registered daily rainfall and maximum runoff from the catchment caused by this precipitation. The test on the rivers flowing within the Krakow agglomeration (Wałęga and Grzebinoga 2014) do not confirm the assumption. Underestimated flood volume was stated for the investigated catchments (Gądek and Bodziony 2015). It seems that the method requires standardization of the computing procedures and that the its regional character cannot be excluded (Radczuk *et al*. 2002). In the other investigations, registered daily rainfall provided a basis for the rainfall-runoff type analyses (Wypych *et al*. 2014; Wójcik *et al*. 2014; Szalińska and Otop 2012; Szalińska *et al*. 2014). Additional procedures correcting water deficit or design hyetographs may be a supplement of the rainfall-runoff dependence. Models with lumped, partly distributed or integral parameters are increasingly more often used, such as e.g. WISTOO model (Ozga-Zielińska *et al*. 2002). Selection of the model structure best matching the appointed goal and range of modelling bases on a catchment characteristics and analysis of the dynamics of processes shaping the runoff volume under specific conditions (Brown *et al*. 1999; Clark *et al*. 2011).

In 2004 the method of hypothetical flood determining in ungauged catchments basing on the volume formula and unit flood SCS UHG (NOHRSC; Gądek 2014] was developed at the Institute of Engineering and Water Management. This method is recommended for the catchments of up to 1000 km^2, as demonstrated by the tests conducted in the area of the Upper Vistula basin. The formula may be used to estimate the volume of hydrographs generated by a hydrological model.

The paper aims to assess if the application of the Cracow method and the volume formula of hypothetical flood wave determining would yield satisfactory results in the catchments of the Odra river basin. The fact, that both methods were developed for the Upper Vistula area, whereas a considerable part of solutions applied in hydrology have a regional character, makes the verification of their implementation difficult. The methods used to determine hypothetical hydrographs should be of a universal character and global range. The Nysa Kłodzka river catchment was selected as the test area in the Odra basin.

DESCRIPTION OF METHODS

The description of the Cracow method was presented elsewhere (Gądek 2010; 2012a; 2012b).The input data constitute one modal historical flood, whose maximum flow is approximate to the maximum registered at a given gauging station. It is recommended to use at least 8 hydrographs, however, basing on the experiment it may be said that application of a lesser number of floods is admissible, however there should be no less than 5.

The following assumptions were adopted:

- a flood is meant a hydrograph whose flows are higher than the limit flow determined on the basis of the initial flow Q_0. The flow with a probability of exceedance $Q_{50\%}$ is regarded as the initial flow;
- observed historical hydrographs are normalized to a universal unit hydrograph for which the time of rising t_k [h] and the time of falling t_o [h] are established, as well as the duration of flood t_b (base time), which is the sum of the time of rising and time of falling $t_b = t_k + t_o$.

Hypothetical flood is determined at the following stages:

a) development of a unified course of unit flood (UHJ$_i$, where *i* is the number hydrograph unified) for each observed flood, however the time of rising and time of falling are treated as independent;
b) determining an average unit hydrograph UHJ on the basis of partial hydrographs UHJ$_i$;
c) determining the linear dependence between the flood duration t_b and the time of rising t_k, $t_b = f(t_k)$, Fig. 1;
d) determining the dependence between the reduced flood volume and reduced maximum flow $V\_z = f(Q_{max} - Q_{50\%})$, Fig. 2. However, the reduced flood volume is defined as the hydrograph volume above the limit flow $Q_0 = Q_{50\%}$;
e) determining the course of a hypothetical flood wave on the basis of: unified average unit hydrograph UHJ, given volume established from the dependence $V\_z = f(Q_{max} - Q_{50\%})$ and interrelations between the flood duration and the time to peak $t_b = f(t_k)$.

It has been assumed that the value of maximum flow of a normalized flood unit hydrograph in a dimensionless form equals 1. For each normalized time coordinate t_i within the range 0 to 2, flows q_i are computed as dimensionless values:

$$q_i = \frac{Q_i - Q_{50\%}}{Q_{max} - Q_{50\%}} \tag{1}$$

where:

Q_i – value of flow [m^3/s] for normalized time step t_i

t_i – time coordinates assuming the following values:

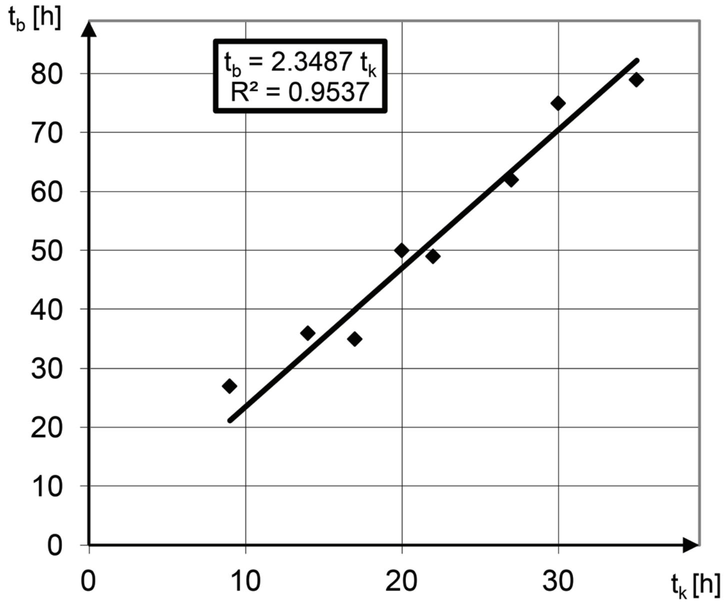
time of rising – t_k
t_i = 0.0; 0.1; 0.2; 0.3; 0.4; 0.5; 0.6; 0.7; 0.8; 0.9; 0.95; 1.0;
time of falling – t_0
t_i = 1.05; 1.1; 1.2; 1.3; 1.4; 1.5; 1.6, 1.7; 1.8; 1.9; 2.0;
i – the number of time step;
Q_{max} – maximum flood flow (maximum flow) [m³/s];
$Q_{50\%}$ – value of flow [m³/s] with a given probability of exceedance p=50%.

A unit hypothetical hydrograph is a result of averaging unit flows q_i for each of the normalized time steps t_i.

$$q_i = \frac{\sum_{j=1}^{m} q_{j,i}}{m} \tag{2}$$

where:

q_i – a coordinate of average unit flow of hypothetical unit hydrograph for a given time step t_i;
i – the number of time step;
m – number of floods;



(source: own results)

Figure 1. Dependence of the base time, t_b, on the time to peak, t_k, for floods included in the calculations

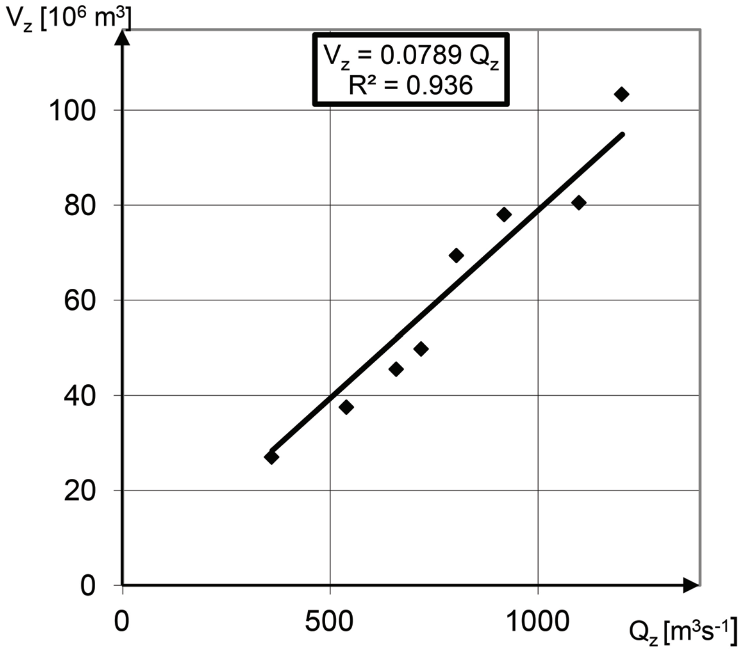


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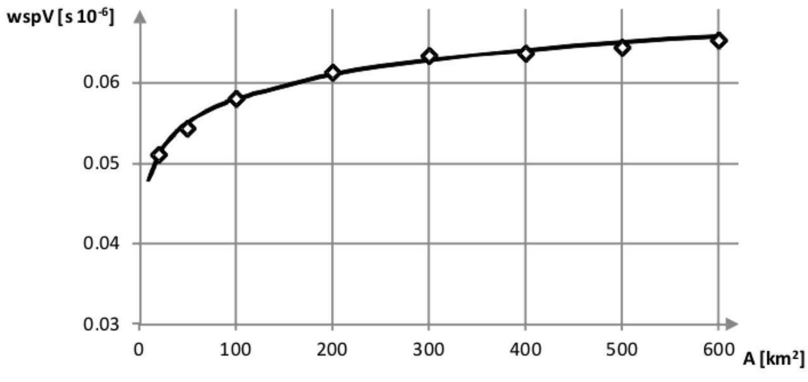
Figure 2. The dependence of the reduced volume, V_z, on the reduced flow, Q_z, included in the flood calculations



(source: own results)

Figure 3. Dependence of the coefficient changing the reduced flow volume on the hypothetical wave reduced volume *wspV* for developed empirical formula

A unit hydrograph is a basis for determining a theoretical flood. The final shape of the theoretical flood with its parameters requires determining two regression dependencies between the base time t_b and the time to peak t_k (Fig.1), and between the reduced volume V_z and reduced flow $Q_z = Q_{max} - Q_{50\%}$ (Fig.2).

Analysis of results of the Cracow method (Gądek 2010; 2012b) made possible confirmation of a relationship between reduced maximal value of flow and reduced volume of hypothetical flood wave. It contributed to developing a formula, in which *wspV*, the coefficient changing the reduced flow to reduced flood volume was made dependant on the catchment surface area. The changes of this coefficient presented in Fig 3.

The suggested formula has the following form:

$$wspV = 0.0044\ (\pm\ 14\%) ln(A) + 0.0377 (\pm\ 9\%) \tag{3}$$

where:

wspV – coefficient binding the volume of reduced wave with maximum flow reduced in peak [s 10^{-6}];

A – catchment surface area from 10 to 1000 km^2.

$$V_z = wspV \cdot Q_z \tag{4}$$

where:

V_z – reduced volume of hypothetical flood wave [10^6m^3];

Q_z – maximum given reduced flow of hypothetical flood wave, $Q_{maxp\%}$ diminished by $Q_{50\%}$ [m^{3}s^{-1}];

The volume formula was determined on the basis of 48 hypothetical flood waves determined by the Cracow method. The criterion for a catchment selection comprised: catchment surface area and location in the researched area, i.e. in the Upper Vistula basin. The researched catchments were of various physical-geographical, morphological and climatic character. Selected were mountain, sub-mountain, upland and lowland catchments, with surface areas from 22.8 to 362 km^2.

CHARACTERISTICS OF SELECTED CATCHMENTS

The catchments of the Nysa Kłodzka river were selected for the assessment of the spatial range of the analysed methods applicability, for which 15 gauging stations were analysed. The list of the catchments and the dynamics of flows in the form of a ratio of maximum annual flows with given probability of exceedance (dependence 5) was compiled in Table 1.

$$IQ_{p\%} = \frac{Q_{1\%}}{Q_{50\%}} \tag{5}$$

$IQ_{p\%}$ – ratio of maximum annual flows with given probability of exceedance [-];

$Q_{1\%}$, $Q_{50\%}$ – maximum annual flow with given probability of exceedance $p = 1\%$ i 50%, [$m^3 \cdot s^{-1}$].

Table 1. Characteristics of analysed partial catchments of the Nysa Kłodzka River.

NO	River	Gauging station	Surface area A [km^2]	$IQ_{p\%}$ [-]
1	Nysa Kłodzka	Międzylesie	49.7	9.42
2	Nysa Kłodzka	Bystrzyca Kłodzka	260	4.53
3	Nysa Kłodzka	Kłodzko	1084	5.37
4	Nysa Kłodzka	Bardo	1744	4.85
5	Nysa Kłodzka	Nysa	3276	6.75
6	Nysa Kłodzka	Kopice	3759	8.61
7	Nysa Kłodzka	Skorogoszcz	4514	7.18
8	Wilczy Potok	Wilkanów	35.1	15.59
9	Bystrzyca	Bystrzyca Kłodzka	64	4.44
10	Biała Lądecka	Lądek Zdrój	166	7.26
11	Biała Lądecka	Żelazno	305	14.55
12	Bystrzyca Dusznicka	Szalejów Dolny	175	6.68
13	Ścinawka	Tłumaczów	256	5.58
14	Ścinawka	Gorzuchów	511	4.46
15	Biała Głuchołaska	Głuchołazy	283	6.91

Source: own results

Following the initial analysis it was found that a cascade of retention reservoirs on the Nysa Kłodzka may negatively influence the calculation results. Therefore, three gauging stations situated below the reservoir on the Nysa (Nysa, Kopice and Skorogoszcz) were excluded from the analyses.

RESULTS

A hypothetical flood wave was determined using the Cracow method (Gądek 2010; 2012a) for each gauging station on the basis of real flow hydrographs. At the first step, analysis of two regression dependencies was conducted between the base time and the time of rising and between the reduced volume and reduced flow. A positive result of regression dependencies denotes that this method may be applied.

Conducted analyses checked also if the volume determined using the volume formula may be applied in this area. Moreover, the volume of a hypothetical flood was determined, established on the basis of one historical flow hydrograph, whose maximum flow was the highest registered flow. The course of this hypothetical flood was worked out on the basis of real shape of the flow hydrograph, whereas the values were determined on the basis of the maximum flow using flow unification, retaining the time course and flood duration. Applied computation procedure is a great simplification of the hypothetical flood wave determining method by Hydroprojekt (Gądek and Środula 2014b). Exemplary hypothetical flood waves for catchments of various areas, for the water gauges: Międzylesie on the Nysa Kłodzka, in Bystrzyca Kłodzka on the Nysa Kłodzka, Gorzuchów on the Ścinawka and Bardo on the Nysa Kłodzka were presented in Fig. 3.

Table 2. Volumes of hypothetical waves determined using the Cracow method (*V mk*), from the volume formula *V for* and on the basis of the course of the highest registered hydrograph (*V hyd*) for given maximum flow $Q_{1\%}$ for the Nysa Kłodzka catchment

No	River	Gauging station	*V mk* $[10^6\ m^3]$	*V for* $[10^6\ m^3]$	*V hyd* $[10^6\ m^3]$
1	Nysa Kłodzka	Międzylesie	3.17	3.81	3.18
2	Nysa Kłodzka	Bystrzyca Kłodzka	13.4	15.5	**20.4**
3	Nysa Kłodzka	Kłodzko	45.3	42.4	43.6
4	Nysa Kłodzka	Bardo	68.0	61.3	57.5
5	Wilczy Potok	Wilkanów	4.81	4.64	3.50
6	Bystrzyca	Bystrzyca Kłodzka	1.61	1.43	**0.84**
7	Biała Lądecka	Lądek Zdrój	16.5	12.4	16.9
8	Biała Lądecka	Żelazno	**48.6**	**28.3**	**54.7**
9	Bystrzyca Dusznicka	Szalejów Dolny	**4.74**	**9.3**	5.55
10	Ścinawka	Tłumaczów	8.09	9.79	8.23
11	Ścinawka	Gorzuchów	13.7	11.4	11.3
12	Biała Głuchołaska	Głuchołazy	21.7	18.3	21.5

Source: own studies

The examples presented above reveal a satisfactory compatibility – both concerning the course of flood and the parameters describing the flood. Conducted analyses give grounds to state that all three methods may be applied in the Nysa Kłodzka catchment area.

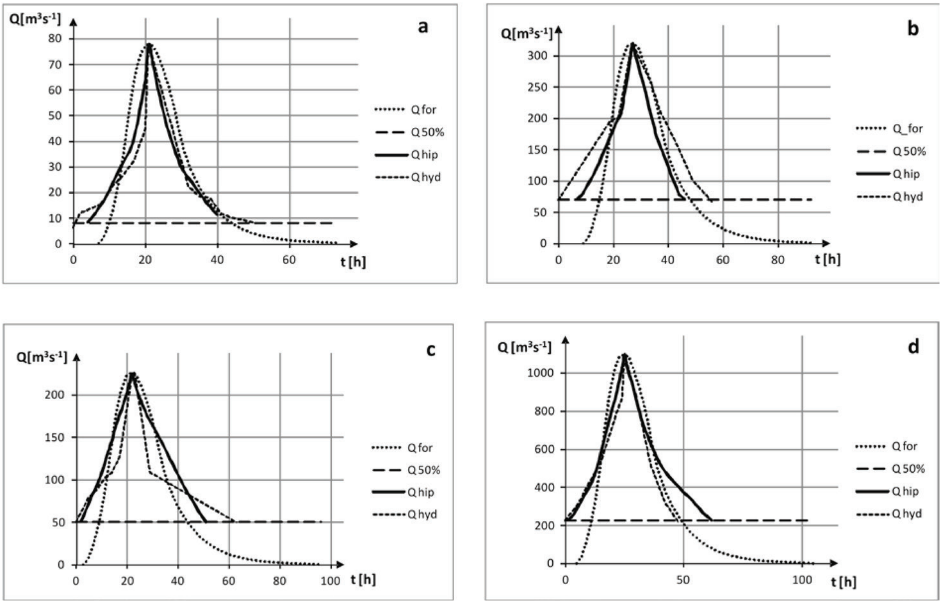


Figure 4. Hypothetical flood waves designed on the basis of the Cracow Method (*Q hip*), the volume formula and SCS UHG hydrograph *Q for*), and on the basis of the highest registered flood (*Q hyd*) for the gauge cross sections: a) Międzylesie on the Nysa Kłodzka, b) in Bystrzyca Kłodzka on the Nysa Kłodzka, c) Gorzuchów on the Ścinawka, d) Bardo on the Nysa Kłodzka (source: own results)

CONCLUSIONS

In the framework of the experiment aimed at testing possible application of methods for hypothetical flood waves determining developed for the Upper Vistula catchment area, calculations were conducted for 12 gauging stations situated in the Nysa Kłodzka catchment in the Odra basin. Assessment covered the Cracow method designed for gauged catchments and the volume formula recommended to use in non-gauged catchments.

In most cases hydrological formulas have a regional range, which makes difficult their transposition to other areas. The maximum flows in the Nysa Kłodzka catchment during flood in 1997 were higher than $Q_{1\%}$ flow, which in the Upper Vistula area is observed rarely. Moreover, it was tested whether such different input data affect the course, volume and duration of hypothetical floods determined using a method approximate to the Hydroproject method (Gądek and Środula 2014b). Conducted analyses confirmed that all three methods of hypothetical flood waves determining worked for a majority of cases in the Nysa

Kłodzka catchment. Only the values of flood volume calculated for the Żelazno gauging station on the Biała Lądecka exceeded the assumed 30% deviation range. In the case of Szalejów Dolny gauging station on the Bystrzyca Kłodzka, in result of the volume formula application, the value of computed volume of hypothetical flood was much lower than the value of volume obtained using the Cracow method. Very high flow variability ratio $IQ_p\%$ in the Żelazno gauging profile may be the cause of this discrepancy.

Conducted tests may be regarded positive and on their basis it may be stated that both the Cracow method and the volume formula may be applied in the Odra basin. Moreover, the volume formula may be applied for catchments of up to 1000 km^2, similar as for the Upper Vistula catchment.

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