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Catchment responses to heavy rainfall events in a changing environment

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Introduction

Environmental changes influence the size of flood discharges and the amount of sediment yield. Climate changes would cause, in many parts of the world, the increase of number and size of heavy rain storms, and on the other hand the land use changes, i.e. expansion of croplands, pastures, plantations, and urban areas, as well as construction of airports, roads and motorways – causing considerable losses of biodiversity. They would additionally decrease the retention capacity of the river catchments. These problems have been often investigated and discussed in recent decades, at international level (Leopold 1968; Bosselman and Callies 1971; Changnon and Demissie 1996; Bhuyan et al. 2002; Foley et al. 2005; Blöschl et al. 2011) and also at the project partner institutions (Banasik 1989 and 1991; Banasik et al. 1999; Byczkowski et al. 2001; Ciepielowski and Stolarek 1995; Lundekvam et al. 2003; Bechmann et al. 2008; Nowakowski et al. 2008; Hejduk and Banasik 2010) using various tools. The aim of this consideration is to demonstrate an application of a simple rainfall-runoff model to predict flood hydrographs as river catchment responses to heavy rainfall events in current environmental situation, and under environmental changes. It will be demonstrated for Zagożdżonka catchment at Płachty gauge, described in previous chapter (Banasik and Hejduk 2011).

The problem, the tool and recorded events description

Environmental variability as land use and climate changes require the development of tools to predict the hydrological consequences, which would form a base for adaptation strategies. Adaptation strategies to climate changes have constituted important programs of government agencies of many developed and developing countries (EEA 2010, Goodrich 2010). In UNDP Adaptation to Climate Change Report (2010) it is said that "adapting to climate change means that we must *do development better.* In coming decades, greater progress is needed to develop national capacity and to support cross-sectoral policy processes as the foundation for sustainable adaptation. However, better development is only part of the challenge – the complexity of climate change adaptation means we must also *do development differently*. Changes in planning and practices are crucial for reducing climate change risks". To develop such strategies it is not enough to be able to asses the hydrological consequences of climate and land use changes in a quality means, but it is a must to have procedures which allow predicting the consequences in a quantitative means. This is also very important for small river catchments, which are very sensitive to environmental changes, and for which long term hydrological data exists very rarely. In cases such as discussed in this study, results of application of rainfall-runoff procedure for Zagożdżonka catchment for the current conditions could be confronted with results of statistical analysis.

A procedure, called SEGMO (Sediment Graph Model) was developed at the Department of Water Engineering of Warsaw University of Life Sciences – SGGW (Banasik 1994a and b; Banasik and Walling 1995; Banasik et al. 2000) for predicting catchment response, as flood hydrograph and sedimentgraph, to heavy rainfall. The model consists of two parts; a hydrologic sub-model and sedimentology sub-model. The hydrologic submodel uses the Soil Conservation Service CN-method to estimate effective rainfall and the instantaneous unit hydrograph (IUH) procedure to transform the effective rainfall into a direct runoff hydrograph. The sedimentology submodel uses a form of the modified Universal Soil Loss Equation to estimate the amount of suspended sediment produced during the rainfall-runoff event and the instantaneous unit sedimentgraph (IUSG) procedure to transform the produced sediment into a sedimentgraph. Only the first one i.e. hydrological submodel, called later rainfall-runoff model, will be used for analyses of recorded events and for prediction. Schematic representation of the model is shown in the Figure 1. Parameters of the model, i.e. CN parameter of SCS method for effective rainfall computation and Nash model parameters of IUH for transformation of the effective rainfall into direct runoff could be estimated on the basis of existing guidelines and formulas or could be identified on the basis of recorded rainfall-runoff events (see: Step 1 on Figure 4.1). The last one is applied, as recording of rainfall-runoff events in the catchment of Zagożdżonka River at Płachty gauge have been carried out since 1980 (Banasik 1983 and 1994b; Banasik and Ignar 1983). Main characteristics of the 35 recorded events in the period of 1980–2010 (including current project investigation) are presented in Table 4.1.

For further analysis, the value of the parameter of CN has been accepted as 71.5 (Banasik 1994b) on the basis of soil type and land use in the catchment, however the value has been confronted with measured data in this catchment (Banasik 1994b;

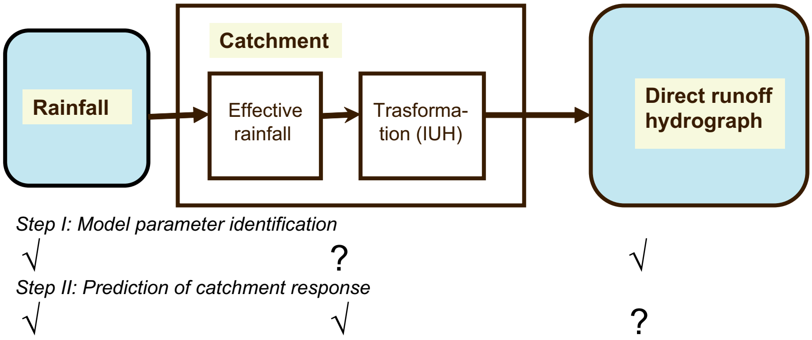

FIGURE 4.1. Schematic representation of rainfall-runoff model with steps of its application

TABLE 4.1. Characteristics of the 35 recorded rainfall-runoff events at Płachty gauge in the period of 1980–2010

Category	Unit	Value:		
		avg./event	range	standard deviation
1	2	3	4	5
Rainfall depth – P	mm	28.8	8.0–89.7	18.4
Runoff (effective rainfall) depth – H	mm	3.41	0.27–18.7	4.88
Runoff coefficient – c	–	0.103	0.011–0.604	0.128
Rain duration – D	hour	19.1	2–70	15.0
Peak discharge – Q_{max}	$m^3 \cdot s^{-1}$	4.43	0.51–21.0	6.15
$Q_{max}/Q_{max\ 50\%}$	–	1.51	0.17–7.17	2.10
Curve number – CN	–	79.1	52.2–95.5	11.7
LAG	hour	10.7	6.20–16.0	2.78
Time to peak of IUH – t_p	hour	6.11	0.0–11.3	3.28
Max ordinate of IUH – u_p	h^{-1}	0.082	0.048–0.123	0.022
	$l\ s^{-1} \cdot km^{-2}\ mm^{-1}$	22.9	13.2–34.2	6.13

$Q_{max\ 50\%}$ is two-year-flood discharge = 2.93 m^3/s

WAU 1995 & 2005; WULS 2009) and the method has been verified in its subcatchment (Banasik and Woodward 2010).

One of the characteristic properties of catchment rainfall-runoff process is the retention of the system or lag time (LAG), which is defined as elapse time between the centroids of effective rainfall and the direct runoff hydrograph.

Using measured data of rainfall-runoff events the lag time can be calculated as:

$$\mathrm{LAG} = M_{1Q} - M_{1P} \tag{1}$$

where M_{1Q} and M_{1P} are first statistical moments of the direct runoff hydrograph and the effective rainfall hyetograph (h), respectively. For the IUH derived by Nash (1957), i.e.:

$$u(t) = \frac{1}{k \cdot \Gamma(N)} \cdot \left(\frac{t}{k}\right)^{N-1} \cdot \exp\left(\frac{t}{k}\right) \tag{2}$$

where:
$u(t)$ are ordinates of IUH, N and k are model parameters (N – number of reservoirs [–] and k – time of retention of each reservoir [h]) and t is time; the lag time is related to model parameters according to the formula:

$$\text{LAG} = N \cdot k \tag{3}$$

Main characteristics of the IUH are defined on Figure 4.2, and the values of lag time of recorded events and the computed once – on the basis of the records, i.e. the time to peaks as well as peaks if IUHs are presented on the Figure 4.3, 4.4 and 4.5, respectively.

As one can notice from the recorded values of lag time, time to peak and peak (max ordinate) of IUH, presented in Table 4.1 and on the Figures 4.3–4.5, there is big scatter of the characteristics. As Nash model parameters, needed later for prediction of flood hydrographs in the accepted lumped parametric approach of rainfall-runoff modelling, are estimated on the basis of time to peak and peak value of IUHs (Banasik et al. 2000), those characteristics were accepted as mean weighted values according to maximum peak discharges. Model parameters estimated for the catchment, according t_p = 8.13 h and u_p = 0.071 h^{-1}, were N = 3.27 and k = 3.58 h.

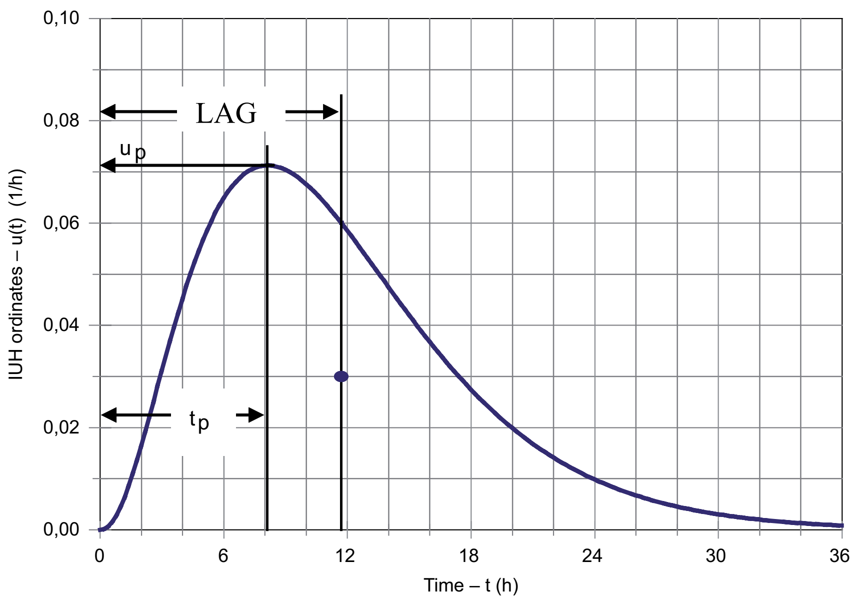

FIGURE 4.2. Definition of the IUH characteristics: LAG – lag time, t_p – time to peak, u_p – maximum ordinate

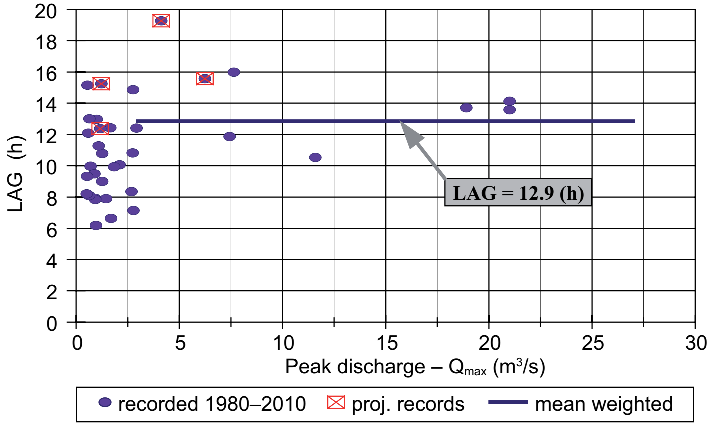

FIGURE 4.3. Lag time of rainfall-runoff events recorded in the period 1980–2010 and the mean weighted values according to and versus flood peak discharges

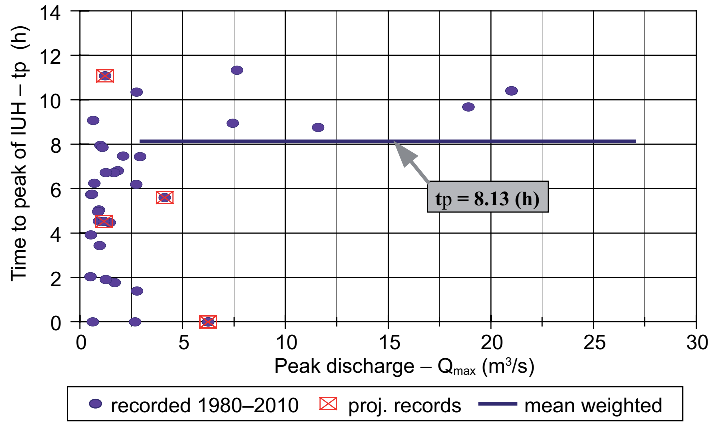

FIGURE 4.4. Time to peak of IUHs estimated for the recorded rainfall-runoff events versus flood peak discharges

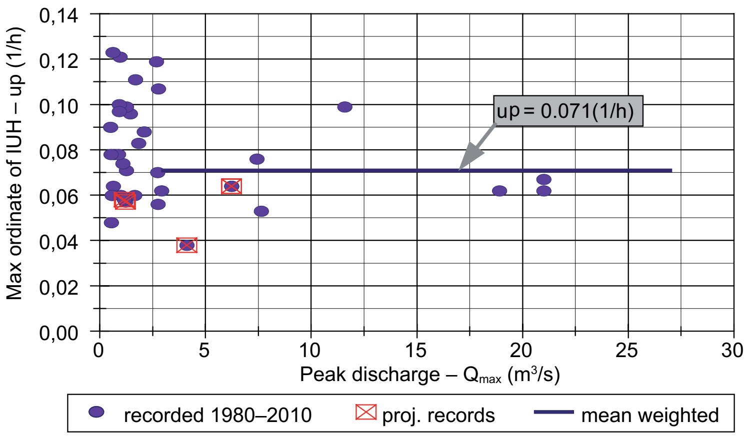

FIGURE 4.5. Maximum ordinate of IUHs estimated for the recorded rainfall-runoff events versus flood peak discharges

Prediction flood hydrographs as catchment responses to design current rainfall events

A formula of Bogdanowicz and Stachy (1998) on relationship of intensity-duration-return period, applicable also for region of centre of Poland, has been used to find rainfall depths of the events with probability of exceedance of 1% (return period of 100 years) and various duration (i.e. D = 6, 12, 18, 24, 30, 36, 42, 48, 60 and 72 h), as input data for runoff hydrograph simulation. Rainfall intensity has been assumed as a constant during rain duration. The computed relationship of rainfall intensity, rainfall depth, as well as runoff depth, estimated according to SCS-CN (1986) method for current land use in the catchment (CN = 71.5), versus rain duration are presented in Figure 4.6. The computed direct runoff hydrographs are presented in the Figure 4.7.

The above described computation has been repeated for rainfall probability of exceedance of 0.5% and 5% (i.e. for return period of 200 years and 20 years). The rainfall and runoff values are presented on the Figure 4.8 and the results in form of peak of direct hydrographs versus the rain duration for the three rainfall sets (i.e. also for the p = 1%) are presented in the Figure 4.9. Base flow has not been considered in the computation.

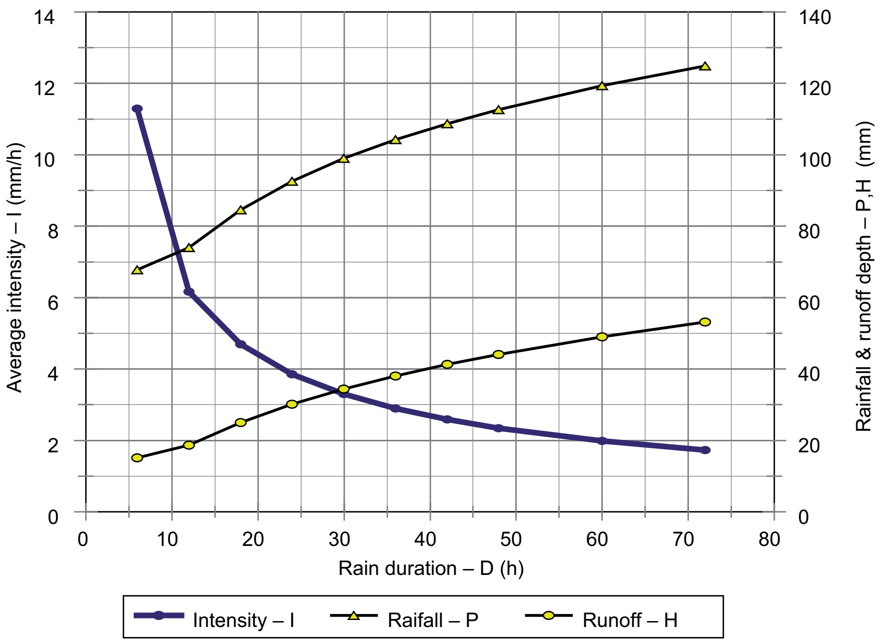

FIGURE 4.6. Rainfall intensity-duration and depth-duration relationship of return period of 100 years with runoff depth for investigated site at current land use

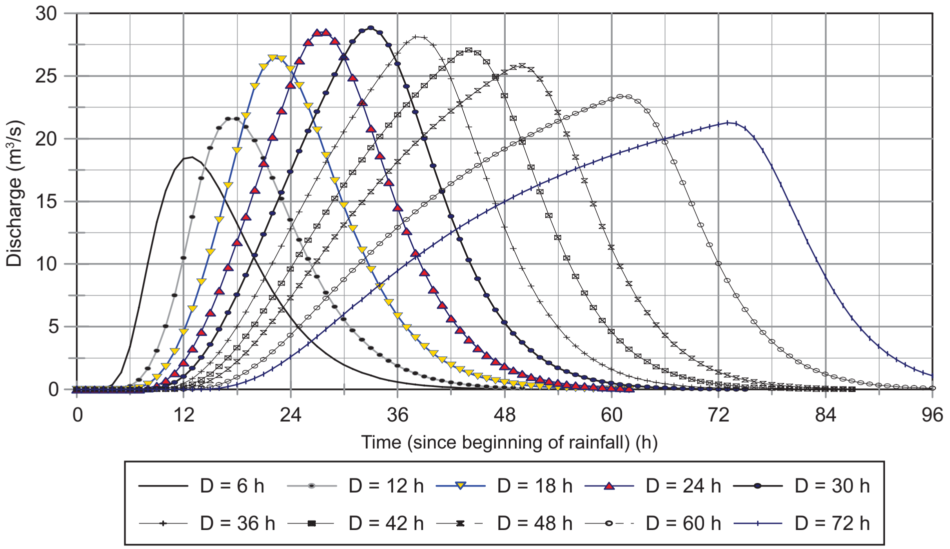

FIGURE 4.7. Simulated direct runoff hydrographs for rainfall of return period of 100 years (p = 1%) and various duration (D = 6–72 h)

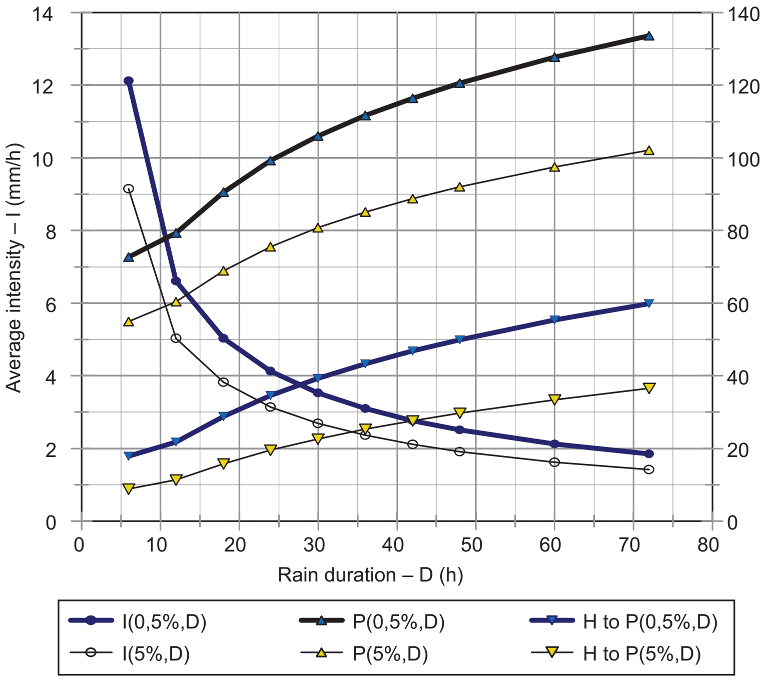

FIGURE 4.8. Rainfall intensity-duration and depth-duration relationship of return period of 200 years (i.e. p = 0,5%) and 20 years (p = 5%) with runoff depth for the respective rainfall events

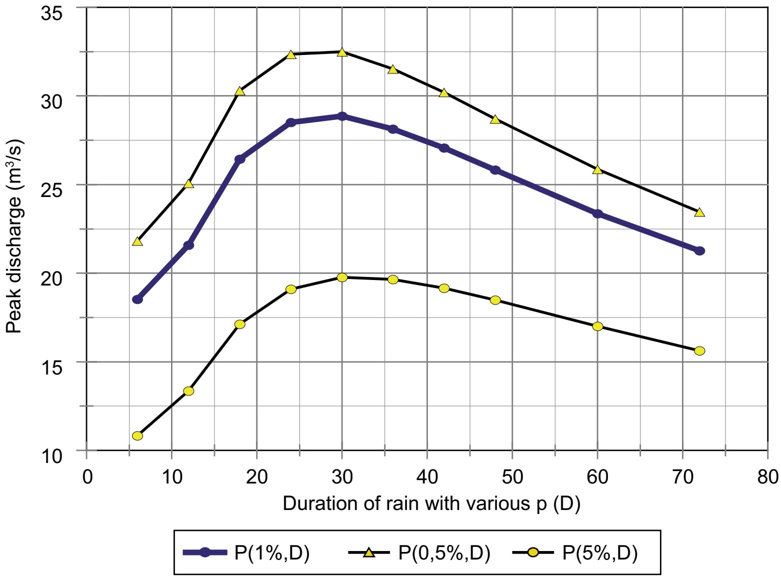

FIGURE 4.9. Relationship of peak of direct hydrographs caused be rainfall events of the probability of p = 1%, 0,5% and 5% [P(p%,D)] versus rainfall duration

Discussion on results of rainfall-runoff simulation and on former and potential model applications

The rainfall-runoff simulation has shown that the highest runoff hydrographs at the assumed conditions were caused be rainfall events of duration of 30 hours (which is called critical rain duration – D_{cr}). However the shapes of the graphs on Figure 4.9 may indicate that the D_{cr} would be a bit shorter for $P_{1\%}$ (ca 1–2 h) and for $P_{0.5\%}$ (ca 2–3 h) if the rain duration is assumed differently. The graphs on the Figure 4.9 indicate also that within wide scope of rain duration (from 17–20 h to 45–50 h) the hydrographs peaks are the only 10% smaller then the higher values for respective rain probability. The highest computed peak discharges were 32.5 m^3/s, 28.9 m^3/s and 18.9 m^3/s for the rain events of return periods of 200, 100 and 20 years, respectively. These values are compared with annual maxima estimated on the basis of seasonal flood frequency analysis (Table 4.2).

The data presented in Table 4.2 indicate relative good agreement between Q_{max_p} and peak of runoff hydrograph simulated as catchment response to P_p for p = 1% and 0.5 %, as the relative difference is within 13%. The difference is significant (ca 70%) for more often events (p = 5%). It is worth to note that in former simulation, with the use of shorter set of data for model parameters estimation and with the use of earlier

TABLE 4.2. Comparison of food flows in the Zagożdżonka River at Płachty gauge estimated on the basis of flood frequency analysis and rainfall-runoff simulation

Return period T (years)	Probability p (%) (1-CDF)	Annual flood flows Q_{max} (m³/s) estimated on the basis of:		Relative difference $\frac{Q_{max}^{RpR} - Q_{max\_p}^{WS-M}}{Q_{max\_p}^{WS-M}}$ (%)
		seasonal flood frequency analysis (Chapter 3, Table 4.2) – $Q_{max\_p}^{WS-M}$	rainfall-runoff simulation as maximum response to $P_{p\%,\,Dcr}$ – Q_{max}^{RpR}	
1	2	3	4	5
200	0.5	35.8	32.5	–9.2
100	1.0	25.6	28.9	12.9
20	5.0	11.6	19.8	70.7

rainfall intensity-duration relationship, the maximum peak discharge for $P_{1\%}$ was 28,2 m³/s (Banasik 1996; Banasik and Byczkowski 1996).

Assuming relative good simulation of the rainfall-runoff process by the procedure for $P_{1\%,D}$, it has been used for predicting catchment responses to 24-h rainfall of constant intensity, with depth increase of 5%, 10%, 15% and 20% in comparison to the current one, as possible results of climate change. Results of computation are presented in Figure 4.10 and in Table 4.3.

The results indicate that increase of rainfall depth $P_{1\%,24h}$ of 20% would cause the increase of runoff depth (i.e. also runoff volume) of 42% and increase of peak discharge of 39%.

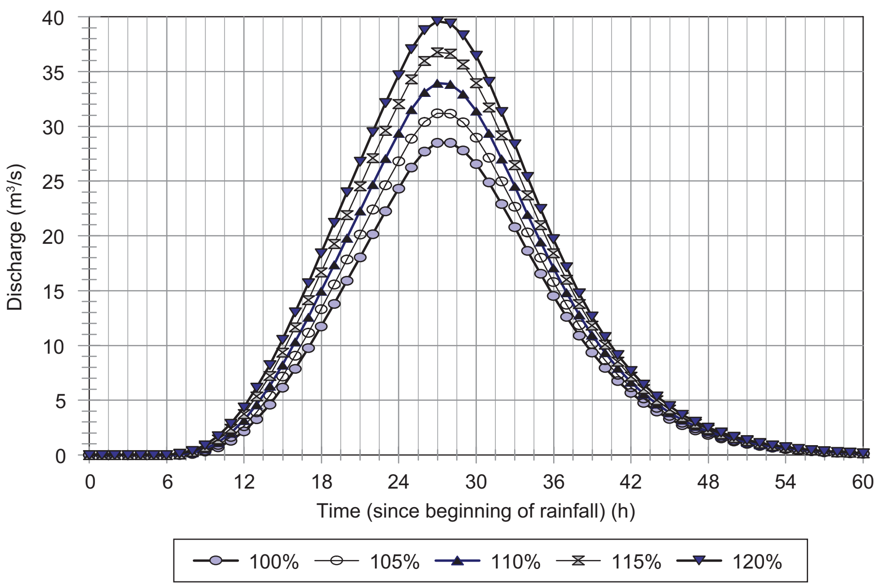

FIGURE 4.10. Runoff hydrographs as catchment responses to rainfall depth of 100%, 105%, 110%, 115% and 120% of the current $P_{1\%,24h}$

TABLE 4.3. Relative increase of runoff depth and peak hydrograph due to 100 year 24 h rainfall depth increase up to 20%

Rainfall		Runoff		Relative increase in comparison with current situation (%)	
amount of current $P_{1\%, 24\,h}$	depth – P (mm)	depth – H (mm)	peak hydrograph Q_{max} (m^3/s)	in runoff depth	in peak hydrograph
1	2	3	4	5	6
100%	92.7	30.2	28.5	0	0
105%	97.3	33.3	31.2	10.3	9.5
110%	101.9	36.5	34.0	20.7	19.1
115%	106.6	39.8	36.8	31.6	29.1
120%	111.2	43.0	39.6	42.5	39.0

The former application of the procedure for assessing land use changes (deforestation) on flood hydrographs has indicated that the decrease of the forest area from the current 40.5% in the catchment to 30.5% would cause increase in the peak of the hydrograph as the largest response to rainfall of $P_{1\%,D}$ of ca. 11% i.e. from 28.2 m^3/s to 31.4 m^3/s (Banasik and Byczkowski 1996).

Other usefulness of the procedure has been demonstrated by its application for predicting an influence of drainage works in the catchment on flood hydrographs (Banasik 1996). There was a project to activate a part of the catchment, currently hydrological inactive, by constructing a channel. The drainage works would influence on increase of catchment area, contributing to direct runoff formation and sediment yield production, as well as on model parameters. Increase of the hydrological active catchment area of ca 15% i.e., from current one of 62.8 km^2 to 72.1 km^2 would cause increase of peak discharge of ca 20% i.e. form 28.2 m^3/s to 33.9 m^3/s. The increase in volume of runoff hydrograph would be also ca 20%.

Conclusions

The presented lumped parametric approach, incorporated in the SEMO model, seems to be a useful tool for predicting flood hydrographs, as catchment response to heavy rainfall events, from small ungauged catchment for current condition as well as predicted influence of environmental changes i.e. land use and climate changes. This is especially important in the recently often considered regional and national strategies for adaptation to environmental changes.

In the further investigation on the model development special attention should be put on:

- applicability of the Curve Number method in the ungauged catchment in Poland and variability of the method parameter with time of the year and wetting condition of the catchment,
- selection and estimation of the characteristics of IUH, used for computing the model parameters,
- selecting or adapting empirical formulas for estimation of IUH characteristics, to make the model possible for application in ungauged catchments.

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