Modelling of natural water retention in the catchment basin of the Opava river during flood

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Abstract: Palát M. Sr., Palát M. Jr., J. Prudký J. 2013: Modelling of natural water retention in the catchment basin of the Opava river during flood. – *Beskydy*, 6 (2): 109–116

The aim of the analysis involved in the article is to define the significance of separate factors affecting the natural process of retention in the catchment basin thus can assess the priorities in undertaking flood protection. The analysis was based on results achieved by using a new method how to determine water retention in the catchment basin. Resulting dependent variables of effective long-time retention, effective short-time retention, effective total retention and maximum specific runoff for single catchment basins of the Opava river, were evaluated statistically by means of linear regression and correlation analysis, stepwise regression and multiple regression. It is possible to say, that the results achieved may suggest to re-evaluate some established views concerning the role of separate factors influencing natural retention of the landscape. The results of the research testify the fact that in case of densely settled floodplain regions the combined flood protection measures, i.e. as technical and nature friendly ones should be applied. Due to relatively small collection of observations it is not possible to generalize all the conclusions absolutely, nevertheless they have a certain validity at least for the given area.

Keywords: catchment basin, natural water retention, effective short-time and long-time retention, effective total retention, maximum specific runoff, stepwise regression, multiple regression

Introduction

Water belongs to the most important and, at the same time, also to the most widespread natural resources, being the condition of life and an unsubstitutable component of the environment. In connection with a climatic change and methods of management, time and spatial uniformity of its occurrence (which is very affected by the landscape retention capacity) it becomes a considerable problem. Fig. 1 shows the schematic distribution of the total natural retention od catchment basin on the individual components The significance of the landscape retention capacity consists in balancing runoff conditions and reducing dangerous culmination discharges causing otherwise disastrous

impacts on population and the landscape (Palát et al. 2010, Mašíček et al. 2011, Prax et al. 2010).

From the point of view of the landscape retention capacity the organization of land resources and using the landscape play an important role at storm rainfalls unlike long-term precipitation.

The occurrence of storm floods caused by rainfalls of very high intensity, short term duration and limited extent show evidence of the urgency of changes in the structure, use and the landscape arrangement resulting in the support of infiltration and thus increasing the soil retention capacity. For example, Dostál et al. (1997) and Kulhavý, Kovář (2000) dealt with changes in the land resources organization and using the landscape affecting hydrological and water-management conditions within partial drainage areas.

The subject of our research was to evaluate statistically the effects of physical-geographical factors on the retention of water and runoff conditions in parts of the Opava catchment area. Statistical analyses were preceded by the assessment of hydrological conditions of the studied drainage area at the design storm rainfall depending on the actual condition of the landscape cover.

This work is based on the data about precipitations and runoff for 16 particular basins of the Opava river. The data were given to the Research institute of melioration and soil conservation Prague (VÚMOP) by the Czech meteorological institute Praha (ČHMÚ) within the framework of government project "Evaluation of flood situation in July 1997" (Hladný 1998).

Material and methods

Preparation and analyses of source data necessary to express the drainage basin characteristics from the aspect of retention and runoff conditions were carried out in the UNISTAT system. As for hydrological characteristics, potential retention, the flood wave volume, concentration time and culmination discharge were monitored. The significance of particular physical-geographical factors affecting the retention of water and runoff conditions in particular parts of the Opava drainage basin was quantified by the statistical method of multiple regression and correlation analysis.

To determine hydrological characteristics of particular parts of the Opava drainage basin and the subsequent statistical evaluation it was necessary to describe the present condition of the landscape cover, topography, to determine the proportion of hydrological groups of soils in the drainage basin.

To evaluate the significance of physical and geographical factors showing the highest effect on the retention of water and runoff conditions in particular parts of the Opava drainage basin modelled on the design storm rainfall a statistical method was used of the multiple regression and correlation analysis. Calculations were carried out using the UNISTAT calculation system. As dependent variables entered the statistical program, i.e. the drainage basin potential retention, the volume of direct runoff from 1 km², the time of concentration and specific discharge. As for independent variables (physical-geographical factors) affecting dependent variables the significance was assessed of geometrical and geomorphological factors (the thalweg length, the thalweg average inclination, slope area, the slope average inclination), soil characteristics and the landscape cover, the relative area proportion of arable land and permanent grassland, forests, town residential area (Dumbrovský 1998; Chow Ven Te 1964; Mašíček 2010; Patera
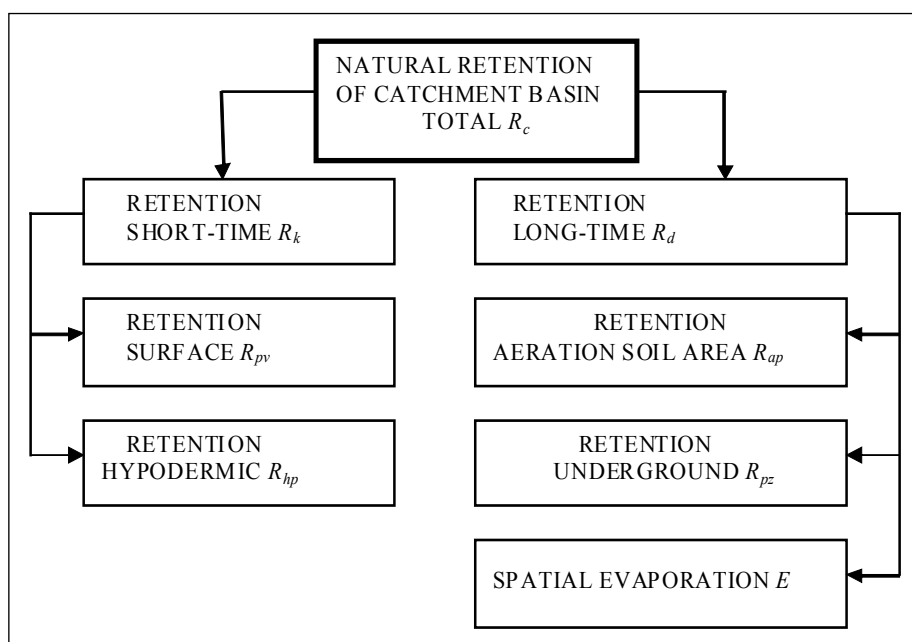

Fig. 1: Schematic distribution of the total natural retention of catchment basin R_c on the individual components.

2002; Prudký 2002, 2003; Prudký, Palát 2006; Spitz et al. 2000; Spitz, Prudký 2001; Trnka 2004, 2007).

For the selection of independent variables – factors important for the quantitative determination of each of the dependent variables mentioned above, the method of step analysis by forward selection was used. The method makes it possible to select independent variables by successive steps from the most significant to the least significant ones. In the final stage, a certain number of independent variables affecting most the size of a respective dependent variable was selected though the step linear regression together with quantification of their effect through regression coefficients.

The significance of the selection was assessed on the basis of the correlation index I. The regression coefficient value of the respective independent variable expresses a change of the dependent variable by this value in case of a change of the respective independent variable by one unit. The closer to one the higher dependence (Mašíček, 2010). For the statistical evaluation of hydrological conditions methods described in papers of Palát et al. (2008), Seger et al. (1998), Palát (1991, 1997) and Palát et al. (2010) were used.

Basic concepts of the process of natural water retention are:

Total natural water retention of catchment basin R_c is water temporarily delayed on the terrain surface, in the soil, in the stream bed, etc. in a natural way, i.e. without retention in artificial water reservoirs and in inundations. It can be further divided into five sub-components:

● *surface retention R_{pv}*, containing water delaying on the surface and in the stream bed,

● *hypodermic retention R_{hp}*, containing subsurface water moving in the immediate layer below the surface without reaching the water table,

● *retention in the aeration soil area R_{ap},* consisting of water trapped in the capillaries of the unsaturated soil area and water infiltrating into the groundwater,

● underground retention R_{pz}, consisting of infiltration water increasing of groundwater supplies,

● spatial evaporation E, i.e. evaporation from the soil surface area with transpiration (evaporation by the plants) and interception (evaporation of the precipitation that sticks to the surface of the plant).

Results and discussion

Basic data of 16 sub-basins of the river Opava selected for statistical analysis is given in Tab. 2. They are all river basins in the closing profiles as they were measured during the flood in 1997 by hydrometric stations of the Czech Hydrometeorological Institute.

For effective long-time retention for single catchment basin R_{def} [mm] a following relation was derived:

$$R_{def} = -464.7 + 0.1066\ \Sigma H'_i + 4.79 F'_{OP} + 7.30\ F'_{TTP} + \ 5.54 F'_L - 1.117 s_t \qquad \text{[mm]} \quad (1)$$

where: $\Sigma H'_i$ – average depth of flood precipitation in catchment basin [mm], F'_{OP} – relative area proportion of arable land [% area of the basin],

F'_{TTP} – relative area proportion of permanent grasslands [% area of the basin],

F'_L – relative area proportion of forests [% area of the basin],

s_t – average terrain slope [angular degrees].

In this relation (1) more or less the expected characteristics (independent variables) are represented such as surface proportion of forest, grassland and field crops, the average slope of the terrain and of course the average depth of the flood precipitation in the catchment basin. If we make a step back in stepwise regression and reduce the value of F-value to 0.25 or 0.30, other characteristics enter into the relation such as catchment area F in km², stream length L in km, coefficient of catchment basin shape ω, and percentage of other areas (paved areas from hydrological point of view) with infamous rapid drainage. Due to the area occupied in the basin (often 3-5%) they are not negligible. An interesting characteristic (though not unexpected) is the coefficient of previous precipitation API (Kulhavý, Kovář 2000).

For effective short-time retention of catchment basin R'_{kef} [mm] the following initially relation was derived:

$$R_{kef} = 309.204 + 1.11\ H'_{max} - 2.36\ F'_{OP} - 4.48\ F'_{TTP} - \ 2.40\ F'_L - 8.33\ s_t \qquad \text{[mm]} \quad (2)$$

where: H'_{max} - average maximum depth of flood daily precipitation in catchment basin [mm · day⁻¹],

F'_{OP}, F'_{TTP}, F'_L a s_t see relation (1)

Again, in step backward in step linear regression and setting the F-value to 0.9 or 1.0 we gain a further 8 characteristics, where in addition to recurring $H'_{max}, F'_{TTP} F'_L$ a s_t and we can see a further characteristic of surface drainage percent of

the basin area F'O, then the length of the stream L in km, index of previous precipitation API and shape coefficient of catchment basin ω. Compared to the relationship remained unclassified arable land expressed as a percent of the basin area F'_{OP}.

Since the total size of the effective natural retention of catchment basin R_{cef} expressed in mm is the sum of effective long-term and short-term retention of catchment basin it can be determined by the sum of equations (1) and (2) modified in the expression:

$$R_{cef} = -155.496 + 0.1066\ \Sigma H'_i + 1.11\ H'_{max} + 2.43\ F'_{OP} + 2.82\ F'_{TTP} + 3.14\ F'_L - 9.447\ s_t$$
$$[\text{mm}]\quad (3)$$

where: $H'_i, F'_{OP}, F'_{TTP}, F_L, s_t$ see relation (1),

H'_{max}, see relation (2).

Again it is clear that for the wider relationship, as described above, it would be needful to include into both relationships the further already investigated and mentioned characteristics. It is not the aim of this work to treat the creation of new, expanded relationships even if it was not impossible and the authors of this post have them at their disposal. However, they consider that the disclosure of these enhanced relations will only make this work crowded. It will only be done for the maximum specific runoff from the catchment area q_{max} as an example.

Maximum specific runoff from the catchment basin q_{max} in l·s⁻¹·km⁻² is determined by the relation:

$$q_{max} = 3284 + 5.147 H'_{max} - 30.968\ F'_{OP} - 53.26\ F'_{TTP} - 34.729\ F'_L + 37.746\ s_t \qquad [\text{l·s}^{-1}\text{·km}^{-2}]\quad (4)$$

where: H'_{max}, see relation (2),

$F'_{TTP}, F'_{OP}, F'_L, s_t$ see relation (1).

Tab. 1: *Overview of the dependent and independent variables entering the statistical analysis*

Dependent variables Independent variables	Effective long-time retention for single catchment basin R_{def}	Effective short-time retention for single catchment basin R_{kef}	Maximum specific runoff for single catchment basin q_{max}
Coefficient of catchment basin shape ω	NO	NO	YES
Catchment basin area	YES	YES	YES
Stream length L	YES	YES	YES
Flood precipitation height	YES	YES	YES
Coefficient of previous precipitation API	YES	YES	YES
Effective long-time retention of catchment basin	NO	NO	YES
Effective short-time retention of catchment basin	NO	NO	YES
Maximum depth of daily precipitation	YES	YES	YES
Proportion of arable land in catchment basin	YES	YES	YES
Proportion of permanent grasslands in catchment basin	YES	YES	YES
Proportion of the other types of land in catchment basin	YES	YES	YES
Proportion of hydrological group of soils B	YES	YES	YES
Proportion of forests in catchment basin	YES	YES	YES
Average terrain slope in catchment basin	YES	YES	YES
Proportion of drainage in catchment basin	YES	YES	YES

Even this relationship can be imagined in a rather widespread form of a step backwards in step linear regression analysis. Determining the F-value 1.8 to 1.5, compared with the original ones, other terms appears such as the catchment area F in km², then F'_{OSP} the percentage of other areas in the basin, coefficient of previous precipitation API, proportion of hydrological group of soils B and the proportion of drainage in catchment basin.

Maximum specific runoff from the catchment basin q_{max} v l·s⁻¹·km⁻² in extended form with seven independent variables determined by the relation:

$$Q_{max} = 1221 + 8.86\ F_{OSP} - 47.64\ F_{TTP} - 0.331 F +$$
$$+ 2.35\ API + 1.636\ \Sigma H'_t + 35.44\ s_t - 36.25 B$$
$$(5)$$

The above mentioned equations were derived for the floods of summer extreme long-standing regional rainfalls in the Opava catchment basin. The equation is valid for the following ranges of values independent variables: average amount of flood precipitation $\Sigma H'_t$ from 167.6 mm to 686.0 mm, maximum daily precipitation H_{max} from 46.7 mm to 198.8 mm, proportion of the area of arable land in catchment basin F'_{OP} from 0% to 53.51%, permanent grasslands F'_{TTP} from 0.81% to 26.55% and forests F'_L from 23.38% to 98.07%, the average terrain slope from 4.9° to 11.3° (Prudký 2003).

Conclusion

Based on the evaluation of the statistical analysis of floods caused by extreme regional rainfall in July 1997 in Opava River basin it is possible to draw conclusions on the significance of the various factors affecting the size of the retention capacity of the landscape. These factors can be simultaneously viewed as the hydrological characteristics of the catchment or landscape. For a broader generalization of these results a larger set of observations should be statistically evaluated.

Results of statistical analysis can be summarized in the following findings:

a) The magnitude of the effective retentions of catchment basin R_{def}, R_{kef}, R_{cef} and maximum specific runoff from the catchment basin q_{max} most affects either the average depth of flood precipitation in catchment basin Σ H'i, (for variables R_{def}, R_{cef}) or the average maximum depth of the flood daily rainfall in the catchment H 'max (for variables R_{kef}, R_{cef}, q_{max}).

b) Higher relative area proportion of arable land F'_{OP} increases the effective long-term retention of the catchment basin R_{def} and

Tab. 2: Basic data on the Opava river sub-basins selected for statistical analysis

Catchment basin serial number	Data bank number	Name of hydrometric station in the conclusion profile of catchment basin	Stream name	Number of hydrological catchment basin	Catchment basin area [km²]
1.	2851	Mnichov	Černá Opava	2-02-01-003	51.46
2.	2590	Železná	Střední Opava	2-02-01-008	54.28
3.	2612	Karlovice	Opava	2-02-01-011	151.29
4.	2630	Krnov	Opava	2-02-01-037	370.50
5.	2650	Krnov	Opavice	2-02-01-056	175.98
6.	2660	Opava	Opava	2-02-01-089	929.65
7.	2680	Malá Morávka	Bělokamenný potok	2-02-02-006	16.50
8.	2690	Rýmařov	Podolský potok	2-02-02-016	50.67
9.	2700	Velká Šťáhle	Moravice	2-02-02-021	168.06
10.	2701	Valšov	Moravice	2-02-02-027	243.28
11.	2711	Mezina	Černý potok	2-02-02-048	92.16
12.	2723	Slezská Harta pod nádrží	Moravice	2-02-02-055	464.31
13.	2730	Kružberk pod nádrží	Moravice	2-02-02-065	566.67
14.	2740	Branka	Moravice	2-02-02-077	716.33
15.	2741	Jakartovice	Hvozdnice	2-02-02-080	31.08
16.	2750	Děhylov	Opava	2-02-03-023	2039.11

reduces the maximum specific runoff from the catchment basin.

c) Higher relative area proportion of permanent grasslands in the catchment basin F'_{TTP} increases the effective long-term retention of catchment basin R_{def} and reduces the maximum specific runoff from the catchment basin q_{max}.

d) Higher relative area proportion of forests F'_L increases the effective long-term retention of catchment basin R_{def}, and reduces the maximum specific runoff from catchment basin q_{max}.

e) With a higher average terrain slope of catchment basin s_t the effective long-term retention catchment basin R_{def} adversely reduces, the maximum specific runoff from the catchment basin q_{max} adversely increases and the effective short-time retention of catchment basin R_{kef} reduces.

f) Higher index value of the previous precipitation API adversely reduces the effective long-time retention R_{def} and adversely increases the maximum specific runoff from the catchment basin q_{max}.

g) With a higher relative abundance of other surfaces (hard surfaces) the maximum specific runoff for catchment basin q_{max} increases and the effective long-term retention R_{def} reduces.

h) With a higher proportion of hydrological group of soils B (percolation 0.06 to 0.12 mm/min) the effective long-time retention increases and the maximum specific runoff from catchment basin q_{max} reduces.

i) A higher value of effective long-time retention for catchment basin R_{def}, reduces the maximum specific runoff from the catchment basin q_{max}.

j) Effective long-time retention of catchment basin R_{def}, that expresses what proportion of torrential or regional rain is the catchment basin harmlessly able to delay and distract (i.e. what proportion is trapped in the soil and evaporates) has a positive effect on reduction of flood flow as well as on harmful overflowing. However, in landslide areas it may cause landslides.

k) The influence of effective short-time retention of catchment basin R_{kef}, containing water delays on the ground, in the bed of the stream and hypodermic water is not unambiguous for positive transformation floods. During large floods it is usually a harmful component of overall retention, as it may cause harmful water overflow. For smaller floods, however, it can help to reduce flood discharge.

l) The significance of individual factors expressing the hydrological characteristics of the catchment basin referred to in points from a) to e) can be judged by the size of their coefficients in the regression equations.

m) The positive effect of arable land emerged from the state of all crops in the first half of July 1997, when particularly root system of cereals and fodder had already been developed enough to support the infiltration of water.

It is also necessary to mention briefly the quantitative process of natural water retention of the catchment basin, as it has great practical significance. Due to a certain ambiguity effect of effective short-time retention of catchment basin R_{kef}, (see point h), the effective long-time retention R_{def} for monitoring the effects of retention was selected. The coefficient of effective long-time retention ρ_{def} is the ratio between the value of effective long-time retention and flood volume of precipitation.

Values ρ_{def} vary for different sub-basins as follows: 0.22 for the river Moravice under Kružbersk reservoir, 0.23 for the river Opava at Karlovice and in Krnov, 0.24 for Bělokamenný stream in the Morávka, 0.25 for Černá Opava in Mnichov and Opava, Opava, 0.26 for Opavice in Krnov 0.27 for Moravice profile Slezská Harta under the reservoir and Střední Opava in Železné, 0.28 for Černý potok in Mezina, 0.32 for Opava in Děhylov, 0.35 for Moravice in Velká Šťáhle, 0.36 for Moravice in Valšov, 0.37 for Hvozdnice in Jakartovice and 0.48 for Podolský potok in Rýmařov.

Long-time effective retention, expressed in millimeters, has the following values in the same order: 67.7, 143.5, 10.9, 85.9, 169.5, 100.1, 78.8, 120.2, 83.7, 130 , 1, 83.6, 78.7, 129.9, 127.1, 62.6 and 134.9.

Acknowledgements

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