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Tomáš Mašíček, František Toman, Milan Palát

USING THE STEP LINEAR REGRESSION AT THE ANALYSIS OF HYDROLOGICAL CONDITIONS OF THE FRYŠÁVKA DRAINAGE BASIN

Summary

Problems of the retention capacity of the landscape and related runoff conditions are at present, at the time of the occurrence of frequent storm floods, a topical problem. Our research was aimed at the evaluation of effects of physical-geographical factors on hydrological conditions of the Fryšávka River drainage area occurring in the southern part of the Žďárské vrchy CHKO (Žďárské Hills Protected Landscape Area) depending on the current position of the landscape cover. Preparation and analyses of source data were carried out in ArcGIS 9.2 in the ArcView software product by means of the set of integrated software applications ArcMap, ArcCatalog and ArcToolbox. To determine hydrological conditions at the absence of hydrometric observations a method was used of numbers of runoff curves CN in a modification of the DesQ-MAXQ deterministic episode model. Based on hydrological characteristics, potential retention was monitored as well as the volume of flood wave, concentration time and peak discharge. Hydrological modelling was carried out on a design storm precipitation with the return period of 100 years. The significance of physical-geographical factors affecting the landscape retention capacity and runoff conditions was quantified by the statistical method of multiple regression and correlation analysis on the set of 95 partial drainage areas of the studied region. The analyses were carried out using the UNISTAT system. The method makes possible to select independent variables by gradual steps from most important down to least important. Finally, using the step linear regression, a certain number of independent variables was selected mostly affecting the size of a respective dependent variable together with the quantification of their operation through regression coefficients. Results achieved could be used at the implementation of preventive measures resulting in increasing the retention capacity of partial drainage areas, which served for the registration of major runoffs from a unit area.

Key words: runoff curve number, correlation index, landscape cover, DesQ–MAXQ model, runoff, regression and correlation analysis, retention

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) become a considerable problem. The significance of the landscape retention capacity consists in balancing runoff conditions and reducing dangerous peak discharges causing otherwise disastrous impacts on population and the landscape. 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 and 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 effects of physical-geographical factors on the retention of water and runoff conditions in parts of the Fryšávka 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. Modelling the hydrological conditions was carried out for the design storm rainfall of 100-year return period.

The area of the Fryšávka drainage basin is situated in the Vysočina Region, the central part of the Bohemian-Moravian Upland being the territorial part of the Žďárské vrchy Protected Landscape Area. The significance of the selected drainage area is emphasized by a fact that already at the end of the 70s of the last century Professor Vaníček (University of Agriculture, Brno) prepared an interdisciplinary team of experts, which began to monitor the Fryšávka drainage basin within the newly formulated World Conservation Strategy as its regional model. Thanks to this research, the landscape of the Fryšávka drainage basin unknown till then was included into the "Green book of 44 notable European landscapes" published in 1978 by IUCN (at present World Conservation Union) [Trnka, 2004, 2007].

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 ArcGIS 9.2 program, the ArcView software product by means of the set of integrated software applications ArcMap, ArcCatalog and ArcToolbox. All operations occurring in the GIS environment resulted in the creation of outputs entering the DesQ-MAXQ model [Hrádek, Kuřík, 2001] serving for the calculation of hydrological characteristics of small drainage basins (Mašíček, 2010b). As for hydrological characteristics, potential retention, the flood wave volume, concentration time and peak discharge were monitored. The significance of particular physical-geographical factors affecting the retention of water and runoff conditions in particular parts of the Fryšávka drainage basin was quantified by the statistical method of multiple regression and correlation analysis.

With respect to the size of the monitored area (66.45 km^2), the DesQ-MAXQ model character based on the method of numbers of runoff curves CN and the character of storm rainfalls affecting significantly smaller areas than regional precipitation the Fryšávka drainage basin has to be divided to particular parts of an area < 10 km^2. According to a procedure described in a paper of Mašíček (2010b), a boundary was laid down of the whole drainage basin by editing tools in the ArcGIS program, a watershed divide limiting a partial drainage basin in the form of an “open book” with a right and left side of the slope (subbasin LP) and partial drainage basins with one slope (subbasin S) and their thalweg (valley line). Data on areas of slopes of partial basins and lengths of their thalwegs were automatically generated in the data model “geodatabase**.mdb*”, where a subbasin and thalweg were originally generated.

To determine hydrological characteristics of particular parts of the Fryšávka 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 (HSP) in the drainage basin and to evaluate each of subbasins by a CN number and the coefficient of surface roughness.

On the basis of the descriptive characteristics of the monitored area, analyses could be carried out in the ArcGIS program environment resulting in the determination of the mean value of numbers of runoff curves CN and the slope surface roughness of partial basins and the mean inclination of slopes and thalwegs. At the conclusion of analyses in the ArcGIS program, calculation was carried out of the area proportion of particular categories of the landscape cover and hydrological groups of soils within each of the partial basins. The procedure of data preparation, processing and analyses in the ArcGIS program environment are given in a paper of Mašíček [2010a].

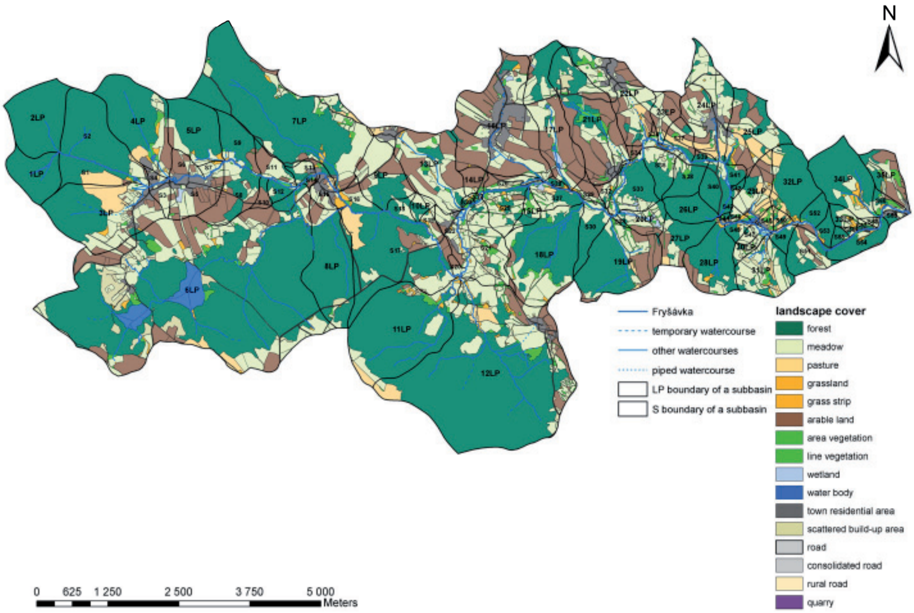
The database of basic geometrical and geomorphological characteristics (thalweg length, average inclination of the thalweg, slope area, average slope inclination), characteristics of soils and the landscape cover (runoff curve number CN, roughness, proportion of particular types of land and hydrological groups of soils) of partial basins entering the DesQ-MAXQ model and statistical analyses served as the output of descriptive characteristics and analyses carried out in the environment of the ArcGIS program according to procedures given by Mašíček [2010a].

For the calculation of hydrological characteristics (potential retention, flood wave volume, concentration time, peak discharge) the DesQ-MAXQ model according to Hrádek and Kuřík [2001] was used. The DesQ-MAXQ (DesignQ-MAXQ) model is a deterministic episodic model with partly divided input parameters, average for the left and right slopes of the basin. The model based on a modification of the method of numbers of runoff curves CN is utilizable for the calculation of maximum discharges caused by storm rainfalls in non-monitored profiles of small drainage basins up to 10 km^2, where direct hydrometric measurements are not available [Hrádek, Kuřík, 2001]. For the calculation of hydrological characteristics, values are entered into the model of maximum daily precipitation totals with the *n*-year return period for places on the area of the Czech Republic [Šamaj et al., 1985]. In our case, it referred to a maximum 24-hour precipitation with the 100-year return period of the nearest station of the monitored area, namely Nové Město na Moravě. Complete description of the methodology of the DesQ-MAXQ hydrological model is given by Hrádek and Kuřík [2001].

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 Fryšávka drainage basin modelled on the design storm rainfall with the 100-year return period a statistical method was used of the multiple regression and correlation analysis. Calculations were carried out using the UNISTAT statistical package. As dependent variables, partly modified resulting values of basic output quantities from the DesQ-MAXQ model entered the statistical program: the drainage basin potential retention, the volume of direct runoff from 1 km^2, 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 CN runoff curve number, roughness, the area proportion of arable land and permanent grassland, forests, town residential area, hydrological groups of soils (HSP B, HSP C and HSP D) [Janeček et al., 2007]. To select 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 chooses independent variables by successive steps from most significant to least significant. In the final stage, a certain number of independent variables affecting most the size of a respective dependent variable was selected through the step linear regression together with quantification of their effect through regression coefficients. 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 unity, the higher dependence is [Mašíček, 2010a]. For the statistical evaluation of hydrological conditions the methods described in the papers of Palát et al., [2008], Seger et al. [1998] and Palát [1991, 1997] were used.

RESULTS AND DISCUSSION

A map of the landscape cover of the studied area with division to partial drainage basins including their numerical indication is given in Fig. 1. The Fryšávka drainage basin consists of 35 partial catchments in the form of an "open book" with a right and left side of the slope (subbasin LP) and 60 partial catchments with one slope (subbasin S). The most important area of the Fryšávka drainage basin is occupied by forest stands (52.79%), permanent grasslands (TTP) (23.93%) and arable land (12.44%). As for hydrological groups of soils, soil groups B, C and D are represented.



Source: Orthophotomap, © Geodis, s.r.o. Provided by the Land Register Office for the South-Moravian Region. ZM 1:10 000, © ČÚZK. Registr půdy (LPIS), © Ekotoxa Opava. Forest typological map, © ÚHUL Brandýs nad Labem. ZABAGED – hypsography, © ČÚZK.

Figure 1. A map of the division of the Fryšávka drainage basin to subbasins on the basis of the landscape cover map [Mašíček, 2010a]

The retention potential of the drainage basin and related runoff conditions were evaluated on the basis of fundamental hydrological characteristics (output quantities from the DesQ-MAXQ model), namely the drainage basin potential retention, concentration time and peak discharge with the flood wave volume as characteristics of a theoretical flood wave caused by the design precipitation of a storm rainfall H_{1d100} (1-day maximum precipitation in mm with the return period N = 100 years), Nové Město na Moravě station (78.1 mm).

With respect to a fact that the maximum discharge and volume of a flood wave, as basic characteristics to evaluate runoff conditions, were calculated in absolute values [$m^3.s^{-1}$] or [m^3], and thus it would not be possible to compare them due to the different size of partial catchments, these output quantities were related to a unit area of 1 km^2. Maximum discharge was expressed as specific discharge [$m^3.s^{-1}.km^{-2}$] and the flood wave volume as the direct runoff volume from an area of 1 km^2 [$m^3.km^{-2}$].

At the classification and evaluation of output quantities from the DesQ-MAXQ model quantile distribution of determined ranges of their values was carried out into several classes of roughly the same size within the ArcGIS program. The categorization of partial basins into classes at each of the evaluated quantities (hydrological characteristics of subbasins) is always demonstrated in the form of map outputs in Figures 2 to 5.

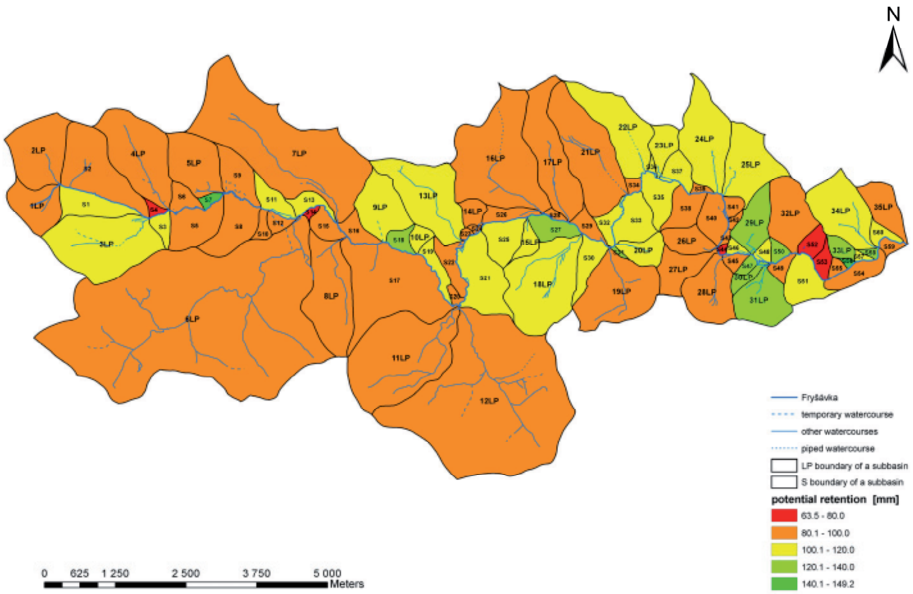


Figure 2. A map of potential retention in the Fryšávka drainage basin [Mašíček, 2010a/b]

A map demonstrating the potential retention [mm] of partial catchments of the area is given in Fig. 2. The determination of potential retention expressing the maximum possible amount of water that can be potentially caught by the basin results from the landscape cover and the proportion of hydrological groups of soils (HSP) in each of the partial catchments expressed collectively by the number of a runoff curve CN. Values of potential retention were determined within the range from 63.5 (S4) to 149.2 mm (S7) [Mašíček, 2010b].

Volumes of direct runoff (Fig. 3) were noted ranging from 11 800 (subbasins S7 and S56) to 33 167 $m^3.km^{-2}$ (S4).

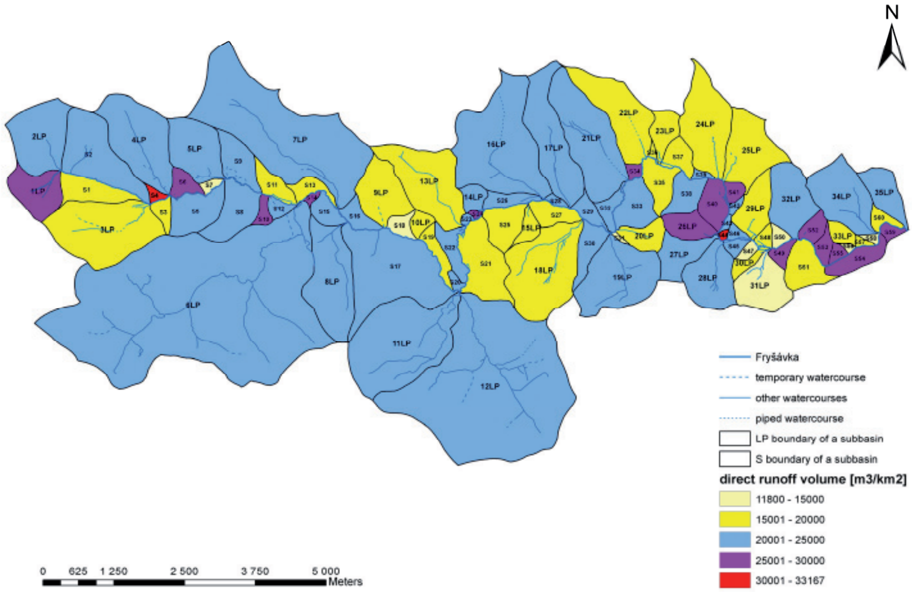


Figure 3. A map of the volume of direct runoffs in the Fryšávka drainage basin [Mašíček, 2010a]

Concentration times of particular slopes of partial catchments are noted in Fig. 4. The shortest time of concentration, 27 minutes, was noted at subbasin S43 and the longest time, 304 minutes, at the left slope of the partial catchment area 12LP.

As evident from Fig. 5, values of specific discharges at the design precipitation H_{1d100} ranged at particular subbasins from 0.61 (8LP) to 7.57 $m^3.s^{-1}.km^{-2}$ (S44).

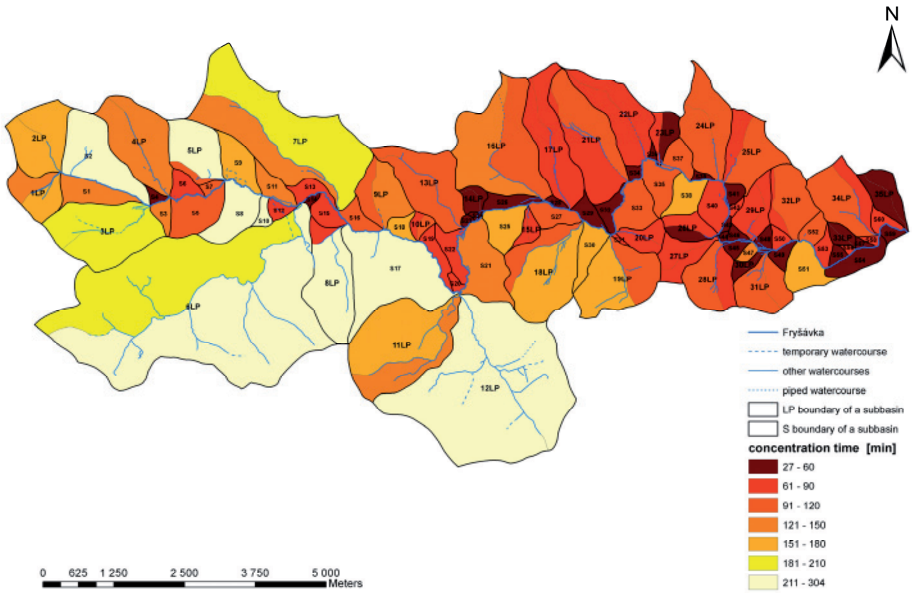


Figure 4. A map of concentration times in the Fryšávka drainage basin [Mašíček, 2010a]

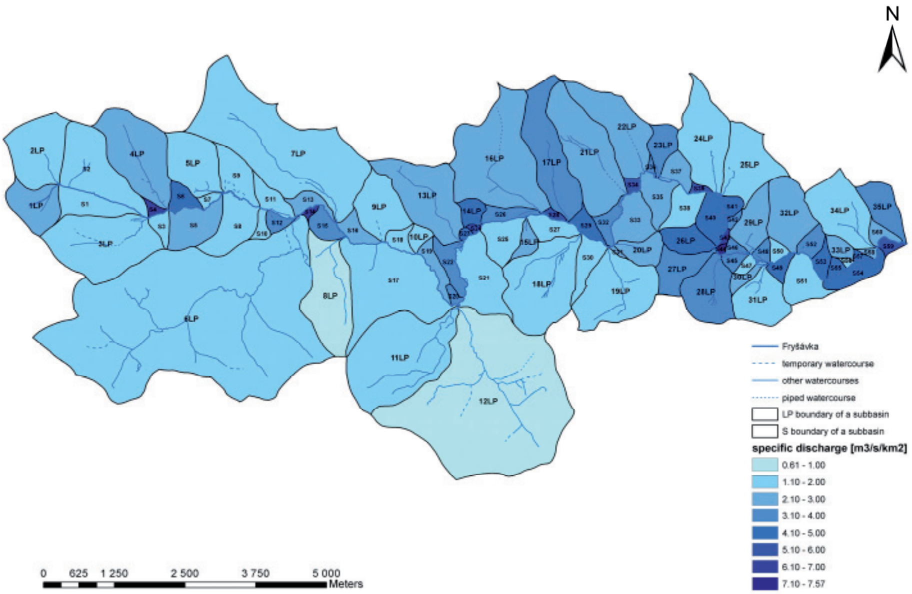


Figure 5. A map of specific discharges in the Fryšávka drainage basin [Mašíček, 2010a]

The survey of dependent and independent variables with notations (symbols) entering the statistical analyses carried out for the set of 95 partial catchments of the Fryšávka River is given in Table 1.

Table 1. An overview of dependent and independent variables entering the statistical analysis

Dependent variable / Independent variable	Potential retention *A*	Direct runoff volume from 1 km^2 O_{pH}	Specific discharge Q_{SPEC}	Concentration time T_C
Thalweg length $D_{ÚDOL}$	NO	NO	YES	YES
Average slope of the thalweg $S_{ÚDOL}$	NO	NO	YES	YES
Slope area P_{SV}	NO	NO	NO	YES
Average slope inclination S_{SV}	NO	NO	YES	YES
Average roughness *N*	NO	NO	YES	YES
Runoff curve number *CN*	NO	NO	YES	YES
Relative area proportion of arable land P_{OP}	YES	YES	YES	YES
Relative area proportion of permanent grasslands P_{TTP}	YES	YES	YES	YES
Relative area proportion of forests P_L	YES	YES	YES	YES
Relative area proportion of town residential area P_I	YES	YES	YES	YES
Relative area proportion of the hydrological group of soils B HSP_B	YES	YES	YES	YES
Relative area proportion of the hydrological group of soils C HSP_C	YES	YES	YES	YES
Relative area proportion of the hydrological group of soils D HSP_D	YES	YES	YES	YES

(Mašíček, 2010a)

Considering the CN characteristics, which affect types of the area use and soil characteristics this independent variable was intentionally excluded from the step regression analysis (based on aspects mentioned above), in order to be possible to quantify better the proportion of other characteristics on dependent variables. Elimination of CN values from the step regression analysis was carried out for those dependent variables where very high tightness was demonstrated resulting from the character of their calculation. It referred to potential retention (correlation index 0.9967) and the direct runoff volume (correlation index 0.9953). Elimination of other independent variables from particular regression analyses starts from logical relationships with dependent variables.

Information on the elimination of independent variables from regression analyses in given in Table 1.

For potential retention *A* [mm] the following relation was derived:

$$A = 72.90 + 0.86\, P_{TTP} - 0.46\, P_{I} + 0.13\, P_{L}, \quad (1)$$

where:

P_{TTP} – relative area proportion of permanent grasslands [% area of the subbasin],

P_{I} – relative area proportion of the town residential area [% area of the subbasin],

P_{L} – relative area proportion of forests [% area of the subbasin].

Relation (1) shows that the dependent variable values *A* increases with the relative proportion of permanent grasslands and forests and, vice versa, it decreases with the relative area proportion of the town residential area. Correlation index is 0.8811.

For the direct runoff volume from 1 km^2 O_{pH} [m^3.km^{-2}] the following relation was derived:

$$O_{pH} = 27869.57 - 200.27\, P_{TTP} + 131.46\, P_{I} - 26.83\, P_{L}, \quad (2)$$

The equation (2) shows that the dependent variable value O_{pH} decreases with the relative area proportion of permanent grasslands and forests and, vice versa, it increases with relative area proportion of the town residential area. Correlation index is 0.8726.

For the concentration time T_C [min] the following relation was derived:

$$T_C = 187.69 + 35.15\, P_{SV} - 3.38\, S_{SV} + 20.31\, N - 3.09\, CN - 1.94\, S_{ÚDOL}, \quad (3)$$

where:

P_{SV} – slope area [km^2],

N – average roughness,

$S_{ÚDOL}$ – thalweg average slope [%].

Equation (3) shows that the value of dependent variable T_C increases with the slope area size and average roughness and decreases depending on the average slope inclination, value of the runoff curve number CN and the thalweg average slope. Correlation index is 0.8236.

For specific discharge Q_{SPEC} [$m^3.s^{-1}.km^{-2}$] the following relation was derived:

$$Q_{SPEC} = -22.51 + 0.35\ CN + 0.09\ S_{SV} - 0.02\ P_L - 0.94\ HSP_B, \qquad (4)$$

where:

CN – runoff curve number,
S_{SV} – average slope inclination [%],
HSP_B – average area proportion of the hydrological group of soils B [% area of the subbasin].

According to the relation (4) the dependent variable value Q_{SPEC} increases with the runoff curve number CN and the average slope inclination and, vice versa, it decreases with the relative area proportion of HSP B and forests. Correlation index is 0.8478.

Equations (1) to (4) were derived for runoff conditions in the Fryšávka river drainage basin simulated for the design storm rainfall with the return period of 100 years. On the basis of results of a statistical analysis for 95 partial catchments potential retention *A* is most of all factors affected by the relative area proportion of permanent grasslands, town residential areas and forests. Through the comparison of coefficients of given factors in the regression equation referring to their significance we can come to a conclusion that the relative area proportion of permanent grasslands with a regression coefficient 0.86 is the most important factor, in negative sense relative area proportion of the town residential area with a regression coefficient -0.46 and again, in positive sense relative area proportion of forests with a regression coefficient 0.13. Prudký (2002), who dealt with the calculation of water retention in partial drainage basins of the Opava River for a flood caused by extreme long regional rainfalls in 1997, assessing the significance of the most important factors influencing the course of water retention in the landscape, found also very favourable effects of permanent grasslands and forests on the total effective retention. According to the author, this finding is very important from the aspect of a possibility to create conditions of increasing the drainage basin resistance to floods because in case of grassing (grass regeneration) it refers to a factor which can be easily affected by human activities. This fact can be also related to the improvement of conditions of water infiltration into soil at storm rainfalls and thus to contribute to increasing the landscape retention potential.

The volume of direct runoff from an area of 1 km^2 O_{pH} is most affected (as well as in case of potential retention, of course, to the contrary) by the relative area proportion of permanent grasslands with a regression coefficient -200.27, further the relative area proportion of town residential areas with a regression coefficient 131.46 and third the relative area proportion of forests with a regression coefficient -26.83. The unity of factors mostly affecting the direct runoff volume and potential retention are given by the principle of calculations of these quantities as mentioned by Janeček et al. (2007).

The concentration time T_C is mostly (positively) affected by the slope area (regression coefficient 35.15) and average roughness (20.31), on the contrary, the time of concentration shortens with the increasing slope inclination (-3.38), CN value (-3.09) and the average thalweg slope (-1.94).

Specific discharge Q_{SPEC} is mostly affected (in terms of reducing its size) by the relative area proportion of HSP B (regression coefficient -0.94) and the relative area proportion of forests (-0.02) and, on the contrary, increasing the specific discharge is mostly affected by the runoff curve value CN (0.35) and the average slope inclination (0.09). Also in case of extreme long regional rainfalls, as proved by Kříž [2003] and Prudký [2002], forest stands occupy an important position among other factors (independent variables) showing the highest effect on reducing the specific discharge.

Regression equations (1) and (2) show that according to regression coefficients, the relative area proportion of grasslands has the highest effect on potential retention and the direct runoff volume. Dependence, although not too close, between grasslands and independent variables mentioned above, is evident from Figures 6 and 7 and respective correlation indexes (I).

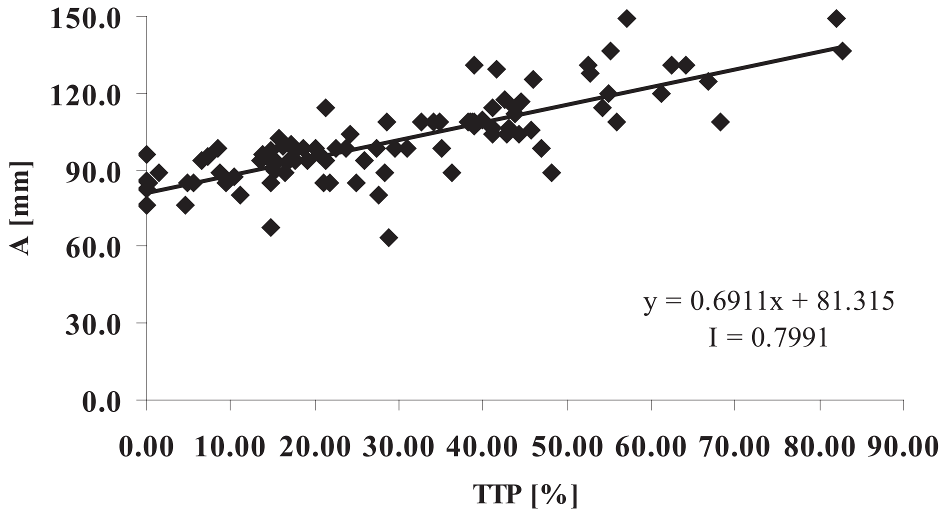


Figure 6. Dependence of potential retention on grasslands (TTP) [Mašíček, 2010a]

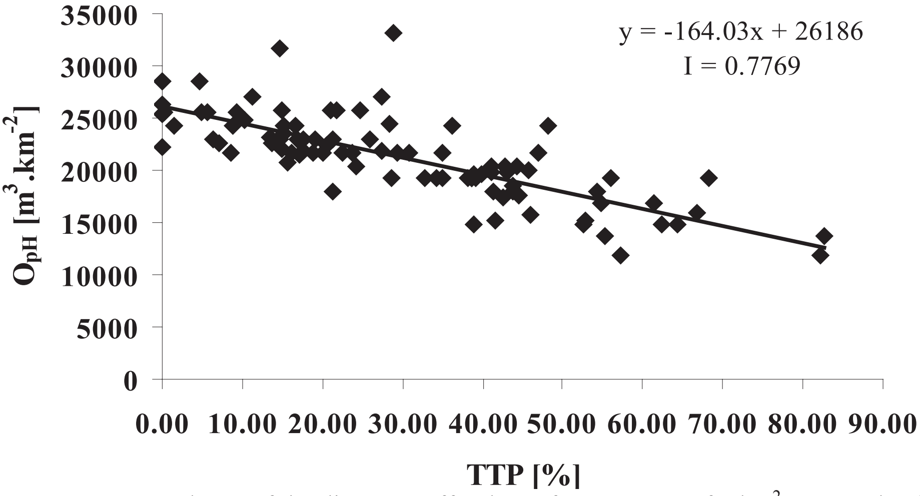


Figure 7. Dependence of the direct runoff volume from an area of 1 km^2 on grasslands (TTP) [Mašíček, 2010a]

In case of the concentration time significant dependence was demonstrated only for the slope area. The tightness of their dependence including the correlation index is demonstrated in Fig. 8.

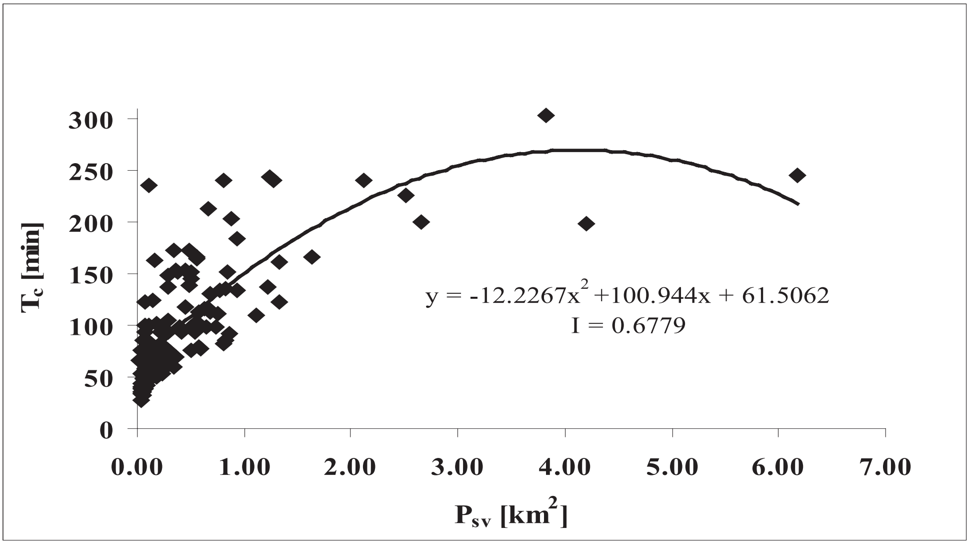


Figure 8. Dependence of the concentration time on the slope area [Mašíček, 2010a]

Close relationships between dependent variables and an independent variable, as presented in Figures 6, 7 and 8 (potential retention and grasslands (TTP), direct runoff volume and grasslands, concentration time and slope area) in addition to highly close relationships between potential retention and the direct runoff volume with the CN values (correlation indexes 0.9967 and 0.9953) resulting from the character of their calculation were not proved. Also results of regression analyses, i.e. values of correlation indexes of particular relations (equations (1) to (4)) do not bear evidence of their excessive tightness, which can be given by the diversity of physical-geographical characteristics in particular subbasins, as commented by Patera et al. [2002]. Facts mentioned above correspond also with the expression of Šercl [2009] that the effect of particular physical-geographical factors in the process of creating flood is very often conditioned and, therefore, it is questionable to detach their effects and to evaluate them separately. Effect conditionality of particular physical-geographical factors acting during the flood creating is given by their antagonistic or affirmative effect, affecting the retention capacity of the landscape and its drainage conditions, such as species composition of lands, hydro-pedological characteristics, slope conditions and more.

CONCLUSION

The aim of our research was to evaluate hydrological conditions of the Fryšávka drainage basin for a design storm rainfall with the 100-year return period and by means of the multiple regression and correlation analysis to quantify the significance of physical-geographical factors affecting retention potential, the direct runoff volume from an area of 1 km^2, concentration time and specific discharge. With respect to the size of the studied area, the character of storm rainfall and a method used at hydrological analyses (DesQ-MAXQ model), hydrological characteristics were evaluated separately for each of the partial catchments. In this way, parts of the drainage basin with reduced retention capacity and the increased creation of surface runoff could be identified. Results of regression analyses refer to the complexity and interconnections of the effect of many factors on the retention capacity and runoff conditions in parts of the Fryšávka drainage basin. In spite of the complexity of effects, there are factors influencing most hydrological characteristics mentioned above. These factors are affected by human activities. These findings could be used at the subsequent proposal of the whole set of measures resulting in the improvement of runoff conditions, namely particularly in partial catchments, which were identified as potentially most risk from the aspect of retention capacity and runoff (for example contour, strip or conservation tillage, grassing, afforestation). Thus, possible preventive measures should be particularly oriented in this direction.

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Ing. Tomáš Mašíček, Ph.D.
Mendel University in Brno
Zemědělská 1
613 00 Brno
Czech Republic
tel.: +420 545 132 479
tomas.masicek@mendelu.cz

Prof. Ing. František Toman, CSc.
Mendel University in Brno
Zemědělská 1
613 00 Brno
Czech Republic
tel.: +420 545 132 406
frantisek.toman@mendelu.cz

Prof. Ing. Milan Palát, CSc.
Mendel University in Brno
třída Generála Píky 2005/7
613 00 Brno
Czech Republic
tel.: +420 545 136 313
milan.palat@mendelu.cz