Extreme Runoff Formation in the Krkonoše Mts. in August 2002

Miroslav TESAŘ[1], *Miloslav ŠÍR*[1], *Ľubomír LICHNER*[2] *and Jaroslav FIŠÁK*[3]

[1]*Institute of Hydrodynamics of the ASCR, Praha, Czech Republic;* [2]*Institute of Hydrology SAV, Bratislava, Slovakia;* [3]*Institute of Atmospheric Physics of the ASCR, Praha, Czech Republic*

Abstract: The role of the water movement and retention during extreme runoff formation was demonstrated in the Modrý Důl catchment (Krkonoše Mts., Czech Republic). A cyclone, which moved from Hungary to Poland, caused an extreme rainfall (120 mm) and subsequent extreme runoff in August, 2002. The precipitation, discharge, air and soil temperatures, tensiometric pressure, and soil moisture were recorded. The maximum retention capacity of the catchment was evaluated (70 mm). Depending on the actual retention capacity and the precipitation amount, two situations were recorded: (1) the precipitation amount lower than the actual retention capacity where the precipitation was fully absorbed in the catchment and the discharge in to the stream was not influenced by rain, (2) the precipitation amount higher than the actual retention capacity where the precipitation caused a saturation excess of the soil profile, generating extreme outflow into the stream. Neither the soil cover in the catchment or fluvial deposits along the Modrý potok stream were able to retain the extreme rain and inhibit the catastrophic flood.

Keywords: mountain hydrology; runoff formation; extreme rain; soil-water retention

Several crucial factors contribute to the runoff formation; the rainfall amount, the actual water retention capacity of a catchment, and hydrophysical properties of the soil and subsoil (Kutílek 1978; Kutílek & Nielsen 1994; Kostka & Holko 1997). Hydrophysical properties of the soil cover are influenced by organic substances (Kutílek & Nielsen 2007), soil morphology (Lin *et al.* 2005), and soil crust (Kutílek 2003). The possibility of macropore flow and instability-driven flow in the soil cover should be taken into account (Tesař *et al.* 2004b). To understand better the role of water in the land/atmosphere interactions and the role of the land/atmosphere interactions in regional and global climates, spatial and temporal observations of water in the soil surface can be more comprehensively analysed, utilising the knowledge of the soil science (Nielsen *et al.* 1996).

Heavy rain in August 2002 was caused by a cyclone of Mediterranean origin, which moved from Hungary to Poland over the eastern part of the Czech Republic (Řezáčová *et al.* 2005; Brázdil *et al.* 2006; Řezníčková *et al.* 2007). Orographic reinforcement accompanying the crossing of the

Supported by the Academy of Sciences of the Czech Republic, Research Plan No. AV0Z20600510 and Project No. 1QS200420562, by Czech Science Foundation, Projects No. 205/05/2312 and 205/06/0375, by the Ministry of Environment of the Czech Republic, Project No. SP/1a6/151/07, and by the Scientific Grant Agency VEGA, Project No. 2/6003/26.

cyclone over the Bohemian mountains caused a precipitation exceeding the typical water retention capacity of 60 to 90 mm in the mountainous catchments in Bohemia (Doležal *et al.* 2004). An extreme level of the runoff was consequently generated in the mountainous areas, causing catastrophic floods in a larger part of Bohemia.

Our study is devoted to the analysis of the runoff formation in the mountainous catchment Modrý Důl (Krkonoše Mts., Czech Republic), taking into account the soil water movement and water retention.

EXPERIMENTAL CATCHMENT AND METHODS

The Modrý Důl catchment area is situated in the eastern part of the Krkonoše Mts. (crystalline complex of the Krkonoše Mts., Czech Republic). The drainage area of this catchment area is 2.62 km^2. The highest point is Studniční hora Mt. (1554 m a.s.l.) and the minimum elevation of the closing profile is 1010 m a.s.l. The coordinates of the closing profile are 15°42'49"E and 50°42'48"N. There are deposits of fluvial or fluviodeluvial sediments along the Modrý potok brook. The soil types are Humic Podzols and Lithic Leptosols (WRB 1998) with a very thin humic layer while deeper soil of about 60 cm can be found in the bottom part of the valley. The soil profile under the dwarf pine stand in the area of Studniční hora Mt. is described in Table. 1. This basin represents the original spruce forest in the lower part, and artic-alpine tundra with dwarf pine covers the upper part above the timberline. The climatic conditions correspond to the characteristics of the cold humid climatic zone. The mean annual precipitation ranges from 1200 to 1300 mm. The mean air temperature in July is 12.1°C. The maximum total retention of water in the basin is about 70 mm. Detailed characteristics of the basin are presented in the article of Tesař *et al.* (2004a). Physical geographic situation of the Modrý Důl catchment is depicted in Figure 1.

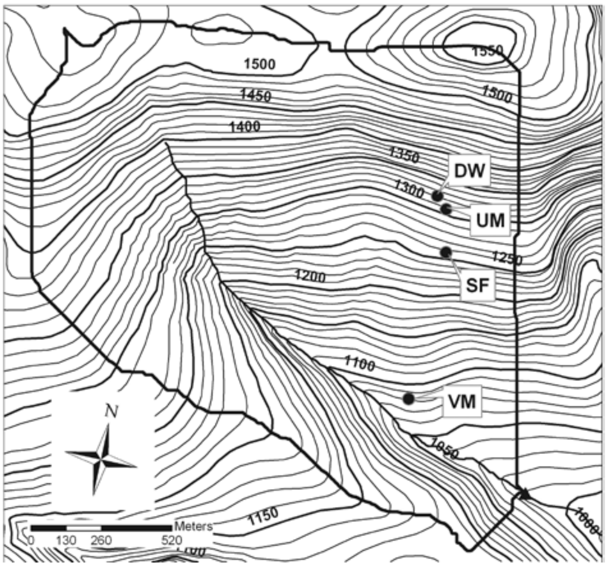

Figure 1. Physical geographic situation of the Modrý potok experimental catchment and monitoring stations located in four localities differing in vegetation cover (DW – sporadic dwarf pine bushes, UM – upper mountain meadow above the spruce forest margin, SF – spruce forest, VM – valley mountain meadow below the forest margin)

An automatic meteorological station recording meteorological data was placed on Studniční hora Mt. (1554 m a.s.l.). Automatic monitoring stations were installed at four localities in differing positions and types of the vegetation cover: mountain meadow in a valley below the forest margin, spruce forest, mountain meadow above the spruce forest margin, sporadic dwarf pine bushes (Figure 1). In every locality, the following data were measured and recorder at 20 minutes intervals: the rain intensity, the air temperature at two levels (5 and 200

Table 1. Soil profile under dwarf pine stand in the area of Studniční hora Mt. (1450 m a.s.l.)

Depth (cm)	Horizon	Profile description
0–10	A_0	surface raw freshly damp horizon, sharply separated from the subsoil
10–16	A_1	darkly fuscous sandy clayey soil, loose, row fresh, slightly gravelled, moderate coloured conversion underneath
16–24	A_2	greyish whitish sandy clayey soil slightly gravelled
24–35	B_1	darkly grey sandy clayey soil middle gravelled, unconfined
35–55	B_2	grey sandy clayey soil middle gravelled, damp, mild coloured conversion underneath
> 55	C	lightly ochre clayey sandy hard gravelled, damp to wet

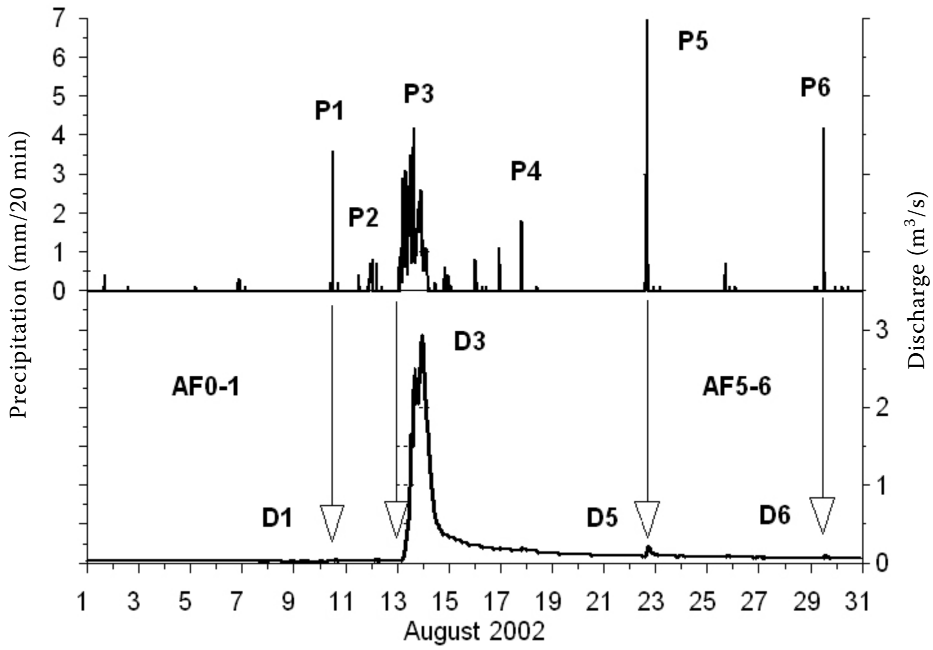

Figure 2. Precipitation and discharge in the closing profile of the Modrý Důl catchment in August 2002

cm above the soil surface), the soil temperature in three depths (15, 30, 60 cm), the tensiometric pressure in the soil cover in four depths (15, 30, 45, 60 cm), and the soil moisture in two depths (15, 60 cm). Tensiometric pressure was measured with the help of water tensiometers equipped by a vacuum gauge on the top of a plastic tube. The soil moisture was determined using a method based on the high frequency permittivity measurement (Lichner *et al.* 2004). The moisture values above 50% (vol.) were biased due to the sensor nonlinearity. The discharge at the closing profile (1010 m a.s.l.) was continuously recorded using an ultrasonic device.

The catchment retention capacity was derived as the difference between the cumulative precipitation and the cumulative runoff. The Runoff is the discharge in the closing profile of a catchment divided by the catchment area.

RESULTS

The extreme runoff event in the Krkonoše Mts. during the summer of 2002 (marked as P3 in Fig-

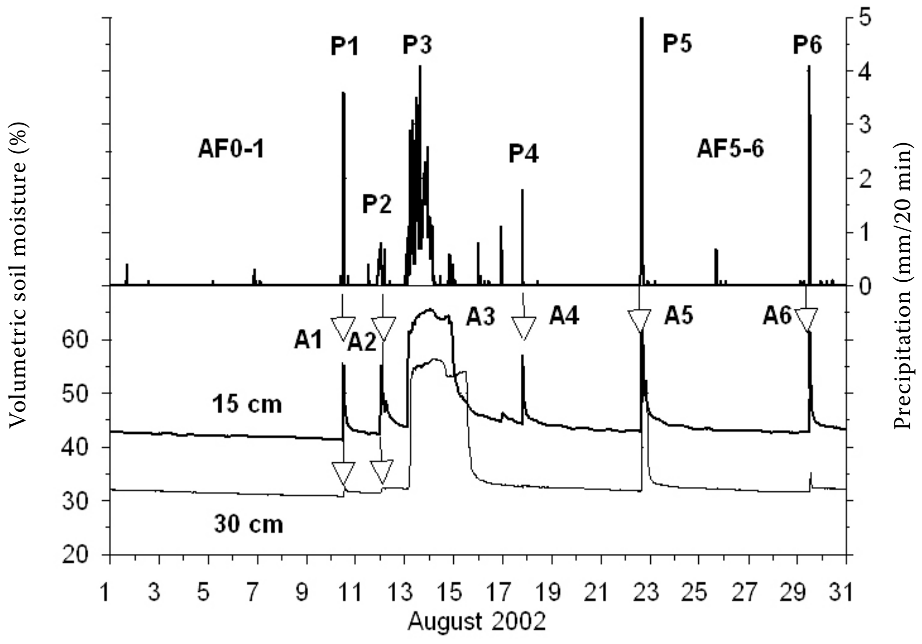

Figure 3. Precipitation and soil moisture in the depth of 15 cm (thick line) and 30 cm (thin line) in dwarf pine forest in August 2002

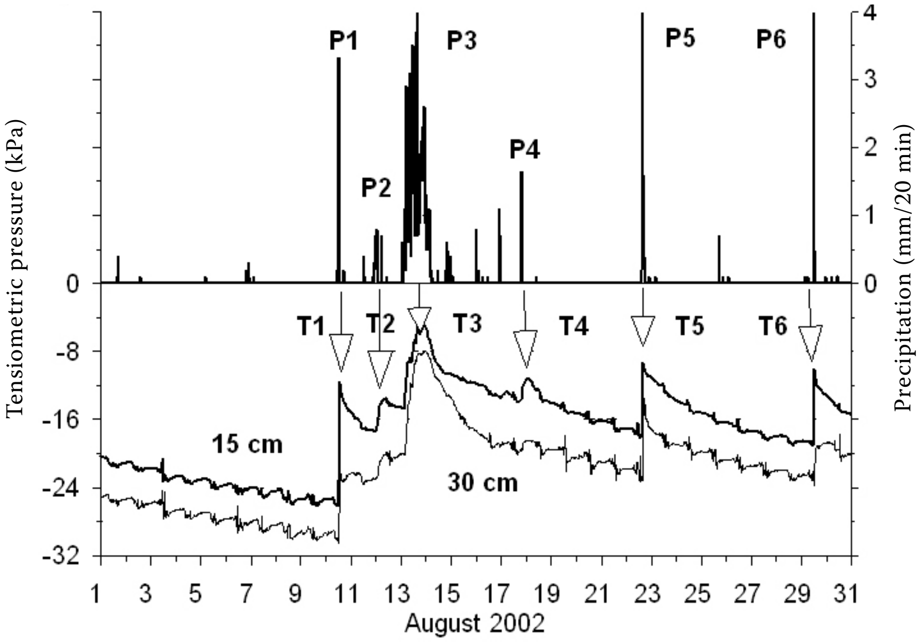

Figure 4. Precipitation and tensiometric pressure in the depth of 15 cm (thick line) and 30 cm (thin line) in dwarf pine forest in August 2002

ures 2–6) was caused by rains associated with the cyclone which moved from Hungary to Poland in the period of August 11–14. The cold occlusion connected with a low pressure brought the precipitation to the area of the Czech Republic during the noon hours of 11th August. The precipitation area spread gradually in the northwest direction. The catchment of Modrý Důl in the Krkonoše Mountains was hit by a very intensive long-lived precipitation during 13th and 14th August. The cyclone moved afterwards over Poland and dissipated.

The frontal line was well pronounced and the temperature gradient at the 850-hPa level was rather high (more than 10°C). Behind the cyclone, which came to the Central Europe from Mediterranean, the high-pressure ridge widened. The temperature gradient of the occlusion front connected with the cyclone was fortified by the fact that above Poland, the warm and humid air from the Mediterranean met the cold and also humid air coming from the Barents Sea over Scandinavia. The reinforcement of the temperature contrast and the

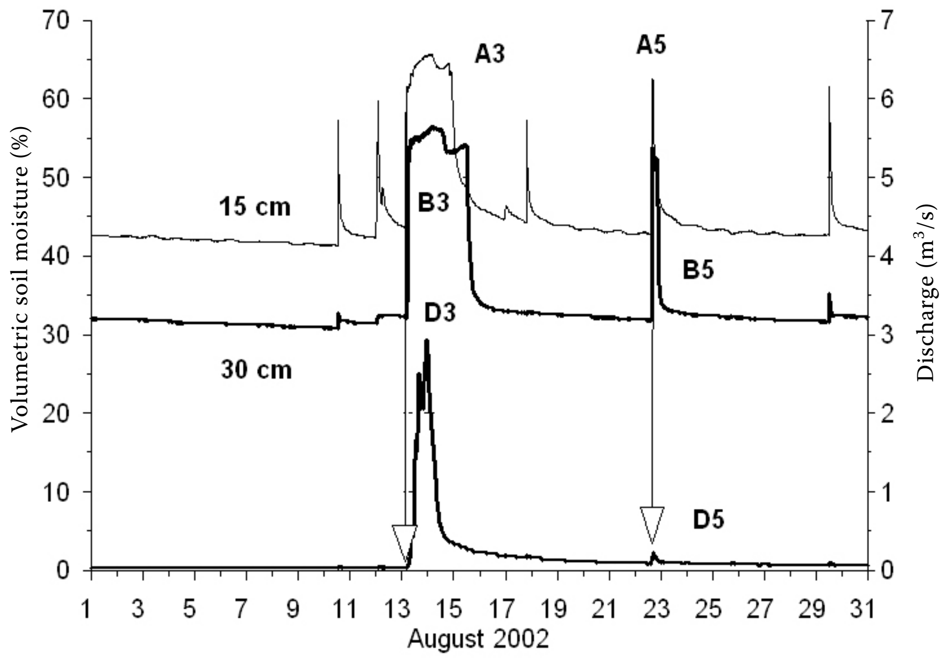

Figure 5. Soil moisture in the depth of 15 cm (thin line), 30 cm (thick line) in dwarf pine forest and discharge in the closing profile of the Modrý Důl catchment (thick line) in August 2002

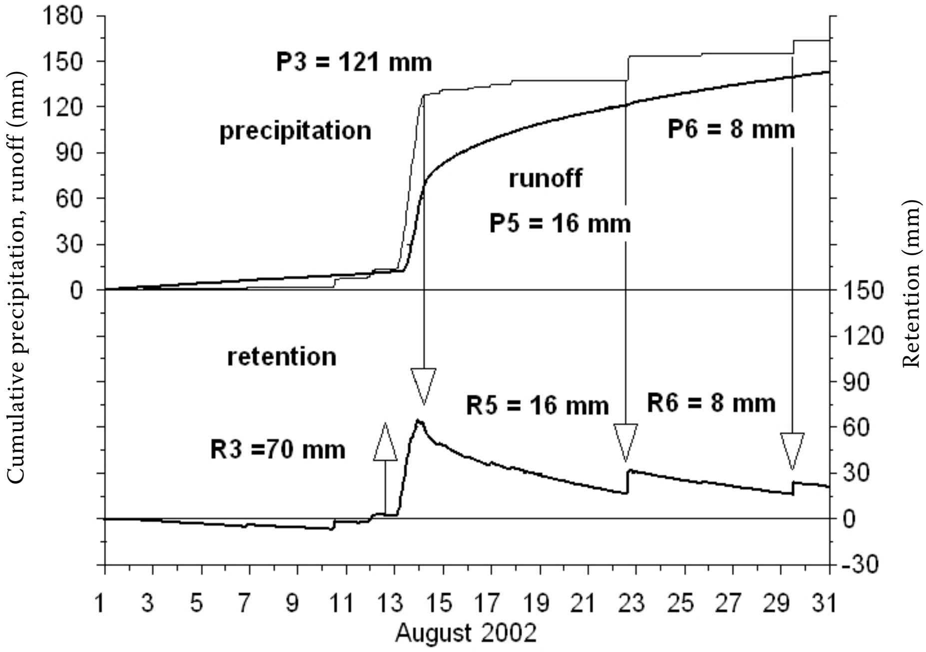

Figure 6. Cumulative precipitation (thin line), cumulative runoff (thick line) and water retention in the Modrý Důl catchment in August 2002

air moisture probably caused the extreme rainfalls in the area. The attenuation of the temperature contrast and the formation of high-pressure ridge led to the weakening of precipitation.

In Figure 2, the discharge measured in the closing profile of the Modrý Důl catchment is related to the precipitation. P3 and P5 denote the rain events which caused the perceptible discharge peaks D3 and D5. The P3 rain was caused by the cyclone described above. The response of the soil moisture to the rain is demonstrated in Figure 3. The soil moisture in the depth of 15 cm reacts markedly (A1 to A6) on precipitations P1 to P6, but the soil moisture in the depth of 30 cm (B3, B5) reacts markedly on events P3 and P5 only (Figure 3). Similarly, the reaction of the tensiometric pressure on the rain is demonstrated in Figure 4. The tensiometric pressure in the depth of 15 cm reacts markedly (T1 to T6) on precipitations P1 to P6, but the tensiometric pressure in the depth of 30 cm reacts markedly on events P1, P3, P5, and P6 only (Figure 4). It means that the soil layer of

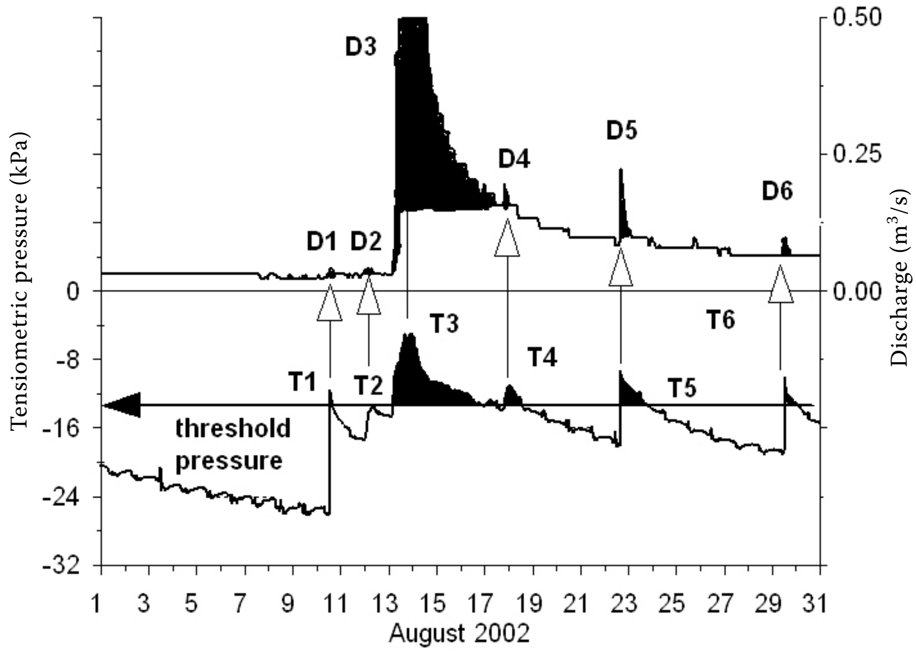

Figure 7. Discharge in the closing profile of the Modrý Důl catchment and tensiometric pressure in the depth of 15 cm in dwarf pine forest in August 2002

15 to 30 cm fully absorbed precipitations P1, P2, P4, and P6.

In event D3, the heavy rain P3 = 121 mm caused the soil oversaturation (A3, B3) lasting for three days and the discharge peak with the maximum of 3 m^3/s. In the event D5, the small rain P5 = 16 mm caused a short (3 h) soil oversaturation (A5, B5) and a small discharge peak with maximum of 0.1 m^3/s. The role of the soil saturation excess is shown in Figure 5. Two events, D3 and D5, show the dependence of the discharge on the duration of the soil saturation excess and the rain amount. This figure shows that the discharge peak formation is markedly influenced by the water retention in the soil profile.

The catchment retention was derived as a difference between the cumulative precipitation and the cumulative runoff (Figure 6). The runoff is the discharge in the closing profile of a catchment divided by the catchment area. The maximum catchment retention during precipitation P3 can be estimated at 70 mm (R3 in Figure 6). The precipitation reached about 120 mm at the moment of maximum retention (P3 in Figure 6). During the rainfall, a surface runoff occurred because the retention capacity of the surface layer of 20 mm was strongly exceeded (high moisture A3 in Figure 5). This capacity can be estimated as a difference between the maximum total retention of 70 mm during the extreme precipitation event and 50 mm during maximum precipitation which does not cause any surface runoff (Tesař *et al.* 2004a).

DISCUSSION

In the runoff formation analysis, the key problem is to separate the infiltrating precipitation into the part directly flowing in the soil and the part that is stagnant on the soil surface. This stagnant water may be a source of the surface runoff if the soil surface is sloped. Another separation may occur of the flowing water into the soil – the part flowing vertically and the part flowing in the direction of the sloping soil horizons or the subsoil layer. The sloping flow in a horizon near the soil surface is called the subsurface flow (Tesař *et al.* 2004b). It may be also called exfiltration or run-on. This occurs in other regions with sand dunes and high water tables as well as very high precipitation rates. A new approach for improving the process conceptualisation in hillslope hydrology is presented in the article of Weiler and McDonnel (2004). According to the articles cited above, the runoff formation will be analysed from the point of four processes: (1) partition of rainwater into infiltration and surface runoffs, (2) hydrodynamics of the soil water movement and water regime, (3) pathways transporting water from the catchment area into the stream, (4) hydrograph formation in the closing profile of a catchment.

Partition of rainwater into infiltration and surface runoff

In the Modrý Důl catchment approximately 20 mm of the whole retention capacity of 70 mm can be influenced by the presence of the vegetation cover (Tesař *et al.* 2004a). These values are in good accordance with the published data concerning other mountainous areas in Bohemia (Doležal *et al.* 2004). Simultaneous Hortonian surface flow and subsurface stormflow in situation D3 is probable because the maximum retention capacity of the soil profile was highly exceeded.

Hydrodynamics of the soil water movement and water regime

Following the tensiometric pressure, different hydrodynamic mechanisms act in the soil water movement. If the tensiometric pressure is lower than some threshold values, an unsaturated flow (described by Richards' equation) can be expected. On the other hand, the instability driven flow can occur if the tensiometric pressure is higher (Tesař *et al.* 2004b). The threshold value of the tensiometric pressure splitting these two hydrodynamics mechanisms is depicted in Figure 7. This threshold is about –14 kPa in the depth of 15 cm in the Modrý Důl catchment. In the periods when the pressure is higher than the threshold value, the rate of the unsaturated flow in soil is very slow. This testifies to the small value of the discharge from the catchment (Figure 7). In the periods when the pressure is lower than the threshold value (marked by black areas T3, T4, T5, T6 in Figure 7), the rate of the instability driven flow is sufficiently high to produce a strong discharge peak (marked by black areas D3, D4, D5, D6 in Figure 7). In situations T1 and T2, only a small overrun of this threshold invoked the instability driven flow producing very small but fully evident discharge peaks D1 and D2. This means that the pressure threshold splitting both hydrodynamic mechanisms was very sharp (Figure 7).

The article by Tesař *et al.* (2001) demonstrates that two alternative types of the soil-water movement (the diffusion type flow in drier soils and the instability-driven flow in soils with a higher soil-moisture content) correspond to two phases of the soil water regime – the accumulation phase and the percolation phase. In the course of the percolation phase, the infiltrating rain water flows through the soil causing an increment of the soil-water content to maximum value which is characteristic for the actual soil (A1 to A6 peak values of about 60% in Figure 3). During the accumulation phase, rainwater accumulates in the soil practically without flowing through (AF0-1, AF5-6 in Figures 2 and 3). The sequence of the percolation and the accumulation phases elucidates the "fill and spill" hypothesis described in the articles by Tromp-van Meerveld and McDonnell (2006a, b).

Pathways transporting water from the catchment area into the stream

In the percolation phase, two water pathways are possible. (1) If a high permeable subsoil layer exists, the rainwater infiltrates vertically through the soil into the subsoil, the subsoil layer acting as a pathway. (2) If the subsoil is impermeable, the rainwater flows through the sloped soil surface layer to the stream. In both cases, the discharge wave contains a mixture of new water (infiltrating rain) and the old one (soil water stored in the soil or subsoil layer originating from a series of antecedent rainfalls). The old water is pushed out from the soil or subsoil mainly during the instability driven flow. In this situation, a large volume of water flows through the soil; therefore on the hydrological scale, the instability driven flow causes a rapid growth of the rising hydrograph limb (Tesař *et al.* 2004b). The sudden rise of the tensiometric pressure in a deeper soil layer can be considered as the proof of the instability driven flow (T1, T3, T5 and T6 in Figure 4).

In the accumulation phase, two water pathways can be identified. (1) If a high permeable subsoil layer exists, water outflows from the subsoil layer and forms the base flow into a stream. (2) If the subsoil is impermeable, the rainwater moves in the unsaturated and sloped soil horizon to the stream. In both cases, the water in the stream is mainly new (originating from the causal rainfall). In this situation, the outflow empties the porous reservoir (soil cover or subsoil layer) so that the discharge into a stream decreases during the time and the falling hydrograph limb is generated (between T3 and T5 in Figure 4, between B3 and B5 in Figure 5).

Hydrograph formation in the closing profile of the catchment

Figures 2 to 6 clearly illustrate the mechanism of the hydrograph formation. In the percolation phase (D3 and D5 in Figure 5), the perceptible discharge wave into the Modrý potok brook is produced by water percolating vertically from the oversaturated soil profile into the highly permeable and sloped subsoil layer and transported through this layer to the stream. The falling hydrograph limb is concave (D3 in Figure 5) and the cross section of the Modrý Důl catchment is V-shaped (Figure 1). This means that the discharge in the closing profile is a direct transformation of the outflow from the sloped soil or subsoil layer. It can be supposed that the water retention capacity of fluvial deposits along the Modrý potok stream is negligible compared to the amount of the extreme rain P3.

In the percolation phase, the rising hydrograph limb grows very quickly and its duration is short; perhaps a few hours (D5 in Figure 2) or days (D3 in Figure 2). It is due to the rapid vertical transport of water through the soil into a very permeable subsoil layer caused by overfilling the soil with rainwater. The greatest value of the discharge in the stream is reached during a rain and a simultaneous instability driven flow (D3 in Figure 5). There after, the soil water content and, consequently, the runoff decreases, and therefore, the accumulation phase begins and the falling hydrograph limb is generated. Its source is the water stored mainly in the porous subsoil layer. The runoff decreases according to the decline of the water content in the subsoil layer (Figure 5, between D3 and D5).

CONCLUSIONS

The soil water movement and retention play the leading role in the runoff formation in Modrý Důl catchment. The maximum retention capacity of the catchment (mainly soil cover) reaches about 70 mm. It can be supposed that the retention capacity of fluvial deposits along the Modrý potok stream is negligible compared to the amount of the extreme rain (120 mm). The concave shape of the falling hydrograph limb indicates that the maximum retention capacity of the catchment studied is rather small. It means that the extreme runoff in August 2002 was generated by the saturation excess caused by the extreme rain. Neither the soil cover in the catchment or the fluvial deposits along the Modrý potok stream were capable to catch the rain water and prevent the catastrophic flood.

References

Brázdil R., Dobrovolný P., Kakos V., Kotyza O. (2006): Historical and recent floods in the Czech Republic: causes, seasonality, trends, impacts. NATO Science Series. Vol. 67. Springer, Dordrecht, 247–259.

Doležal F., Kvítek T., Soukup M., Kulhavý Z., Tippl M. (2004): Czech highlands and peneplains and their hydrological role, with special regards to the Bohemo-Moravian Highland. IHP/HWRP-Berichte. Vol. 2. Koblenz, 41–56.

Kostka Z., Holko L. (1997): Soil moisture and runoff generation in small mountain basin. Publication of the Slovak Committee for Hydrology. Vol. 2. Slovak Committee for Hydrology, Bratislava.

Kutílek M. (1978): Soil Science in Water Management. SNTL/ALFA, Praha. (in Czech)

Kutilek M. (2003): Time-dependent hydraulic resistance of the soil crust: Henry's law. Journal of Hydrology, **272**: 72–78.

Kutílek M., Nielsen D.R. (1994): Soil Hydrology. Catena Verlag, Cremlingen-Destedt.

Kutilek M., Nielsen D.R. (2007): Interdisciplinarity of hydropedology. Geoderma, **138**: 252–260.

Lichner Ľ., Holko L., Čipáková A., Šír M., Tesař M. (2004): New devices and techniques for hydrological observation. In: Webb B. (ed.): Proc. Conf. Hydrology: Science & Practice for the 21st Century. Volume 1, British Hydrological Society – International Conference Imperial College, London, 447–452.

Lin H., Bouma J., Wilding L.P., Richardson J.L., Kutílek M., Nielsen D.R. (2005): Advances in Hydropedology. Advances in Agronomy, **85**: 1–89.

Nielsen D.R., Kutilek M., Parlange M.B. (1996): Surface soil water content regimes: Opportunities in soil science. Journal of Hydrology, **184**: 35–55.

Řezáčová D., Kakos V., Kašpar M., Müller M., Pešice P., Sokol Z. (2005): A comparison of flood precipitation in August 2002 with historical extreme precipitation events from the Czech territory. Atmospheric Research, **77**: 354–366.

Řezníčková L., Brázdil R., Tolasz R. (2007): Meteorological singularities in the Czech Republic in the period 1961–2002. Theoretical and Applied Climatology, **88**: 179–192.

Tesař M., Šír M., Syrovátka O., Pražák J., Lichner L., Kubík F. (2001): Soil water regime in head water regions – observation, assessment and modelling. Journal of Hydrology and Hydromechanics, **49**: 355–375.

Tesař M., Šír M., Dvořák I.J., Lichner Ľ. (2004a): Influence of vegetative cover changes on the soil water regime in headwater regions in the Czech Republic. IHP/HWRP-Berichte. Vol 2. Koblenz, 57–72.

Tesař M., Šír M., Pražák J., Lichner Ľ. (2004b): Instability driven flow and runoff formation in a small catchment. Geologica Acta, **2**: 147–156.

Tromp-van Meerveld H.J., McDonnell J.J. (2006a): Threshold relations in subsurface stormflow 1. A 147 storm analysis of the Panola hillslope. Water Resources Research, **42**: W02410.

Tromp-van Meerveld H.J., McDonnell J.J. (2006b): Threshold relations in subsurface stormflow 2. The fill and spill hypothesis. Water Resources Research, **42**: W02411.

Weiler M., McDonnel J.J. (2004): Virtual experiments: a new approach for improving process conceptualization in hillslope hydrology. Journal of Hydrology, **285**: 3–18.

WRB (1998): World Reference Base for Soil Resources. World Soil Resources Reports. Vol. 84. FAO, Rome.

Corresponding author:

Ing. Miroslav Tesař, CSc., Ústav pro hydrodynamiku AV ČR, v.v.i., Pod Paťankou 30/5, 166 12 Praha 6, Česká republika

tel.: + 420 388 426 801, e-mail: tesarihas@iol.cz