Physical Characteristics Affecting the Infiltration of High Intensity Rainfall into a Soil Profile

Ladislav KOUTNÝ, Jaromír SKOUPIL and David VESELÝ

Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic

Abstract

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Flooding caused by intensive precipitation has been in the centre of attention of both general public and scientists. From the flood risk management perspective, an integrated approach to catchment management is necessary, in particular with regards to water retention capacity. Our research has been focused on the high intensity rainfall, its short duration, and an adequate infiltration capacity into the soil profile in the upper parts of the catchment, the same as on the impact of soil characteristics such as moisture content and suction pressure, in particular. The five-year research period in two sub-catchments – Červík A and B – in the Beskydy Mts. enabled monitoring of about 300 events, and seventy of them with higher rainfall intensity were selected for further analysis. The analysis showed that the retention of an intensive precipitation was positively dependent on the instantaneous soil moisture and suction pressure. A continuous monitoring of these properties made it possible to quantify the potential runoff and the tendency to cause flooding. The analysis also showed an inverse situation in terms of the relationship between retention (and consequently runoff), suction pressure, and soil moisture content. It was therefore necessary to eliminate these by proposing suitable preventive bio-technical measures.

Keywords: flood; variable source areas; soil retention capacity; soil moisture; suction pressure

For centuries humans have been studying the laws of nature in order to improve their understanding of natural processes. Despite our advances in this area and the scientific and technical progress, in most cases we have not been successful in changing the natural processes. Due to the greater medialization and increased urbanization of exposed sites, the negative impacts of climatic changes, for example flooding, appear more dramatically pronounced.

From the historical point of view, flooding has occurred periodically. The latest argument in connection with the climate change is global warming. However, even this argument has not been accepted unequivocally. It has been opposed e.g. by the hypothesis of the natural development of climate change during the glacial period.

Due to these uncertainties in our understanding the climatic changes, the only option left with regards to managing flood risk is to monitor the potential for flood generation and to undertake precautionary measures at such scale that would be acceptable both in terms of funding and the level of flood risk and hazard.

Extreme precipitation events and infiltration

As mentioned in the introduction, the floods (as well as droughts, for example) cannot be completely avoided Koutný (2003), but their damaging impact on properties and on human lives can be reduced (Patera & Votruba 2004). However, there are many approaches to flood mitigation, including biotechnical measures in the catchments through to purely engineering flood defence. These usually include the promotion of the precipitation retention in the soil profile particularly in agricultural and forested areas (Herynek 2000).

In this article, we would like to highlight the importance of the retention of short-term extreme precipitation particularly in the upper parts of catchments in headwaters, the regulation of which falls within the category of biotechnical flood mitigation measures. Although these measures can reduce flood peak by only a limited percentage (scientists typically quote 5–10%) with a degree of uncertainty, it is important to give them due consideration in flood risk management (Koutný & Skoupil 2011).

In order to better understand the retention potential of the upper parts of catchments, it is necessary to understand how flooding is generated at first place. In recent years, a model of variable source areas has been used for this purpose (Šach *at al.* 2000). The model uses the principle of expansion and retraction of the variable source areas and hence also of the hydrographic network during the flood. This can be expressed by the following equation:

$$RO = CI + OF + SSSF + BF \quad (1)$$

where:
RO – discharge at the catchment outlet
CI – runoff caused by precipitation falling directly into the watercourse (negligible)
OF – surface runoff
SSSF – hypodermic discharge
BF – base flow

Hypodermic discharge forms 50–80% of the total discharge. In order to assess the potential for increasing water retention in the upper parts of a catchment and the effect on flood generation and flood peak, the above mentioned model has to be considered, focusing on the hypodermic discharge (Šach *et al.* 2000). The ability of the soil profile to retain water, i.e. the potential soil retention capacity, can be explained as such amount of water that the soil can hold for a prolonged period after infiltration. However, the soil's potential to instantaneously infiltrate high intensity rainfall is also important.

The retention capacity and the infiltration potential can generally be influenced by:
– improvements of soil structure by increasing the content of organic matter, optimizing the density and type of plant roots and soil texture;
– optimizing the type of land cover with sufficient percentage of soil covered by vegetation. This increases not only the surface roughness, resulting in slower surface runoff, but it also helps prevent soil loss and destruction of the soil surface structure caused by the dynamic effect of raindrops hitting the surface;
– changes to slope of the terrain by introducing levees, bunds, terraces, etc. These measures are, however, technically and financially demanding and cannot often be implemented at a sufficient scale.

The measures presented above are likely to have an effect on the retention capacity of the upper parts of catchments, while also enhancing the landscape character.

MATERIAL AND METHODS

The study site. The site chosen for the purpose of researching the physical characteristics impacting the water retention potential during high intensity rainstorms is located in the Beskydy Mts. in the Moravskoslezský Region (Czech Republic). It lies in the local protected area of natural water accumulation (CHOPAV). The site is in the catchment of the Červík Brook and has the hydrological order of 2-03-01-008. For the purpose of this research, the catchment was split into two sub-catchments, A and B (Figure 1).

To illustrate the topography of the area, a digital terrain model was developed using the program ATLAS 3D (Figure 2). The morphological characteristics of the catchment are presented in Table 1.

Runoff was measured not only at the outflow from each sub-catchment, but particularly at the outflow from the entire catchment downstream of the confluence of the sub-catchments (Figure 3).

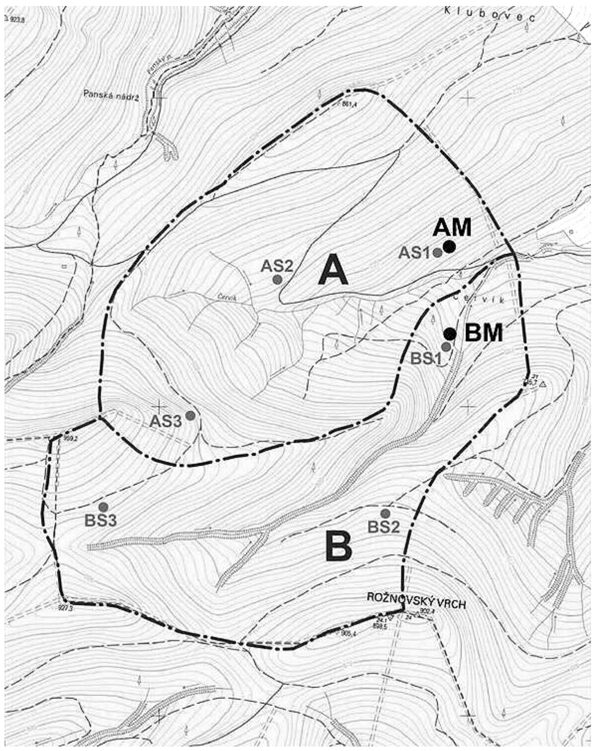

Figure 1. The catchment of Červík Brook and its subcatchments A and B (AM, BM – measuring probes; AS1-3, BS1-3 – soil samples)

Table 1. Catchment characteristics

Catchment characteristics	A	B	Entire catchment (A and B)
Catchment area (S, m^2)	999 701.8	895 587.7	1 895 289.5
Catchment length (L, m)	1 407.2	1 973.2	1 407.2
Catchment shape (α)	0.50	0.23	0.96
Maximum elevation (*H*max, mAOD)	956.0	959.0	959.0
Minimum elevation (*H*min, mAOD)	634.0	634.0	634.0
Average elevation ($H_{\varnothing}$, mAOD)	795.0	796.5	796.5
Average catchment slope (*Ip*, %)	32.2	34.3	23.6
Length of watercourses (*Li*, m)	1 349.8	2 284.3	3 584.2
Density of watercourses (*Ht*, m/ha)	13.5	25.5	18.9

Methodology. Soil moisture and soil suction pressure appear to be the crucial factors influencing the infiltration of rainwater into the soil profile and hence its retention in the research area (Kovář *et al.* 2004). In order to evaluate the degree of impact of these two factors on the soil retention, it was necessary to measure basic climatic and hydrological characteristics in the catchment. These measurements were carried out in cooperation with the Forestry and Game Management Research Institute at Jíloviště-Strnady, Frýdek-Místek office. Their rainfall-runoff monitoring history is presented in Vícha *et al.* (2009).

A standard flow and level gauge was built downstream of the confluence of the A and B sub-catchments for the purpose of this research. Level is measured by a staff gauge and level recorder, flow is measured by an ultrasonic gauge (model MS-03; FIEDLER-MÁGR elektronika pro ekologii, České Budějovice, Czech Republic). The gauging station consists of a microprocessor, a registration control unit V2042 (FIEDLER-MÁGR) and an ultrasound probe S100 (FIEDLER-MÁGR). The set also includes a data processing program IBN PC/AT FLOW 02 (FIEDLER-MÁGR), which enables plotting and averaging of the recorded data, the calculation of cumulative flows over any time period, and printing the data.

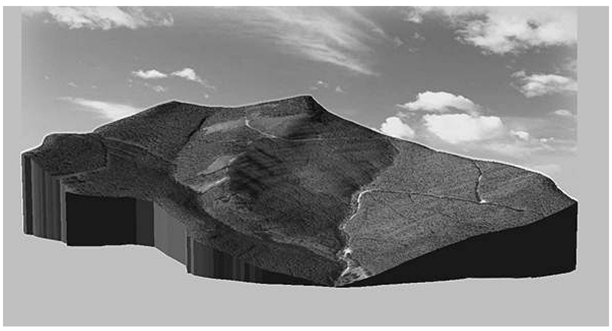

Figure 2. Digital terrain model of the study catchment

Climatic data are recorded by four permanent totalizers, ombrometers and pluviographs. These data enabled us to evaluate the rainstorms and to demonstrate graphically how the physical characteristics impact the retention of rainfall.

Moisture gauges VIRRIB (AMET, Velké Bílovice, Czech Republic) were used for soil moisture monitoring. They were placed 30–50 cm under the soil surface (Figure 4).

Figure 3. Flow and level gauging structure measuring the total flow from sub-catchments A and B

Figure 4. Soil moisture gauge VIRRIB

Figure 5. Tenziometer

Parallel with the soil moisture monitoring, the soil suction pressure as kPa was also recorded using dial tensiometers (Soilmoisture Equipment Corp., Santa Barbara, USA) filled with water and capped by a ceramic probe Jetfill (Soilmoisture Equipment Corp.). The tenziometers were suspended in a drill hole to the depth of 50–90 cm (Figure 5).

Methodological steps undertaken in order to validate the impact of soil moisture and soil suction pressure during extreme precipitation included the following:

– soil samples were extracted in the sub-catchments A and B in order to measure soil porosity and its texture. These included three samples per catchment taken from the depth of up to 1.2 m;
– a digital terrain model of the entire catchment was constructed and used in further analysis (e.g. slope, flow concentration);
– soil moisture gauges and tenziometers were put in place at depths 30 and 90 cm in the sub-catchments A and B;
– test monitoring started on November 7, 2005;
– monitoring of soil moisture, soil suction pressure, and weather during the period April–October started in 2006;
– runoff was measured regularly and recorded at 10-min time steps;
– precipitation was measured continuously throughout the research;
– results were processed using MS Excel 2XXX.

RESULTS AND DISCUSSION

Improving the instantaneous soil retention capacity. The potential of soil to retain water, the potential soil retention capacity, is in real world reduced by a number of factors. In particular, these include soil porosity and the antecedent conditions of soil moisture, which define the remaining available saturation capacity, i.e. the actual soil retention capacity.

Important factors influencing the actual soil retention capacity are deemed to be the physical characteristics that improve the instantaneous infiltration of a short-duration, high-intensity rainstorm into the soil profile. These include:

– instantaneous soil moisture content
– soil suction pressure

We studied these aspects in considerable depth as part of our research into possible improvements of the soil retention capacity in the headwaters of forested catchments. Our case study area was the Červík catch-

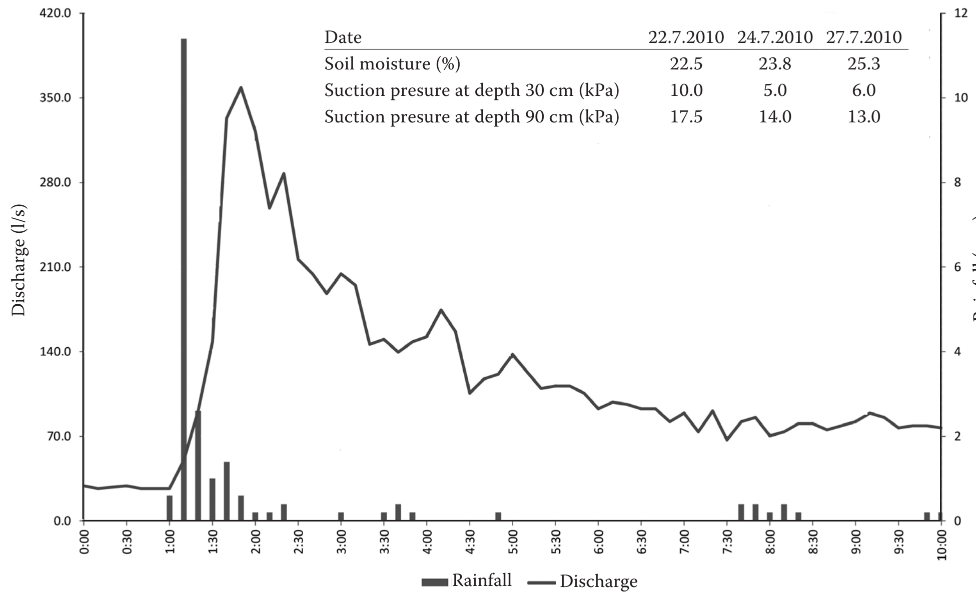

Figure 6. A plot showing the rainfall event on July 24, 2010 and the consecutive discharge; the table shows the soil moisture, suction pressure at the depth of 30 and 90 cm before, during, and after the storm event

ment in the Beskydy Mts. In particular, we measured soil moisture and suction pressure. These measurements were undertaken during extreme precipitation events, alongside with measurements of discharge at the gauging station at the catchment outlet.

The results (presented in the form of graphs such as in Figure 6) show that an extreme precipitation event was followed by a very quick increase in discharge and the flood peak (originating in overland flow), which was in turn followed by a rapid decrease in discharge due to the retention of the hypodermic runoff in the soil profile. These observations occurred due to the dry antecedent conditions (which increased the soil retention capacity), steady soil moisture and, in particular, steady suction pressure (see the table in Figure 6). The suction pressure immediately after the high intensity precipitation event suddenly dropped to a half of its level before the event. This confirms the hypothesis that suction pressure has a significant influence on the instantaneous infiltration into the soil profile.

Using the quantification and statistical evaluation of the observations, it is possible to limit the susceptibility of the area to flooding. This would be particularly important in an area with frequent flooding, but generally at any location. However, soil moisture, suction pressure, and rainfall forecast would have to be continuously monitored to enable actual quantification of the potential runoff and its flood risk.

The rainfall events measured during the long-term, five-year research period in the Červík catchment also caused two inverse situations. The suction pressure following an extreme rainstorm did not drop as expected and the peak flow receded slowly. This was further complicated by the fact that there was practically no soil retention, the runoff was in the form of overland flow and later concentrated into the outflow point in the stream (Figure 7).

The explanation of these unusual observations is attributed to the preceding prolonged dry periods, which disturbed the soil structure and increased evapotranspiration (Kozak 2005). The superficial layer of soil was filled with air, causing the high-intensity, short-duration rainstorm run off immediately in the form of overland flow without any substantial infiltration into the soil. This was further enhanced by the steep slopes.

These conclusions draw upon the five-year worth of soil moisture and soil suction pressure data measured in the sub-catchments of the Červík catchment before and during a rainfall event and during the fall of the flow. The recorded values of soil moisture and suction pressure, together with the graphical representation of flows and significant rainstorms specify the impact of the studied physical characteristics on soil retention.

The evaluation results from the flow charts are shown in Figures 6 and 7.

The results were evaluated using a minimum of 300 sets of rainstorms monitored during the periods April–October of each year of the five-year research. Of these, 70 sets were analyzed further.

Due to the fact that the data were collected continuously during the research, it was possible to evaluate the soil moisture and suction pressure for the entire duration of each single month, i.e. also during times of less severe rainstorms. Based on this, it was possible to confirm the hypothesis that optimum soil moisture at an increased soil suction pressure is needed for the instantaneous retention of water in the soil

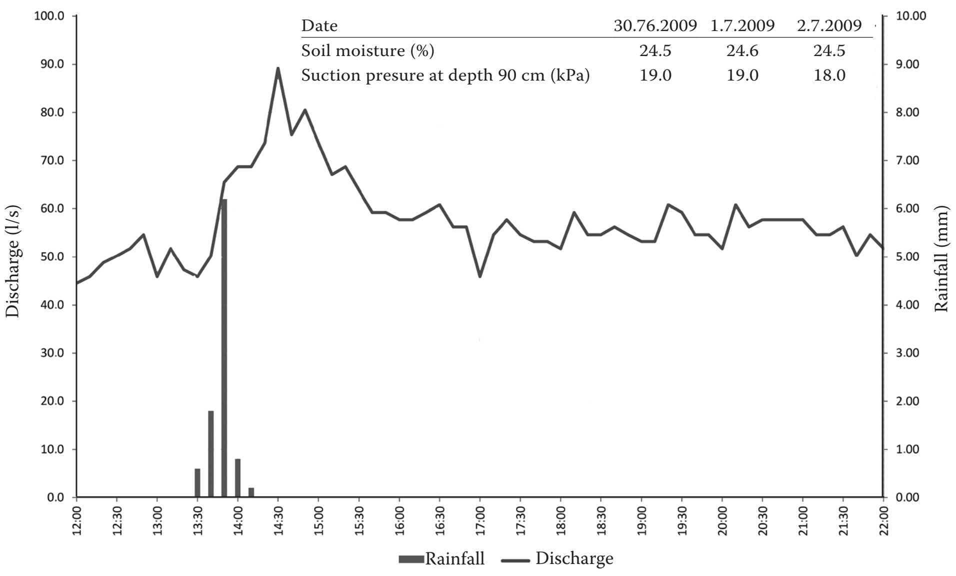

Figure 7. A plot showing rainfall and discharge during an antecedent prolonged dry spell (July 1, 2009)– an inverse situation, alongside with the table of soil moisture and suction pressure, preceded by a prolonged dry period

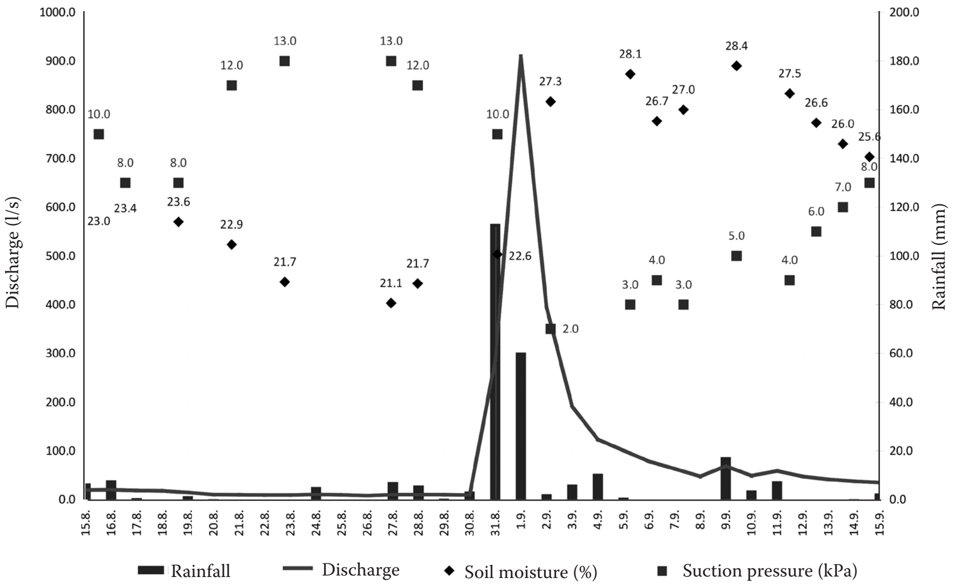

Figure 8. Rainfall, runoff (discharge), soil moisture, and suction pressure in August–September 2010

profile, as shown in Figure 8. The figure shows the low precipitation events preceding a high intensity rainstorm, which contributed to retaining optimum soil moisture at increased suction pressure. This was followed by a drop in discharge, implying increased retention of hypodermic runoff into deeper layers of the soil. The increased discharge was followed by increased soil moisture and decreased suction pressure.

Similar trend can be also seen in Figure 9. It shows two extreme rainstorms in a short time span, bearing in mind that the impact of the second and more intensive rainfall event is influenced by the antecedent rainstorm.

The data obtained during the monitoring imply that the retention of the high-intensity, short-duration rainfall events in the soil profile is highly dependent not only on the physical characteristics of soil, but also the imbalance in rainstorm frequency, which has recently become more pronounced, causing greater ecological impacts. Despite the fact that the meteorological statistics show that long-term average rainfall has not been changing in the Czech Republic, the infiltration of intensive rainstorms into the soil profile and the consequent deceleration of catchment runoff cannot be achieved without the aid of precautionary ecological, soil erosion prevention and water management measures (Dostál *et al.* 2012). The magnitude of runoff (and potentially also soil erosion) is directly dependent on the topography, land cover (Cerdan *et al.* 2010), and on the impacts of anthropogenic activities (Húska *et al.* 2013).

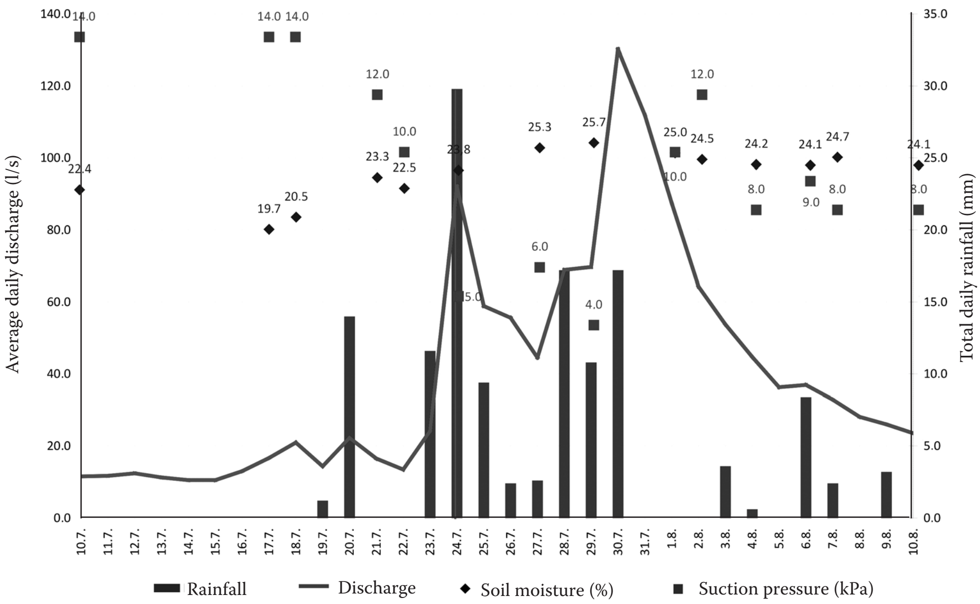

Figure 9. Rainfall, runoff (discharge), soil moisture, and suction pressure in July–August 2010

Transferring the outcomes of this research into practice consists in implementing flood prevention measures in areas of frequent intensive rainstorms causing flooding. These measures should be based on the evaluation of the physical characteristics of the catchment, together with weather forecast by the Hydrometeorological Institute. Statistical evaluation of the quantitative values of each physical characteristic can be used in producing a site-specific methodology for flood prevention in the particular area.

CONCLUSION

The findings presented in this paper show that the retention of rainfall events at high intensities and short durations is affected by physical characteristics of the soil, namely the soil moisture and suction pressure. Importantly, it is also affected by the imbalance in the frequency of rainfall events and dry spells, which causes the soil profile to re-dry on one hand, and intensive short-duration precipitation on the other.

However, long dry periods disturb the superficial soil structure, the formation of a crust and air bubble. This causes the inverse situation whereby an intensive precipitation does not infiltrate into the soil profile despite its high suction pressure, but instead the precipitation runs off quickly as surface runoff, as documented in the results.

Therefore, it is important to implement precautionary measures in the catchment that would help maintain the optimal soil moisture and structure, increase the soil retention capacity and thereby slow down the runoff. It would also be beneficial to introduce biotechnical measures to reduce the overland flow. These include:
– full-scale quality land cover;
– suitable composition of species in the land cover with deep branching root system;
– agrotechnical measures that prevent increased evapotranspiration from the soil surface all year round;
– technical measures that help optimize soil moisture.

These interventions, however, become sufficiently effective only when used across the entire catchment as part of the integrated catchment management approach.

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Corresponding author:

Doc. Ladislav Koutný, Mendelova univerzita v Brně, Fakulta lesnická a dřevařská, ústav inženýrských staveb, tvorby a ochrany krajiny, Zemědělská 3, 613 00 Brno, Česká republika, e-mail: koutnyl@seznam.cz