Storm Runoff in the Foothill Headwater Area Senotín

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Abstract: The purpose of the pilot project Senotín (1993–2000) was to prove the methods of revitalization of sub-mountain headwater area (0.38 km^2) in the Novobystřická Vysočina Highland (610–725 m a. s. l.) in the Czech Republic. This area was tile-drained and ploughed in 1985. Seven underground clay shields newly constructed in 1995 stopped the function of the tile drainage. Four balks prevented the surface and subsurface runoff. These adaptations improved water retention capacity of the whole catchment, which is demonstrated using an example of runoff formation in the revitalized area. A typical storm rain (total 15 mm, duration 5.6 h, max. intensity 4 mm/20 min) and the consequent runoff was analysed, including the role of the soil in the runoff retardation and water retention. The runoff started in two hours since the rain beginning. The retention reached 98% of the rain total. The runoff lasted for 85 h. The concave-upward shape of the falling hydrograph limb indicates that the maximum retention capacity of the studied catchment is high.

Keywords: headwater area; storm runoff; water retention; runoff retardation

Economical, social and cultural wastes caused by extreme weather events (floods, extremely dry and warm periods, whirlwinds etc.) motivated the implementation of principles of sustainable development (Agenda 21 1992; Syrovátka 1996; Antrop 2006) in the landscape management in the Czech Republic. Its basic goal is a systematic revitalisation of the landscape in headwater areas (Syrovátka *et al.* 1994). On the basis of a broad spectrum of research activities, it was concluded that the root of landscape revitalisation is: (1) retardation of runoff from some artificially drained areas (Syrovátka *et al.* 1994), (2) renaturalisation of streams (Luderitz *et al.* 2004), (3) formation of biocentres and biocorridors (Kubeš 1996). It was proved that a holistic approach to the landscape revitalisation is to be preferred (Syrovátka 1995; Naveh 2000; Váchal *et al.* 2006).

Regarding insufficient experience in this field, the pilot project Senotín was established by the Ministry of Environment of the Czech Republic in 1994 (Syrovátka *et al.* 1994; Meruňka *et al.* 1995). Its purpose was to create a methodological basis of revitalisation of foothill headwater areas

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Table 1. Characteristics of the Senotín experimental catchment.

Maximum elevation (m a.s.l.)	725
Minimum elevation (m a.s.l.)	610
Drainage area (km^2)	0.38
Average slope	0.066
Brook length (m)	200
Vegetation cover and land-use(%)	forest (spruce) 26, submontane meadows 74
Soil type	Cambisol
Bedrock	Granite
Mean annual of air temperature (°C)	6
Mean air temperature in January (°C)	–4
Mean air temperature in July (°C)	16
Mean annual precipitation (mm)	700
Mean number of days with snow cover	80

that had been tile-drained and ploughed. The Senotín project history and results were described in several research reports (Syrovátka *et al.* 1995, 1997, 1998, 1999).

The aim of this paper is to demonstrate how the direct runoff is formed in the revitalized spring area of the Senotín catchment. A typical storm rain and the consequent runoff is analysed, including the role of the soil water movement.

EXPERIMENTAL AREA AND METHODS

The Senotín catchment is located in the Novobystřická Pahorkatina Highlands. It lies at a distance of about 1 km from the village of Senotín in the district of Jindřichův Hradec. This catchment lies in the area of acid crystalline rocks. The climatic conditions correspond to the characteristics of a mild-cold humid climatic zone (Table 1). The catchment has a form of a shallow valley with mild slopes. Its cross section has a typical U-shape.

Slopes are covered by Cambisol-type soils with a humic A-horizon of medium thickness (0–40 cm). On the slopes, the subsoil, created by a cambic B-horizon (40–70 cm) and a weathered granite C-horizon (below 70 cm), has a very low hydraulic conductivity. More permeable C-horizon (70–100 cm) can be only found close to the brook. It is formed by fluvial or fluviodeluvial sediments.

The spring area (9 ha), which has the form of a shallow valley, lies in the bottom part of the catchment. It is this area that had been drained using systematic tile drainage and subsequently ploughed in 1985. In 1995, the spring area was revitalised on the basis of the ideas proposed by Syrovátka *et al.* (1994). The surface, subsurface and tile-drainage runoff was disabled (717 m of underground clay shields stopped the function of drainage, 657 m of balks were constructed, 200 m of drainage ditches were destroyed). The Potočná brook was renaturalised (6 pools in the brook were constructed, 126 m of the brook were reconstructed and a small pond was created). The balks were planted by woods and shrubs, resulting

Table 2. Analysis of discharge wave in the Senotín catchment

Beginning of precipitation	21. 5. 02:00
End of precipitation	21. 5. 07:40
Beginning of runoff	21. 5. 04:00
Precipitation amount (mm)	15
Duration of precipitation (h)	5.6
Duration of discharge wave (h)	85
Precipitation volume (m^3)	5700
Runoff volume (m^3)	106
Runoff depth (mm)	0.28
Runoff coefficient (–)	0.02
Total retention (m^3)	5594
Retention as a fracture of rain volume (%)	98
Rising hydrograph limb	
Duration (h)	8
Volume (m^3)	8
Falling hydrograph limb	
Duration (h)	77
Volume (m^3)	98

in a biocorridors connected to the shrubs bordering the Potočná brook. The pond in the Potočná brook formed a biocentre. Seven underground clay shields were located along the contour lines. Their breadth is 30 cm and depth is 100 cm. Four balks, lying above the underground clay shields, were constructed. Their height is 50 cm.

A monitoring station, measuring precipitation and tensiometric pressures in the soil profile covering the fluvial deposits, was situated in the middle part of the revitalised area, approximately 20 m far from the Potočná brook and 5 m below a balk. Precipitation intensity and tensiometric pressures were recorded at 20-min intervals. The tensiometric pressures were measured at the depths of 30 and 90 cm, using water tensiometers (Tesař *et al.* 2001). In the closing profile of the catchment, the discharge was measured with the help of an ultrasonic device and recorded at 20-min intervals.

RESULTS

Rain and discharge in the Senotín catchment over the period 15 April to 10 July 1999 is shown in Figure 1. The analyzed rainstorm and the corresponding discharge wave are labelled by arrows.

Causal rain. The causal rain on 21 May 1999 had a total of 15 mm, lasted for 5.6 h and its maximum intensity was 4 mm/20 min. The shape of the causal rain corresponds to a typical summer rainstorm (Figure 2).

Tensiometric pressure. The soil was sufficiently humid during the whole period examined so that the plant transpiration was not restricted by water shortage. The infiltrating water was accumulated in the A-horizon of the soil during the rain, which is demonstrated by the tensiometric pressure at the depth of 30 cm (Figure 3). The maximum tensiometric pressure –21 kPa (corresponding to the maximum soil moisture content) was reached at the depth of 30 cm in 4.5 h after the end of rain. It means that the filling of the topsoil horizon at the measuring site lasted for 10 h. After the cessation of the rainstorm, the filling went on due to the run-on from adjacent slopes. The time development of the tensiometric pressure in the C-horizon shows that the infiltrating water percolated but very slowly to the depth of 90 cm (Figure 3). The maximum tensiometric pressure –33 kPa at the depth of 90 cm was reached in 30.0 h after the end of rain. This pressure was very near to the value of –40 kPa before the rain.

Runoff retardation. The beginning of runoff was recorded at 2 h after the beginning of the causal rain.

Hydrograph. The baseflow before and after the rain was 0.2 l/s. The causal rain caused a discharge wave with a peak discharge 0.42 l/s. The discharge wave lasted for 85 h. Its volume was 106 m^3. The rising hydrograph limb rose very quickly and had a very short duration, 8 h. The volume of direct runoff generating the rising hydrograph limb was 8 m^3, which is 7.5% of the whole volume of the discharge wave. The falling hydrograph limb had a concave-downward shape with the duration of 77 h and volume of 98 m^3, which is 92.5% of the

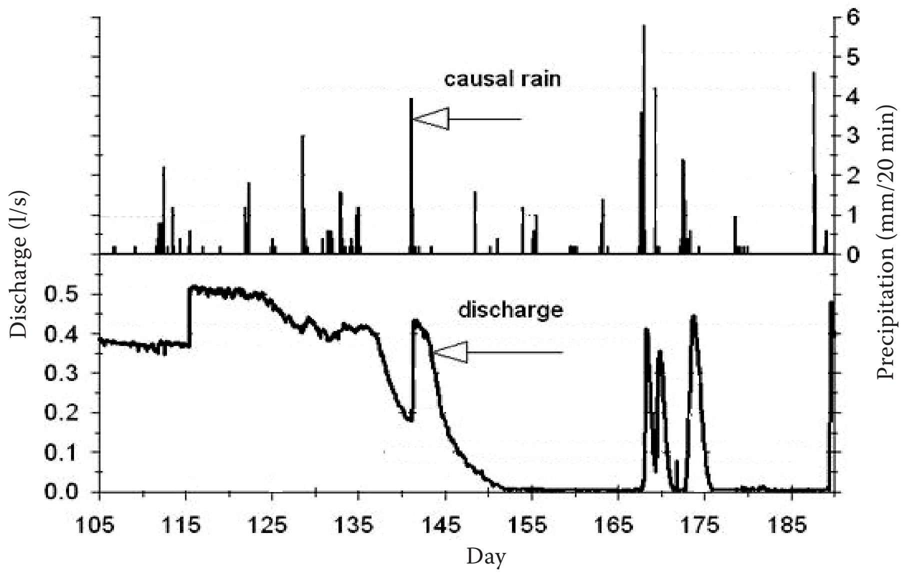

Figure 1. Rain intensity and brook discharge in the Senotín catchment over the period 15 April to 10 July 1999; the analysed rainstorm and the corresponding discharge wave are labelled by arrows

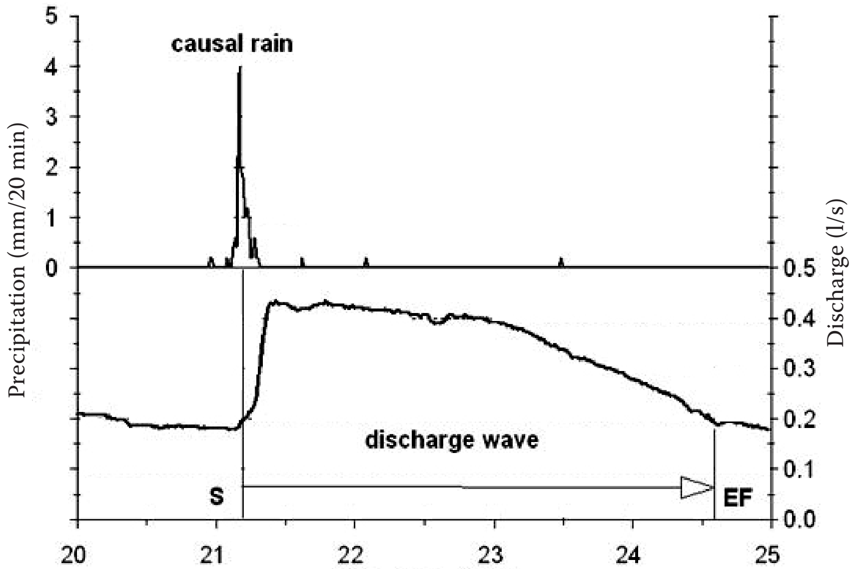

Figure 2. The causal rain intensity and the brook discharge in the Senotín catchment during the period 20–24 May 1999; S – beginning of the discharge wave, EF – end of the discharge wave

whole volume of the discharge wave. Particularly in the rising hydrograph limb, the shape of the hydrograph is very similar to the time course of the tensiometric pressure at the depth of 30 cm in the soil (Figure 4).

Water retention. The volume of discharge wave 106 m^3 is very little in comparison with the volume of rain water 5700 m^3, which corresponds to a very small runoff depth 0.3 mm and a very small direct runoff coefficient 0.02. Total retention of rain water is thus 5 594 m^3, which means that 98% of the rain water was retained in the catchment and only 2% of the rain water was lost by direct runoff.

Table 2 recapitulates features of the analyzed discharge wave in the Senotín catchment.

DISCUSSION

The variable contributing area hypothesis states: "Rapid delivery of water into the stream during the stormflow is attributed to a shrinking and expanding of the saturated area that can occur anywhere

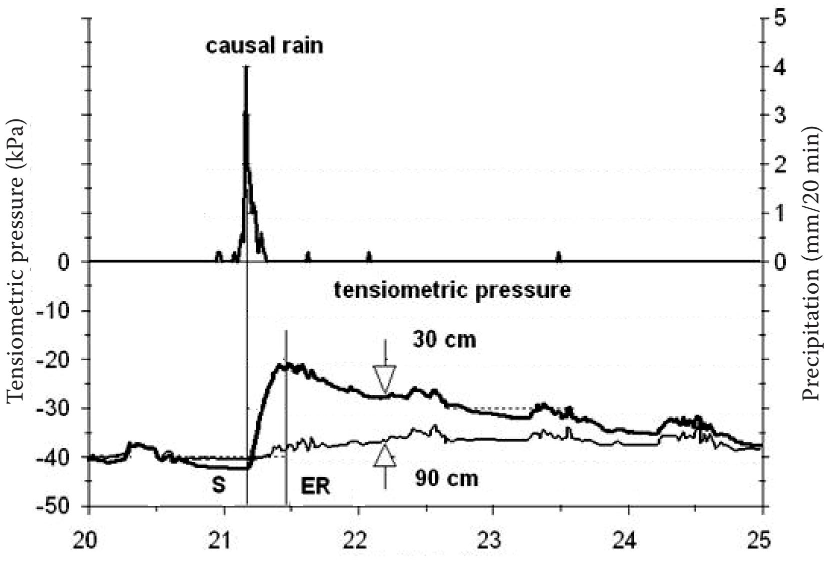

Figure 3. The causal rain intensity and the tensiometric pressures at the depths of 30, 60 and 90 cm in the Senotín catchment during the period 20–24 May 1999; S – beginning (start) of the rising hydrograph limb, ER –end of the rising hydrograph limb

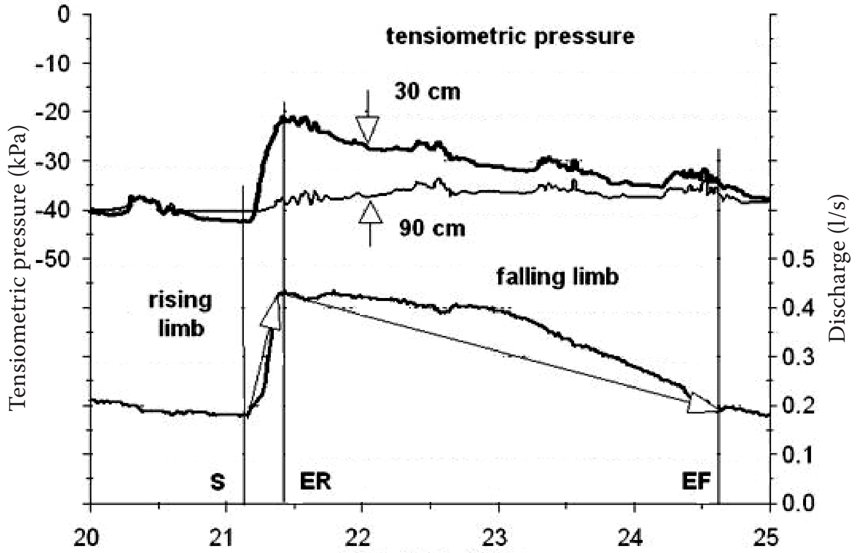

Figure 4. Brook discharge and the tensiometric pressures at the depths of 30, 60 and 90 cm in the Senotín catchment during the period 20–24 May 1999; S – beginning (start) of the rising hydrograph limb, ER – end of the rising hydrograph limb = beginning of the falling hydrograph limb, EF – end of the falling hydrograph limb

in the catchment where the infiltrated water cannot be transferred through the soil. Nevertheless, the majority of saturated areas occur near streams" (cited after Kostka & Holko 1997). The source of water for the direct runoff delivered into the stream is, in our case, mainly the shallow subsurface flow through the topsoil layer. The concept of "saturated area" does not mean, in our case, that the soil must be completely filled with water. Rather it means that water is not sufficiently held in the topsoil pores against gravity and, therefore, it quickly flows through the topsoil in the downslope direction. During the episode investigated, the tensiometric pressure in the soil's A-horizon was sufficiently high (–22 to –42 kPa) to enable a saturated contributing area to occur.

An *ad hoc* empirical relation between the tensiometric pressure at the depth of 30 cm and the discharge during the rising hydrograph limb is depicted in Figure 5. This relation seems to be quite an unequivocal function. On the other hand, an analogous relation for the falling hydrograph limb, plotted in Figure 6, looks rather erratic. This behaviour is, however, mostly an artefact caused by plant transpiration. Every day around the noon time the transpiration affects the tensiometric pressure substantially, while the brook discharge is influenced negligibly (Figure 4). The short rising hydrograph limb occurred during the night and early in the morning, while a much longer falling hydrograph limb lasted for more than three days and experienced four peaks of the demand of water

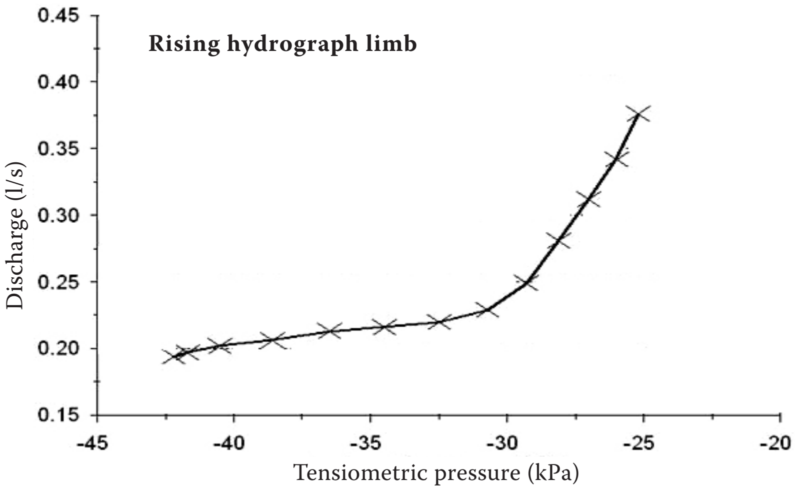

Figure 5. Relation between the tensiometric pressure in the depth of 30 cm and the brook discharge during the rising hydrograph limb in the Senotín catchment

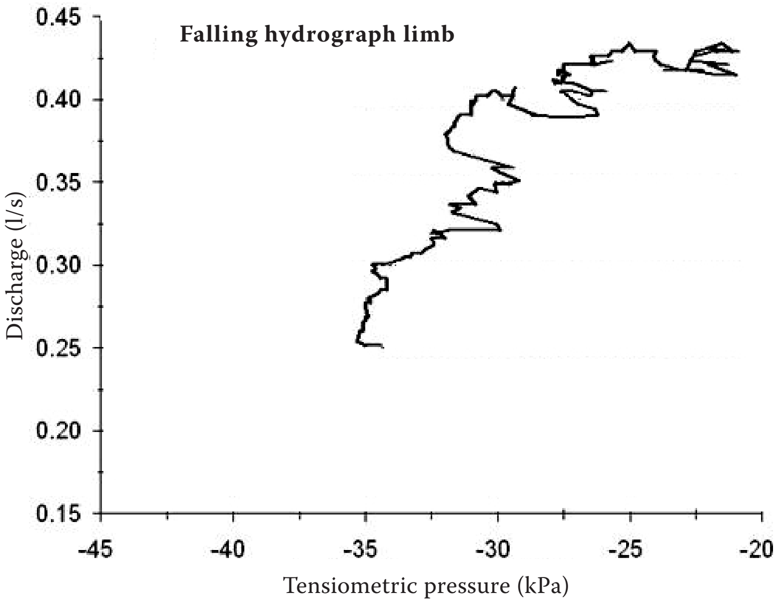

Figure 6. Relation between the tensiometric pressure in the depth of 30 cm and the discharge during the falling hydrograph limb in the Senotín catchment

for transpiration. Despite of the transpiration effect, the overall similarity between the tensiometric pressure hydrograph at the depth of 30 cm and the falling discharge hydrograph limb supports a hypothesis that the saturated contributing area was formed in the surface soil layer and, probably, only in this layer. Similar functional dependence between the tensiometric pressure and the discharge was observed for other natural conditions, similar to those in the Senotín catchment (Šanda & Císlerová 2000).

Four more storm runoff events were selected in 1998 and 1999 and analysed. The results, described in study Syrovátka *et al.* (1999), are consistent with the finding presented in this contribution.

The hydrodynamic mechanisms causing runoff retardation are broadly discussed by Tromp-van Meerveld and McDonnell (2006a, b). However, it is difficult to quantify these effects under particular conditions. The physics of the soil water retention and movement is still a subject of scientific discussions. We believe that new approaches to the transport in porous media should be applied in order to properly describe the role of soil water movement in runoff formation (Tesař *at al.* 2008).

CONCLUSIONS

The above analysis arrives at the following quantification of the storm runoff in the Senotín catchment:

– The causal rain, 15 mm in total, lasted for 5 h. Its maximum intensity was 4 mm/20 min.
– The rising hydrograph limb started (the runoff was retarded by) 2 h after the beginning of the causal rain. The rain water infiltration and the downslope run-on caused the increase of the tensiometric pressure at the depth of 30 cm in the valley area from –42 kPa to –22 kPa . Duration of the rising hydrograph limb was 8 hours.
– During the falling hydrograph limb, the unsaturated flow in the 30–40 cm thick topsoil layer covering the catchments slopes drained the soil water into the brook. This caused a gradual decrease of the tensiometric pressure at the depth of 30 cm and the rapid drainage of the topsoil virtually stopped when the tensiometric pressure decreased under about –35 kPa (which can be regarded as corresponding to the field capacity of the soil). The duration of the falling hydrograph limb was 77 h.

The concave-upward shape of the falling hydrograph limb indicates that the maximum retention capacity of the revitalised catchment is high. The underground clay shields stopped the function of tile-drainage and the balks effectively prevented the surface runoff from occurring. Thereby, these structures significantly increased the water retention capacity of the whole catchment.

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