Influence of Drainage System Maintenance on Storm Runoff from a Reforested, Waterlogged Mountain Catchment

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Abstract

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The maintenance of a drainage system in a waterlogged mountain catchment impacted by earlier harvesting operations was assessed on the basis of a hydrological analysis (hydrological balance, three linear reservoirs method). To restore pre-harvest hydrological conditions, the water-saturated localities were experimentally drained both by restoration of existing ditches and digging of additional open ditches. The rainwater retention of the soil was illustrated by two comparable storm flow events occurring before and after the draining treatment. Pedohydrological analysis revealed the important involvement of static retention in capillary pores in the rainfall-runoff process during rainstorm events. Restoration and addition of the drainage system yield more favourable generation and better proportioned distribution of storm flow discharge. There would be no danger of water depletion in the catchment during dry periods in connection with the draining treatment. In comparison with the state before drainage system maintenance, the static retention after draining treatment became greater than zero. Both the dynamic retention (detention) and static retention helped balancing storm flows in terms of flood and drought control. The successive drop of the raised water table level following drainage system maintenance resulted in changes of actual retention and subsequent runoff. The drainage procedure proved its positive influence on reforestation and the environment, as no negative impact on soil and stream hydrology was found.

Keywords: drainage treatment; forest soil; mountain catchment; storm flow runoff; waterlogging; water retention

During the 1980s, air pollution had affected forests in the Sudeten (Orlice) Mountains (NE Bohemia). To study the effects of forest die-off on pedohydrological processes, the U Dvou louček (UDL) experimental catchment was established in 1991 at the site of a clear-cut headwater area. As the dying trees were logged, patches of peat and Podzol (Spodosol) soils became water-saturated. These changes are in accordance with Heikurainen and Päivänen (1970) as they mentioned an adverse effect of clear felling on hydrology of peatland by raising the water-table level.

This changed water retention of forest soil which is considered to be the main driving factor affecting runoff from forest stands (Brandt *et al.* 1988; Badoux *et al.* 2006), while water storage and movement in forest soils are the main pedohydrological regulators in the forest (Weiler & McDonnell 2004). Within the UDL, the soil surface was damaged (rutted) by forestry machinery. These ruts are a visually distinct type of wet-site harvesting disturbances (Aust *et al.* 1995) and can significantly alter surface soil properties (Eisenbies *et al.* 2007) affecting both surface and shallow-subsurface flows (Aust *et al.* 1993). To restore the pre-harvest hydrological conditions, the water-saturated patches were experimentally drained by restoration of existing ditches and digging of additional open ditches in 1996. The drainage is used to lower the water table in order to ensure successful establishment of trees (Holden *et al.* 2004). Forest ditch network maintenance has already been studied in terms of suspended solid matter (Joensuu *et al.* 1999) and chemistry of run-off water (Joensuu *et al.* 2002). The principal objective of this paper is to elucidate the influence of the catchment drainage on the rainstorm-runoff process. Specific objectives of the study are to quantify parameters of storm flow runoff using a storm flow hydrograph analysis by the method of three linear reservoirs and to identify the retaining function of forest soil using the equation of storm flow hydrological balance before and after drainage restoration.

MATERIAL AND METHODS

The catchment area takes in 32.6 ha and its altitude is in the range 880–950 m a.s.l. GPS coordinates at the catchment outlet are: 50°13'11.817''N, 16°29'47.350''E. Mature Norway spruce (*Picea abies* (L.) Karsten) and European beech (*Fagus sylvatica* L.) share 17.5% of the catchment forest. The remaining area is a former clear-cut that is now covered with a spruce stand 15–20 years old with 70% canopy and sparse ground vegetation.

The mineral soils were derived from gneiss and mica schist. In the catchment, a patch of peat, Podzol, and Cambisol occurs. The long-term mean annual precipitation is 1350 mm, out of which 910 mm is converted to runoff. Mean annual temperature is 4°C. Atmospheric precipitation in the catchment is measured weekly by 8 ombrometers that are placed in a polygonometric network and calculated according to the Thiessen polygon method (Hewlett 1982). Time behaviour of rainfall is registered at hourly intervals by 2 recording rain gauges connected with an automatic meteorological station. The stream flow was registered at the catchment outlet by mechanical float water level recorder. Since September 1996, the discharge has been registered by a manometer water level recorder with automatic data collection.

Before the maintenance, the drainage system had a total length of 2285 m and consisted of small streams and shallow ruts originating from harvesting operations. The watercourses density on that part of the catchment area under the influence of waterlogging (4.5 ha) reached 508 m/ha (Figure 1). Additional open ditches were manually trenched in July 1996. The treatment aimed to restore drainage system function within the 3 ha waterlogged area. Total length of streams and open ditches (dug to a depth of 0.8 m) after the reconstruction of the drainage system reached 1709 m on 4.5 ha (partial area of the catchment), meaning 380 m/ha (Figure 2).

The coefficient of saturated hydraulic conductivity was derived from the measurement of infiltration in the field and verified by calculation from drainage coefficients (drainage porosity) and soil particle size distribution curves.

Soil water retaining capacity was divided into two components: dynamic and static. Dynamic retaining capacity of the soil (RK_D) expresses the total volume of gravitational pores. RK_D was determined by calculating the total porosity of undisturbed samples and deriving from retention curves. Static retaining capacity of soil (RK_{ST}) was determined as the volumetric water content at the maximum capillary water capacity (*MKVK)* hydrolimit (Novák 1954) reduced by volumetric water content at the point of decreased availability (*BSD*) hydrolimit. It is necessary to compare two pattern profiles of the same depth and to convert the volume percentage of soil water content to millimeters of precipitation. The retaining capacity of both Podzol and Cambisol is given in Table 1. Variability in soil properties remained the same for the storm flows before and after draining treatment, because the hydrographs before and after treatment reflect solely a lumped model.

The runoff generation process during a rainstorm is characterized by great forest soil infiltration rates that frequently exceed the rainfall input to the soil surface. Due to the high infiltration rate of forest floor,

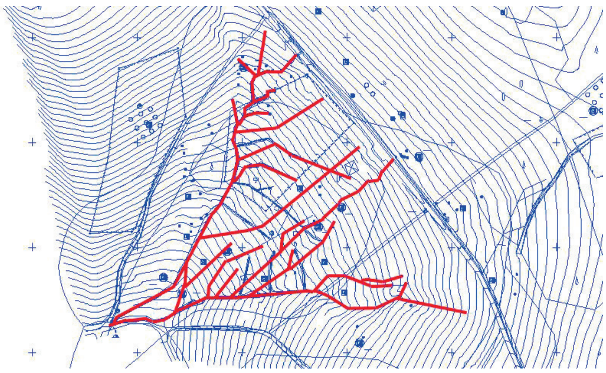

Figure 1. Design of streams and ditches before the drainage system maintenance

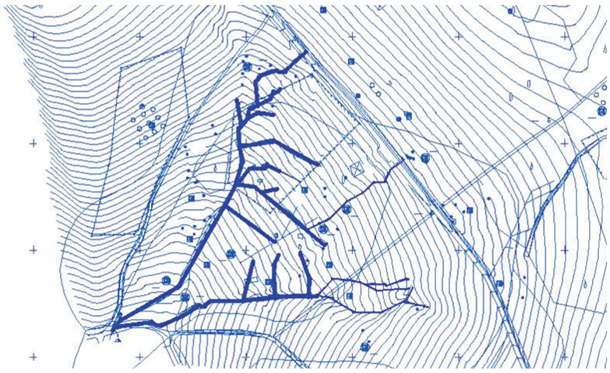

Figure 2. Design of streams and ditches after the drainage system maintenance

Table 1. Water retaining capacity by soil types (comparison of pattern solum, if stoniness was taken into account and subtracted) (in mm)

Soil	Profile thickness	RK_D	RK_{ST}	RK (total)
Humus Podzol	600	21.57	82.36	103.93
Cambisol	600	36.29	96.64	132.93
Weighted mean	600	31.38	91.88	123.26

RK_D – dynamic water retaining capacity of soil expressed as the total volume of gravitational pore volume; RK_{ST} – static water retaining capacity of soil determined as the volumetric water content at maximum capillary water capacity (*MKVK*) hydrolimit reduced by volumetric water content at point of decreased availability (*BSD)* hydrolimit

overland flow generated by infiltration excess does not occur during the majority of events. This does not apply to logging roads and other low-permeability areas, such as compacted soils that are likely to produce infiltration excess and overland flow. In forests, infiltration excess overland flow occurs less frequently than in the open area nearby (Holko *et al.* 2011); it is more often generated by saturation excess under forested conditions. Saturation overland flow is most common in areas where soils are waterlogged (Weiler & McDonnell 2004). As for hillslopes, water infiltrating into the soil is either stored in the A and B soil horizons (static retention), it moves vertically through gravitational macropores to a depth of ca 1.0–1.2 m, and proceeds as lateral subsurface flow to streams (dynamic retention), or it recharges local groundwater. Dynamic effects of the flow process in soil were examined by analyzing hydrographs of storm flow at the catchment scale. Modifications of the following balance equation were used (see Hewlett 1982):

$$H_S = Q_Z + Q_H + Q_P \pm Q_{NZ} \pm \Delta Z + U_V \qquad (1)$$

where:
H_S – total rainfall
Q_Z – base flow
Q_H – subsurface flow
Q_P – surface flow
Q_{NZ} – exchange with deeper aquifers
ΔZ – change in water storage within soil
U_V – total evaporation represented by interception

All Q components are given as flow depth (mm); ΔZ is expressed as depth of the water column (mm), and U_V is expressed as total depth (mm).

To compare the rainstorm-storm flow changes, events occurring before and after the draining treatment were selected. Two representative storm flows were selected from the collection of analyzed storm flows so that both storm flows might meet the criteria for application of the three linear reservoirs model (De Zeeuw 1973; Linsley *et al.* 1982; Chow *et al.* 1988), which is to say there are roughly equal proportions of rainfall infiltrated into soil and similar runoff dynamics characterized by model parameters as follow: $c(Z)$, $c(H)$, and $c(P)$ (Table 2). The three linear reservoirs model was used only for purposes of comparing formation of the two studied storm flow hydrographs.

Storm flow events prior to and following draining treatment were chosen because the soil profile might represent maximum capillary saturated solum and overland quickflow might be generated. Solum saturation was characterized by antecedent precipitation index (API) in mm (Kulhavý & Kovář 2000). As a consequence of the high permeability of soil profiles, we used only the 11-day time series. API for the events in 1996 and 1997 were 89 and 83 mm, respectively. This small difference was also confirmed by volume soil moisture recorded at the depth of 0.3 m, and illustrative volume soil moistures for the events beginning in 1996 and 1997 were 28.8 and 29.1%, respectively.

The runoff process was simulated using the runoff model having three linear reservoirs. The first, second, and third reservoirs represent drainage source areas delivering rapid (Q_P), accelerated (Q_H), and slow (Q_Z)

Table 2. Responsive parameters *c* before and after drainage treatment

c	Before drainage	After drainage
$c(Z)$	0.9794	0.9667
$c(H)$	0.8283	0.8633
$c(P)$	0.6999	0.6586

Z – relating to slow runoff (base flow); H – relating to accelerated runoff (subsurface flow); P – relating to rapid runoff (surface runoff); c – by De Zeeuw (1973) slope of line characterized runoff component runoff into the outlet of the catchment. The runoff functions of the particular drainage areas simulate the *c* coefficients (Table 2) obtained from analysis of the falling limb of the storm flow hydrograph (De Zeeuw 1973).

Solving the problem of peak flow decrease of storm water through forest soil is determined using the retention function of forest soil. For that purpose, dynamic retention expressed as groundwater content in forest soil at the time of peak flow (i.e. water content of the declining limb of the storm flow hydrograph) and static retention expressed as difference between water amount infiltrated into soil and water discharged from soil were chosen, both as measured parameters. This approach constitutes an original contribution of the paper.

RESULTS

Loamy-sand soils dominate the UDL catchment, while clay soils were found only in some horizons (B_v). The soils have high infiltration capacity (90–100% precipitation). Although the groundwater table is raised locally, gley processes do not occur.

Hydrological balance before draining treatment

$$R_{ST} = Inf - Q_Z - Q_H = 29.4 - 18.2 - 11.2 = 0 \quad (2)$$

$$R_D = Inf - \varepsilon - R_{ST} = Q_Z + Q_H - \varepsilon = 18.2 + 11.2 - 5.7 = 23.7 \quad (3)$$

where:

R_{ST} – static retention (mm)

Inf – water infiltrated into soil (mm)

ε – total runoff until peak flow, expressed by runoff depth (mm)

R_D – dynamic retention of soil (mm)

then hydrological balance equation (in mm) is:

$$\begin{gathered} H_S = Q_P + Q_H + Q_Z + U_V + R_{ST} \\ 39.0 = 3.7 + 11.2 + 18.2 + 5.9 + 0 \end{gathered} \quad (4)$$

Based on the hydrological balance equation the runoff coefficient was calculated as follows:

$$C = \frac{Q_Z + Q_H + Q_P}{H_S} = \frac{18.2 + 11.2 + 3.7}{39.0} = 0.849 \quad (5)$$

Dynamic retention amounted to 60.8% of H_S, which was 71.6% of the total storm flow ΣQ. Until peak flow, ε-runoff amounting to 5.7 mm equalled 14.6% of H_S, which was 17.2% of ΣQ. Surface runoff amounting to 3.7 mm was 9.5% of H_S, which was 11.2% of ΣQ.

The proportion of the depth of actual runoff to potential runoff (runoff on the surface of frozen or waterlogged soil) was calculated as follows:

$$PO_1^C = \frac{Q_{SK}^C}{Q_{POT}^C} = \frac{Q_Z + Q_H + Q_P}{H_S - U_V} = \frac{33.1}{33.1} = 1.0 \quad (6)$$

where:

PO_1^C – proportion of the total actual and total potential runoff before treatment

Q_{SK}^C – actual total runoff depth of the storm flow (mm)

Q_{POT}^C – total potential runoff (mm)

All infiltrated water flowed away because the static retention equalled 0. The proportion of the total amount of actual runoff to the total potential runoff was thus 1.0. Before the rainstorms, the catchment was partially saturated by water (to 78 and 88.8%) and runoff passed through the forest soil because capillary space was full. At the time of peak flow, the dynamic (gravitation) retention space detained 80.6% of subsurface and base ($Q_H + Q_Z$) (i.e. hypodermal) runoff. The total runoff was transformed to 11.2% surface flow, 33.8% subsurface flow, and 55% base flow. The total retention was 19.2% of the total retaining capacity ($\Sigma R/RK_{TOT}$). The corresponding balance components are clearly charted in Figure 3 and proportionally to rainstorm in Figure 4.

Hydrological balance after draining treatment

$$R_{ST} = Inf - Q_Z - Q_H = 34.3 - 8.1 - 8.3 = 17.9 \quad (7)$$

$$R_D = Q_Z + Q_H - \varepsilon = 8.1 + 8.3 - 5.6 = 10.8 \quad (8)$$

$$\begin{gathered} H_S = Q_P + Q_H + Q_Z + U_V + R_{ST} \quad \text{(mm)} \\ 46.5 = 2.7 + 8.3 + 8.1 + 9.5 + 17.9 \quad \text{(mm)} \end{gathered} \quad (9)$$

$$C = \frac{Q_Z + Q_H + Q_P}{H_S} = \frac{8.1 + 8.3 + 2.7}{46.5} = 0.411 \quad (10)$$

For explanation of equation components see equations describing the event before drainage maintenance.

Until peak flow, ε-runoff amounting to 5.6 mm equalled 12% of H_S, which was 29.3% of the total storm flow ΣQ. Surface runoff amounting to 2.7 mm was 5.8% of H_S, which was 14.1% of ΣQ. The proportion of the depth of actual runoff to potential runoff (runoff on the surface of frozen or waterlogged soil) was calculated using the formula:

$$PO_2^C = \frac{Q_{SK}^C}{Q_{POT}^C} = \frac{Q_Z + Q_H + Q_P}{H_S - U_V} = \frac{19.1}{37.0} = 0.516 \quad (11)$$

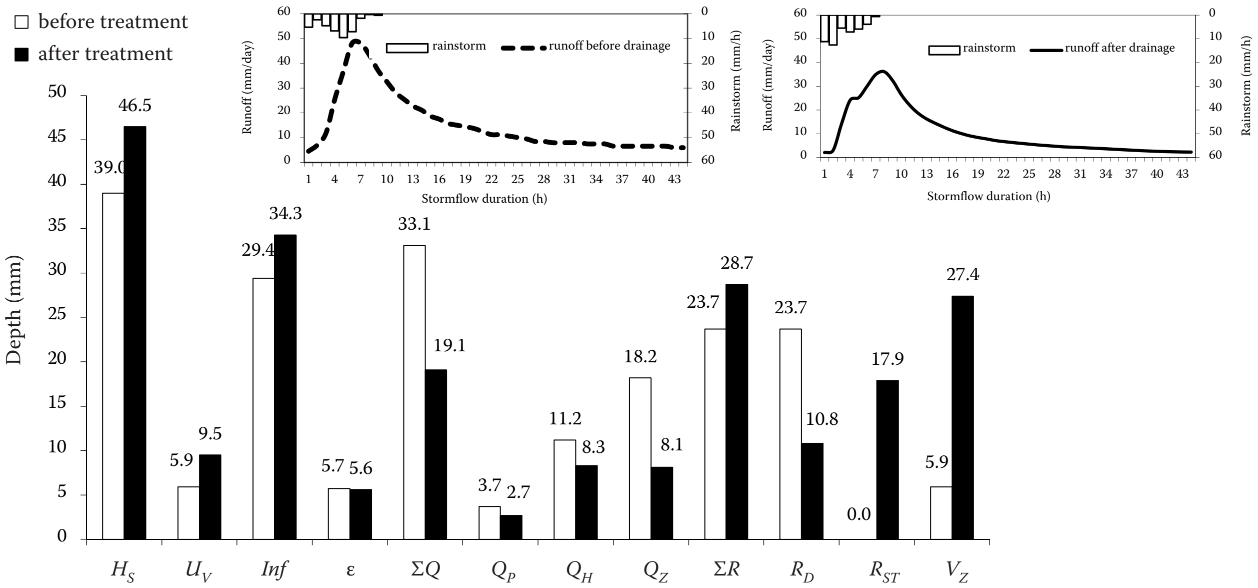

Figure 3. Components of balance analysis of storm flow hydrograph before and after draining treatment; greater soil water retention and lower peak flow occurred after drainage system maintenance
H_S – total rainfall; U_V – total evaporation represented by interception; *Inf* – water infiltrated into soil; ε – total runoff until peak flow, expressed by runoff depth; ΣQ – total storm flow; Q_P – surface flow; Q_H – subsurface flow; Q_Z – base flow; ΣR – total retention; R_D – dynamic retention of soil; R_{ST} – static retention; V_Z – water retained in the watershed ($U_V + R_{ST}$)

where:
PO_2^C – proportion of the total actual to the total potential runoff after treatment
Q_{SK}^C – actual total runoff depth of the storm flow (mm)
Q_{POT}^C – potential total runoff depth of the storm flow (mm)

As the static retention equalled 17.9 mm, 47.8% of infiltrated water flowed away. Due to forest soil retention, only 51.6% of potential runoff flowed away. Some 73.8% of H_S infiltrated into forest soil, 35.3% of H_S flowed away from soil through gravitation pores, and 38.5% of H_S was retained in capillary pores of the soil. Before the rainstorm, forest soils of the catchment were saturated by water to 65%. This consisted of the static retention of 17.9 mm (38.5% of H_S, 19.5% of static retaining capacity). During the time of peak flow, the dynamic (gravitation) retention space retained 65.8% of subsurface and base ($Q_H + Q_Z$) (i.e. hypodermal) runoff. The summary runoff was transformed to 14.1% surface flow, 43.5% subsurface flow, and 42.4% base flow. In the rainstorm-runoff process, some 23.3% of the total retaining capacity of the forest soil was used ($\Sigma R/RK_{TOT}$ = 28.7/123.3).

Summarizing our results in part, the dynamic retention (23.7 mm before and 10.8 mm after) regulated 72 and 56% of ΣQ (33.1 and 19.1 mm, respectively) from the studied storm flows. Total retention from total retaining capacity of the studied forest soils (123.3 mm) was 19% (23.7 mm) and 23% (28.7 mm), respectively. The

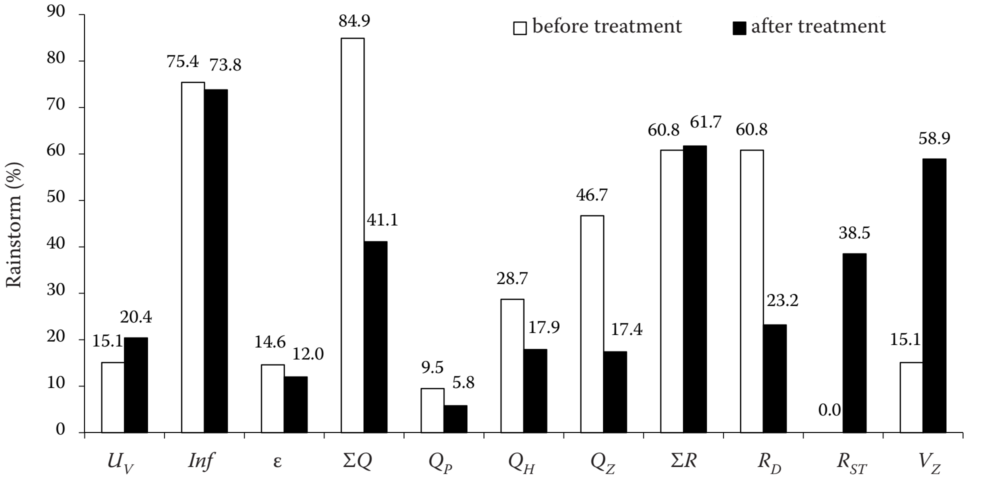

Figure 4. Components of storm flow hydrograph by proportion of corresponding rainstorms For abbreviations explanation see Figure 3

volume of gravitation pores (31.4 mm) was important for turning rainstorm into storm flow. In the first storm flow, 76% (23.7 mm) of the gravitation pore volume was employed and 34% (10.8 mm) of that dynamic retaining capacity was used in the second storm flow. Corresponding balance components were again charted in Figure 3 and proportionally to rainstorm in Figure 4.

DISCUSSION

As for the influence of peat land drainage on flood peaks, Beheim (2006) reviewed the existing literature and presented some calculations as to the effects of drains and soil moisture storage on runoff generation. Despite small changes in the water balance, Beheim (2006) stated that the drainage treatment changes water pathways and affects the individual storm flow peaks. Regarding the effect of drainage on peak flow, this review study provided diverse results. Lundin (1994) also reported both decreased peak flows and increased floods after drainage in the majority of cases. It seems that drainage has both reducing and increasing effects on peak flows. Decreasing effect on peak flow is attributable to increased soil water storage (i.e. total retention) and an increasing effect is related to a more effective channel network (Beheim 2006).

Before draining treatment (1992–1996), the average components of total runoff (9.1% rapid, 36.1% accelerated, and 54.8% slow) showed proportions analogous to those for runoff components of the storm flow hydrograph (11.2, 33.8, and 55.0%) analyzed in this paper. After draining treatment (1996–2001), the components of total runoff were 4.9% rapid, 33.4% accelerated, and 61.7% slow, thus a little different from the proportions of the storm flow hydrograph (14.1, 43.5, and 42.4%) analyzed in this paper. Lower proportions of rapid and accelerated runoff in comparison with the analyzed storm flow hydrograph were probably caused by an earlier event after draining treatment.

On the other hand, when the moisture storage is filled up, continuing rain results in rapid runoff as the channel network allows rapid overland and accelerated subsurface flow (Beheim 2006). Lundin (1994) found increases in peak discharge only when the groundwater level was in the uppermost 0.2 m of topsoil. In most cases, we assume that the drainage network is able to carry the excess water away rapidly.

Following remedial drainage after clear-cutting, Lundin's results (1994) also indicated a possible decrease in peak discharges. These results are consistent with our findings after the maintenance draining treatment. The data generally agree also with the study by Sun *et al.* (2001).

When the canopy water storage is filled up, excess water will be infiltrated into the peat. When the field capacity has been reached, excess precipitation results in an immediate increase in groundwater level. The immediate increase in groundwater level can be derived from effective porosity and rainfall. Right here dynamic retention can be employed.

At comparable rainstorms prior to and following draining treatment, greater soil water retention and lower peak flow were recorded immediately after drainage system maintenance (see Figure 3). That is similar to the Model B by Starr and Päivänen (1986), which is to say that drainage leads to decreased peak flow and increased base flow and base time.

If considering the pre-treatment (1992–1995) and post-treatment (1996–2001) periods assessed on the basis of constructing unit hydrographs (Černohous & Kovář 2009), the events (separated by their duration were equal to 24, 44, and 60 h) showed increased peak flows (by ca 0.3–0.5 mm/h) and steeper decrease of discharge on the recession limbs during the post-treatment period, similar to the Model A by Starr and Päivänen (1986). That is to say that drainage leads to increased peak flow and decreased base flow and base time. Robinson (1986) stated also that the open drains helped quickly remove surface layer flows, leading to shorter flow response times and higher peaks.

Analysis of the recession limb of discharge event culminations (Černohous *et al.* 2010) proved that the 0.6–40% rapid runoff constituent of total flood-event runoff occurred in the forest environment. The determination of a rapid runoff amount within that range indicates the assignment of a particular storm flow hydrograph to one of the models defined by Starr and Päivänen (1986). If the rapid runoff constituent approaches 0.6%, then it is Model B. If the rapid runoff constituent oscillates around 10%, then it is Model A. If the rapid runoff constituent approaches 40%, then it represents a transition to Model C, meaning that drainage leads to increased peak flow and increased base flow and base time. Robinson *et al.* (2003) conclude that short-term increases in both peak flows and base flows at the local scale are also attributable to forest cutting.

We can conclude that the water retention of the wetland was higher after the open drainage system had been maintained. The successive drop of the raised water table level following maintenance resulted in changes of actual retention and subsequent runoff (Figures 3 and 4). The drainage proved its positive influence on reforestation and the environment, as no negative impact on soil and stream hydrology was found. Nevertheless, the benefit from the treatment must be considered in view of the aforementioned hydrograph combined models (Starr & Päivänen 1986) and also has to be compared with the conceptually generalized model for the effects of management on wetland hydrology by Sun *et al.* (2001).

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