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Effects of drainage treatment and stand growth on changes in runoff components from a forested watershed

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ABSTRACT: Runoff generation under various natural conditions has often been studied in forested watersheds for a long time. In 1967, Hewlett designed a variable source area model. The model is based on the expansion and shrinkage of variable source areas and consequent changes in a drainage network during a discharge event. The runoff investigation was carried out in a forested watershed situated in the summit area of the Orlické hory Mts. The watershed has a drainage area of 32.6 ha with the land-surface elevation ranging from 880 to 940 m a.s.l. Runoff components, their amounts and ratios were calculated using a simple graphical-mathematical method of the hydrograph recession limb analysis according to a reservoir model representing the particular components (base flow, subsurface flow and overland flow, in other words slow, accelerated and rapid flows). Comparing the amount of slow and rapid runoff constituents (89.5–99.4% and 0.6–10.5%, respectively), the greater amount of slowly moving water confirmed that overland flow was absent under conditions of forest environment. Not even the drainage treatment altered this positive ratio of the runoff constituents. During the third period, under stabilized hydrology and stand conditions, the accelerated and rapid runoff increased again, however maximally by 10% and 4%, respectively, not reaching the initial size of the calibration period.

Keywords: drainage treatment; forested watershed; recession limb; runoff components; stormflow hydrograph

Generation of runoff within forested watersheds has often been studied for many years under various natural conditions. Šach reported Horton's model (Horton 1933) constructed in the 1930's as the design used for a long time to determine runoff from watersheds under forested-site conditions (Krečmer et al. 2003; Šach et al. 2003). According to this model, runoff is generated due to the gradual concentration of overland flow as the precipitation rate exceeds the rate of infiltration (Satterlund, Adams 1992). In 1967, Hewlett devised a variable source area model (Hewlett, Hibbert 1967). The model is based on the expansion and shrinkage of variable source areas and consequent changes in a drainage network during a discharge event (Fig. 1). Comparing both models, the variable source area model reflects the nature of discharge event generation much better under conditions of forested watersheds since the prevailing amount of runoff is represented by subsurface flow.

Total runoff from watershed including its components is driven by both the hydrological cycle constituents and the characteristics of watershed. Neither human-induced nor site-specific conditions are necessarily leading to the total runoff alteration, however the components change certainly. Therefore if we need to find changes in runoff in a watershed using the total runoff investigation, we have to evaluate the components. The total runoff is usually divided into three components: base flow (groundwater outflow), subsurface flow (interflow or throughflow) and overland flow (Blažková 1991a,b, 1993; Tarboton 2003). The total runoff is sometimes divided into two constituents by the procedure of hydrograph separation: basic (base flow) and direct runoff (sum of both interflow and overland flow). The direct flow

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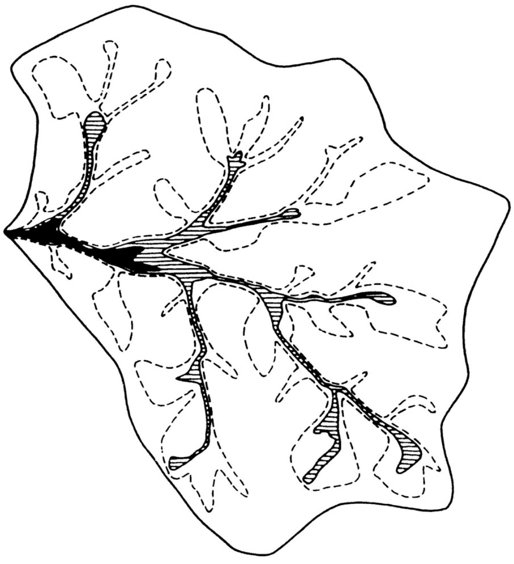

Fig. 1. Illustration depicting the theory of variable source areas (Satterlund, Adams 1992) generating subsurface flow in a small forested watershed. The picture shows a periodical variability of the runoff generation. Black area is a permanent stream runoff source. Horizontally-hatched areas generate runoff seasonally in late winter, spring and early summer. Areas enclosed with a dashed line act as source areas only during wet periods rich in precipitation. The only periods when the whole area of watershed generates runoff are heavy-rainfall events for several days or during snow melting

is considered as the amount of precipitation minus interception, infiltration, evaporation and storage losses (Hrádek 1988; Kemel 1996).

First, the effects of drainage treatment and stand growth on changes in runoff were analyzed and interpreted employing the frequencies of mean daily streamflows and master hydrograph falling limbs – simple modelling recession and depletion curves (Černohous 2006b; Černohous, Šach 2007), then using the unit hydrograph method (Černohous, Kovář 2009). In the present paper, we articulate this principal research question: Do both the drainage treatment and the growth of young forest stands affect the constituents of total runoff in the watershed?

MATERIALS AND METHODS

Study area

The U Dvou louček (UDL) study area is a small forested watershed situated in the summit part of the Orlické hory Mts., East Bohemia (Švihla et al. 2005; Černohous 2006a). The watershed has a drainage area of 32.6 ha with the land-surface elevation ranging from 880 to 940 m a.s.l. Soils in the UDL study area are classified as Podzols and Cambisols derived from the gneiss and mica schist bedrock; there was also found a small patch of peaty Gleysol. The forest site belongs to the spruce with beech vegetation type situated on acidic, waterlogged and locally peaty soils. The total thickness of Quaternary unconsolidated material (sandy and clayey soil with 20–50% amount of coarse fraction) ranges from 1 to 2 m. Soils formed under such conditions are mostly well drained except the Gleysol patch, which is affected by a rising water table. The waterlogged area occurs above the gneiss-mica schist tectonic boundary acting as a hydraulic barrier. There were found many natural springs near tectonic faults as well.

Long-term average annual precipitation is 1,350 mm, discharge 910 mm and evaporation 440 mm. A stream discharging into the watershed is a tributary of the Anenský potok brook. Average annual air temperature is 4.4°C. Because of locally waterlogged soils, drainage treatment was conducted in order to restore discharge conditions in the watershed. In 1996, drainage ditches were dug to meet the following requirements in the core area of the watershed of approximately 3 ha, i.e. to drain surplus water away from waterlogged patches, to restore natural streams and to interrupt discharge through artificial channels formed by logging machinery (ČSN 75 0140; ČSN 75 4306; ČSN 75 4200; Hartman 1995; ČSN 75 0146). The ditches (60–70 cm in depth) are situated within the 3 ha core area in the middle of the watershed.

Experiment performance and data assessment

Runoff is divided into components. Their amount and ratios are calculated using many mathematical and graphical-mathematical methods. We have chosen a simple analysis of the recession (falling) hydrograph limb (Drainage 1973; Linsley et al. 1975; Chow et al. 1988; Stehlík 1998). This method is based on Boussinesq's linear reservoir (Boussinesq 1904) and Kraijenhoff's reservoir (Kraijenhoff van de Leur 1958) including their dividing system representing the particular components of total runoff, i.e. base flow, subsurface (storm)flow (interflow, throughflow) and overland (storm)flow, in other words slow, accelerated and rapid flow.

The time series of the investigation were divided into particular periods in order to calculate the mean unit hydrograph comparison using double-mass curves of both runoff and precipitation. The annual rainfall-runoff ratio is nearly constant under temperate climatic conditions during a year. In other words, the ratio provides a straight line for long-term periods. The double-mass curve method helps verify the stability of

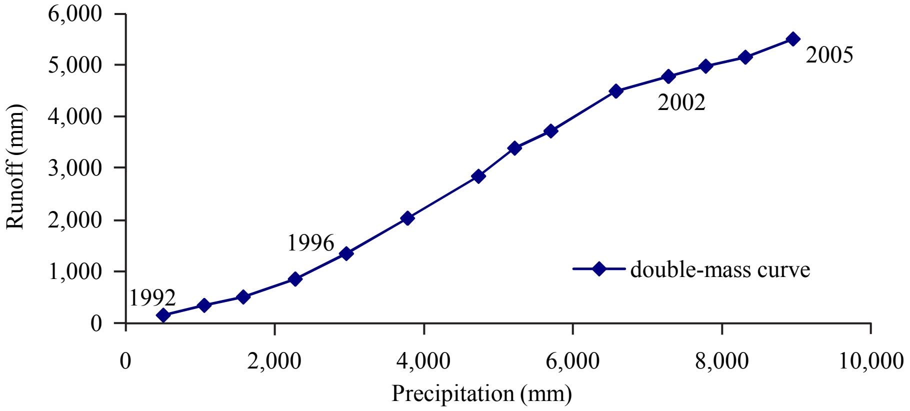

Fig. 2. Double-mass curve of summer water in 1992–2005

natural conditions of the study area. If the line changes its form (slant), a cause is to be found in the particular year (e.g. inhomogeneity of data caused by recording equipment, road-construction disturbance including drainage treatments, land-use management within the watershed and climate) (Šír et al. 2004).

The data collected during the investigation provide the following information. The investigation span includes three periods reflecting runoff changes: first – a calibration period represents runoff conditions before drainage treatment (water years 1992–1995), second – post-drainage period (1996–2001) and third – period of forest stand hydrology restoration (2002–2005).

The periods were determined using the construction of double-mass curves describing rainfall-runoff ratios for both growing and dormant seasons and for water years. The change in the trend that was found in growing seasons in 1996 and 2002 helped to determine the post-drainage period typical of increased runoff (Fig. 2). On the other hand, the restoration period (2002–2005) was determined using a comparison with the calibration (pre-treatment) period; the trends of double-mass curves for both periods were nearly identical at the 95% statistical significance level suggesting a restoration of the runoff coefficient value back to the initial level. Similar trends were found by Krečmer et al. (2003) and Bíba et al. (2005), though they were interested in clearcut-induced runoff. The restoration was considered as subsequence reflecting the development of regenerated forest stand. Under such conditions, the fluctuation of runoff can be related to the loss and restoration of both interception and transpiration. On the other hand, the drainage-induced change led to different runoff situation persisting till the drainage system efficiently worked. However, we suppose that both vegetation and drainage ditches influence runoff from the UDL study area as synergy factors. More than 80% of the area cover was a young spruce thicket which influenced runoff due to the uptake of water and transpiration. Also flowpaths of infiltration are multiplied due to extending roots as water is driven to percolate along them. Rainfall water enters the forest soil and percolates through large pores allowing soil water to move faster in both saturated and unsaturated profiles (Sidle 1980; Nižnanská 2005). Therefore, the third-period runoff did not represent a restoration of initial conditions but it most likely showed stabilization at new a level resulting in double-mass curve similarity (of its slant).

We chose 76 suitable discharge events from summer water half-years (with distinct inflection points on the hydrograph falling limb and without excessive fluctuation caused by marginal precipitation events) to separate the runoff components. In particular, 11 belong to the calibration period, 37 to the period after draining treatment and 28 to a subsequent period with stabilized hydrological and silvicultural conditions. The years of break were determined using the double-mass curve method. Hydrograph analysis of the stormflows was done by separating single runoff components (groundwater outflow, subsurface and surface runoff). The runoff amount of separated components was calculated and percentage in total runoff was expressed. The amount of surface (rapid), subsurface (accelerated) and groundwater (slow) discharge was assessed for stormflow events before and after drainage network reconstruction. Besides, the influence of growing up spruce thicket was also taken into account, because both the drainage system reconstruction and the forest stand regeneration represented changes in conditions for runoff generation. A graph resulting from the recession limb analysis shows a discharge event on the 14th July 1999 (Fig. 3).

The overland flow is nearly negligible under forested-site conditions (Kantor 1983, 1984a,b; Šach et al. 2000; Krečmer et al. 2003), therefore water moves mainly through soil as so called subsurface lateral flow. This is the main reason why we preferred the following terminology expressing the total runoff

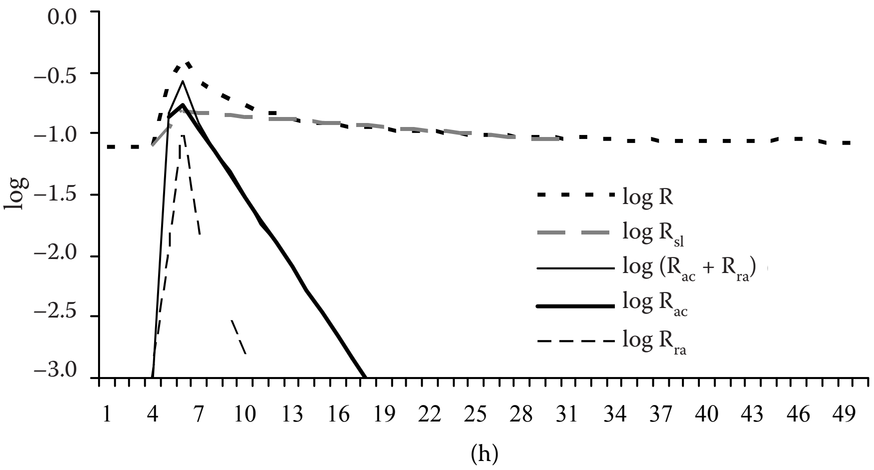

Fig. 3. Separated runoff constituents resulting from the recession limb analysis, hydrograph is from 14th January 1999

components: slow flow, accelerated flow and rapid flow.

We found a strong relationship between the runoff amount and the peakflow rate, therefore discharge events could be divided into three different groups. Each data set represents the extent of peak discharge events, partially related to the division of mean daily discharge reflecting runoff generation and advance. According to the mean daily discharge frequency, these three data sets represent a small discharge of low peakflow rates with the highest frequency, medium discharge of various peakflow rates with variable frequency and the least frequent high peak discharge of large volume. According to the theory of variable source areas (Hewlett, Hibbert 1967) and amount of excess rainfall, these data sets represent: small-volume and low-intensity precipitation related to the active variable area near streams, medium-volume precipitation of fluctuating intensity activating different number of source areas at various distances from streams, large-volume precipitation often of high-intensity activating all source areas within the watershed. The range of peakflow rates of the three data sets was determined as follows: less than 20 $l \cdot s^{-1}$, 20–60 $l \cdot s^{-1}$, more than 60 $l \cdot s^{-1}$.

RESULTS AND DISCUSSION

Existing investigations (e.g. Heikurainen 1980; Waddington et al. 1993; Lundin 1994; Newson 1994; Ambroise et al. 1996), dealing with draining waterlogged forest catchments and growing stands in relation to runoff, assessed total runoff and its extremes in the progress of time. Unlike them we dealt with dividing the runoff into components using the analysis of hydrograph by separation its recession limb and determining only the runoff constituents and their comparison also in the process of time. Similarly, the influence of land use changes on the ratio of runoff components (surface runoff and subsurface water recharge) for small forested catchments was observed and modelled simulating scenarios by Kovář (1998).

The constituents of runoff and their changes were expressed in percentage (Fig. 4). The discharge events typical of peakflow rates less than 20 $l \cdot s^{-1}$ are in accordance with the above-mentioned way the runoff is generated in variable source areas. The proportion of both rapid (R_{ra}) and accelerated (R_{ac}) runoff ($R_{ra} + R_{ac} = 24.4\%$) detects a low-runoff variable source area typical of runoff generated from water-saturated soil layers situated near streams (near-stream saturated zones) and water-logged patches occurring before drainage treatment (less than 1/6 of the total watershed area). The slow runoff (70–90%) compared to other data sets with higher peak flow seems to be permanently supplied with groundwater outflow from more distant source areas.

Moreover, the drainage treatment increased dynamic retention of precipitation in soil, i.e. fall of water table and aeration of soil leading to its moisture change. Consequently the accelerated runoff decreased by 3.9%; in fact the rapid runoff disappeared (the value dropped from 10.5% to 0.6%). Subsequently the water resided in soil was released to increase the slow runoff constituent by 13.8%. Later on during the third, hydrology and stand-stabilized period both rapid and accelerated runoff constituents increased again. We attributed the altered runoff constituents to improved soil porosity due to the growth of forest stand (Tužinský 2004). Some authors also reported that growing roots play an important role in the process of formation of preferential flowpaths for water (Sidle 1980; Krečmer et al. 2003; Nižnanská 2005). The former constituent increased to 4.7% representing a lower level compared to the period before drainage (10.5%). On the other hand, the latter one increased

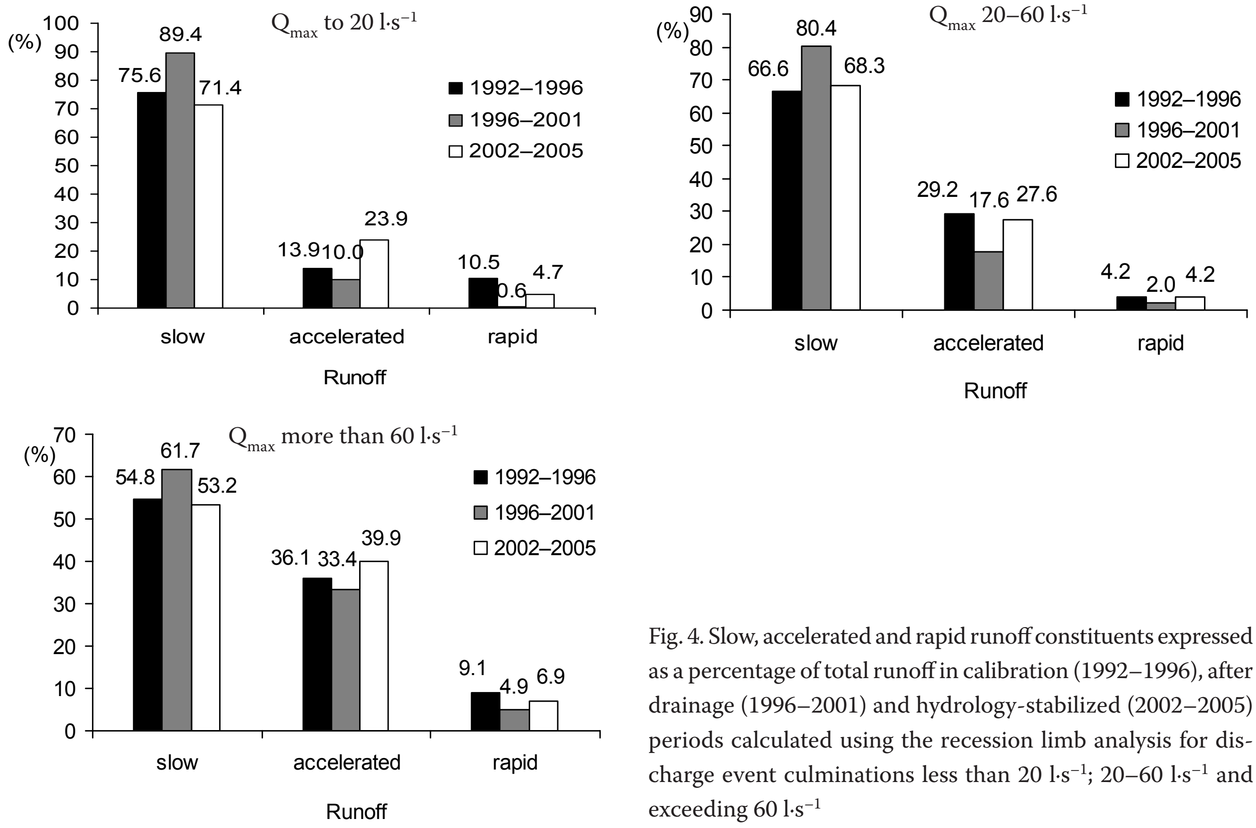

Fig. 4. Slow, accelerated and rapid runoff constituents expressed as a percentage of total runoff in calibration (1992–1996), after drainage (1996–2001) and hydrology-stabilized (2002–2005) periods calculated using the recession limb analysis for discharge event culminations less than 20 l·s^{-1}; 20–60 l·s^{-1} and exceeding 60 l·s^{-1}

substantially compared to the period after drainage (by 13.9%) and calibration period (by 10.0%).

Even though runoff was found to be accelerated, water moves through soil being many times slower compared to surface conditions (Švihla et al. 1992; Kutílek et al. 1996; Krečmer et al. 2003). The slow runoff constituent decreased by 18.0% compared to the period after treatment and by 4.2% compared to the calibration period to 71.4% of total runoff.

The set of hydrographs depicting peakflow rates between 20 and 60 l·s^{-1} characterizes various precipitation-input conditions influencing the number and size of active source areas. These hydrographs represent a middle-runoff interval typical of annual variability of discharge amounts. Compared to lower peakflow rates being less than 20 l·s^{-1}, the above-mentioned set of hydrographs shows a lower proportion of slow runoff (65–80%), higher proportion of accelerated runoff (17–30%) and a little lower proportion of rapid runoff (2–4%). The higher proportion of accelerated runoff indicates the runoff of increased precipitation from more distant variable source areas via subsurface lateral flow.

The drainage treatment influenced runoff conditions in terms of decreasing both accelerated and rapid constituents (by 11.6% and 2.2%, respectively) while the retention and slow runoff constituent increased (by 13.8%) during the period after treatment. The preferential flowpaths were likely to induce similar changes (amounts of runoff constituents) during the hydrology and stand-stabilization period, i.e. for peakflow rates less than 20 l·s^{-1} (accelerated and rapid runoffs increased by 10.0% and 2.2%, respectively while the slow constituent decreased by 12.1%). For peakflow rates between 20 and 60 l·s^{-1}, we found an obvious similarity in the percentage of runoff constituents in both the calibration and the hydrology and stand-stabilization periods (Fig. 4) being also confirmed by double-mass curve analysis.

The least frequent high-precipitation discharge events (peakflow rates over 60 l·s^{-1}) activating all variable source areas within the watershed characterize the distribution of particular runoff constituents, i.e. 53–62% slow runoff, 35–45% accelerated runoff and 5–9% rapid runoff. Both drainage-induced and stand-induced changes are detectable even for high-peakflow events being similar to low-peakflow ones (less than 20 l·s^{-1}) though not so conspicuous. The highest proportion of accelerated runoff proves that a high amount of precipitation water moves through the soil profile via lateral flow from more distant source areas.

The overland flow is considered absent under conditions of forested environment; it is proved that the slow and accelerated subsurface runoff is proportionally higher (89.5–99.4%) compared to the rapid runoff constituent (0.6–10.5%). This positive ratio was found even after the drainage treatment. Moreover, the rapid runoff was nearly eliminated (0.6%) during the low-peakflow events and this constituent also decreased by 2.2–4.2% during higher peakflows.

CONCLUSION

The results showed hydrographs expressing altered runoff in the watershed. The changes were influenced by both the drainage treatment and the forest stand growth. The concurrence of both events increases peakflow while the runoff amount in the recession limb of hydrograph decreases. We suppose an increased suction effect of the growing forest stand as the forest turns to small-pole and last-growth stages. The runoff components separated using the analysis of the recession limb hydrograph of U Dvou louček watershed origin are in accordance with the variable source area method (Hewlett, Hibbert 1967; Krečmer et al. 2003; Figs. 2 and 4). Increased amount of precipitation, larger source areas and longer travel time to the stream led to an increased part of lateral discharge through the soil. Comparing the amount of slow and rapid runoff constituents (89.5–99.4% and 0.6–10.5%, respectively), the greater amount of slowly running water confirms that overland flow is absent under conditions of forest environment. Not even the drainage treatment has altered this positive ratio of the runoff constituents. On the contrary, the rapid runoff diminished (0.6%) during the low-peakflow events and also decreased by 2.2–4.2% during the greater ones. During the third hydrology-stabilized period the forest stand growth led to an increased number of preferential flowpaths due to the growth of roots (Sidle 1980; Krečmer et al. 2003; Nižnanská 2005); the accelerated and rapid runoff increased again, however maximally by 10% and 4%, respectively, not reaching the initial level of the calibration period.

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