Forest watershed runoff changes determined using the unit hydrograph method

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ABSTRACT: Unit hydrograph is a basic method to show changes in runoff in the watershed. The investigation of runoff changes was carried out in the U Dvou louček watershed situated at the summit part of the Orlické hory Mts., East Bohemia. The waveform ordinates of recession limbs of unit hydrographs obtained using a common approach had to be approximated by the least-squares method. Final hydrographs reflected both drainage treatment and forest stand growth influencing the runoff from the watershed. Both factors increase culmination in synergy and reduce runoff on the recession limb of the hydrograph. We confirmed increased maximum runoff taking up 25–30% of the total runoff time when waterlogged sites were drained. The culmination increased by 0.2–0.8 mm/hour indicates the runoff increased by 2–8 m^3/ha/hr.

Keywords: forest watershed; drainage; runoff; double-mass curve; unit hydrograph

Unit hydrograph is meant to describe basic runoff components reflecting changes in watersheds. Waveforms of hydrographs, shape of runoff curve depend on the particular duration of rainfall and amount of precipitation since both physical and terrain conditions of watershed are considered constant. Therefore when the watershed changes in terms of these stable conditions, a subsequent change in hydrograph showing a difference of runoff is expected as well (Sherman 1932). That was the reason why the described method has been often used to develop hydrological models (Chow et al. 1988; Kovář 2000). Chow et al. (1988) described the unit hydrograph as a simple linear model that can be used to derive the hydrograph resulting from any amount of excess rainfall, though it is rather difficult to satisfy all assumptions under natural conditions of the watershed. We have chosen the method of unit hydrograph in order to evaluate runoff changes following drainage treatment. The study addresses the main research question: Does drainage treatment affect runoff from the watershed?

MATERIAL AND METHODS

The U Dvou louček (UDL) study area is a small forested watershed situated at the summit part of the Orlické hory Mts., East Bohemia (Švihla et al. 2005; Černohous 2006). The watershed has a drainage area of 32.6 ha with land-surface elevation ranging from 880 to 940 m above sea level. Soils in the UDL study area are classified as Podzols and Cambisols derived from the gneiss and mica schist bedrock; a small patch of peaty Gleysol was also found. 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 excepting

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the Gleysol patch which is affected by an increased water table level. The waterlogged area occurs above the gneiss-mica schist tectonic boundary acting as a hydraulic barrier. Many natural springs near tectonic faults were also found (Šeda 2003). Average annual precipitation is 1,350 mm, average annual air temperature is 4.4°C. The forest site belongs to the spruce with beech vegetation type situated on acidic, waterlogged and locally peaty soils. The UDL study area was 100% forest cover, of which approximately 90% was Norway spruce (*Picea abies*) and 10% European beech (*Fagus sylvatica*). The watershed forest experienced a heavy air-pollution load at the end of the eighties; thereafter almost all forest stands were logged over. Since that time the forests have been established again using artificial planting of Norway spruce. Nowadays, the 15-years-old spruce thickets make up approximately 85% of the watershed cover. Because of locally waterlogged soils, drainage treatment has been conducted in the watershed in 1996. Drainage ditches are situated in the core area of the watershed of approximately 3 ha.

Investigations were divided into particular time periods in order to calculate the mean unit hydrograph comparison using the double-mass curve of both the 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 to verify stability of natural conditions of the study area. If the line changes its form, the cause is to be found in the particular year (e.g. non-homogeneity of data caused by recording equipment, road-construction disturbance including drainage treatments, land-use management within watershed and climate) (Šír et al. 2004).

Data acquired during the investigation provide the following information: the investigation span includes three periods reflecting runoff changes. The first period – calibration period represents runoff conditions prior to drainage treatment (hydrological years 1992–1995), the second – post-drainage period (1996–2001) and the third – restoration period (2002–2005).

The periods were determined using the construction of double-mass curves describing rainfall-runoff ratios for both vegetation and dormant seasons and for hydrological years. The change of trend that was found in vegetation seasons in 1996 and 2002 helped determine the post-drainage period typical of increased runoff (Fig. 1). On the other hand, the restoration period (2002–2005) was determined using a comparison with calibration (pre-treatment) period; the trends of double-mass curves of both periods were nearly identical at the 95% statistical significance level suggesting the restoration of runoff coefficient value back to the initial level. Similar trends were found by Bíba et al. (2005) and Krečmer et al. (2003), though they were interested in a clear-cut-induced runoff. The restoration was considered as a consequence 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. The drainage-induced change led to a different runoff situation persisting till the drainage system worked efficiently. However, we suppose that both vegetation and drainage ditches affect runoff from the UDL study area as synergic factors. More than 80% of the area cover was a young spruce thicket which influenced runoff due to the intake of water and transpiration. Extending root systems also made water prefer these pathways of infiltration. Water of precipitation origin 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 was not the restoration of initial conditions but it was likely the stabilization at a new level resulting in double-mass curves similarity.

Constructing unit hydrograph

The form of unit hydrograph related to the duration of excess rainfall describes the rainfall-runoff process within the watershed depending on the shape, area, length and slope of valley line, hydraulic properties of soil etc. The unit hydrograph is defined as a function describing certain runoff (usually 10 mm) induced by excess rainfall of given duration being uniformly distributed throughout the whole drainage area (Hrádek 1988; Chow et al. 1988).

We have chosen the method by Hrádek (1988). He proposed to follow this procedure to derive the unit hydrograph related to rainfall using the measured duration of discharge waves:

– from a group of hydrographs of measured discharge waves we have chosen those induced by rainfall of certain duration t_d with steady intensity;
– both the direct and base runoff were separated;
– the amount of direct runoff is transformed to unit runoff H_o = 10 mm;
– average ordinates of the hydrograph related to the specific duration of rainfall (t_d) were calculated for all chosen time intervals.

The unit hydrographs for excess rainfall 10 mm and duration of 1 hour were calculated using appropriate

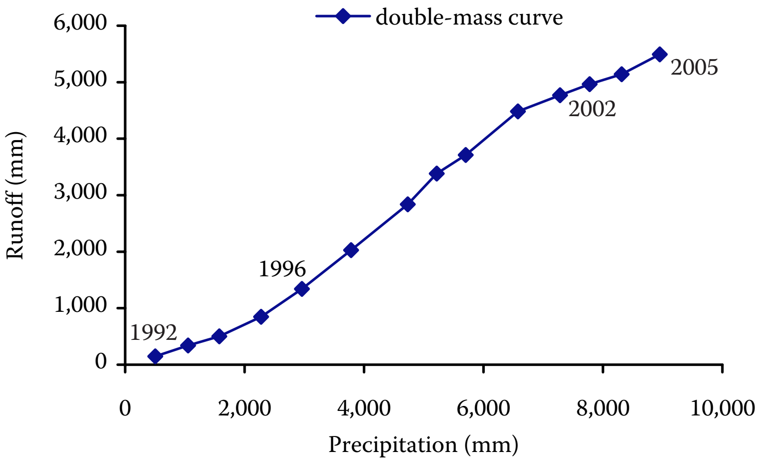

Fig. 1. The cumulative sum line of precipitation and runoff in the summer hydrological half-years 1992–2005

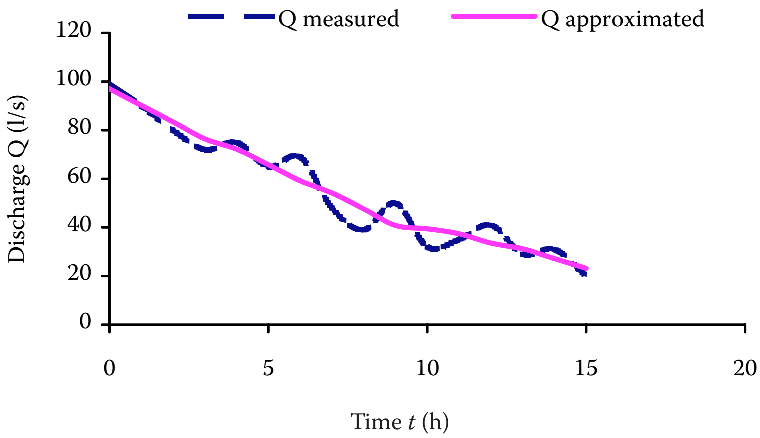

Fig. 2. The approximation of measured data using the least-squares method

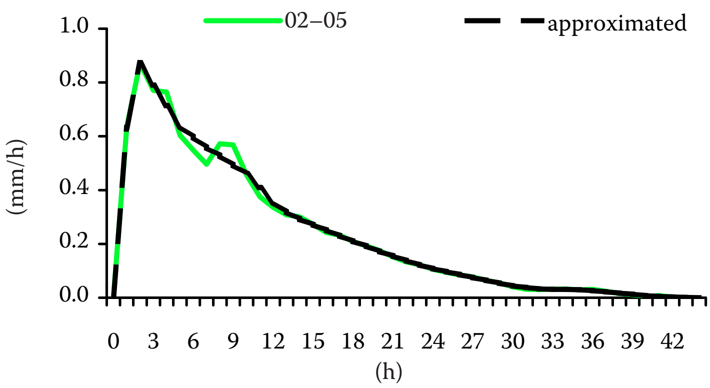

Fig. 3. Comparison of the mean hydrograph (green continuous line) with the approximated hydrograph (black dashed line) within a 44-hour period

discharge waves measured during the investigation period (1992–2005). Afterwards, the calculated hydrographs were divided into three groups of the above-mentioned periods (26 hydrographs – calibration, 33 hydrographs – post-treatment and 31 hydrographs – restoration). The hydrographs within the groups were separated according to the duration of the event (24, 44 and 60 hours, respectively). Finally, the calculation of average unit hydrographs for given duration followed with respect to both the form and length of original hydrographs including the unit runoff of 10 mm.

Approximation of unit hydrograph waveform

Only a smooth form of hydrograph reflects the continuous rainfall-runoff process properly, thus inflexion points have to be approximated in order to avoid the curve oscillation resulting from measured data. The ordinates of hydrograph were approximated (i.e. smoothed) using the least-squares method (Fig. 2). We chose Gram's polygons method using the dual-parametric function $F_{m,n}$ (t); parameter m means the degree of approximation and parameter n represents the number of approximation arguments

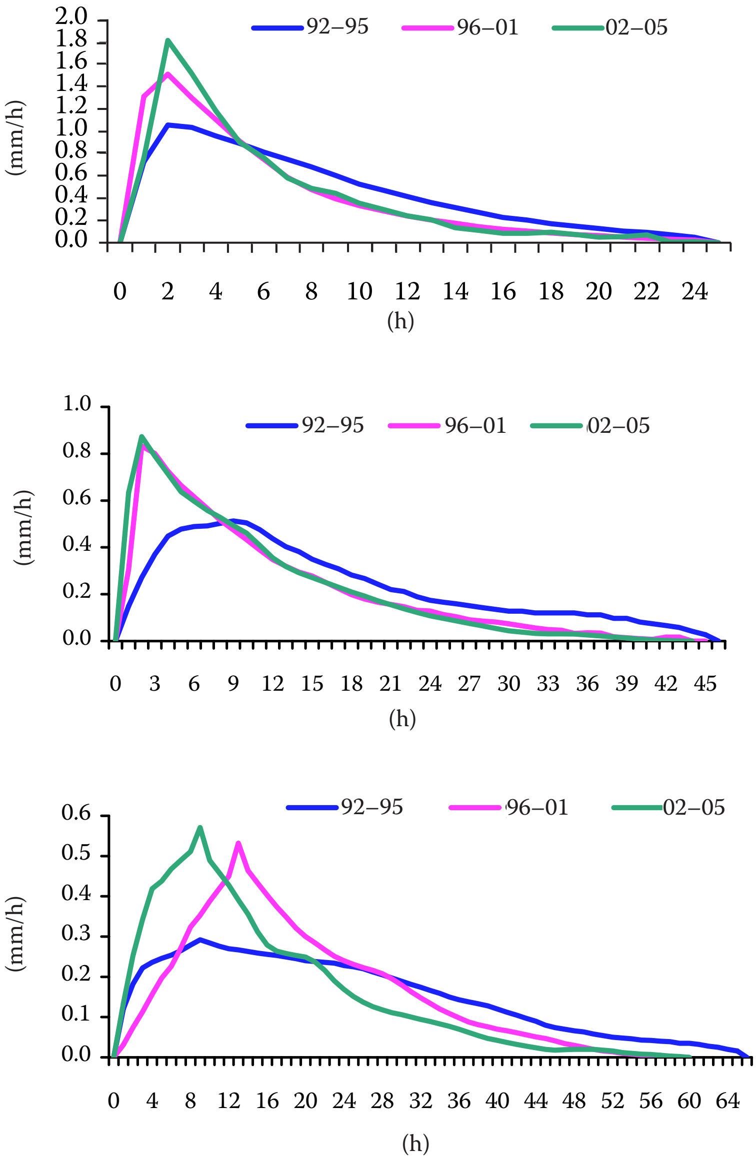

Fig. 4. Final approximated unit hydrographs in the investigated periods (92–95; 96–01; 02–05)

(Rektorys 1995). We also followed the recommendation (Olehla, Tišer 1975) to choose higher n ($n = 5$ instead of $n = 3$) to get a smoother curve. The list of approximated hydrographs is reported in Table 1.

RESULTS AND DISCUSSION

A comparison of both measured and approximated hydrographs (duration of event 44 hrs) shows the

Table 1. Approximated hydrographs by the duration of event and period

Duration of event	Period	Approximated part
24 h	1992–1995 (blue)	recession limb
	1996–2001 (red)	recession limb
	2002–2005 (green)	none
44 h	1992–1995 (blue)	both rising and recession limbs
	1996–2001 (red)	none
	2002–2005 (green)	recession limb
60 h	1992–1995 (blue)	both rising and recession limbs
	1996–2001 (red)	both rising and recession limbs
	2002–2005 (green)	both rising and recession limbs

Table 2. The ordinates of original mean hydrograph (X, Y) and approximated (X, F) ones obtained using the least-squares meters method within 44-hour periods in 2002–2005

X (I)	Y (I)	F (I)	X (I)	Y (I)	F (I)
0	0.000	0.000	23	0.122	0.122
1	0.633	0.633	24	0.106	0.108
2	0.873	0.873	25	0.095	0.097
3	0.771	0.790	26	0.085	0.086
4	0.765	0.714	27	0.078	0.075
5	0.604	0.637	28	0.064	0.065
6	0.548	0.597	29	0.055	0.054
7	0.496	0.558	30	0.041	0.044
8	0.572	0.528	31	0.032	0.038
9	0.568	0.493	32	0.030	0.033
10	0.456	0.461	33	0.032	0.031
11	0.375	0.409	34	0.032	0.031
12	0.336	0.355	35	0.029	0.030
13	0.308	0.318	36	0.031	0.026
14	0.301	0.292	37	0.024	0.022
15	0.272	0.271	38	0.016	0.017
16	0.242	0.251	39	0.011	0.013
17	0.233	0.230	40	0.005	0.008
18	0.209	0.210	41	0.008	0.005
19	0.193	0.192	42	0.002	0.003
20	0.175	0.172	43	0.000	0.001
21	0.152	0.155	44	0.000	0.000
22	0.133	0.138			

hydrograph ordinates (Table 2, Fig. 3) in the period 2002–2005. In addition to the changes of hydrograph waveform, the distribution of variable source areas (Hewlett, Hibbert 1967) has to be considered in the UDL study area since they affect the duration of discharge events; waterlogged patches also play a role in this process. Concerning the form and culmination points of hydrographs we found it difficult to show how the two main streambeds act in the watershed. We must also take into account that all described changes occur in the soil where water moves much more slowly compared to surface conditions (Švihla 1992; Kutílek et al. 1993; Krečmer et al. 2003). Moreover, the runoff at the surface of forest soils is so rare that it is often considered as insignificant (Kantor 1982, 1984a,c; Šach et al. 2000).

The changes of unit hydrograph waveforms (both limbs) proved significant changes of runoff after drainage treatment in the UDL study area (Fig. 4). There are obvious increased culmination points of both post-treatment periods (Table 3) including a steep decrease in discharge on the recession limbs reflecting faster discharge through large soil pores and a subsequent decrease in discharge due to increased soil retention compared to the calibration (pre-treatment) period (Švihla 1992; Švihla et al. 2005). On the other hand, the waveforms of pre-treatment period generally have no such culmination points. Discharge occurring on the recession limb of the hydrograph decreased gradually during this period.

Lower levels of the recession limbs of the hydrograph are related to the increased soil retention due to drainage treatment and lower saturation of water in soil induced by the progress of young forest stand evapotranspiration (Kantor 1984b,d;

Table 3. Culmination of unit hydrograph (mm per hour) during the investigated periods

1996–2001 (red)	2002–2005 (green)
1.51	1.81
0.83	0.87
0.53	0.57

Kantor 1989). The higher point of culmination and faster response to a precipitation event after drainage and event in the stabilization period may be affected by extended root systems forming preferential infiltration pathways (Sidle 1980; Švihla 1992; Nižnanská 2005). The short hydrographs (less than 24 hrs) did not show any change of the initial response to precipitation (culmination point in 2 hrs) after drainage treatment. These events occur within the smallest variable source area situated in the waterlogged part of watershed and near-stream zones within the shortest travel time to the stream.

Middle-span hydrographs (44 hrs) of larger source area show a longer travel time to the stream. They have a faster response to precipitation and higher culmination points in comparison with the calibration (pre-treatment) period. However, the recession limbs of the hydrograph show a similar downward trend in the calibration period; the only difference is the level of the values. 60-hour hydrographs showed the same response to precipitation compared to both the above-mentioned shorter ones. The form of the rising limb is similar, though the culmination points differ in height suggesting a certain trend of response similarity to long-term discharge events causing large amounts of runoff from the watershed even in different periods (calibration and stabilization). The faster response in the calibration period depends on an earlier reduced soil retention capacity of waterlogged patches in the watershed. Later, during the stabilization period, it is a process caused by manifold preferential pathways being formed due to extending root systems. The long-term hydrographs describe a delayed response during the post-treatment period; the water is stored due to increased soil retention and then it is released reaching the stream in a long travel time since more distant source areas are involved.

CONCLUSION

The results confirm the expectation that drainage of waterlogged sites increases the span of maximal runoff; therefore, maximum runoff takes 25–30% of the total runoff time. The culmination increased by 0.2–0.8 mm/hr, i.e. 2–8 m^3/ha/hr. The culmination depends particularly on the size of variable source areas. Surprisingly, increased post-treatment culmination was also found even in the case of long-lasting and large-amount events from larger variable source areas. Herynek (1980) and Švihla (1992) reported lower culmination (increased discharge); they investigated watersheds which were not artificially drained in the whole area (within the UDL study area – approximately 1/6 of the area is drained). Švihla (1992) also reported fast discharge from large pores within the drainage-treated area. Subsequently, an adjacent non-drained area releases more water compared to the treatment. This relationship is not likely to be valid for the small watersheds having important hypodermic outflow where the drainage treatment is situated in lower parts. The ditches work to drain water reaching the stream laterally from the higher parts of steep mountain slopes. Final unit hydrographs show changes of hydrological conditions (runoff) affected by drainage treatment including the influence of forest stand in the watershed. Both factors acting together increase culmination and decrease runoff on the recession limb of the hydrograph. However, further investigations are needed. One of the suggested research questions is whether the forest stand will affect the form of the hydrograph due to expected increased uptake of water.

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Změny odtoku z lesního povodí určované metodou jednotkového hydrogramu

ABSTRAKT: Jednotkový hydrogram je základní metodou ukazující změny odtoku v povodí. Toto sledování změn odtoku bylo provedeno v rámci povodí U Dvou louček, nacházejícího se ve vrcholové partii Orlických hor. Souřadnice křivky poklesové větve jednotkového hydrogramu získané klasickým postupem musely být aproximovány metodou nejmenších čtverců. Konečné hydrogramy ukazují změny odtoku z povodí jak v důsledku vlivu hydromelioračního zásahu, tak vlivu vyvíjejícího se lesního porostu. Oba tyto faktory společně zvyšují kulminaci a redukují odtok vyjádřený poklesovou větví hydrogramu. Bylo potvrzeno, že odvodnění v hydromorfních stanovištích zvyšuje odtok po dobu 25–30 % celkového trvání odtoku. Zvýšení kulminace o 0,2–0,8 mm za hodinu představuje odtok navýšený o 2–8 m^3/ha/hod.

Klíčová slova: lesní povodí; odvodnění; odtok; dvojitá součtová čára; jednotkový hydrogram

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