Analysis of rainfall-runoff events in four subcatchments of the Kopaninský potok (Czech Republic)

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Analyse von Niederschlags-Abfluss-Ereignissen in vier Teileinzugsgebieten des Kopaninský potok (Tschechische Republik)

1 Introduction

Approximately a quarter of agricultural land in the Czech Republic is artificially drained (Kulhavý et al., 2007). Understanding the hydrological flow pathways and rainfall/runoff relationships in catchments with tile drainage systems is crucial for modelling stream outflow response and water balance as well as for water quality issues. Tile drainage combined with preferential pathways in soil may form a rapid route of runoff generation (Heppell et al., 2000; Chapman et al., 2001). It may also be a significant source of sediment transfer to streams (Deasy et al., 2009) and a factor in high nutrient loads arising from drained catchments (Doležal et al., 2003; Honisch et al., 2002; Hirt et al., 2005).

When analysing nutrient balance in the Kopaninský potok catchment, it becomes evident that, due to the high runoff volume, a large proportion of total nitrate flux occurs during rainfall-runoff events. Rainfall-runoff process analysis is a pre-requisite for understanding of nutrient concentration changes in streams. Rapid subsurface runoff in hilly regions of the Czech Republic with prevailing shallow cambisols may be generated by such mechanisms as: a) macropores and cracks (Šanda & Císlerová 2000; 2009); b) sudden release of capillary water due to hydraulic instability (Tesař et al., 2003; 2004); and c) rapid increase of groundwater level when water from an event infiltrates soil via macropores and fissures (Zajíček et al., 2011). A general understanding of runoff response volume, timing changes, and major influencing factors is a necessary prerequisite to develop hypotheses about the main rainfall-runoff processes in any catchment situation.

2 Materials and methods

2.1 Subcatchments

The Kopaninský potok catchment is the site of a long-term (since the 1980s) hydrologic research (Doležal & Kvítek, 2004). It is situated in the crystalline area of the Bohemo-Moravian highlands of the Czech Republic. The average annual precipitation is 665 mm and average annual temperature is 7 °C. The altitude ranges from 467 to 578 m a.

Zusammenfassung

An vier Teileinzugsgebieten wurden Niederschlags-Abfluss-Ereignisse mit Niederschlägen größer als 10 mm für die Jahre 2005 bis 2012 analysiert. Die Einzugsgebiete (0,07–0,649 km^2) unterscheiden sich im Ausmaß der Drainagierung und der vorherrschenden Landnutzung. Vierzig Ereignisse wurden hinsichtlich Abflussvolumina und der Konzentrationszeit analysiert. Die Abflussbeiwerte der landwirtschaftlichen Gebiete lag bei 10 % (max. 18 %), während die bewaldeten Einzugsgebiete normalerweise weniger als 3 % (max 6 %) zeigten. Es wurde kein starker Zusammenhang zwischen Abflussbeiwert und Anfangsfeuchtegehalt im Gebiet oder der Niederschlagsintensität festgestellt. Die Scheitelverzögerungszeit betrug 12–50 min für hohe Niederschlagsintensitäten (15–50 mm/h), sie verdoppelte sich nahezu bei Niederschlagsintensitäten von 5–15 mm/h und erreichte 18 h bei niederen Intensitätswerten kleiner 3 mm/h. Teilgebiete mit geringerem Drainageanteil zeigen oftmals doppelte Abflussscheitel. Hier traten auch die schnellsten Abflussreaktionen auf.

Schlagworte: Niederschlags-Abfluss-Beziehung, Kleineinzugsgebiete, Drainagierung.

Summary

We analysed runoff events caused by rainfalls exceeding 10 mm at four subcatchments of the Kopaninský potok experimental catchment in years 2005–2012. The subcatchments (0.07–0.649 km^2) differ in extent of tile drainage and prevailing land use. Forty events were analysed together for runoff volume and the time between the center of gravity of the rainfall event and peakflow recorded at the catchment outlet. Agricultural subcatchments usually discharged up to 10 % (maximum 18 %) of rainfall volume, while the fully forested subcatchment typically discharged less than 3 % (maximum 6 %) of precipitation. We did not find strong relationships between the percentages of discharged rainfall and initial wetness of the subcatchments or precipitation intensity. The lag time of peak flow was 12–50 min for the high intensity rainfalls (15–50 mm/h). The lag times nearly doubled for rainfall intensities 5–15 mm/h time and reached 18 h for the low rainfall intensity (below 3 mm/h). Two runoff peaks were commonly observed in hydrograph records at the outlets of the two subcatchments with lower percentage of drained agricultural area. At those subcatchments, the fastest response was also recorded.

Key words: Rainfall-runoff relationship, small catchments, tile drainage.

s. l. Bedrock is shallow, consisting of partly weathered paragneiss. Soil is about 1–2 m deep, formed chiefly by three soil types (haplic and dystric cambisols; stagnic cambisols; and histic gleysols).

Table 1: Basic data of four subcatchments
Tabelle 1: Basisdaten der vier Teilgebiete

Subcatchment	P51	P52	P53	P6
Area (km2)	0.049	0.649	0.0712	0.157
Arable area (%)	0	31	98	96
Forest (%)	100	64	2	0
Prevailing soil type	Dystric Cambisols	Stag. Cambisols; Hist. Gleysols	Dystric. Cambisols	Dystr./ Stagn. Cambisols
Tile drainage area (%)	0	16	98	61
Average slope (%)	9.9	8.8	11.1	5.3

Subcatchments P51, P52, P53 and P6 (Table 1) were equipped with ultrasonic devices for water level recording. The records were recalculated to a 10-minute average discharge time series. The P53 flow gauge collected runoff directly at the tile drainage system outlet. 10-minute precipitation totals were collected by a 500 cm^2 tipping-bucket rain gauge at a distance of 1.2 km (rain gauge station VR in Fig. 1). Since 2011, precipitation totals were measured by two rain gauges at P53 and P52 sub-catchments (Figure 1).

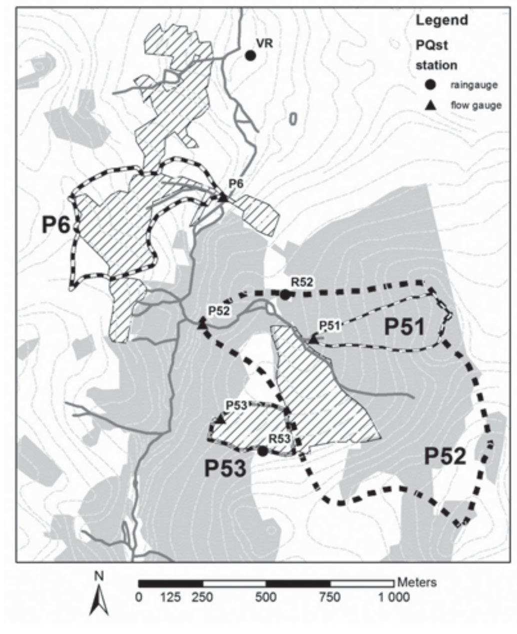

Figure 1: The four subcatchments of the Kopaninský potok catchment; the black and grey dashed lines represent water divides and contour lines, the hatched and light grey areas show tile drainage and forest, respectively

Abbildung 1: Die vier Teilgebiete des Einzugsgebiets Kopaninský potok. Die strichpunktierten Linien beschreiben die Gebietsgrenzen, die strichlierten Flächen zeigen Drainageflächen, graue Bereiche die Forstflächen

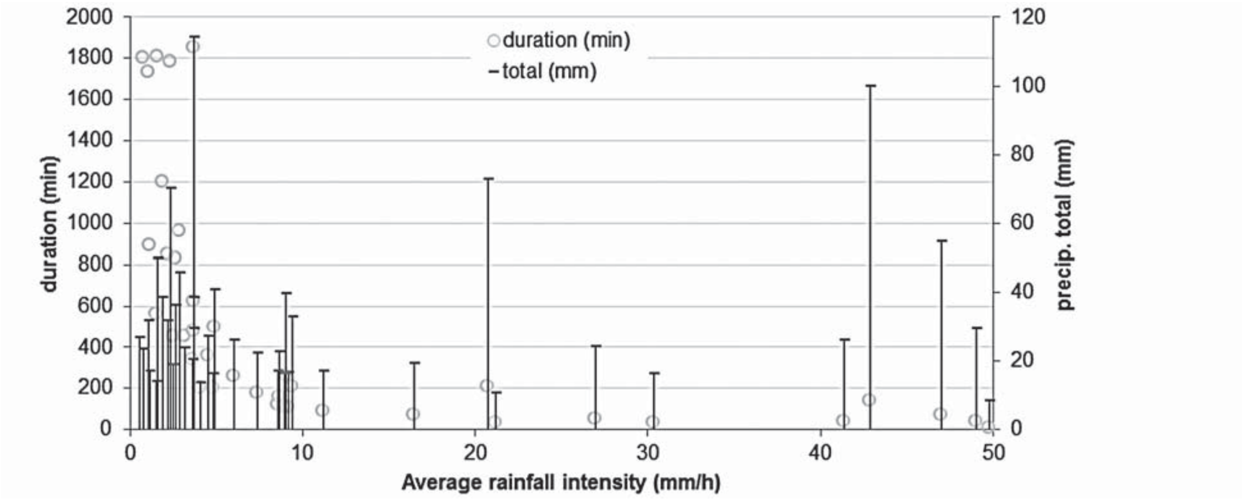

Figure 2: Overview of 40 rainfall events, arranged according to average rainfall intensity. Total precipitation (line) and duration (circle) is shown
Abbildung 2: Überblicksdarstellung von 40 Regenereignissen nach Regenintensität sortiert. Niederschlagssumme (Linie) und Dauer (Kreis) sind ebenfalls dargestellt

2.2 Data set

A data set consisting of 40 rainfall-runoff events in 2005–2012 during which total precipitation exceeded 10 mm was established (Figure 2). Data recorded during vegetation periods (May 1 to October 31) of 2005–2012 contained 11 short-term high intensity (> 10 mm/h) rainfall events and 12 long-term events with low precipitation intensity (< 3 mm/h).

2.3 Methodology

The following parameters were computed for each of the 40 rainfall-runoff events: total precipitation, total runoff, average precipitation intensity, lag time between the center of gravity of the precipitation event and peak discharge.

A subset of 26 events with total precipitation above 18 mm was used for the analysis of main factors influencing direct runoff volume. Direct runoff was calculated by subtraction of the constant value of base flow (equal to runoff at the beginning of the event) from the total catchment runoff. The runoff coefficient (ratio of direct runoff to precipitation total) was calculated for individual events. Catchment wetness conditions at the beginning of every event were characterised by antecedent precipitation index API (5 days) and by precipitation totals for 4 h, 8 h, 12 h, and 24 h prior the rainfall events. Relationships between rainfall intensity, rainfall total for an event, antecedent rainfall and direct runoff volume were tested. Three groups of events were distinguished: high average rainfall intensity (> 15 mm/h), wet conditions (precipitation total before an event > 10 mm), and all remaining events.

Second analysis focused on the differences in the response time during all 40 events in individual subcatchments. Lag time between the center of gravity of the precipitation event and peak discharge was computed for all events and subcatchments.

3 Results and discussion

Relationships between runoff coefficients, rainfall and catchment wetness characteristics are shown in Figure 3. The subcatchments drained for agriculture generally generated higher runoff than the forested subcatchment. However, none of the measured rainfall characteristics may be considered key to explain the varying runoff coefficients in individual subcatchments. We did not find strong correlations between runoff coefficient and rainfall intensity. The direct runoff volume in subcatchments P52, P53 and P6 was usually less than 10 % (maximum 18 %) of total precipitation for rainfall intensities 1–49 mm/h. Total precipitation for these rainfalls varied between 19 and 100 mm. The direct runoff volume in subcatchment P51 volume for the same rainfall intensities was typically below 3 % (maximum 6 %). These results correspond to the findings of Zajíček et al. (2011), who reported runoff coefficients of 5 to 12 % at the nearby experimental catchment Dehtáře.

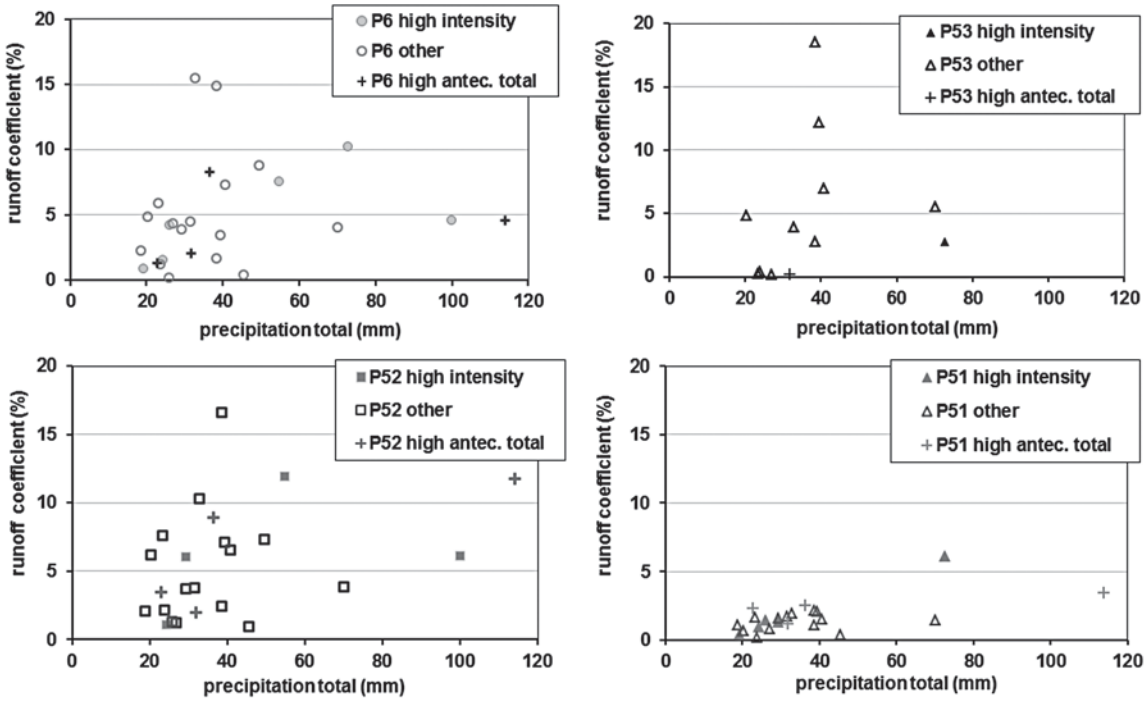

Figure 3: Relationships between runoff coefficients and total precipitation calculated for 26 events in four subcatchments with total precipitation exceeding 18 mm

Abbildung 3: Beziehung zwischen Abflussbeiwert und Gesamtniederschlag für 26 Ereignisse der vier Teilgebiete mit Niederschlägen größer als 18 mm

Weak correlations between runoff coefficients and rainfall and catchment wetness characteristics corresponds to the findings of e.g. CERDAN et al. (2004), KOSTKA & HOLKO (2003), but not to those of other studies (e.g. by MERZ et al., 2006). Further analysis with more complete data is required to reveal the main variables driving runoff volume differences.

The differences in runoff response of the subcatchments are shown in Figure 4. The figure shows an example of the events with two rain pulses. Hydrographs measured in subcatchment P52 had frequently two peaks (as seen in Figure 4). For this reason, lag times of fast (initial) and slow (secondary) response peaks of P52 were introduced into the analysis.

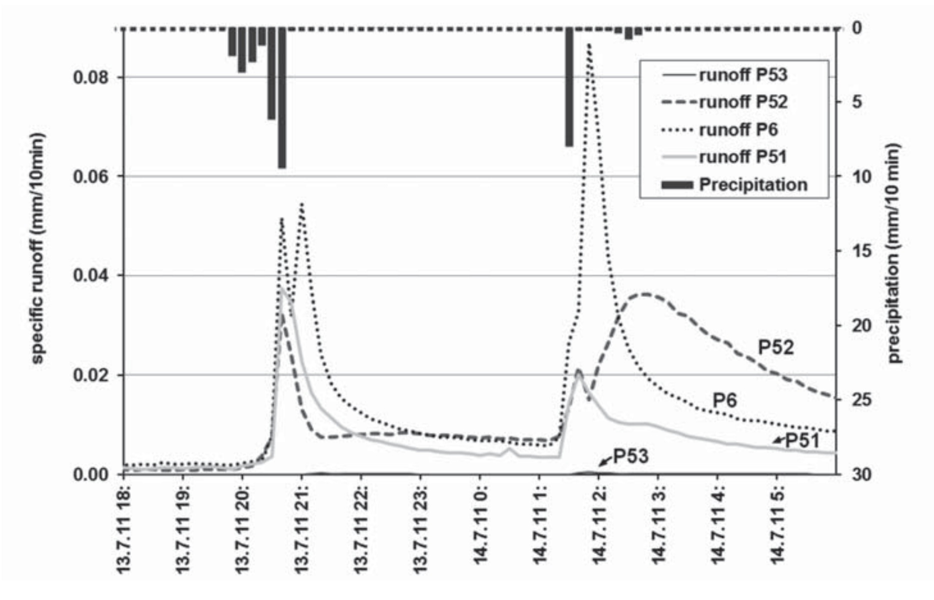

Figure 4: Typical rainfall-runoff event (24.5 mm + 10.9 mm total precipitation)

Abbildung 4: Typisches Niederschlags-Abfluss-Ereignis

Typical lag times are given in Table 2. The lag times of the initial (fast) response of subcatchment P52 form one group of the data, while the lag times of catchments P6 and P53 together with P52 (secondary response) form another group. A power function was fitted to data of P6, P53, P51, and P52 (secondary response) values. The linear correlation coefficient was greater than 0.79 in all cases. A subjectively established envelope (a power function) was added to data (Figure 5).

Lag times of the drained subcatchments P6 and P53 (Figure 5), and also of the secondary runoff response of forested subcatchments P51 and P52 was approximately in range of 30–70 min for high intensity precipitation events. The initial response of the forested subcatchments differs from them significantly, because fast runoff response (lag time less than 20 min) is observed there.

The response of all subcatchments was highly non-linear. It varied inversely with the flow rate. Such a behaviour was described e.g. by PILGRIM & CORDERY (1992).

4 Summary and conclusion

Volume of direct runoff during rainfall-runoff events in the fully forested subcatchment (about 3 % of precipitation total) is notably smaller than in the agricultural subcatchments with drainage (about 10 % of precipitation total).

Table 2: Typical lag time between the center of gravity of the precipitation event and peak discharge. Subcatchments of Kopaninský potok catchment, 40 events (2005–2012)

Tabelle 2: Typische Verzögerungszeit zwischen Niederschlagsschwerpunkt und dem Abflussscheitel anhand von 40 Ereignissen (2005–2012) am Einzugsgebiet Kopaninský potok

Mean rainfall intensity	P52 (fast)	P52 (slow)	P6	P53	P51
Low 0.6 – 5 mm/h	No response			380–1200 min	
Medium 5 – 12 mm/h	10–20 min	150 min	55 min	125 min	35 min
High 12 – 50 mm/h	0–15 min	70 min	28 min	50 min	12 min

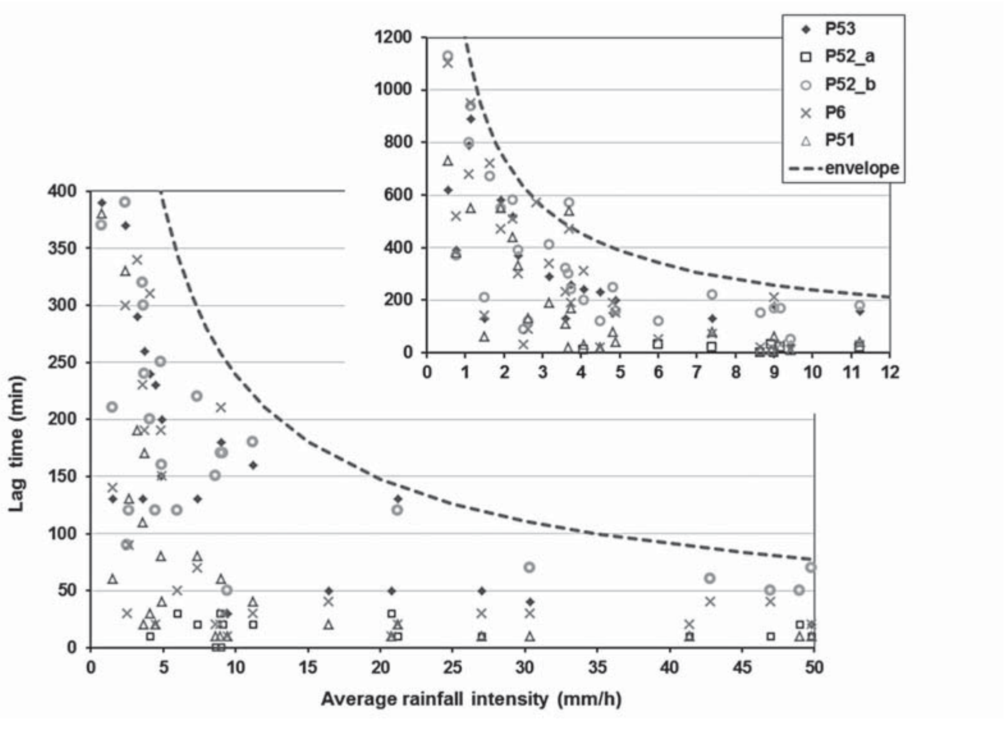

Figure 5: Relationship of the lag time and mean rainfall intensity in the subcatchments of the Kopaninský potok catchment, 40 events 2005–2012; initial response peak of subcatchment P52 is marked by the rectangle (P52_a)

Abbildung 5: Beziehung zwischen Scheitelverzögerungszeit und mittlerer Niederschlagsintensität der vier Teilgebiete. 40 Ereignisse zwischen 2005 und 2012. Der Anfangsscheitelwert bei Teilgebiet 52 ist durch das Quadratsymbol (P52_a) gekennzeichnet

We may conclude that a common rainfall-runoff mechanism for all subcachments emerges for mean rainfall intensities below 12 mm/h. For higher mean rainfall intensities, fast response observed in the forested subcatchments is not recorded at the drained subcatchments. A secondary runoff peak in the forested subcatchments is observed with lag time similar to that of the drained agricultural subcatchments.

Further analysis is required to reveal the precise role of additional factors such as initial soil moisture distribution and temporal changes in vegetation cover along with the runoff formation mechanisms in subcatchments of the Kopaninský tok catchment.

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