Hydrograph separation of runoff components based on measuring hydraulic state variables, tracer experiments, and weighting methods

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Abstract Hydrograph separation with natural tracers or isotopes has become a popular method to gain comprehensive insights into runoff processes. The mass balance approach, which uses the measured chemical signature of the rainfall as the signature of the event water, is generally used for this purpose. However, temporal variations in the composition of rainfall must be taken into account by an appropriate weighting technique that describes the time response of event water in a drainage basin. A conservative tracer was added to an artificially simulated intense rainfall event on a small forested hillslope plot. A simple mass balance approach coupled with an appropriate weighting technique was used to separate the event and pre-event water fractions of the surface and subsurface flow. Runoff processes and their relation to mixing between event and pre-event water are identified for both flow paths by means of a detailed survey of both soil water changes and soil properties, as well as through a dye tracer experiment. The experiment demonstrates the importance of event water contributions to subsurface runoff by preferential flow.

INTRODUCTION

Hydrograph separation using isotopes or natural tracers has become a frequently used technique in catchment hydrology. The simplest concept of hydrograph separation distinguishes between event and pre-event water. Event water is water from rain or snowmelt that enters and flows through the system during the flood, and pre-event water is soil or groundwater that is already stored in the system at the beginning of the event. Usually, it is assumed that the event water has the same bulk composition as the rain during the event. However, large variations in tracer concentration or isotopic composition are common during rainstorms (McDonnell *et al.*, 1990). These variations have to be taken into account by an appropriate weighting technique that describes the time response of event water in a drainage basin. If the hydrograph separation results are used to explain runoff processes in a catchment, it is commonly assumed that the event water dominates the surface flow (Pearce *et al.*, 1986). Harris *et al.* (1995), however, pointed out that event water can only be used as a value for surface flow if:

- the temporal variation of tracer concentration in the rain is small,
- the residence time of rain on the surface is short, and
- return flow (subsurface to surface) is negligible or its effects can be estimated by other means.

Usually the tracer composition of surface or subsurface flow during a rain event is not measured and therefore its composition has to be assumed. Rice & Hornberger (1998) have demonstrated that field hydrometric measurements and hydrograph separation should be coupled to allow a meaningful identification of flow components and their generation mechanisms. The present study implements an adequate weighting method to describe the time delay of rainfall reaching the sampling point. Some considerations on the potential limitations of these techniques are accordingly discussed. Moreover, a hydrograph separation for distinct hydrometric measurements (surface and subsurface flow) is presented in combination with the measurement of hydraulic state variables on a hillslope plot. These results allow a more detailed explanation of runoff processes and flow paths. Further considerations with respect to hydrograph separation in the total catchment are discussed.

FRAMEWORK OF THE ANALYSIS

Experimental set-up

The experimental work was carried out on a 17° to 25° steep forested hillslope plot (Fig. 1). The near-stream plot, with an area of 60 m^2, is located in the pre-alpine Swiss research basin of Vogelbach (Weiler *et al.*, 1998). A rainfall event of constant intensity of 60 mm h-1 was artificially applied for 195 minutes. A conservative tracer (bromide) was added to the artificial rainfall. The bromide concentration was 106.7 mg l-1 during the first 80 minutes of the experiment and 71.7 mg l-1 for the remaining time. The initial bromide concentration in the soil water was below the detection limit. The composition of pre-event water is therefore well defined and constant in time and space.

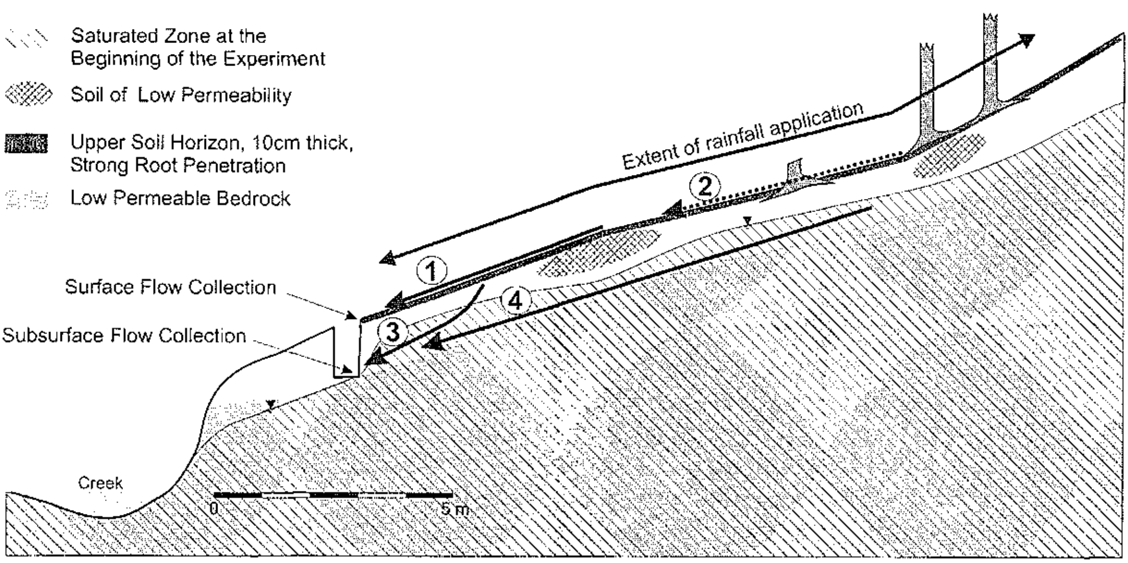

Fig. 1 Longitudinal cross section of the experimental hillslope showing the water table at the beginning of the experiment and the observed runoff processes.

Both the surface and subsurface runoff, as well as their bromide concentrations, were measured at the base of the plot. Hydraulic state variables were surveyed by measuring the soil moisture content with TDR probes (time domain reflectrometry), the matric potential with tensiometers and the extent of the soil saturation with piezometers. An additional dye tracer experiment under steady-state conditions was performed to obtain insight into the flow paths and flow velocities (Weiler *et al.*, 1998).

Hydrograph separation

Hydrograph separation is based on the mass balance approach to distinguish runoff from two sources and calculate the fraction or runoff from each source:

$$Q(t) = Q_e(t) + Q_p(t) \tag{1}$$

$$Q_p(t) = f_p(t)\,Q(t) \qquad \text{with} \qquad f_p(t) = \frac{C(t) - C_e(t)}{C_p(t) - C_e(t)} \tag{2}$$

where $Q(t)$ is measured runoff; $C(t)$ is concentration of a tracer; the subscripts e and p represent event water and pre-event water, respectively; and $f_p(t)$ is the fraction of pre-event water in runoff. Equations (1) and (2) rely on an assumed conservative behaviour of tracers in water flowing through the system, meaning the tracer concentration changes only by mixing.

As already pointed out (for details see McDonnell *et al.*, 1990), hydrograph separation requires an appropriate weighting technique to account for the time response of a system to event water, when temporal concentration variations in rainfall are observed. A response function $h(t)$ can be defined to consider the distribution of travel times along all possible flow paths of the hillslope. In the present experiment, the maximum travel time can simply be estimated as the length of the hillslope L divided by the average flow velocity v ($T = L/v$). The average flow velocities of the surface flow ($8.3*10^{-3}$ m s^{-1}) and subsurface flow ($4.5*10^{-3}$ m s^{-1}) were determined through the dye tracer experiment using an instantaneous injection (Weiler *et al.*, 1998). Hence, for the 15 m long hillslope, a maximum travel time of 30 minutes for the surface flow and 55 minutes for the subsurface flow was calculated. For this rectangular hillslope plot, the response function is approached by a pulse function of duration T. According to linear system theory, the temporal variation of the precipitation depth p, the tracer concentration of the rain c, and the response function $h(t)$ are convoluted:

$$C_e(t) = \frac{\int_0^t c(\tau)\,p(\tau)\,h(t-\tau)\,\mathrm{d}\tau}{\int_0^t p(\tau)\,h(t-\tau)\,\mathrm{d}\tau} \tag{3}$$

The resulting event water concentration $C_e(t)$, derived from this *travel time weighting method* (equation (3)), can now be used to perform hydrograph separation.

RESULTS AND DISCUSSION

The most important flow paths investigated at the experimental plot are sketched in Fig. 1. The longitudinal cross-section of the hillslope shows the water table at the beginning of the experiment. The four main runoff processes were derived from additional measurements of hydraulic state variables and the dye tracer experiment. These processes are:

(1) saturation overland flow (SOF) in the lower part of the hillslope,
(2) a combination of SOF and Hortonian overland flow in the upper part of the hillslope,
(3) rapid subsurface flow through macropores and root channels, and
(4) slow lateral subsurface flow within saturated areas.

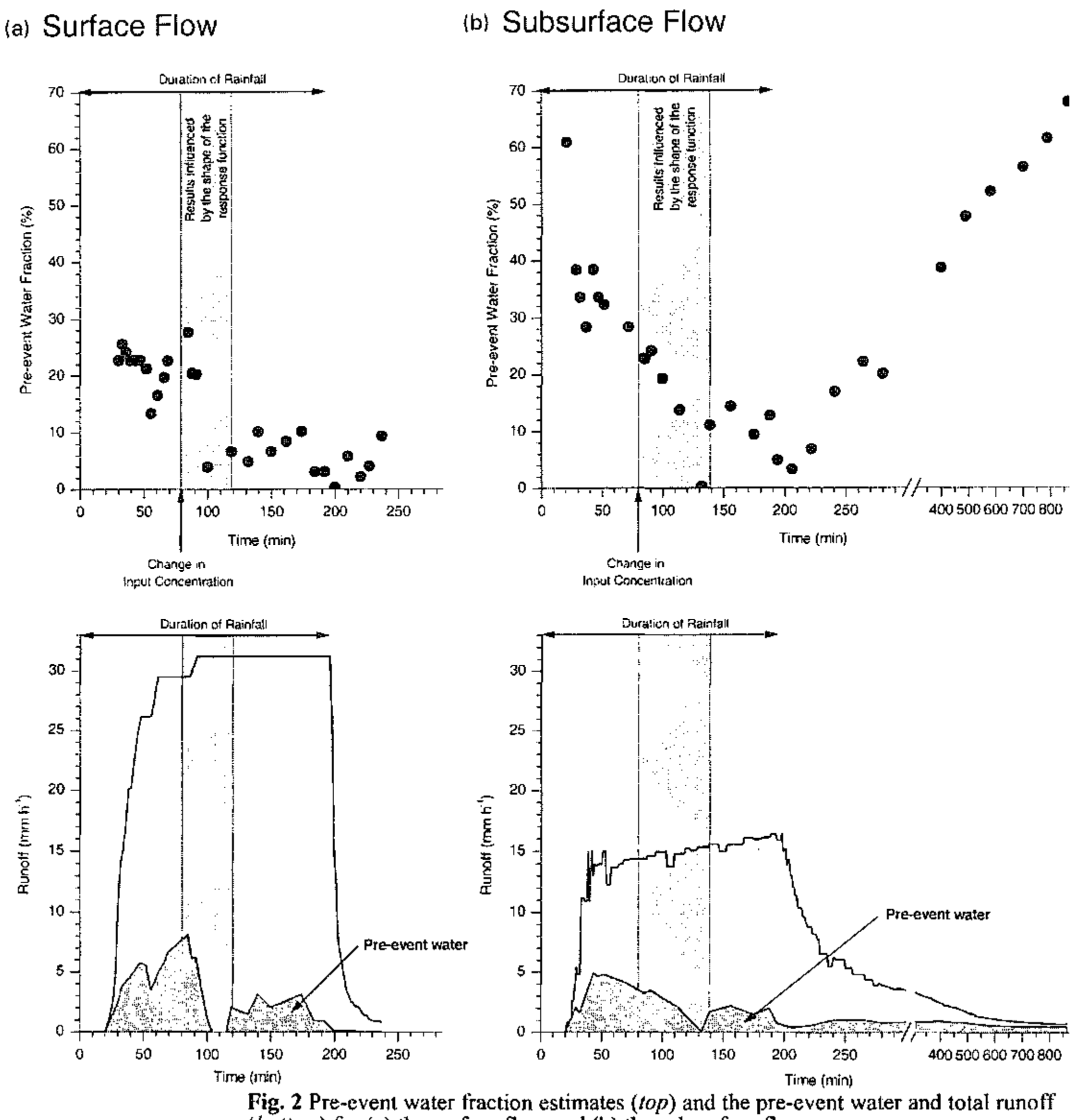

Fig. 2 Pre-event water fraction estimates (*top*) and the pre-event water and total runoff (*bottom*) for (a) the surface flow and (b) the subsurface flow.

The described hydrograph separation technique and weighting method were applied to estimate the pre-event water fraction ($f_p(t)$ in equation (2)) and the pre-event water runoff ($Q_p(t)$ in equation (2)) for the surface (Fig. 2(a)) and the subsurface flows (Fig. 2(b)). In the time window after the change in the tracer concentration of the rainfall, the calculated event water concentration depends on the shape of the response function. Therefore, the results in this time window can vary slightly, because the true shape of the response function is not known. However, the travel time weighting method has the advantage that the time response is directly considered, in contrast to the usually applied method of a weighted average or incremental mean method (McDonnell *et al.*, 1990). A comparison of the different methods showed that the latter give widely different results. Consequently, the travel time weighting method is recommended if the maximal travel time and the shape of the response function of the catchment can be determined independently. If the travel time of the catchment cannot be determined or an appropriate weighting method cannot be applied because of variations in the tracer concentration of the rainfall, a reasonable hydrograph separation can only be performed for time steps that are longer than the concentration time of the catchment.

For the present experiment, the hydrograph separation of the surface and subsurface flow, in combination with measured hydraulic state variables, leads to the following results. The pre-event water fraction of the surface flow (Fig. 2(a)) is around 20% at the beginning of the experiment and levels off around 5% after 100 minutes, after the upper soil horizon has been saturated. This pre-event water comes from return flow and from soil water (pre-event water) in the upper soil layer. Obviously, surface flow does not consist of event water alone, but is a mixture of event and pre-event water. Similar behaviour was observed by Elsenbeer *et al.* (1995), where it was shown that saturated overland flow is usually a mixture of flow on the soil surface and flow in the upper saturated soil layer.

During the experiment, the pre-event water fraction of the subsurface flow decreases continuously until 200 minutes. This decrease can be attributed to the mixing of rapid-flowing event water in the macropores with pre-event water in the surrounding soil matrix. The latter is successively replaced by event water, which results in a runoff peak of pre-event water at the beginning of the runoff reaction followed by a decline (Fig. 2(b)). This fast and dominating response of event water is due to preferential flow through macropores. This idea is supported by the observation of a sharp, simultaneous increase of the soil water pressure in macropores at different depths after the beginning of the rainfall application and the presence of a dense macropore network in the upper soil layer (Weiler *et al.*, 1998). During the recession of the subsurface flow, the runoff of pre-event water remains constant, such that the fraction of pre-event water increases. This behaviour can be attributed to slow lateral subsurface flow, represented by runoff process (4) in Fig. 1. The physically-based numerical hillslope model QSOIL (Faeh *et al.*, 1997) was used to calculate the macropore flow and the slow lateral flow in the soil matrix (Weiler *et al.*, 1998). The computation of the slow lateral flow (1.2–1.7 mm h^{-1}) in the lower soil layers, using a saturated hydraulic conductivity of $5.0*10^{-5}$ m s^{-1}, corresponds well with the separated pre-event water runoff of the subsurface flow (1.0–2.0 mm h^{-1}). Hence the continual, but low amount of pre-event water in the subsurface flow can be attributed to the lateral subsurface flow of soil water already stored in the saturated soil matrix prior to the experiment. The increase of the potential difference due to the applied rainfall generated this lateral subsurface flow in the soil matrix ("plug-flow"). But this plug-flow is only a small amount of the observed pre-event water.

In summary, the amount of event water in the surface and subsurface flow is high (Table 1). During the experiment, the total surface flow reached 85 mm while the pre-event water proportion amounted to 8.5 mm (10%). The total subsurface flow reached 66.9 mm, but only 15.1 mm (22.5%) could be attributed to pre-event water. These values can be compared to the water stored in the hillslope prior to the experiment. The amount of water stored in the soil can be estimated as the product of the soil thickness and the water content. The average soil thickness measured in the experimental plot was 1.0 m while the average water content was 32% (determined by TDR probes and soil samples). Thus, the soil held about 320 mm of water before the experiment. From this pre-event water, only 22.8 mm was transformed to runoff. Consequently, these figures again prove that plug-flow for the complete displacement of pre-event water was a minor process in this forested, near-stream plot.

Table 1 Event and pre-event water amounts of different flow paths from the experiment.

Components	Total (mm)	Pre-event water (mm)	Event water (mm)	Pre-event water fraction (%)
Precipitation	200.0	–	200.0	
Surface flow	85.1	8.5	76.6	10.0
Subsurface flow	66.9	15.1	51.8	22.5
Total flow	152.0	23.6	128.4	15.5
Storage and losses	48.0	-23.6	71.6	

A hypothetical estimation, assuming an intense rainfall event with a moderate depth of 50 mm instead of 200 mm on the experimental plot, results in a total pre-event water fraction of 37%. Thus, it can be assumed that smaller events produce more pre-event water due to the importance of mixing between event and pre-event water during the beginning of runoff generation. Similar relations were found in the whole Vogelbach catchment (1.55 km^2). According to hydrograph separation on four storm events in the creek using electrical conductivity (EC) as a natural tracer, the total pre-event water fraction was estimated to range from 60% for smaller events (30–35 mm of rainfall) to 46% for larger events (51–58 mm of rainfall). Thus, the order of magnitude between the whole catchment and the experimental hillslope is comparable, even if the uncertainty of the results using EC as a natural tracer in catchments (e.g. Pilgrim *et al.*, 1979) is considered.

CONCLUDING REMARKS

To obtain meaningful results for the identification of runoff processes and their related flow paths, hydrograph separation has to be applied to the surface and subsurface runoff separately in combination with measured hydraulic state variables. Hydrograph separation in the stream for the total catchment is not capable of identifying flow components and runoff processes (see also Rice & Hornberger, 1998). This experiment demonstrates the importance of event water contributing to runoff by preferential flow.

Pre-event water contributes to runoff mainly at the beginning of the event due to the mixing of event and pre-event water, and after the event due to lateral subsurface flow of activated water already stored in saturated areas prior to the event. Therefore, the event water proportion increases with an increase of precipitation depth. It can be assumed that this behaviour occurs frequently in similar forested catchments, despite the observed importance of pre-event water contribution in small, forested catchments (Buttle, 1994).

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