

Required integrated approach to understand runoff generation and flow-path dynamics in catchments

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Abstract During the last 20 years, much has been learned about runoff generation processes and lateral flow along different pathways, especially at hillslope to small catchment scales. Nevertheless, this knowledge has only to a small extent contributed to modify model formulations/parameterizations describing runoff generation at the catchment scale. In this paper, we focus on a few examples where detailed field studies describe the essential elements of runoff generation and thus help to achieve a more realistic representation of the underlying mechanisms within process-oriented rainfall–runoff models.

INTRODUCTION

Experiences in hydrological modelling, particularly at large scales, have shown that differentiation of runoff into three components is appropriate and efficient for simulations of runoff *dynamics*: a surface flow component, and two subsurface components; namely baseflow and an intermediate component vaguely called “interflow”. A primary aim of this paper is to help clarify whether this is adequate and under what circumstances modifications may need to be made to our modelling concepts based on the new process understanding.

A characteristic parameter used to classify the three components is the average *response time* T_r of streamflow increases due to rainfall or snowmelt: less than a day for surface flow, from one day up to a few weeks for interflow, up to more than a year for baseflow. These *response times* differ significantly from the *travel times* T_t for subsurface flow components, which tracer studies have determined to be larger than T_r by at least one order of magnitude (e.g. Sklash & Farvolden, 1979; McDonnell, 1990).

Tracer studies and related field research in small catchments have also provided evidence that, from a *process-oriented* point of view, the above characterization of runoff components, although efficient for large scale modelling, is often too simplistic. The terms surface flow, interflow and baseflow originate from a rather dated process understanding, where quick responses were equated with surface flow processes (Hewlett & Hibbert, 1967). To avoid misunderstandings, strictly process-related terms will be used in the following, namely *overland flow* only for flow at the terrain surface and *subsurface stormflow* for all short-term subsurface flow processes.

Current understanding of these processes considering their source areas, response times and travel times is outlined in a recent review paper by Bonell (1998). The following discussion of selected research results is intended to support this understanding and to point out some further demands in research.

ASSESSMENT OF THE VARIABILITY OF SATURATED SOURCE AREAS

For quantification and modelling of catchment-scale saturation-excess overland flow, the spatial extent of saturated areas and their connectivity to the channel network needs to be assessed. According to the concept of variable contributing areas, the extent of the saturated areas is commonly understood to vary with time. Their dependence on topography was conceptualized by the topographic index (Kirkby, 1975) and later dynamically incorporated into rainfall-runoff modelling, notably within TOPMODEL (Beven & Kirkby, 1979).

Spatial distribution and variability of saturated areas has been mapped based on *in situ* observations (e.g. Ambroise, 1986), hydromorphic soil characteristics (Merot, 1988), wetness-indicating vegetation (Güntner *et al.*, 1999) and remote sensing (Franks *et al.*, 1998). The observed variation with time in the extent of saturated areas is considerably different between catchments (Table 1). One may conclude from these studies that gentle, concave hillslopes and soils with low hydraulic conductivity favour large spatial variations of saturated areas (e.g. Dunne *et al.*, 1975; Merot, 1988). In mountainous catchments, however, with saturated areas located in narrow steeply sided depressions, or constrained to source areas of return flow, or with persistent humid conditions throughout the year due to high elevation, the variation of their extent is often small (e.g. Tanaka *et al.*, 1988; Güntner *et al.*, 1999; Kirnbauer & Haas, 1998). Further studies are required to generalize these findings.

In the case of TOPMODEL, for instance, the location and variable extent of saturated areas is originally based on topography only. Characteristic differences between modelled and mapped patterns of saturated areas may help to identify other factors controlling their occurrence and varying extent, e.g. variable soil properties, geology or bedrock topography (Merot *et al.*, 1995; Becker & McDonnell, 1998; Güntner *et al.*, 1999). It may then be possible to adequately modify the purely

Table 1 Seasonal or event-dependent variation in the extent of mapped saturated areas in 10 investigated catchments.

Study no.	Authors	Catchment area (km ²)	Range of elevation (m)	Variation of saturated areas (% of total catchment area)
1	Dunne <i>et al.</i> (1975)	0.2	180–210	3–11
2	Dunne <i>et al.</i> (1975)	0.5	290–360	15–51
3	Dunne <i>et al.</i> (1975)	4	270–420	12–36
4	Dunne <i>et al.</i> (1975)	0.2	250–270	4.4–17.8
5	Ambroise (1986)	0.36	748–1000	1.3–7.9
6	McDonnell & Taylor (1987)	1.2	330–400	4.5–14.1
8	Merot (1988)	0.1	15–22	~2–20
7	Tanaka <i>et al.</i> (1988)	0.022	142–183	0.9–4.2
9	Güntner <i>et al.</i> (1999)	40	440–1496	6.2 (small variation)
10	Kirnbauer & Haas (1998)	16	1100–2200	8 (small variation)

topography-based model (e.g. Ambroise *et al.*, 1996). In general, the combination of different approaches, such as remote sensing, field mapping, groundwater table measurements and hydrological modelling is considered to be the most promising approach to understand and quantify surface runoff generation from saturated areas in a spatially distributed way, thereby reducing uncertainties of each individual method.

THE CONTRIBUTION OF SUBSURFACE STORMFLOW PROCESSES TO FLOOD RUNOFF

Subsurface stormflow is a generic term for different subterranean runoff generation mechanisms which respond rapidly enough to a rainfall or snowmelt event to contribute to flood runoff. Three mechanisms are often identified for this quick response (Pearce *et al.*, 1986, Anderson & Burt, 1990, Bonell, 1998):

- *Fast subsurface flow (of event water) in preferential pathways* such as discrete macropores (Beven & Germann, 1982), highly permeable soil layers, debris covers and subsurface channels often referred to as soil pipes (Jones, 1971).
- *Displacement of pre-event water* due to lateral as well as vertical pressure transmission as a consequence of new water entering zones in the subsoil which are saturated or close to saturation (Sklash *et al.*, 1986, Beven, 1989).
- *Groundwater ridging* due to a quick rise of the capillary fringe, leading to an increased hydraulic gradient towards the stream bed (Sklash & Farvolden, 1979).

Subsurface stormflow is clearly supported by a high infiltration capacity, the presence of preferential pathways and shallow soils underlain by less permeable bedrock. Both event and pre-event water mobilized by subsurface stormflow mechanisms can enter the stream network either as return flow or, under effluent conditions, directly through the stream bed.

Sklash & Farvolden (1979) have demonstrated the use of tracer hydrology in combination with hydraulic measurements to quantify the significant contribution of subsurface stormflow to flood runoff. Since then, numerous studies have been undertaken to validate and refine their findings and hypotheses and to develop new ideas concerning the nature of subsurface flow processes, e.g. Pearce *et al.* (1986), McDonnell (1990) or Peters *et al.* (1995). Buttle (1994) provides an overview on the magnitude of the pre-event water contribution to flood runoff as derived from various case studies. As shown in Table 2 and Fig. 1, these results are confirmed by more recent case studies which make use of more than one natural tracer for hydrograph separation (^{18}O , ^2H , NO_3 , Si, Ca, Cl and electric conductivity). It should be pointed out that most of the investigated catchments are very small and are characterized by a rather distinct topography as well as highly permeable soil layers underlain by less permeable layers or bedrock. These characteristics make small mountainous catchments best suited for investigations of subsurface stormflow processes and their contribution to runoff generation.

In principle, the mechanisms listed above are considered to be sufficient to explain the high percentages of pre-event water which have been detected in streamflow during flood events. However, questions still unsolved are (1) how to make use of this new understanding within hydrological models, and (2) how to transfer this knowledge

Table 2 *Upper part:* Pre-event water contributions to flood runoff as measured in several small catchments (two observed events separated by a slash, several events indicated as a range). *Lower part:* Overview on average contributions to peak discharge taken from various older studies.

Authors	Land cover	Area (km ²)	Pre-event water contribution to: Peak discharge (%):			Flood volume (%):		
			Soil water	Ground-water	Sum	Soil water	Ground-water	Sum
Bazemore <i>et al.</i> (1994)	forested	0.08	65/50	20/45	85/95	36/25	54/71	90/96
DeWalle & Pionke (1994)	mixed	0.20	71/36	17/41	88/77	42/17	47/73	89/90
Peters <i>et al.</i> (1995)	forested	0.03	-	-	73	-	-	77
Laudon & Slaymaker (1997)	alpine	0.36	-	-	50–80	-	-	60–90
Tanaka & Ono (1998)	forested	0.14	52	38	90	36	51	87
Buttle (1994); Summarized	forested	-	-	-	77	-	-	-
from various studies	agricult.	-	-	-	65	-	-	-
	urban	-	-	-	2	-	-	-
	others	-	-	-	67	-	-	-

to larger scales of regions and river basins? A promising theoretical attempt in this regard has been made by Beven (1989), who used a kinematic wave description to explain the observed fast subsurface stormflow response. However, as Bonell (1998) points out, a lot has still to be done to overcome the existing uncertainties and to provide a framework for a more realistic modelling of subsurface stormflow and associated solute transport.

IMPLICATIONS OF DOUBLE FLOOD PEAKS FOR RUNOFF GENERATION

The phenomenon of double flood peaks is visible in the discharge hydrograph in Fig. 2 (from Burt & Butcher, 1985). In each of the two documented rainfall events, an initial flow peak is observed due to direct overland flow. About one and a half days later a secondary smaller peak occurs caused by subsurface stormflow. As illustrated in Fig. 2

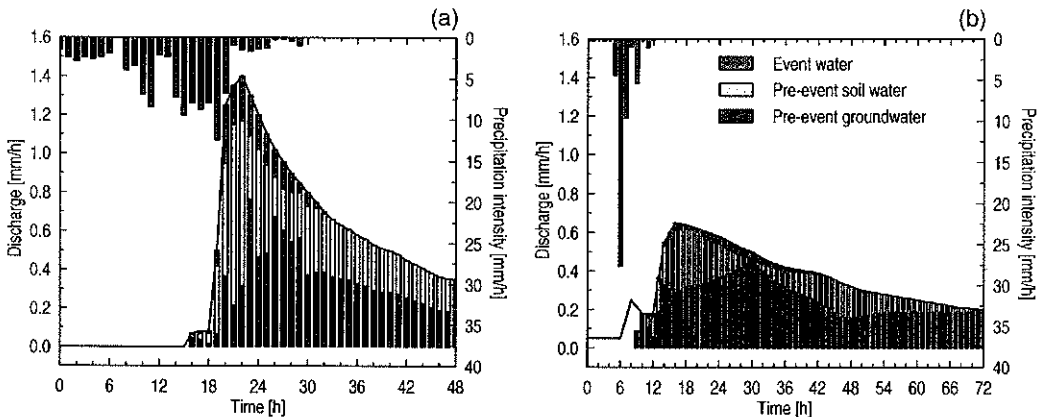


Fig. 1 Example for a three component hydrograph separation, derived from results of Bazemore *et al.* (1994); uncertainty ranges shown in the original diagrams are dropped for reasons of clarity. (a) large event. (b) small event

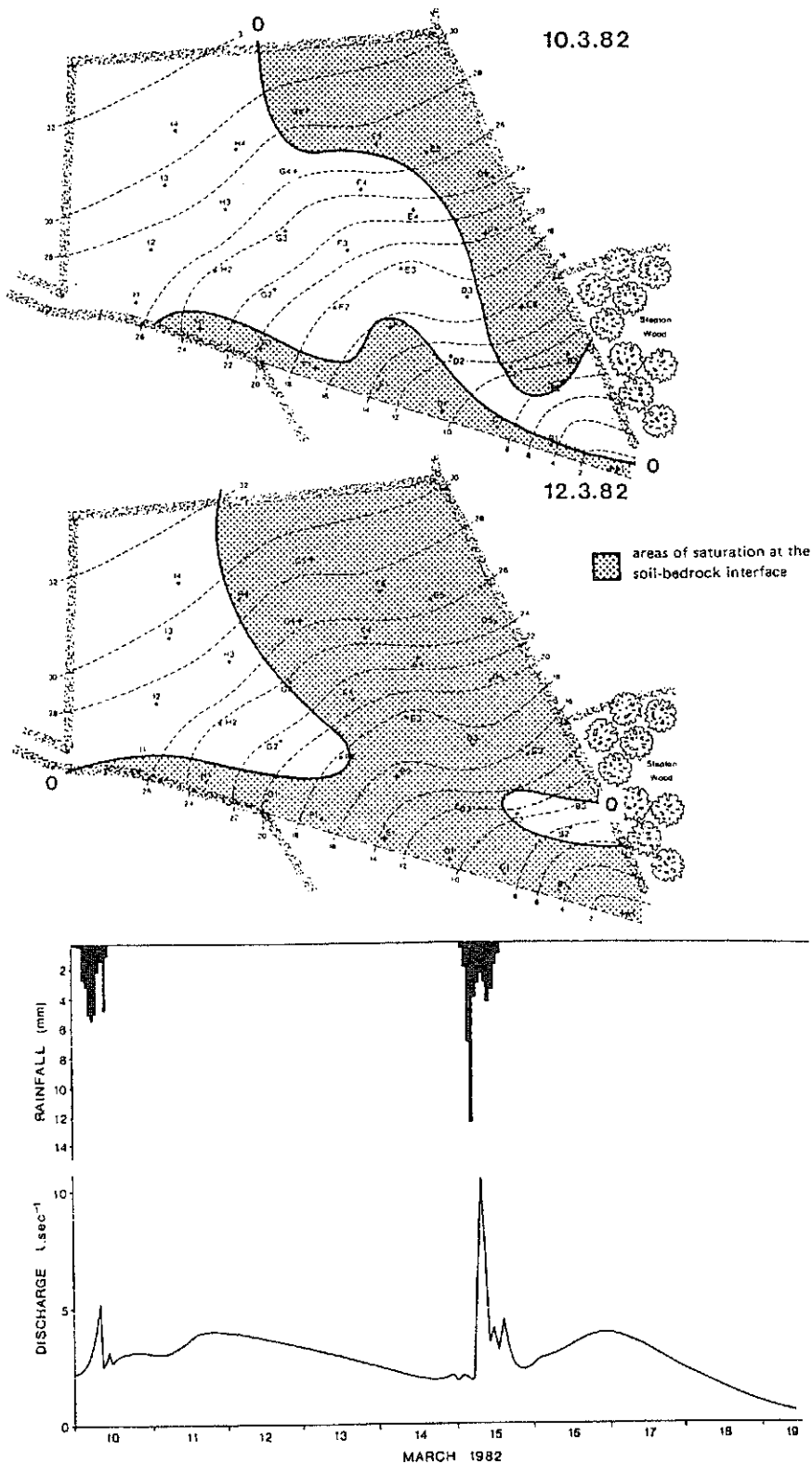


Fig. 2 Merging of subsurface saturated areas during a rainfall/flood event on a 1.4 ha hillslope. *Upper parts:* Spatial extent of saturated areas at the soil-bedrock interphase for two days. *Lower part:* Corresponding rainfall and storm hydrograph (after Burt & Butcher, 1985).

it is generated as soon as different transient groundwater bodies (pillows) at the soil-bedrock interface merge together due to percolation during the event. While on 10 March the two saturated zones in the investigated catchment are disconnected, they merge together between 11 and 12 March, generating the secondary flood peak. Similar observations were made by Becker (1989), which are discussed in Becker & McDonnell (1998), and by Bazemore *et al.* (1994). Such observations are well suited to test new hypotheses and models aiming at a more realistic description of subsurface stormflow processes.

CONCLUSIONS

During the last decade a new understanding of runoff generation mechanisms and subsurface flow has been developed, but still a lot is not sufficiently known. Therefore further field studies combined with modelling are needed, most appropriately in the framework of a comprehensive and integrated approach, which allows us to assess the controlling hydrological, soil, vegetation, topographical and geological conditions in the watershed under study in the best possible way. All available techniques should be applied in a coordinated way including (a) classical field measuring techniques, (b) isotope and multi-tracer techniques, (c) remote sensing and (d) GIS-based distributed high-resolution hydrological modelling. Rather than working with only one of these or with selected approaches in more and more different watersheds, it is preferable to combine the application of all of them in a coordinated form in a few selected, well instrumented and investigated research catchments.

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