Journal of Hydrology, 153 (1994) 357–382

[3]

Spatial and temporal variability of stormflow generation processes on a Swiss catchment

J.P. Jordan*

Institut d'Aménagement des Terres et des Eaux, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

(Received 29 October 1992; revision accepted 1 May 1993)

Abstract

This paper presents some results of a study on the identification of flood formation processes and their modelling in the geographic context of the Swiss Plateau. With the help of hydrometric measurements at different scales, groundwater depth measurements or isotopic tracing (^{18}O), it is shown that all three processes mentioned in the literature (subsurface flow, and saturation excess and infiltration excess overland flow) occur in the Haute-Mentue catchment (12.5 km^2). For heavier floods, however, overland flow predominates, with a proportion of new water in the flood rarely encountered in the literature. Under these conditions, the location of contributing areas, which is essential for a physically based model, proves to be difficult to determine. In particular, the use of a topographic index is not entirely satisfactory. An attempt is made to show the difficulties in describing the complexity of the catchment's response to precipitation and, consequently, the limitations when deterministic physically based model are used.

Résumé

Certains résultats d'une recherche sur l'identification des processus de formation des crues et leur modélisation dans le contexte géographique du plateau suisse sont exposés dans cet article. A l'aide de mesures hydrométriques à différentes échelles, de profondeurs de nappe ou de traçage isotopique (^{18}O), il est montré qu'aucun des trois processus reconnu dans la littérature ('subsurface flow', et 'saturation excess' et 'infiltration excess overland flow') ne peut être écarté sur le bassin versant de la Haute-Mentue (12,5 km^2). Pour les plus fortes crues, cependant, le ruissellement est prédominant, avec la présence d'eau nouvelle dans la crue dans une proportion rarement évoquée. Dans ces conditions, la localisation des surfaces contributives, essentielle pour une modélisation à base physique, s'avère difficile. Notamment, le recours à un indice topographique n' apporte pas entière satisfaction. Il est tenté de montrer les difficultés de percevoir la réalité de la résponse du bassin versant dans toute sa complexité et par conséquent de souligner les limites de l'utilisation d'un modèle à base physique entièrement déterministe.

* Present address: Office Fédéral de l'Economie des Eaux, CH-3001 Berne, Switzerland.

SSDI 0022-1694(93)02317-Q

1. Introduction

The need for mathematical models capable of describing runoff generating mechanisms and of handling acute environmental problems is clear (Dunne, 1982; Ward, 1984). The validation of such models requires experimental data from test catchments. For this purpose, the Haute-Mentue catchment has been monitored extensively and measurements have been analysed to identify runoff generating mechanisms.

Identification of runoff generating mechanisms was initiated by the work of Hewlett and Hibbert (1963, 1967) in the USA in the early 1960s. Thereafter, the number of field investigations has increased significantly. Most of these studies indicate that, independently of antecedent moisture conditions and rainfall characteristics, only one runoff generating mechanism is predominant in the studied catchment. In humid temperate climates, subsurface flow seems to be the dominant mechanism for catchments with highly permeable soils and steep slopes (e.g. Weyman, 1970; Harr 1977; Mosley, 1979; Sklash and Farvolden, 1979). Saturated overland flow is also an important runoff generating mechanism at the bottom of valleys or in areas where flow paths converge (e.g. Betson and Marius, 1969; Dunne and Black, 1970; Tanaka et al., 1988). However, infiltration excess overland flow cannot be disregarded completely, especially in areas regarded as impervious or of low permeability because of human activities. Few studies show the simultaneous or sequential occurrence of the various runoff processes (Taylor and Pearce, 1982; Kennedy et al., 1986; Bonell et al., 1990). Considering the high spatial variability of catchment characteristics and the temporal variability of climatic conditions (antecedent moisture conditions and rainfall characteristics), it is surprising that sequential or simultaneous occurrences of mechanisms are not found more frequently.

The lack of consideration of the spatial variability of runoff generating mechanisms comes from the fact that most studies are done in small catchments or basins with relatively homogeneous characteristics. In some cases, the period of records is relatively short and does not include a broad spectrum of situations. Even in the case where only one mechanism predominates, it occurs over variable contributing areas and is controlled by different factors according to the location within the catchment.

This paper presents the results of field investigations of the Haute-Mentue catchment. The climatic characteristics of the region are favourable for analysing the spatial and temporal variability of runoff generating mechanisms. This paper describes briefly the overall framework of the study and shows some preliminary results of the analysis of flow measurements for sub-catchments with different sizes and land use conditions. The results of isotopic analysis on one elementary catchment (Alloux, 3.6 ha) are described. The importance of saturated overland flow will be shown for major events. Finally, the location of saturated areas, and consequently the forecasting of their occurrence will be analysed with respect to topographic characteristics.

2. The Haute-Mentue catchment

2.1. Catchment description

The Haute-Mentue catchment (12 km^2) is located in the Swiss Plateau region 20 km north of Lausanne (Fig. 1). The climate is humid and temperate with continental characteristics. The average annual rainfall is around 1250 mm. In summer, short intense convective storms occur frequently, whereas long-duration low-intensity rainfall predominates during the winter season. The latter occurs frequently with high initial moisture conditions. The 10 year daily rainfall is 70 mm and the hourly maximum intensity for the same return period is around 30 mm h^{-1}

The forest area, mainly spruce (*Picea abies*), covers 55% of the catchment and stretches across the upper part and along the streams. The land cover of the rest of the basin is essentially rural with mixed farming and pasture. The imperviousness ratio is very low, as the area covered by the two villages and the road network does not exceed 2% of the total catchment surface. Altitudes range between 694 and 927 m above sea-level. Slopes are gentle, with an average of 4°, and only 5% of the catchment area has slopes steeper than 10°. Some flat areas can also be found, not necessarily located at the bottom of the valleys.

The bedrock is composed of sedimentary deposits from the erosion of the

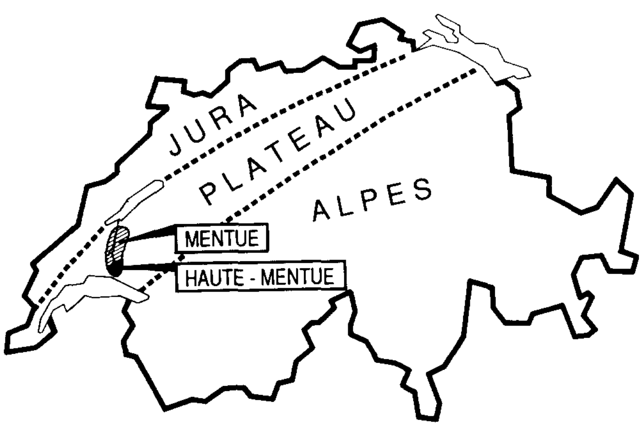

Fig. 1. Geographical location of the Haute-Mentue watershed.

Alps called 'molasse', sometimes overlain by morainic depositions. These layers are practically impervious. Groundwater flow occurs through the soil and the impeding layer of the rock, which varies in thickness. Catchment soils are silts. Soil layers have an average thickness of 1.50 m. They are moderately pervious ($K_{sat} \approx 10\,mm\,h^{-1}$). Several traces of hydromorphism, (presence of pseudo-gley, or in a few cases, gley) indicate the frequent occurrence of temporarily saturated conditions in the soil layer.

Observed runoff coefficients are relatively low and range between 10 and 15% on average. The annual peak flow at the catchment outlet is $5\,m^3\,s^{-1}(4\,l\,s^{-1}\,ha^{-1})$.

2.2. Hydrometric observations

To identify runoff processes at the basin scale, several flow gauges have been installed (Fig. 2). The recording network also includes four rainfall gauges spread throughout the basin. Flows at the outlet of the Haute-Mentue catchment have been recorded since 1975. Since 1988, four first-order catchments (of a few hectares in area) have been monitored to assess the effects of vegetation cover. Stream discharge was measured by prefabricated Venturi flumes (type 'Hydrologic 1253 AZ', Hydrologic, Saint-Martin

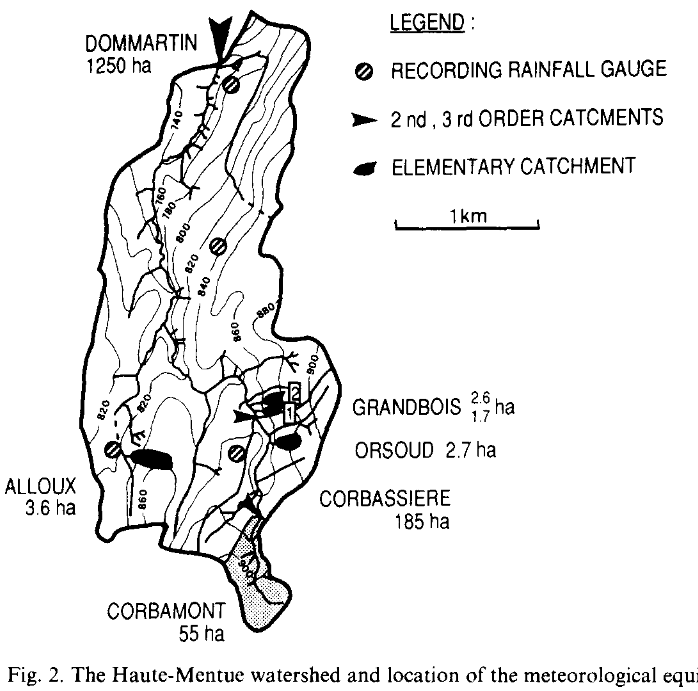

Fig. 2. The Haute-Mentue watershed and location of the meteorological equipment (contour lines at 20 m intervals).

d'Hères, France). Pressure sensors for water levels (VEGA type, Vega Schiltach, Germany), with an accuracy of 0.25% in the range of 0–1 m) and data logging systems (MADD type, Electrelec, Bussigny, Switzerland) guaranteed very high accuracy. More complex field investigations were performed on the elementary catchment of Alloux, which is covered by pasture. Two other nested higher-order catchments were also monitored; these two subcatchments have areas of 55 ha and 185 ha, with 100% and 80% of forest cover, respectively.

2.3. Streamflow generation processes

The study of measurements recorded during 2 years (1988-1990) allowed the definition of a general working scheme for the hydrological behaviour of the Haute-Mentue catchment (Jordan, 1992). This is the result of the analysis of a large amount of data, and will only be briefly presented here. Flows recorded at the outlets of the catchments constitute the basic information from which the working scheme has been built. Two samples of events have been defined according to a threshold value of total rainfall which was taken equal to 10 mm. Only rainfall events with uniform spatial distribution were considered. The first group contains 25 events and the second includes 17 flood episodes. The analysis is based on the comparison of hydrograph characteristics such as peak flows, runoff volumes and runoff coefficients. This comparison involves all the catchments and subcatchments studied (seven monitoring points). Possible correlations with rainfall characteristics and antecedent moisture conditions are also examined.

Comparisons between observed hydrographs at different locations indicate that hydrologic responses become similar when catchment areas exceed a few tens of hectares, even if soil cover characteristics are significantly different. For the smaller catchments, small rainfalls generate lower flood volumes, as shown in Fig. 3, where the runoff coefficient values of the second group for Corbassière (185 ha and 80% forest cover) and for Orsoud (2.7 ha of agricultural land) are compared. On the other hand, when rainfall volumes and/or baseflows occurring at the beginning of the storm increase, the runoff coefficients of the hillslopes start to show values similar to those observed in the wider catchments. Even if the relationship between runoff ratio and peak flow is less significant for the Alloux and Corbassière catchments, the distributions of points show a similar tendency. The comparison between the hydrologic responses of the elementary catchments, based not only on runoff coefficients but also on peak flow and time to peak, did not lead to any significant relationship with land cover.

Baseflow and total precipitation appear to be the most important hydro-

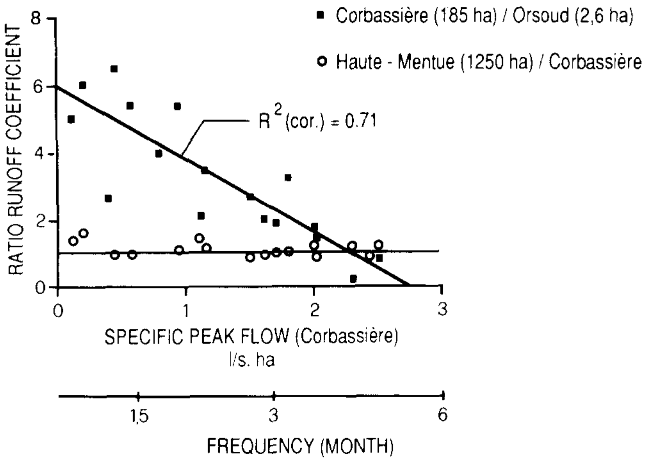

Fig. 3. Comparison between runoff coefficients and peak specific flows at Corbassière (185 ha).

logical variables explaining hydrological response characteristics. Fig. 4 shows the correlation coefficients of the linear regressions between these variables and runoff volume. These values are based on linear regressions using all the events for which total rainfall is greater than 10 mm. The variables studied include some rainfall characteristics (total rainfall P_{tot}), duration, maximum average intensities over different time steps (I_x; x in minutes) and baseflow at the beginning of the flood rise (Q_b ($Q_{b_{corb}}$ for Corbassière)). These results are similar to those derived by Hewlett et al. (1977) for the Coweeta catchment, especially with respect to the rainfall. However, baseflows appear to be more significant for the Haute-Mentue catchment.

The analysis of hydrometric data, combined with visual field information and with the results for the Alloux elementary catchment (described below), allowed the identification of the dominant flood processes occurring in the Haute-Mentue catchment. Infiltration excess overland flow is not a predominant mechanism, although this occurs locally on bare soils, because rainfall intensities are similar to hydraulic conductivities. At small scales and for low flows (return periods less than 1 month) interflow is important. For second- and third-order basins, its importance is still to be assessed, mainly because of the lack of isotopic analysis at this particular scale. Saturation excess overland flow appears to be a dominant mechanism for most of the events. However, contributing areas vary significantly with the return period of the flood. For most of the events of the two samples, contributing areas are relatively small and are located outside the elementary catchments. For larger storms and/or wet antecedent moisture conditions, contributing areas spread out progressively over the larger and the elementary catchments. Therefore, the

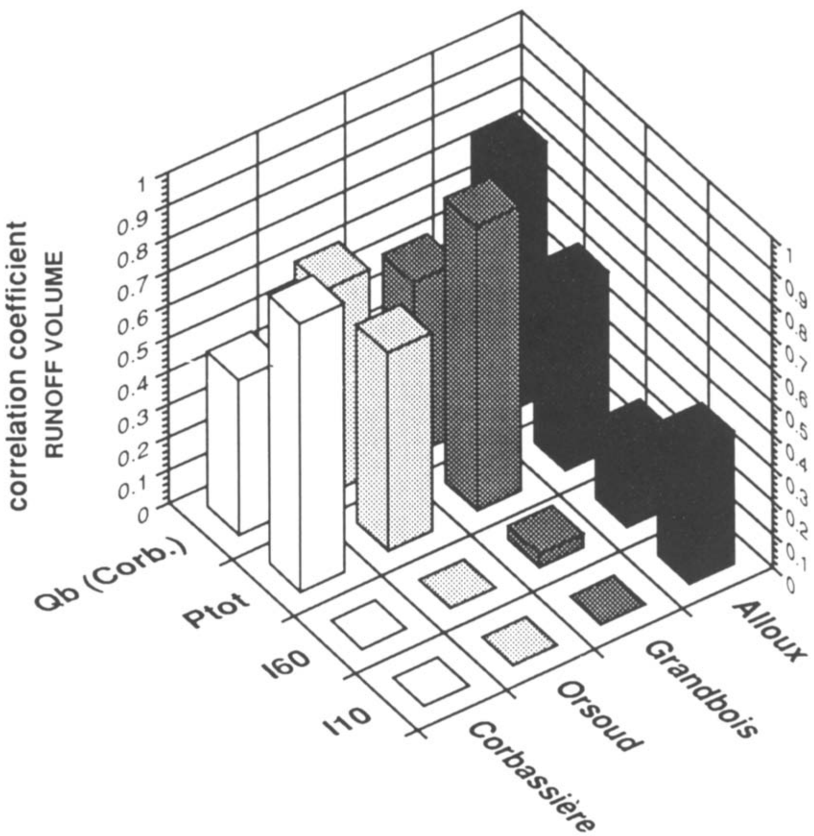

Fig. 4. Correlation coefficients of the linear regressions between runoff volume and rainfall characteristics or antecedent moisture conditions.

elementary catchment can be considered as representative of the overall response of the catchment only when peak flows at the outlet of the Haute-Mentue have a return period greater than 3 months.

3. The Alloux elementary catchment

3.1. Experimental equipment

The flow gauge of this catchment is located on a first-order tributary (Fig. 5). The contour levels are relatively parallel. The convergence of flow lines is limited except in the vicinity of the stream. The topographic catchment is limited in the northern direction by a forestry track that diverts, outside the basin, surface runoff coming from a small hill. The catchment surface is 3.7 ha. It is possible to assess the size of the subsurface catchment by comparing

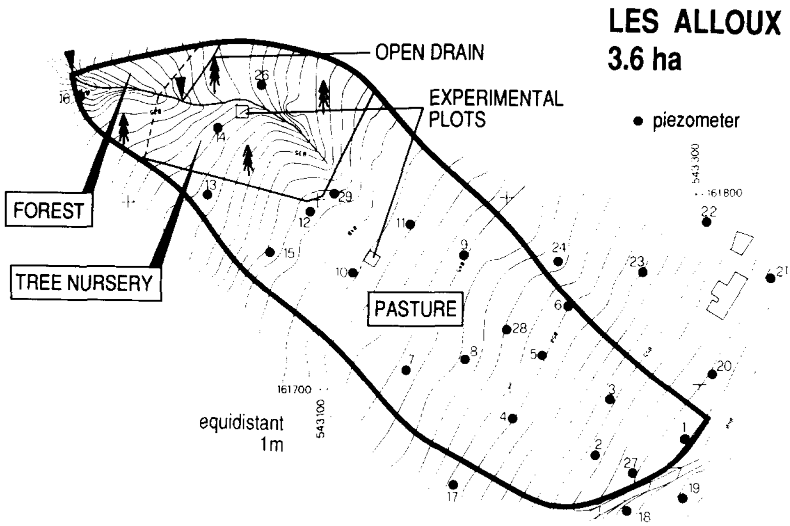

Fig. 5. The Alloux catchment and equipment

baseflow values of catchments of different sizes and considering that the catchment is more accurately defined for second- and third-order basins. A surface of 5.3 ha is derived. This figure is significantly greater than that of the topographic surface; the difference probably comes from the uncertainties when defining the hydrological watershed and from the fact that the contribution of the upstream forestry track was initially neglected. Mean slope is approximately 4°. The entire upstream area of the catchment is covered by grassland. Twenty per cent of the area is covered by forest or tree nurseries in the lower part of the catchment. A network of piezometers monitors water table levels after rainfall events. Two experimental plots provide continuous recording of water tables. Moisture contents and suction head are measured weekly. Tracing with an environmentally stable isotope (^{18}O) is also performed during flood periods at a time step of 10 min with an automatic sampler (ISCO type), which is activated by means of a threshold mechanism. One of the experimental plots is located in the pasture area and is gauged with a pluviometer which has been used to sample rain water every 5 mm automatically. The baseflow representing the water table contribution to the flood is also sampled.

3.2. Basic principles of isotopic tracing

Tracing with environmentally stable isotopes to identify the origin of water has significant advantages over other methods such as intercepting trenches or approaches that require the measurement of moisture and hydraulic potential.

Isotope tracing does not modify the characteristics of the media and applies to a geographic scale similar to that of flow measurements. Isotope tracing is also relatively easy to implement.

Flow separation is based on the isotopic characteristics of water at a given time step and relies on the assumption that water at the outlet at a given time represents the mixing proportions of isotopic content of water coming from various origins. To establish a mass balance equation for a single tracer, it must be assumed that the flow (Q) measured at the outlet is equal to the sum of two contributions Q_s and Q_r representing, respectively, old and new water. This assumption does not imply any presumptions about the water's pathways:

$$Q = Q_s + Q_r \quad (1)$$

The new water comes directly from precipitation (or snowmelt) whereas the old water represents the water stored in the ground before the storm. Each flow component after sampling and analysis has a specific isotopic concentration — δ, δ_s and δ_r for river, new and old water, respectively:

$$\delta Q = \delta_s \cdot Q_s + \delta_r \cdot Q_r \quad (2)$$

Solving Eqs. (1) and (2) for Q_s and eliminating Q_r,

$$Q_s = (\delta - \delta_r)/(\delta_s - \delta_r) \cdot [Q] \quad (3)$$

To separate the different sources of water, the isotopic signal of rainfall must be significantly different from that of baseflow or groundwater (Condition 1).

Four other conditions have to be fulfilled, as defined by Sklash and Farvolden (1982) and discussed, for instance, by Kennedy et al. (1986), Turner et al. (1987), Rohde (1989), Dewalle et al. (1988), McDonnell et al. (1990) and O'Gunkoya and Jenkins (1991):

(2) Rainfall is characterized by a unique isotopic signal. However the sampling of rainfall during the event allows for the effects of the signal variation in particular conditions. Separation tries to account for the input signal variation by considering that the rainfall that has not yet fallen at a given time does not influence flow conditions at the outlet. As information on travel times to the outlet is not available, it is the average signal up to the current time step that is used in the separation.

(3) Underground water and baseflow have a unique isotopic content.

(4) The contribution of stored water in surface retentions, either natural or artificial, is negligible.

(5) The contribution of vadose water is neglible.

Conditions 1 and 2 can be checked when the events are analysed. Condition

Table 1
Main characteristics of published studies on isotopic tracing

Reference	Country	Area (km^2)	Diff. in Alt. (m)	Geology	Land use	Tracer	Old Water volume (%)
Crouzet et al.	France	5.7	–	–	Mixed	T	97
		15					99
		91					46
Fritz et al. (1976)	Canada	1.8	60	Glacial deposits on granite	Forest	^{18}O, ions	45
		22	300	Clay–loam till, shale, alluvial deposits			60
		135	–	Pleistocene sand			> 50
Sklash and Farvolden (1979)	Canada	1.2	120	Glacial deposits on jointed gneiss	Forest	^{18}O,D	> 80
		3.9	60				
Merot et al. (1981)	France	0.1	8	Schist	Cultivated	^{18}O, ions	88
Rodhe (1983)	Sweden	0.04	19	Fractured gneiss, granite	Forest	^{18}O	68–100
		4.0	67				
Bottomley et al. (1984)	Canada	1.2	90	Glacial deposits on amphibolite, schist	Forest	^{18}O,D, ions	40–90
		1.8	90	Till on gneiss			
Kennedy et al. (1986)	USA	620	1200	Greywacke, sandstone shale, limestone	Forest + Pasture	^{18}O D, T	?
Sklash et al. (1986), Pearce (1990)	New Zealand	0.003	65	Compacted gravels (impervious)	Forest	D, Cl	75–85
		0.04	88			CE	*f*(scale)
		2.8	150				
Turner et al. (1987)	Australia	0.82	112	Gneiss, amphibolite	Forest	^{18}O, Cl	60–95

Herrman et al. (1987)	Germany	0.76	160	Sandstone, quartzite	Forest	^{18}O	84
Dewalle et al. (1988)	USA	2.1	–	Shale, sandstone, coal	Forest	^{18}O	100 6–25 (soil)
Bonell et al. (1990)	New Zealand	2.2	210	Loess on colluvium on schists	Pasture	D	65–97
McDonnell et al. (1990)		3.1	210				
Nolan and Hill (1990)	USA	10.6	730	Sandstone, shale, greenstone limestone	Pasture, 6% impervious	^{18}O,D, ions	57
O'Gunkoya and Jenkins (1991)	UK	10	789	Biotite granite partly under boulder clay	Pasture	D, ions	54–90

3 can easily be accepted for the Alloux catchment because of the satisfactory agreement of the isotopic content between regularly monitored samples of underground water and baseflow. Condition 4 is satisfied in the case of the Alloux basin. However, Condition 5 is much more difficult to satisfy. Samples of water in the soil showed an isotopic content intermediate between those of the water table and of rainfall even if the differences between the water table and the soil were small. Therefore, although the contribution of underground water may be underestimated, the errors should not be very significant and do not affect the conclusions of this study.

3.3. Overview of isotopic tracing results

The first attempt at flow separation with isotopic tracers was that by Mook et al. (1974). Before that study, tritium separation had been performed by Hubert et al. (1969) and Crouzet et al. (1970). In the late 1970s, applications of isotopic tracers were commonly attempted. Table 1 shows a summary list indicating the studies on environmental isotope tracing and separation of flow components during flood periods caused by precipitation. This table also shows, for each catchment studied, the area and the predominant land use. The type of tracer and the proportions of old water are also given in the table.

A literature review indicates that most studies have been concerned with temperate humid climates and catchments in wooded areas or covered by pasture. In most cases, the results showed that the contribution of old water is predominant. However, a few studies showed that new water may be an important part of the flood volume. McDonnell et al. (1990) indicated a value of 40% of new water, which is significantly higher than the values proposed in other studies. Runoff over saturated areas may be the main reason for such a high contribution of new water. Bonell et al. (1990) described an event in which 80% of the total flood volume was new water. However, they also indicated that in most cases old water is predominant. The only cases in which the volume of new water is more significant are those corresponding to runoff coefficient values greater than 7% or to runoff depths greater than 10 mm.

3.4. Isotopic analysis at the Alloux catchment

Between 1988 and 1990, five events have been analysed in detail using ^{18}O isotopic tracer, as they satisfy Condition 1 above. Three of these events are representative of frequent floods with return periods less than 2 months (Fig. 6). However, two of these three events (9 September 1988 and 27 June

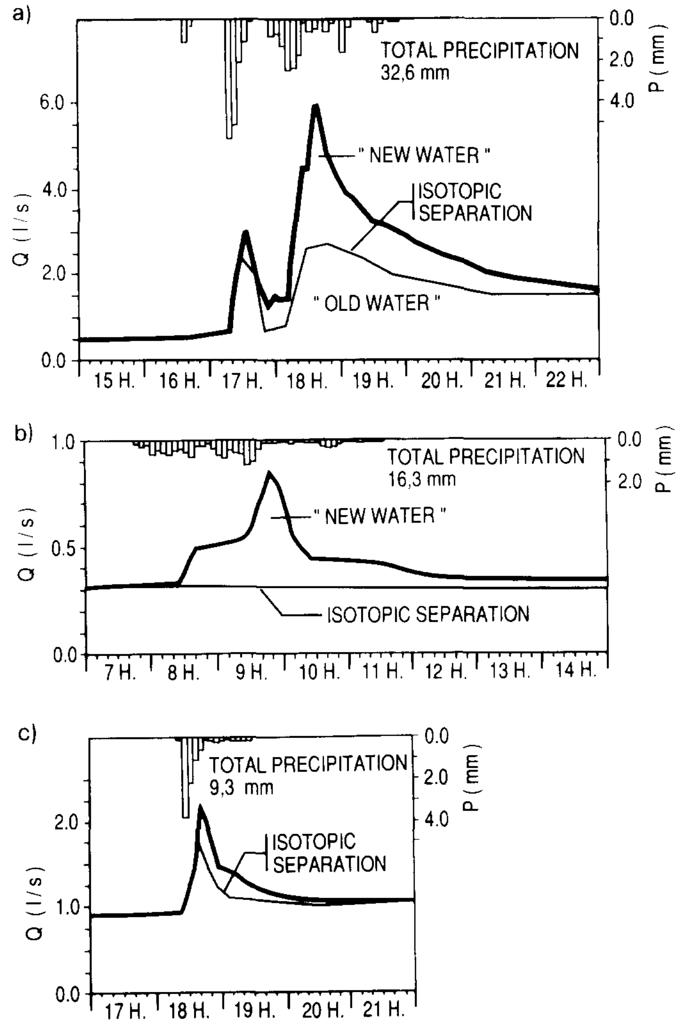

Fig. 6. Isotopic separation of low floods: (a) on 9 September, 1988; (b) on 31st July 1989; (c) on 27 June 1990.

1990) show a large proportion of old water (45% and 75%, respectively), which indicates that subsurface flow was predominant. The last event (31 July 1989) occurred with very dry antecedent moisture conditions and was essentially made up of new water. The low value of runoff coefficients (0.4%) suggests that the new water can be accounted for by direct channel precipitation and surface runoff from riparian zones.

The remaining two events correspond to higher return periods and show a significant proportion of new water. The event on 10 October 1988 (Fig. 7) followed a rainy period with more than 70 mm during the previous 7 days.

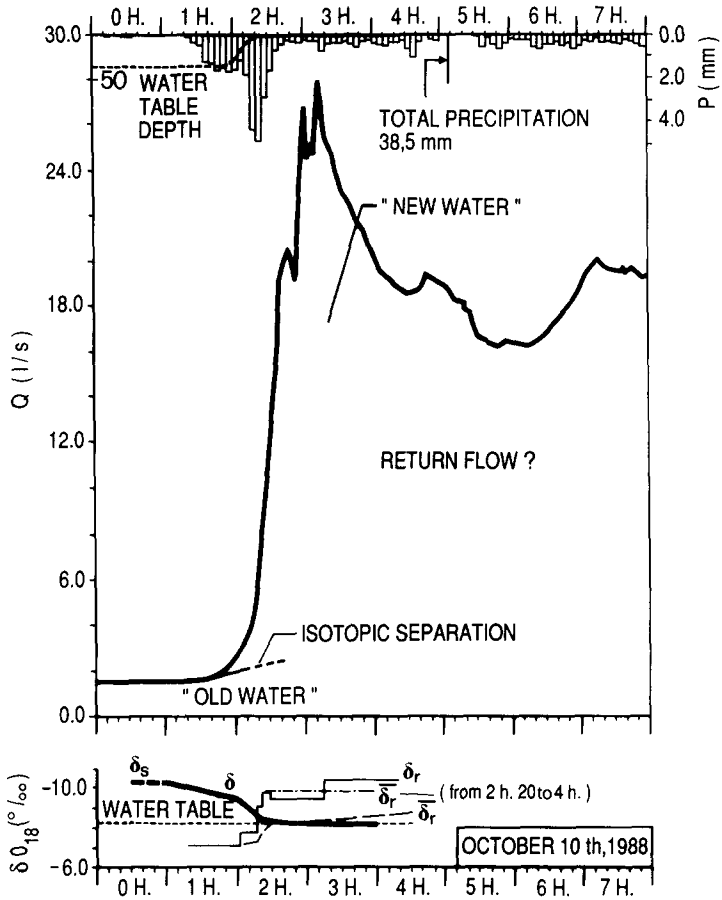

Fig. 7. Isotopic analysis of the event on 10 October 1988.

This flood was generated by a 38.5 mm rainfall. In terms of volume, this flood is one of the highest ever recorded at the outlet of the Haute-Mentue catchment during the last 17 years of measurements. At this location, the runoff coefficient exceeds 30% and the return period of the peak flow is around 2 years. At the outlet of the Alloux catchment, the peak flow is equal to $28 \mathrm{l\,s^{-1}}$.

The event on 13 August 1990 (Fig. 8) occurred with average antecedent moisture conditions but shows a high hourly maximum rainfall intensity ($35.6 \mathrm{mm\,h^{-1}}$). The peak flow for that event is similar to that of the 10 October 1988 event at the outlet of the Alloux catchment ($23 \mathrm{l\,s^{-1}}$). At the outlet of the Haute-Mentue catchment, the return period of the peak flow is somewhat lower, around 6 months, because runoff volume is lower.

For these two events, precipitation was sampled for ^{18}O. In both cases,

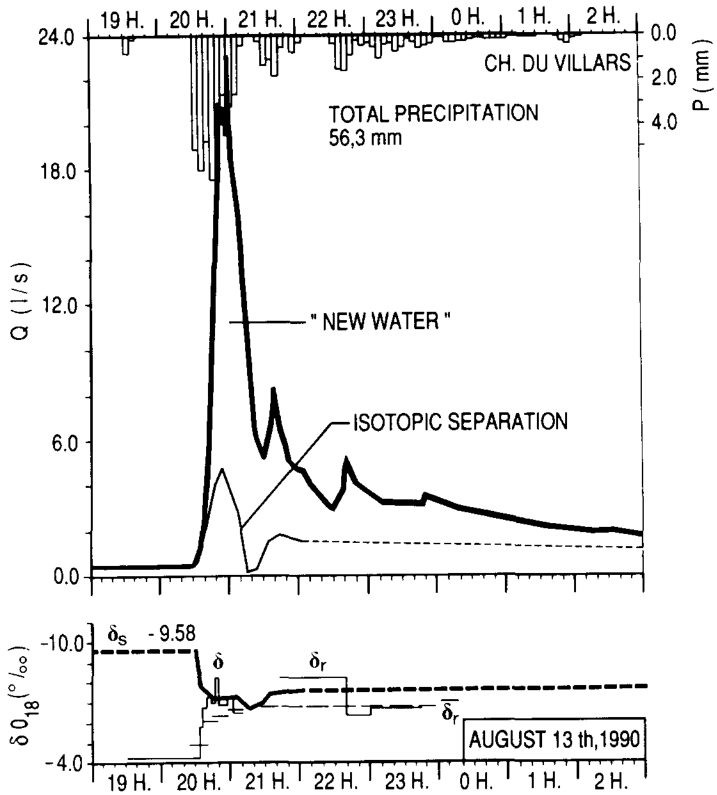

Fig. 8. Isotopic analysis of the event on 13 August 1990.

meteorological conditions are similar, with a cold front and a progressive decrease in ^{18}O concentration of precipitation as theoretically expected, except for the end of rainfall of 13 August 1990. For the event on 10 October 1988 the rainfall signal tends rapidly towards that of old water. In this case, the isotopic separation is no longer possible. In principle, we can analyse only the rising limb of the hydrograph. However, between 3 and 4 h, the isotopic signal of the last rainfall burst is significantly different from that of water in the river. On 13 August 1990, the weaker rainfall signal is still richer than that of the underground water.

Even if a complete separation was not possible for the event on 10 October 1988, the isotopic analysis leads to the following comments:

(1) before the flood, the ^{18}O concentration in the river does not correspond to that of the aquifer in the middle of the basin (sampling was done 6 h before the event at the centre-point of the basin, and the water table level was 40 cm below the ground surface). It seems that there is no apparent relationship with

the temporary aquifer formed at the centre of the basin. However, this fact also raises the question of the representativeness of the groundwater samples.

(2) From the beginning of the hydrograph, the isotopic signal evolves very quickly. Separation is feasible for the first $\frac{1}{2}$h of the event, as the isotopic signal of rainfall was significantly different from that of baseflow. This separation shows that the contribution that can be effectively attributed to deep water tables (with similar isotopic signal) is weak and cannot exceed $2\,l\,s^{-1}$, which is equivalent to a third of the total value at that time. There are no indications of the proportions of direct runoff over saturated areas, subsurface flow and return flow. As the ground water table reaches the ground surface quickly, it seems that runoff over saturated areas is a predominant mechanism in this case.

(3) Isotopic analysis of samples taken after 04:00 h lead to a different interpretation for the analysis of the falling part of the hydrograph. Because of the short travel distances, the assumption that surface runoff, generated by rainfall occurring 1.5 h before 04:00 h, has reached the outlet is reasonable. Thereafter, the signal of new water remains practically constant between 02:20 h and 05:00 h. During that period, the isotopic content of the rainfall water is lower than that of the water table. The river signal corresponds to that of the aquifer, but not to that of rainfall. This result could indicate a substantial contribution of return flow or underground drainage associated with direct runoff over saturated areas.

Based on a variable precipitation signal, the separation of flow components for the event on 13 August 1990 confirms that at the beginning of the flood there is a significant contribution of old water, as was the case for the events on 8 September 1990 and 27 June 1988. The peak flow corresponding to the old water contribution is $4\,l\,s^{-1}$. This flow value corresponds well to most measured flows during the time period of the present field investigations. The rapid decrease of the separation curve and the following slight increase have to be attributed to the lack of accuracy of the separation method.

In comparison with the event on 10 October 1988, the recession limb of the hydrograph is steeper even if rainfall persists longer. The time between the maximum intensity and the peak flow is also shorter. Moreover, the 30 min intensity is around $70\,mm\,h^{-1}$, and can exceed the hydraulic saturated conductivity, which is estimated to vary within the range of $3–30\,mm\,h^{-1}$. These observations suggest that infiltration excess overland flow mechanism may be predominant for this particular event. However, saturation excess overland flow cannot be disregarded for this storm, and the low runoff coefficient can be explained by saturation of the catchment limited to areas in the vicinity of the river.

On the basis of these two events, overland runoff appears to be an important mechanism. The main limitation of isotopic tracing is its inability to identify whether the source of this process is saturation excess overland flow or infiltration excess overland flow. Consequently, the delineation of saturated areas or the simultaneous recording of water table levels appears to be a necessary complement to field investigations.

3.5. *Outline of humidity measurements and water table depths*

Continuous recording of water table depths at the centre of the catchment (Fig. 5) show the frequent presence of a temporary water table developing over the molasse substratum. The period between 1 and 16 May 1990, which presents a sequence of successive significant rainfall events, has been selected to illustrate the variations of this water table (Fig. 9). It rises when antecedent moisture conditions are close to saturation. This is often the case between the months of October and April, when evapotranspiration is low and the number of rainy days is high. When analysing the humidity measurements for different dates, it appears that the saturation deficit over the whole soil layer is low, between 20 and 50 mm. Therefore, this water table can appear after a small rainfall. The rise is rapid, as velocity measurements vary between 30 and 70 cm h^{-1}.

For the event on 10 October 1988, the water table was already close to the ground surface before the rain event (Fig. 7). The ground surface was reached in less than 1 h. Point measurements of water table depths over the whole Alloux catchment indicated that the ground surface was reached in more than

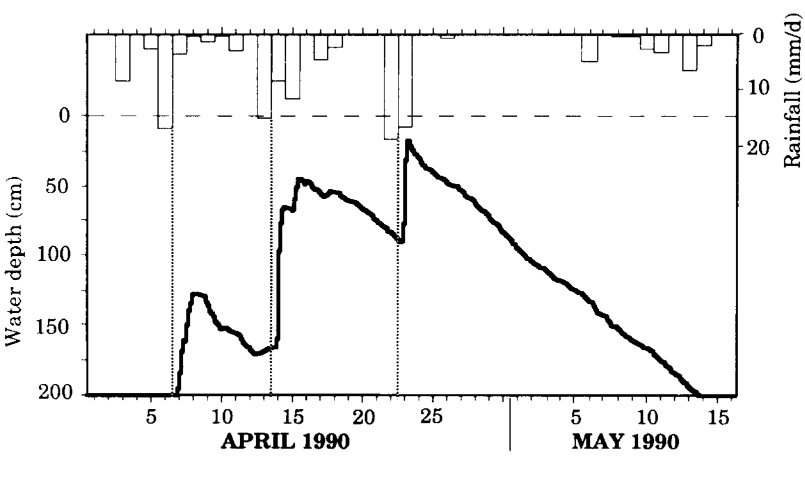

Fig. 9. Rainfall and water table depths on the Alloux site during the period April–May 1990 (land cover is grassland).

three-quarters of cases. There is no doubt that the flood was the result of saturation excess overland flow.

For the event on the 13 August 1990, unfortunately, water table depths were not recorded. However, an indication of initial moisture conditions is given by the value of baseflow before the event. Jordan (1992) developed a relationship between base-flow and saturation deficit for the plot located in the centre of the catchment. A value of 100 mm for the saturation deficit indicates that for a saturation-prone area such as this, the spread of saturated areas must have been very limited.

These considerations raise the question of the spatial distribution of the water table depths. Over the 3 years of records, only seven events for which moisture conditions were high enough to ensure that the water table was well developed throughout the catchment could be used. However, the spatial analysis of these data leads to disappointing results. As no spatial correlation appears, it is not possible to delineate water table depths over the whole catchment. In fact, the correlation coefficients obtained when comparing water table depths for different dates (Table 2) show that there is no systematic behaviour. This lack of consistency was reported by Petch (1988), who found a spatial independence of peak water table depths at each site studied and concluded that hillslope saturation does not respond uniformly to storm rainfall and may not even be spatially continuous.

It seems that this independence can be explained by the fact that water table depths are dominated by several processes whose importance varies in space as a function of site characteristics and in time according to climatic conditions. On the Alloux catchment, these processes are evapotranspiration, surface infiltration, flow through the soil, percolation through the molasse substratum and artificial drainage.

Table 2
Correlation coefficients for various time periods between observed water table depths and topographic index ($\ln(a/\tan\beta)$) (first column) and between water table depths recorded on various dates (remaining columns)

	Index	6/10/88	7/4/88	9/9/88	9/12/88	9/26/88	10/5/88
Index	1.						
6/10/88	0.42	1.					
7/4/88	0.48	0.84	1.				
9/9/88	0.89	−0.08	0.08	1.			
9/12/88	0.17	0.81	0.79	0.24	1.		
9/26/88	0.19	0.69	0.57	0.28	0.74	1.	
10/5/88	0.22	0.59	0.52	0.25	0.69	0.89	1.
2/16/90	0.82	−0.09	0.06	0.42	0.33	0.22	0.22

For instance, between 9 and 12 September 1988, the shape of the water table changed significantly. For the first date, the measurements were taken immediately after the storm (Fig. 6(a)), when the water table depths are governed by antecedent moisture conditions which in turn are strongly influenced by evapotranspiration. On the other hand, on 12 September, water table depths are dominated by flow conditions in the soil. Evaporation and flow through the soil are influenced by different characteristics (vegetation in relation to evapotranspiration and soil characteristics and topography for flow through the soil), which are not spatially correlated. Therefore it is not surprising that the results for these two dates are different. In such conditions, is it possible to show the relevance of topography when locating saturated areas and forecasting their spread? In fact, topography is the most accessible characteristic for input into hydrologic models.

3.6. Analysis of water table depths vs. topographic index

When the hydrological response of a catchment is mainly dominated by flow processes occurring close to the ground surface, flow paths and velocities are, to a great extent, determined by topography. The topography index proposed by Beven and Kirkby (1979) is based on two geomorphological parameters. It relies on the principle that saturation-prone sectors depend on the contributing areas upstream and the ground slope. This index is defined by the Neperian logarithm of $a/\tan\beta$, where a is the partial contributing area upstream per unit length of contour level and $\tan\beta$ is the slope of the ground at that point. This index is used by the hydrological model TOPMODEL (Beven and Wood, 1983; Beven et al., 1984; Beven, 1986, 1987).

3.7. Adequacy of the topographic index

The adequacy of the topographic index depends first on the reliability of the assumption that the flow direction is parallel to that of ground slope. Anderson and Kneale (1982) showed that for areas with mild topography and slopes less than 10%, similar to those found in the Haute-Mentue catchment, gravity forces are no longer dominant and the overall behaviour is controlled by suction forces. The lack of coherence between the topographic index and water table depths has also been demonstrated by Burt and Butcher (1985), as a result of the presence of a tableland on the upstream part of the catchment studied. Taylor and Pearce (1982) expressed serious doubts about the fact that for steep catchments and pervious soils, simple topographic indicators may define the location of saturated areas. Despite these criticisms, other studies have shown the adequacy of the topographic index to represent the spatial distribution of saturated areas (O'Loughlin, 1986).

3.8. Determination of the topographic index

The multiple flow direction algorithm described by Quinn et al. (1991) was used. The cumulative surface for a given grid is distributed in all downstream directions as a proportion of the length of the contour level line perpendicular to the flow line. Therefore, the value of the topographic index can be calculated easily for each grid from a digital terrain model (DTM).

The accuracy of the DTM is important when estimating values of topographic index. This problem has been illustrated by Merot (1988) when testing the topographic index against map scale for two rural catchments. In that study, the comparison between observed saturated areas and the values of the corresponding topographic index showed satisfactory similarities, but significant discrepancies often arose. According to Merot, these differences could be explained by the shape of topography at the plot scale.

The DTM available in Switzerland is based on a grid of 25 m × 25 m. It was developed from the contour lines of the 1/25 000 topographic map with a contour interval of 10 m. A precise levelling was made on our elementary catchments. A DTM with a grid of 5 m × 5 m based on an contour interval of 1 m was derived. Map scale influences significantly the spatial distribution of the index values within the basin. Fig. 10 illustrates the differences for the Alloux catchment when the index values are derived from the precisely surveyed map of the catchment and from the 1/25 000 topographic maps. This

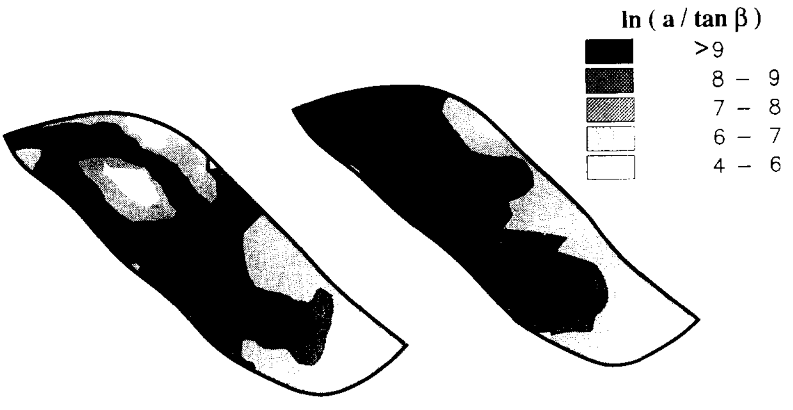

Fig. 10. Spatial representation of the topographic index for Alloux according to two DTMs of different levels of accuracy: detailed DTM (left); DTM derived from a 1:10 000 map (right).

result is very important, as it illustrates the accuracy to be expected in determining the location of saturated areas for a particular event.

3.9. Validation of the topographic index

At the scale of the Haute-Mentue catchment, some areas reach saturation relatively quickly and contribute to runoff for small storms. The spatial distribution of the topographic index shows the occurrence of high values located outside the elementary catchments; this is illustrated by the differences between the topographic index distributions (Fig. 11) of the elementary catchments and that of the whole basin. These areas correspond to flat slopes rather than to sectors where flow paths converge. A field survey after a rainy period confirmed that in the areas where the value of the topographic index is high, the water table reaches or remains close to the ground surface. Therefore, the differences between the response of the first- and third-order basins (Fig. 3) can be explained by the topographic index. This appears to be an accurate approach for the assessment and delineation of the areas which contribute to runoff most of the time.

The fact that contributing areas can easily be identified does not necessarily imply that for larger storms and saturated initial moisture conditions, the delineation of saturated contributing areas can easily be estimated from this topographic index. Water table levels recorded during the field investigations will prove this.

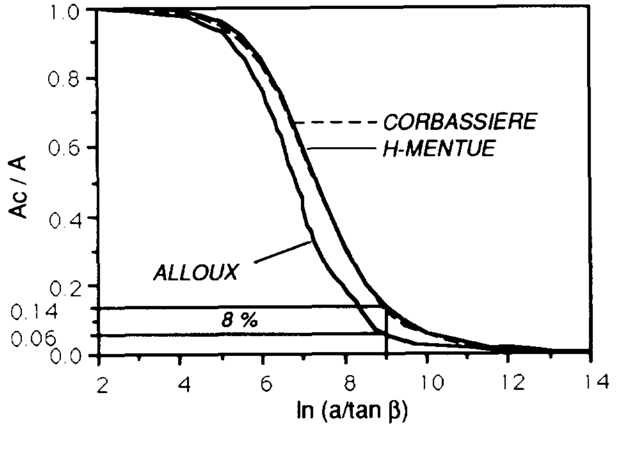

Fig. 11. Comparison between the topographic index distribution of Alloux (3.6 ha), Corbassière (185 ha) and the Haute-Mentue watershed (1250 ha).

3.10. Comparison between the topographic index and water table levels

To study the influence of topography, the adequacy of the topographic index was tested over the entire elementary catchment rather than verifying that high index regions are generally saturated. Therefore, the analysis also involves areas of low saturation potential.

According to the assumption of an exponential decrease of hydraulic conductivity with depth, Beven and Kirkby (1979) demonstrated for steady flow conditions that the local saturation deficit S_i at any point i for a given time t is a function of the global saturation deficit $\bar{S}$ throughout the basin according to the following relationship:

$$S_i = \bar{S} + m\lambda - m\ln(a_i/\tan\beta_i) + m\ln T_{si} \tag{4}$$

where T_{si} is the transmissivity at local saturation (mm h^{-1}), m is a parameter, $\lambda = (1/A)\int_A \ln(a_i/\tan\beta_i - \ln T_{si})\mathrm{d}A$ and λ is a constant for the basin.

If at any given time there is a constant soil moisture content ($\Delta\theta$) with depth z_i so that $S_i = \Delta\theta \cdot z_i$ (Beven, 1986), Eq. (4) may be rewritten as a linear regression between the groundwater depth and the topographic index:

$$z_i = B \cdot \ln(a_i/\tan\beta_i) + C + R_i \tag{5}$$

where B is the slope (proportional to $-m\Delta\theta$), C is a constant (proportional to $(\bar{S} + m\lambda)\Delta\theta$) and R_i is the residue ($R_i = f(\ln T_{si})$).

The relationships obtained for all the analysed events are not significant (Table 2), except for the maximum water table levels recorded on 9 September 1988 and 16 February 1990 (just after the high flood on 14 February 1990), where a satisfactory correlation was obtained (Fig. 12).

Correlation coefficients are equal to 89% for the event on 9 September 1988

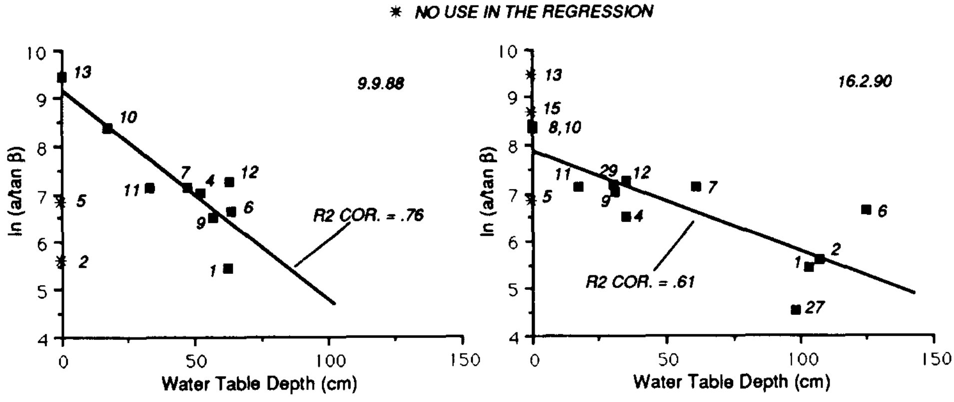

Fig. 12. Comparison between the topographic index and the water table depths recorded for two periods.

and 80% for that on 16 February 1990, with significance levels less than 0.2%. However, correlation coefficients have been calculated by eliminating some points: two for the first event and three for the second. On 16 February, eliminating the records of Piezometers 13 and 15 (Fig. 5) can be justified simply because negative values may introduce a bias in the regression. However, the elimination of the records for Piezometers 2 and 5 is completely arbitrary.

The time discrepancies indicate an extremely complex behaviour and prove that an equilibrium condition is seldom reached. In these conditions, improving the assessment of the spatial variability of the transmissivity will not increase significantly the adequacy of the topographic index. However, for saturated initial moisture conditions after a long rainy period and when the water table levels reach a stable situation, oblique flow processes dominate. In that case, a satisfactory correlation between water table depths and topographic index can be expected.

4. Conclusions

This first research study on the experimental catchment of the Haute-Mentue was able to give insight into the runoff generating mechanisms operating in this catchment and to assess the spatial variability. The results have shown the high complexity of the spatial and temporal variability of contributing areas.

For the saturation excess overland flow mechanism, which is the process occurring most frequently in this catchment, delineation of saturated areas is relatively easy for 10% of the catchment where topographic conditions favour saturation. However, this portion of the catchment can explain the hydrological behaviour only for small frequent events. Therefore, this study has shown the difficulties in forecasting the factors that govern the spread of saturated areas for larger floods.

Outside these saturated contributing areas, there are other sectors with steep slopes close to the streams, bare soils during most of the year and impervious surfaces that can contribute significantly to the flood by means of infiltration excess overland flow or subsurface flow even if the contributing areas remain small. The identification of such contributions is very difficult, and simple flow measurements at specific locations are of limited help.

The difficulty of predicting the spread of contributing areas is of primary importance when physically based models are applied, and raises the question of the required level of detail for field investigations and modelling studies. The difficulties in representing the geometry of the water table on a spatial basis lead to the issue raised by Beven (1987) on the need to develop 'a new macroscale theory that deals explicitly with the problems posed by spatial integration of heterogeneous non-linear interacting processes. Such a theory will be inherently stochastic'.

Acknowledgements

I gratefully acknowledge help in the writing of this paper provided by Professor A. Musy and my colleagues D. Consuegra, D. Devred and I. Iorgulescu.

References

Anderson, M.G. and Kneale, P.E., 1982. The influence of low-angled topography on hillslope soil-water convergence and stream discharge. J.Hydrol., 57: 65–80.

Betson, R.P. and Marius, J.B., 1969. Source areas of storm runoff. Water Resour. Res., 5: 574–582.

Beven, K.J., 1986. Runoff production and flood frequency in catchments of order *n*: an alternative approach. In: V.K Gupta, I. Rodriguez-Iturbe and E.F. Wood (Editors), Scale Problems in Hydrology, Reidel, Dordrecht, pp. 107–131.

Beven, K.J., 1987. Towards the use of catchment geomorphology in flood frequency predictions. Earth Surf. Processes, 12: 69–82.

Beven, K.J. and Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology. Int. Assoc. Sci. Hydrol. Bull., 24: 43–69.

Beven, K.J. and Wood, E.F., 1983. Catchment geomorphology and the dynamics of runoff contributing areas. J. Hydrol., 65: 139–158.

Beven, K.J., Kirkby, M.J., Schofield, N. and Tagg, A.F., 1984. Testing a physically-based flood forecasting model (TOPMODEL) for three U.K. catchments. J. Hydrol., 69: 119–143.

Bonell, M., Pearce, A.J. and Steward, M.K., 1990. The identification of runoff-production mechanisms using environmental isotopes in a tussock grassland catchment, Eastern Otago, New Zealand. Hydrol. Processes, 1: 15–34.

Bottomley, D., Craig, J.D. and Johnston, L.M., 1984. Neutralization of acid runoff by groundwater discharge to streams in Canadian Precambrian Shield catchments. J. Hydrol., 75: 1–26.

Burt, T.P. and Butcher, D.P., 1985. Topographic controls of soil moisture distributions. J. Soil Sci., 36: 469–486.

Crouzet, E., Hubert, P., Olive, Ph. and Siweritz, E., 1970., Le tritium dans les mesures d'hydrologie de surface. Détermination expérimentale du coefficient de ruissellement. J. Hydrol., 11: 217–219.

Dewalle, D.R., Swistock, B.R. and Sharpe, W.E., 1988. Three-component tracer model for stormflow on a small Appalachian forested catchment. J. Hydrol., 104: 301–310.

Dunne, T., 1982. Models of runoff processes and their significance. In: Scientific Basis of Water-Resources Management, Studies in Geophysics by the National Research Council. Natl. Academy Press, Washington D.C., pp. 17–30.

Dunne, T. and Black, T.D., 1970. An experimental investigation of runoff production in permeable soils. Water Resour. Res., 2: 478–490.

Fritz, P.J., Cherry, A., Weyer, K.U. and Sklash, M., 1976. Storm runoff analyses using environmental isotopes and major ions. In: Interpretation of Environmental Isotope and Hydrochemical Data in Groundwater Hydrology. IAEA, Vienna, pp. 111–130.

Harr, R.D., 1977. Water flux in soil and subsoil on a steep forested slope. J. Hydrol., 33: 37–58.

Herrmann, A., Koll, J., Schöniger, M. and Stichler, W., 1987. A runoff formation concept to model water pathways in forested basins. IAHS Publ., 167: 251–263.

Hewlett, J.D. and Hibbert, A.R., 1963. Moisture and energy conditions within a sloping mass during drainage. J. Geophys. Res., 4: 1081–1087.

Hewlett, J.D. and Hibbert, A.R., 1967. Factors affecting the response of small catchment to precipitation in humid areas. In :W.E. Sopper (Editor), Forest Hydrology. Pergamon, New York, pp. 275–290.

Hewlett, J.D., Forston, J.C. and Cunningham, G.B., 1977. The effect of rainfall intensity on storm flow and peak discharges from forest land. Water Resour. Res., 13: 259–266.

Hubert, P., Marin, E., Meybeck, M., Olive, Ph. and Siwertz, E., 1969. Aspects Hydrologique, Gèochimique et Sèdimentologique de la Crue Exceptionnelle de la Dranse du Chablais du 22 Septembre 1968. Arch. Sci (Genève), 3: 581–604.

Jordan, J.P., 1992. Identification et modèlisation des processus de génération des crues. Ph.D. Thesis, Ecole Polytechnique Fédérale de Lausanne.

Kennedy, V.C., Kendall, C., Zellweger, G.W., Wyerman, T.A. and Avanzino, R.J., 1986. Determination of the components of stormflow using water chemistry and environmental isotopes, Mattole River basin, California, J.Hydrol., 84: 107–140.

McDonnell, J.J., Bonell, M., Stewart, M.K. and Pearce, A.J., 1990. Deuterium variations in storm rainfall: implication for stream hydrograph separation. Water Resour. Res., 26: 455–458.

Merot, P., 1988. Les zones de sources à surface variable et la question de leur localisation. Hydrol. Continent., 2: 105–115.

Merot, P., Bourguet, M. and le Leuch, M., 1981. Analyse d'une crue à l'aide du traçage naturel par l'oxygène 18 mesuré dans les pluies, le sol, le ruisseau. Catena, 8: 69–81.

Mook, W.G., Groeneveld, D.J., Brown, A.E. and van Ganswijk, A.J., 1974. Analysis of a runoff hydrograph by means of natural ^{18}O. In: Isotope Techniques in Groundwater Hydrology, No. 1. IAEA, Vienna, pp. 145–155.

Mosley, M.P., 1979. Streamflow generation in a forested catchment, New Zealand. Water Resour. Res., 4: 795–806.

Nolan, K.M. and Hill, B.R., 1990. Storm-runoff generation in the permanent Creek drainage basin, West Central California –an example of flood-wave effects on runoff composition. J. Hydrol., 113: 343–367.

O'Gunkoya, O.O. and Jenkins, A., 1991. Analysis of runoff pathways and flow contributions using deuterium and storm chemistry. Hydrol. Processes, 5: 309–320.

O'Loughlin, E.M., 1986. Prediction of surface saturation zones in natural catchments by topographic analysis. Water Resour. Res., 5: 794–804.

Pearce, A.J., 1990. Streamflow generation processes: an austral view. Water Resour. Res., 26: 3037–3047.

Petch, R.A., 1988. Soil saturation patterns in steep, convergent hillslopes under forest and pasture vegetation. Hydrol. Processes, 2: 93–103.

Quinn, P., Beven, K.J., Chevalier, P. and Planchon, O., 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. Hydrol. processes, 5: 59–79.

Rodhe, A., 1983. Groundwater contribution to stream flow in Swedish forested till soil as estimated by oxygen-18. In: Isotope Hydrology, 1983, Proc. Symp. IAEA, Vienna, pp. 55–66.

Rodhe, A., 1989. On the generation of stream runoff in till soils. Nordic Hydrol. 20: 1–8.

Sklash, M.G. and Farvolden, R.N. 1979. The role of groundwater in storm runoff. J. Hydrol., 43: 45–65.

Sklash, G. and Farvolden, R.N., 1982. The use of environmental isotopes in the study of high-runoff episodes in streams. In: E.C. Perry, and C.W. Montgomery, (Editors), Isotope Studies of Hydrological Processes, Northern Illinois University Press, Dekalb, IL, pp. 65–73.

Sklash, M.G., Steward, M.K. and Pearce, A.J., 1986. Storm runoff generation in humid head-water catchment, 2. A case study of hillslope and low-order stream response. Water Resour. Res., 22: 1273–1282.

Tanaka, T., Yasuhara, M., Sakai, H. and Marui, A., 1988. The Hachioji experimental basin study–storm runoff processes and the mechanism of its generation. J. Hydrol., 102: 139–164.

Taylor, C.H. and Pearce, A.J., 1982. Storm runoff processes and subcatchment characteristics in a New Zealand hill country catchment. Earth Surf. Processes, 7: 439–447.

Turner, J.V., Macpherson, D.K. and Stokes, R.A., 1987. The mechanisms of catchment flow processes using natural variations in deuterium and oxygen-18. J. Hydrol., 94: 143–162.

Ward, R.C., 1984. On the response to precipitation of headwater streams in humid areas. J. Hydrol., 74: 171–189.

Weyman, D.R., 1970. Throughflow on hillslopes and its relation to the stream hydrograph. Int. Assoc. Sci. Hydrol. Bull., 15: 25–33.