Hydrological processes identification by the combination of environmental tracing with time domain reflectometry measurements

C. JOERIN, A. MUSY & F. POINTET

Soil and Water Management Institute, Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland

e-mail: christophe.joerin@dgr.epfl.ch

Abstract This study begins with the application of environmental tracing in order to identify hydrological processes in the Haute-Mentue basin. The application of a three-component model, based on concentrations of silica and calcium demonstrates that the groundwater and soil water dominate streamflows. Mixing models identify volumes, but not water pathways. In this context, in order to specify which physical properties or mechanisms are responsible for the important contribution of subsurface flows, an experiment based on a time domain reflectometry system and additional measurements within the basin (piezometers and rainfall simulator) was conducted. The association of these experiments allows demonstrating that preferential flows are certainly responsible for the important contribution of soil water. Furthermore according field observations and a rainfall simulator experiment, it seems that macropores are at the origin of these preferential flows.

INTRODUCTION

Recently, considerable efforts have been expended in the pursuit of a thorough understanding of storm runoff generation in streams. Among the methods used for these investigations, environmental tracing has probably been utilized most and has provided the most interesting results. Hydrograph separation using mass balance equations for water and chemical tracers to determine runoff sources in streamflow is now a widely used technique in hydrology.

In the particular case of the Haute-Mentue basin, Iorgulescu (1997) developed a three-component mixing model based on two chemical tracers (silica and calcium). This model allows the differentiation in the hydrograph of the following components: direct precipitation, soil water (acid soils) and groundwater (in contact with the carbonate bedrock). The application of this model to the Haute-Mentue hydrographs demonstrates that the contribution of soil water is strongly related to the antecedent moisture conditions of the basin. In wet antecedent moisture conditions, the contribution of soil water to total runoff may reach 58% and subsurface flow (acid soil water and groundwater) 80%.

For the identification of the mechanisms which are responsible for the significant subsurface flows, it appears that the application of environmental tracing or more particularly of mixing models is not sufficient. In fact, mixing models identify volumes but not water pathways. The same water (same age or same chemical characteristics) can follow different pathways or a process can involve different kinds of water (McDonnell 1990). In this context and in order to identify specific hydrological processes within the basin it seems necessary to conduct hillslope measurements.

Since the hydrological behaviour of the Haute-Mentue depends on antecedent wet conditions, it was chosen to conduct a large-scale time domain reflectometry (TDR) experiment. The application of this technique for the determination of soil water content has been well documented and used for 20 years. The utilization of TDR has proved to be a reliable method for the determination of soil moisture.

The present TDR experiment should confirm first that the soil water is potentially an important water reservoir for the flood generation and it may also provide some indication concerning the involved hydrological mechanisms. In connection with that Iorgulescu (1997) hypothesized that preferential flows deliver soil water rapidly and in large quantities to the stream in order to explain the high contribution of subsurface sources in the Haute-Mentue basin. In order to test this hypothesis and/or to identify other hydrological processes, this study is based not only on the combination of environmental tracing and TDR but also on piezometric measurements and on a rainfall simulator experiment.

In summary this study proposes an approach for the identification of hydrological processes, which associates environmental tracing and hillslope measurements. First, hydrological behaviour is studied at a large scale by the application of environmental tracing. Next, hydrometric measurements are conducted to identified contributing areas to study specific mechanisms and to discover the controlling parameters.

THE HAUTE-MENTUE RESEARCH BASIN

Iorgulescu (1997) gives a fully detailed description of the basin. Here only a brief description introduces the geographical context of this study. The basin is located in the Swiss Plateau about 20 km north of Lausanne. The climate is humid temperate with slight continental characteristics. Mean annual precipitation is around 1280 mm, and mean potential evapotranspiration is around 600 mm. The runoff at the outlet of the Haute-Mentue basin has an annual average of 680 mm. The hydrological regime presents a seasonal cycle with a minimum at the end of summer and a maximum during winter. The bedrock is composed of low permeability sedimentary deposits (sandstone and siltstone), called "molasse". A variable layer of bottom moraine deposits overlies this substratum, which is almost impermeable. Soils are moderately permeable sandy loams or loamy sands with an average depth of 1 m. Soils are classified as dystric cambisols and luvic cambisols.

The investigations reported here are concentrated on the Bois-Vuacoz sub-basin (24 ha) situated in the upper and forested part of the Haute-Mentue. The altitude ranges between 900 and 927 m and the average slope is about 7.5%.

METHODS

The environmental tracing and TDR experiments were simultaneously conducted on the Bois-Vuacoz sub-basin during the months of November and December 1997. The following section briefly presents both experiments.

Environmental tracing

The outlet of Bois-Vuacoz basin is equipped with a flow measuring structure (H-flume) and a submerged probe (pressure transducer) flowmeter ISCO. An automatic ISCO sampler connected to the flowmeter was programmed to take a sample every 5 mm of runoff. A recording tipping-bucket raingauge (200 cm^2) is situated in the basin. Bulk samples of open precipitation were collected at the outlet of the raingauge. Furthermore, bulk throughfall was sampled by a trough (300×10 cm^2) situated about 900 m downstream of the Bois-Vuacoz outlet. The soil water was sampled at only two different sites in the Bois-Vuacoz basin during the studied period. This is not enough to adequately define the component of "acid soil water", for the hydrograph separation presented below the chemical signature of this component was defined according to all soil samples collected in the Haute-Mentue basin (at 15 different sampling locations) since 1993. The soil water was collected either by ceramic suction cups (unsaturated zone) or by zero tension lysimeters (saturated zone).

Time domain reflectometry

The TDR technique is used in this study to measure soil moisture in an area of approximately 500 m^2 at Bois-Vuacoz. Thanks to multiplexing, the system records on an hourly basis the apparent length of 64 probes computed from the plotted pulse with the software Pc208e from Campbell. Each probe is composed of two wires, which are 30 cm long. The soil moisture is calculated with the three-phase model of Roth *et al.* (1990).

RESULTS AND DISCUSSION

The study period (5 November 1997–2 December 1997) presents relatively wet conditions. In October it rained 76.3 mm. Nevertheless, a relatively long period without rain occurred between 24 October and 3 November. Thus the chemical signature of the "groundwater" component can be reasonably defined according to baseflows observed just before the study period. The hydrograph decomposition was obtained by the application of the AIDH (Analyse d'Incertitude des Décompositions d'Hydrogramme) program developed at the Soil and Water Management Institute, Lausanne (Joerin, 1997). On the one hand this program allows the decomposition of flood hydrographs and on the other hand it estimates the uncertainty of this separation due to the chemical signature variability of components (Fig. 1(b)). The AIDH program is based on a Monte Carlo approach, which is quite similar to the method proposed by Bazemore *et al.* (1994).

The application of the AIDH program to the events of November 1997 resulted in a high quality hydrograph separation (Fig. 1(b)). In fact, the uncertainties are rather limited and therefore it is possible to identify clearly the general hydrological behaviour of the Bois-Vuacoz basin. The most relevant observations are: that the groundwater dominates the flow almost all the time (GW 36%–99%), and that the soil water contribution increases during the series of four events between the 8 and 13

November (Fig. 1(a) and (b)). Moreover, during the 13 November peak flow soil, water dominates the flood (SW 46%, GW 41% and DP 13%). These results correspond well with the pattern proposed by Iorgulescu (1997). In dry conditions storm flow can

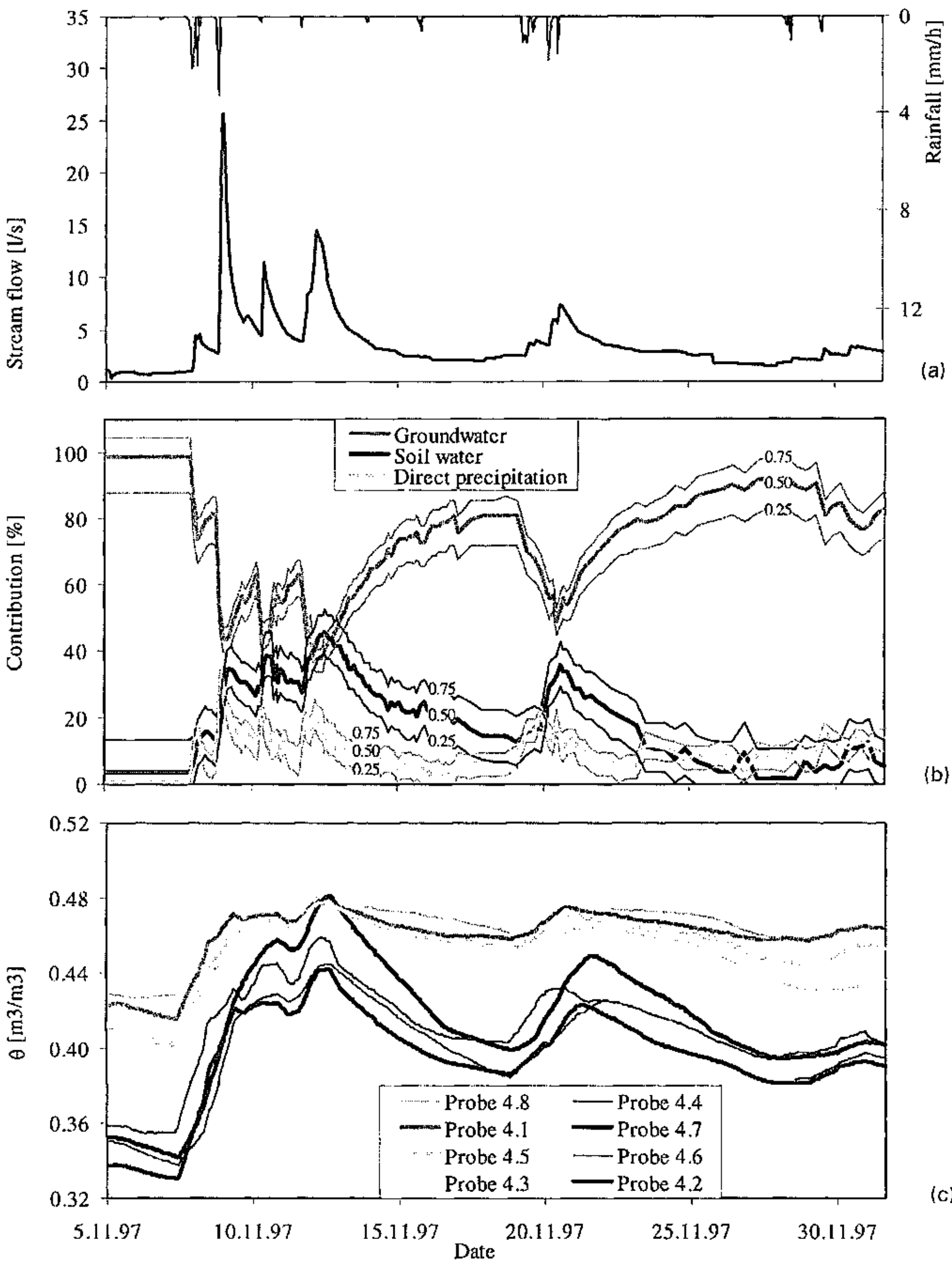

Fig. 1 Hydrological responses in Bois-Vuacoz sub-basin between 5 November and 2 December 1997: (a) rainfall and runoff; (b) hydrograph separation and representation of the contribution of components in quartiles form (0.75, 0.50, 0.25); (c) continuous soil moisture measurements from eight vertical probes (length 30 cm).

be explained as a mixture of pre-event baseflow and precipitation. As the basin becomes wetter, the contribution of soil water increases. Finally, in wet conditions soil water dominates storm flow.

Concerning TDR measurements, it appears that the spatial variability of soil moisture at the local scale is very important. Pointet (1998) studied this spatial variability with a regionalized variables approach and suggested that soil moisture is a random variable at the local scale (<20 m). Differences between the time series dynamics are also important; in this case it is possible to distinguish two patterns. In the first case (e.g. probes 4.4, 4.7, 4.6, 4.2 in Fig. 1(c)), the soil moisture increases more strongly than in the second case (e.g. probes 4.8, 4.1, 4.5, 4.3 in Fig. 1(c)). In the first case the initial soil water content is clearly lower than in the second, but the soil moisture maximums of both series are very close. Nevertheless the time taken to reach soil moisture maximum is similar in both cases varying between 15 and 17 h. In wet conditions differences of soil moisture are less important than in dry conditions. The decrease of soil moisture is also completely different. In the first case this dynamic is clearly stronger and quicker than in the second. These differences of behaviour are observed between very close sites (the distance between probes in Fig. 1(c) is 1–8 m). Actually the spatial variability and the difference of soil moisture dynamic are coherent with the hypothesis of preferential flows.

It is interesting to compare the soil moisture dynamic with the hydrograph separation. Among the three components, the soil water dynamic is obviously the most similar to the soil moisture dynamic. In fact these two series follow the same evolution, and they reach their maximum virtually at the same time on 13 November (lag of 1 h). Overall TDR observations confirm partially the relative importance of the "soil water" component. After significant precipitation, the soil water content increases strongly (Fig. 1(c)) and can reach moisture level close to saturation (the porosity at Bois-Vuacoz is around 50 m^3 m^{-3}). This context, which occurs at the same time the streamflow increases, seems to be favourable for subsurface flows, and more particularly for lateral flows through the soil. So according to environmental tracing and TDR results it seems possible to confirm the importance of the soil water contribution and that of subsurface flow to the flood generation in wet conditions. Furthermore, the TDR experiment indicates clearly that conditions of subsurface flows are not homogeneous within hillslopes. Consequently, hydrological processes such as soil moisture likely depend on very local characteristics. Nevertheless in the present situation, it is still difficult to associate these subsurface flows with particular hydrological processes.

In order to identify mechanisms responsible for subsurface flows and to test more particularly the preferential flow hypothesis, others field experiments were conducted. During the same period the water table at six different points next to the TDR site (at about 20 m) was recorded every two days. The piezometers were screened at a depth of 1.60 m. The piezometer network forms an equilateral triangle with sides of 3 m (approximately 1.5 m separates each piezometer). It can be noted that the water table and soil moisture present similar behaviour, i.e. they follow simultaneously the same dynamic (Figs 1(c) and 2).

According to these piezometric measurements it seems that the soil moisture is well correlated with the groundwater level. The decrease of the water table can be very fast (between 6 and 11 cm per day). Before and during the study period the

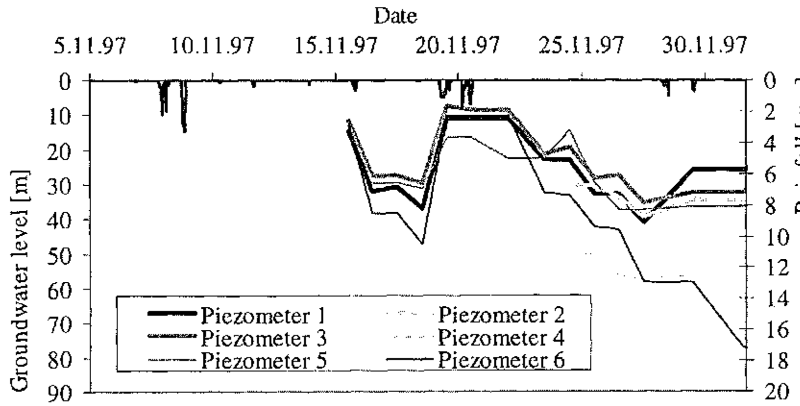

Fig. 2 Water table depth measurements from six piezometers located at Bois-Vuacoz.

evapotranspiration was negligible, so the fall of groundwater level and the decrease of soil moisture have to be due to either subsurface lateral flows or to vertical flows which involve groundwater flows through the basin. Given the spatial variability of the water table, it seems that groundwater flow is controlled by local processes rather than by water flows at the hillslope scale.

The hypothesis of local flows is coherent with both TDR and piezometric observations. In fact preferential flows could explain the spatial variability of soil humidity and differences of saturated areas emptying. It is not possible to confirm in a formal way this hypothesis but hillslope measurements seem to indicate that it is correct. Furthermore field observations corroborate the preferential flows existence. In fact, macropore flows were clearly identified within the basin and more particularly along the river on steep banks. Macropore flows were also observed during an experiment conducted at Bois-Vuacoz using a rainfall simulator (ORSTOM type, cf. Asseline & Valentin, 1978). An area of 1 m^2 was sprinkled with a constant rainfall (intensity 60 mm h^{-1}). At the permanent regime the surface runoff at a first site reached 79% of sprinkled water, but at a second site no runoff occurs. This difference was due to a macropore with a diameter of 1–2 cm, which crossed the second experimental plot. Apparently macropore flows are effective in the Bois-Vuacoz basin. In connection with that Mikovari *et al.* (1995), according to an environmental tracing experiment at hillslope scale (<10 m), suggested that the interconnected macropore system can be very well developed. Nevertheless, for the moment the knowledge about the structure of macropore systems at this scale is insufficient to consider this flow as solely responsible for the important contribution of soil water in the Haute-Mentue basin. Furthermore there are still some doubts concerning the enrichment of rainwater during its path through macropores to the stream (Buttle & Peters, 1997). In this context it is important to still consider and test the eventual contribution of other mechanisms proposed in the literature (see Buttle, 1994, for a review).

CONCLUSIONS

The approach adopted during this study, the combination of several techniques of measurements (e.g. environmental tracing, TDR, piezometers, rainfall simulator), seems interesting in the context of the study of hydrological processes. It is very difficult to identify the specific hydrological behaviour of a basin with the application of only one type of measurements. Each method has a specific area of use and consequently result interpretation is limited. For example, basin-scale environmental tracing does not specify the mechanism by which soil water is delivered to the river during the flood. Therefore it appears that better hydrological processes identification may be obtained by the association of several types of measurements (e.g. global as tracing and local as TDR). A good way to begin such an approach is certainly the application of environmental tracing in order to determine the general behaviour and then to concentrate on local measurements. The choice of point or internal measurements depends on the mechanisms that have to be identified.

The combination of all this information coming from different sources and different scales can be difficult. A possible solution may be the integration of this information using physically-based models. In this framework different hypotheses about hydrological mechanisms can be tested considering both discharge and internal variables.

Acknowledgements Ion Iorgulescu is thanked for his very useful input at various stages of the study. This research was supported in part by the Swiss National Research Foundation (Grant no. 21-43308.95) and by OFES (Grant no. 95.00449) in the framework of the EU funded Project VAHMPIRE.

REFERENCES

Asseline, J. & Valentin, C. (1978) Construction et mise au point d'un infiltromètre à aspersion. *Cah. ORSTOM* **XV**(4), 321–349.

Bazemore, D. E., Eshleman, K. N. & Hollenbeck, K. J. (1994) The role of soil water in stormflow generation in a forested headwater catchment: synthesis of natural tracer and hydrometric evidence. *J. Hydrol.* **162**, 47–75.

Buttle, J. M. (1994) Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. *Progr. Phys. Geogr.* **18**(1), 16–41.

Buttle, J. M. & Peters, D. L. (1997) Inferring hydrological processes in a temperate basin using isotopic and geochemical hydrograph separation: a re-evaluation. *Hydrol. Processes* **1**, 557–573.

Iorgulescu, I. (1997) Analyse du comportement hydrologique par une approche intégrée à l'échelle du bassin versant. Application au bassin versant de la Haute-Mentue. PhD Thesis, Ecole Polytechnique Fédérale de Lausanne, Lausanne.

Joerin, C. (1997) Analyse d'incertitude des modèles de mélange géochimique—application à la décomposition des hydrogrammes de la Haute-Mentue. Master Thesis, Ecole Polytechnique Fédérale de Lausanne, Lausanne.

McDonnell, J. J. (1990) A rationale for old water discharge through macropores in a steep, humid catchment. *Wat. Resour. Res.* **26**, 2821–2832.

Mikovari, A., Peter, C. & Leibundgut, C. (1995) Investigation of preferential flow using tracer techniques. In: *Tracer Technologies for Hydrological Systems* (ed. by Ch. Leibundgut) (Proc. Boulder Symp., July 1995), 87–97. IAHS Publ. no. 229.

Pointet, F. (1998) Analyse de la variabilité spatiale et temporelle de la teneur en eau du sol: application au bassin versant expérimental de la Haute-Mentue. Travail de Diplôme, Ecole Polytechnique Fédérale de Lausanne, Lausanne.

Roth, K., Schulin, R., Flühler, H. & Attinger, W. (1990) Calibration of time domain reflectometry for water content measurement using composite dielectric approach. *Wat. Resour. Res.* **26**, 2267–2273.