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Hydrological behaviour of the granitic Strengbach catchment (Vosges massif, Eastern France) during a flood event

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Abstract A field campaign combining monitoring devices and determination of isotopes and chemical elements has been performed during a summer thunderstorm in the small granitic Strengbach catchment (Vosges, France). The collected ground data were used in a hydrological modelling exercise including two conceptual rainfall-runoff models (GR4, TOPMODEL). The predominant role in flood generation of pre-event water coming from the superficial layers of the water saturated area has been shown and a conceptual scheme has been proposed derived from the field observations. The two tested modelling structures and assumptions are not able to take into account fully the complexity of the physical processes involved in flood generation.

Key words streamflow generation processes; ¹⁸O; silica; hydrological modelling

INTRODUCTION

After the pioneering work of Voronkov (1963) for separating hydrographs on an hydrochemical basis, the understanding of streamflow generation processes in different environmental conditions has been considerably improved by using tracers in hydrograph separation (Pinder & Jones, 1969; McDonnell *et al.*, 1990). Later on, numerous studies on the mechanism of streamflow generation using stable isotopes associated to chemical tracers have been performed (e.g. Hooper & Shoemaker, 1986; Laudon & Slaymaker, 1997; Ladouche *et al.*, 2001). Such an approach combining monitoring devices, determination of isotopes and chemical elements has been undertaken in the small granitic Strengbach catchment where a water saturated area plays an important role in flood generation (Idir *et al.*, 1999). In order to check if the dynamics of these surface or subsurface contributing areas were correctly described, TOPMODEL based on a distributed topographic index (Beven, 1997) has been applied to the data set. A lumped four parameter reservoir-based GR4 model (Perrin *et al.*, 2003) has also been used to know if these two Conceptual Rainfall-Runoff (CRR) models were able to correctly predict lumped hydrographs and also to test their ability to provide a satisfactory conceptualization of runoff processes and contributing reservoirs involved in flood generation.

STUDY AREA

The Strengbach catchment is a site for multidisciplinary studies in hydrological, geochemical and forest research located on the eastern side of the Vosges massif (Eastern France) (Probst *et al.*, 1990). This small catchment (0.8 km²) ranges from 883 m to 1146 m (a.s.l.) and mainly lies on a base-poor granitic bedrock. Soils are acidic and coarse-textured. This catchment is forested mainly with Norway spruce (65% of the area) and mixed beech and silver fir take up the rest of the area. The climate is temperate oceanic-mountainous; mean annual precipitation is 1400 mm regularly spread throughout the year and mean annual runoff is of 850 mm with high flow rates in cold season and low flow rates at the end of summer. The mean water transit time of this fractured granitic catchment is of 38.5 months (Viville *et al.*, 2006). A variable saturated area (up to 3% of the catchment area for a 128 l.s⁻¹ discharge), close to the outlet, is connected to the stream and plays an important role in flood generation (Idir *et al.*, 1999).

During the thunderstorm which occurred in 22 July 1995 on the Strengbach catchment, the different components (rainfall, soil water, groundwater, streamwater) of the water cycle were measured and

sampled in different locations at a variable time step. The major chemical parameters (Na^+ , K^+ , Ca^{2+} , Mg^{2+} , SO_4^{2-} , NO_3^- , Cl^- , NH_4^+), silica, alkalinity, dissolved organic carbon (DOC) and stable isotopes (^2H , ^{18}O), were analysed. These elements were selected to assess the different contributing sources using mass balance equations and end-member mixing diagrams (Viville *et al.*, 2003).

MODELS

The GR4 continuous RR model used in this study corresponds to the hourly version of the daily time step GR4 RR model which is a lumped parsimonious four-parameter RR model (Perrin *et al.*, 2003). The hourly version has the same structural formulation as the daily version and differs only through little change of fixed parameter values for the percolation function, the drainage function of the soil reservoir, and the unit hydrographs (Mathevet, 2005). Through GR4 RR model, the river catchments are represented by two reservoirs, a soil reservoir and a routing reservoir. After an interception step, the rainfall is divided into a component filling the soil reservoir (drained either by evapotranspiration or by percolation towards deep flow), and a component routed with percolation to the outlet via a transfer function. This net rainfall is divided into two parts; the first one (90%) is routed by a unit hydrograph UH1 and fills the routing reservoir, the second is routed by a unit hydrograph UH2 and generates the quickflow. The drainage of the non-linear routing reservoir generates a baseflow. A groundwater exchange term that acts on both flow components is also incorporated into the model for simulating catchment water exchange.

TOPMODEL represents the catchment topography by the mean of the frequency distribution of a topographic index. In the original version of TOPMODEL, the RR model represents catchments using one linear and one nonlinear storage for each index increment. For each increment, water input first enters the unsaturated zone store where it then flows vertically to the saturated zone store at a rate depending on the quantity of water required to fill the unsaturated store to saturation. The saturated zone acts as a nonlinear reservoir, with the baseflow discharge, Q_b , and saturation overland flow, Q_{of} , is generated when the saturation deficit for an increment becomes zero. The frequency distribution of the topographic index is used to compute the fraction of the catchment that generates saturation excess overland flow. For each hourly time step, contributions of Q_b and Q_{of} are summed to give a total discharge for the catchment. As the original limited Windows version (97.01) of TOPMODEL has been used, the model was run on a 3 months period and the calculation of the topographic index was based on the multiple flow direction algorithm of Quinn *et al.* (1995) and a 14-m grid size DTM. The four free parameters of the GR4 RR model were automatically optimized through a step-by-step local method of optimization using a direct start and by using the Nash-Sutcliffe coefficient calculated on the logarithmic transformed discharges values. For TOPMODEL, the optimal values of model parameters have been selected according to a sensitivity analysis applied to each of them with the Nash-Sutcliffe coefficient as objective function

RESULTS

Field Measurements

The 22 July 1995 event occurred during low water flow conditions and the discharge at the outlet was only of 3.5 L.s^{-1} . This event is a typical intensive (up to 60 mm.h^{-1}) summer rain storm with three short rainless periods. The total amount of the four showers is of 30 mm. The corresponding flood hydrograph is characterized by three peaks of discharge (40 , 34 and 17 L.s^{-1}) with a short time to peak (5 minutes) for the main stream as well as the tributaries, suggesting that the contributive areas are close to the brook and especially to the outlet (Fig. 1). Water table measurements present a general 0.4 to 0.5 m water level raising. These hydrological measurements indicate that the downstream zone of the catchment is the most efficient contributive area to streamflow and that the water table reacts very quickly to the rainfall.

The isotopic rain water composition varies between -3 ‰ and -6 ‰ but most of the data are close to a -4 ‰ value while the isotopic composition of stream water at the outlet varies greatly from -9.3 ‰ before the flood event to -7.1 ‰ at the peak flow (Fig. 2). It returns to the initial value during the

recession limb of the flood. The same behaviour was observed for all the tributaries. This variation of $\delta^{18}\text{O}$ value in stream water suggests that the event water contribution is rather important. An isotope hydrograph separation has been performed using the event weighted isotopic signature of each shower (McDonnell *et al.*, 1990) and with a constant pre-event signature of -9.3 ‰ (the stream base flow value). This hydrograph separation shows that the peak flows, which are composed with a non-negligible part of rainfall, are generated by pre-event water coming from the superficial layers of the water saturated area whereas during the limb of the flood, the influence of the deeper layers is increasing.

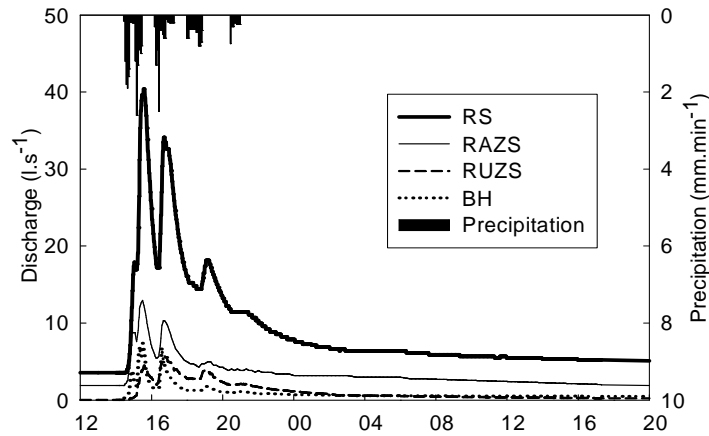


Fig. 1 Hyetograph and hydrographs of the stream at the outlet (RS), at the upper subcatchment (RAZS), and of the tributaries (BH, RUZS).

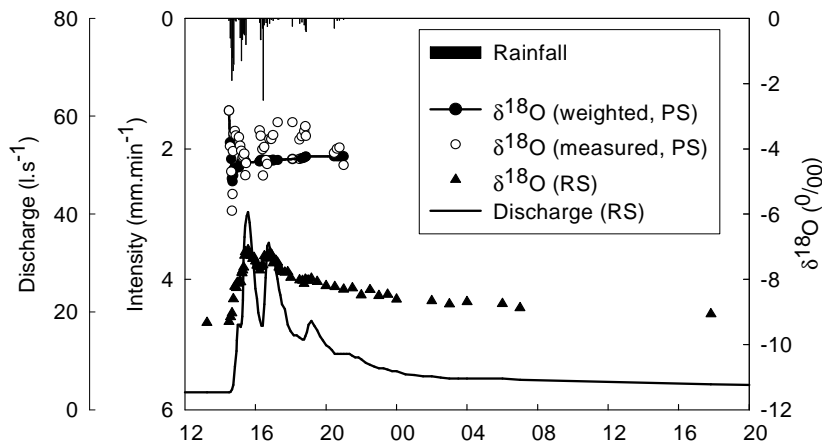


Fig. 2 Variations of $\delta^{18}\text{O}$ in rainfall (PS) and in streamwater at the outlet (RS) and corresponding discharge.

According to their chemical behaviour in relation to the discharge variations, two groups of chemical parameters have been identified: the elements which are diluted with increasing discharges (SO_4^{2-} , Na^+ and H_4SiO_4) and the elements which are concentrating with increasing discharges (e.g. DOC, NO_3^- , Cl^- ...) (Fig. 3). In order to identify the contributing sources to the chemical composition of streamwater, end-member mixing diagrams (Christophersen *et al.*, 1990) have been performed for major elements. Among analysed parameters, the linear mixing diagram between DOC and silica (Fig. 4) shows that streamwater at the outlet (RS) can be explained mainly by two obvious end-members: the component with high DOC and low silica concentrations characterizes the upper horizons of the saturated area, whereas the component with high silica and low DOC content represents the deeper layers of the hillslopes as already observed for another event (Ladouche *et al.*, 2001). The chemical hydrograph separation performed by using silica and DOC with constant end-member values clearly

exhibits that, during the peak flows, the water comes mainly from the upper layers of the water saturated area.

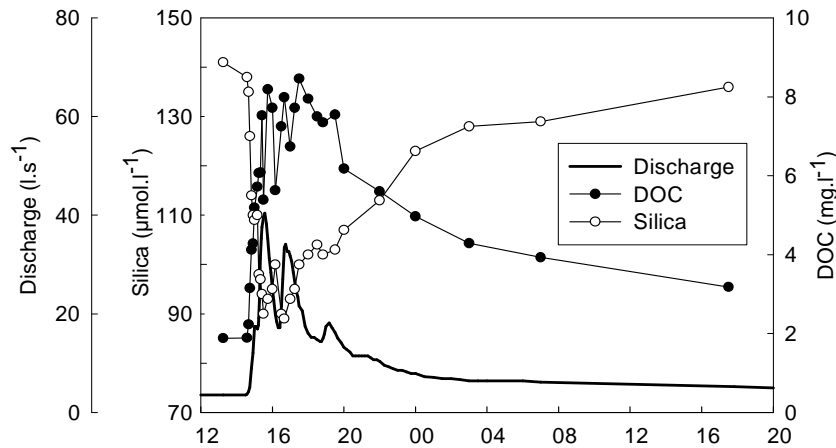


Fig. 3 Variations of DOC, silica and discharge at the outlet.

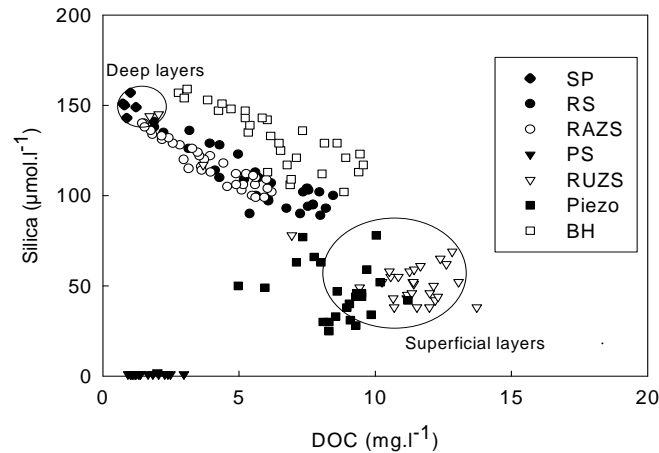


Fig. 4 End member mixing diagram between DOC and silica for the sampling sites.

Considering these experimental results, the conceptual scheme proposed for explaining the flood generation might be the following: before the rainfall event, the streamflow is composed by pre-event water draining the deep layers of the superficial granitic formations. During the peak flows, a rapid infiltration of an important part of rain via preferential pathways (e.g. macropores) could explain the sharp rising of the water table, the variation of the isotopic signature and the decrease of silica content in the superficial layers. This groundwater ridging causes an increasing extent of the saturated area which could induce superficial runoff due to groundwater exfiltration. During the recession limb of the flood hydrograph, most of the water comes from the downstream hydrological zone and the event water proportion decreases whereas the deep layer contribution becomes highly dominant.

Modelling

For this moderate wet antecedent conditions and small rainfall event, the maximum peak discharge and the storm flow volume are both underestimated by the two CRR models and especially by TOPMODEL which completely mismatched this event (Fig. 5).

The GR4 simulated response is underestimated and the peak of discharge is smoothed. The simulated response is mainly due to the soil reservoir contribution which produces quick flow while the routing reservoir presents a very weak variation during the event. We have tried to relate the reservoir contribution to field observations such as piezometers variations (Fig. 6). As only a weak variation of

the routing reservoir was recorded, no relationship has been established with the foot-slope piezometer A (Fig. 6a), but, it seems that some relationship can be established between the soil reservoir and the variations of the water table in the piezometer D which is located in water saturated area (Fig. 6b). That corresponds also to the field observations and flood analysis which have shown that the hydrological response is generated by the riparian reservoir of small spatial extension affected by groundwater ridging. In this case, a physical meaning could be attributed to a component of the lumped GR4 model.

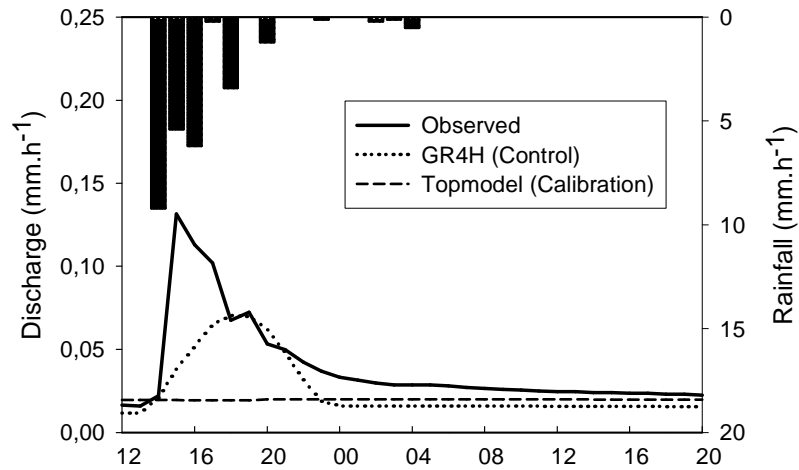


Fig. 5 Observed vs simulated hydrographs (hourly time step) for the flood of July 1995.

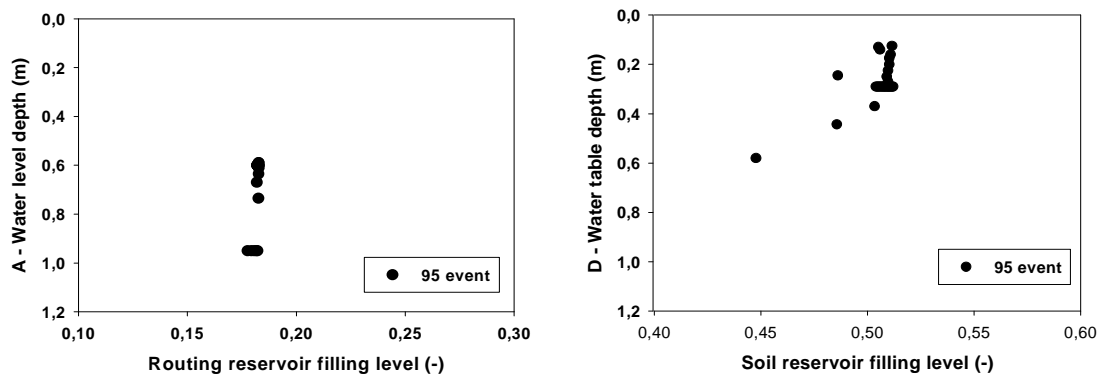


Fig. 6 Scatterplots for the flood event: (a) foot-slope piezometric level vs GR4 routing reservoir level; (b) riparian piezometric level vs GR4 soil reservoir level.

Concerning TOPMODEL, the simulation produces no saturation excess overland flow and therefore, the extension of the saturated area is null. Meanwhile, the field observation indicated that this process was existing during the flood and that the extent of the saturated area could be estimated to 0.6% of the catchment. Small storm flow like the one of July 1995 generated by saturation excess on these areas during low flow periods are systematically underestimated whereas major floods are overestimated (Viville & Drogue, in press). Hence, saturated contributing area based on topography alone, assuming a homogeneous soil, did not adequately reproduce the observations. Moreover, the choice of the best set of parameters - which is based on the Nash-Sutcliffe Efficiency criterion and discharge values- does not permit to describe adequately the location of the existing saturated area. This is due to the set of parameters which is spatially uniform, thus not taking into account the local variability of the topography as well as the small amount of rainfall which is not sufficient to saturate the soil profile.

CONCLUSIONS

The hydrological behaviour and the processes involved during this event have clearly been identified through a mixed approach associating field measurements, isotopes and chemical elements determination. The predominant role of pre-event water coming from the superficial layers of the water saturated area has been shown and a conceptual explanation scheme derived from the field observations has been proposed. A rapid infiltration of an important part of rain via preferential pathways triggers a groundwater ridging which causes an increasing extent of the saturated area and induces superficial runoff due to groundwater exfiltration. The modelling approach on this data set reveals that the two tested modelling structures and assumptions are not able to account fully the complexity of the physical processes involved in flood generation. The topographic index based version of TOPMODEL is not able to predict correctly the lumped hydrograph and the exact location of the potential saturated area while, for GR4, the variation of the groundwater table in the riparian zone can be related to an internal reservoir of the model.

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