Hydrological conceptual models of two Haute-Mentue subcatchments through environmental tracing and TDR soil moisture measurements

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Abstract This paper presents the experimental work that was performed on the Haute-Mentue catchment in Switzerland in order to study the hydrological processes at different scales. First, an analysis of the hydrological response at the catchment scale was performed by means of environmental tracing, which enabled identification of two types of hydrological behaviour, mainly explained by the geological conditions. Second, two other experiments have been conducted at the hillslope scale, using the TDR method in order to monitor soil moisture variations at different depths along two typical topographical profiles on both morainic and molassic deposits. These experiments helped in identifying the mechanisms explaining the two different observed hydrological behaviours. Association of the two techniques led to a general conceptual model of two Haute-Mentue head subcatchments.

Key words environmental tracing; hydrological conceptual models; hydrological processes; TDR

INTRODUCTION

Hydrological processes have been intensively studied over the last few decades and important progress has been made in understanding catchment hydrological behaviour. The present study is in line with last years' research at the Hydrology and Land Improvement Laboratory from the Swiss Federal Institute of Technology of Lausanne concerning the hydrological behaviour of the Haute-Mentue catchment. In a more general context this work is included in hydrological studies that try to take advantage of the advances acquired in the experimental field, and to integrate this knowledge into hydrological modelling in order to not only get a close representation of the modelled time series, but also to get a better one of the hydrological processes involved in the runoff generation. Different experimental techniques (i.e. environmental tracing, different local measurements) have been associated so far in order to identify the main hydrological processes responsible for runoff generation on the Haute-Mentue catchment. The environmental tracing is one of the keys to understanding the hydrological processes that occur at the catchment scale. Application of this technique on the Haute-Mentue catchment has been the subject of several PhD theses at HYDRAM Laboratory. Jordan (1992) was the first to apply the environmental tracing on the Haute Mentue catchment. He used Oxygen-18 to separate the flood hydrograph in new and old water components and demonstrated that the general conditions imposed by the use of such a model were not completely fulfilled. Iorgulescu (1997) separated hydrographs based on a three component chemical mixing model using calcium and silica as tracers. The latter chemical model has been further integrated in a computer program: AIDH® (Analyse d'Incertitude des Décompostions des Hydrogrammes) (Joerin *et al.*, 2002), which is able to perform hydrograph separation and to analyse the hydrograph separation uncertainty. Even if environmental tracing proved to be particularly important to the study of hydrological processes at the catchment scale, nevertheless its application does not allow the identification of the mechanisms responsible for flows through hillslopes (Elsenbeer & Lack, 1996). In order to identify the water pathways and the mechanisms, which are at the origin of flood formation, it is necessary to associate hydrochemical observations to other types of measurements (Jenkins *et al.*, 1994; Joerin, 2000). In this context, several kinds of local measurements have been used on the Haute-Mentue catchment such as rainfall simulator, TDR measurements and dye tracing techniques (Joerin, 2000).

TOOLS AND METHODS

Study region

The Haute-Mentue catchment (12.5 km^2) is located in the Plateau region in the western part of Switzerland (Fig. 1). The gentle morphology, with altitudes between 800 and 900 m, is a consequence of local lithology represented by molassic Tertiary sandstones and clayey Quaternary moraine (Balin, 2004). Climate is moderate temperate with the annual mean for the precipitation of about 1200 mm and potential evapotranspiration (600 mm). Vegetation is essentially composed of spruce forests.

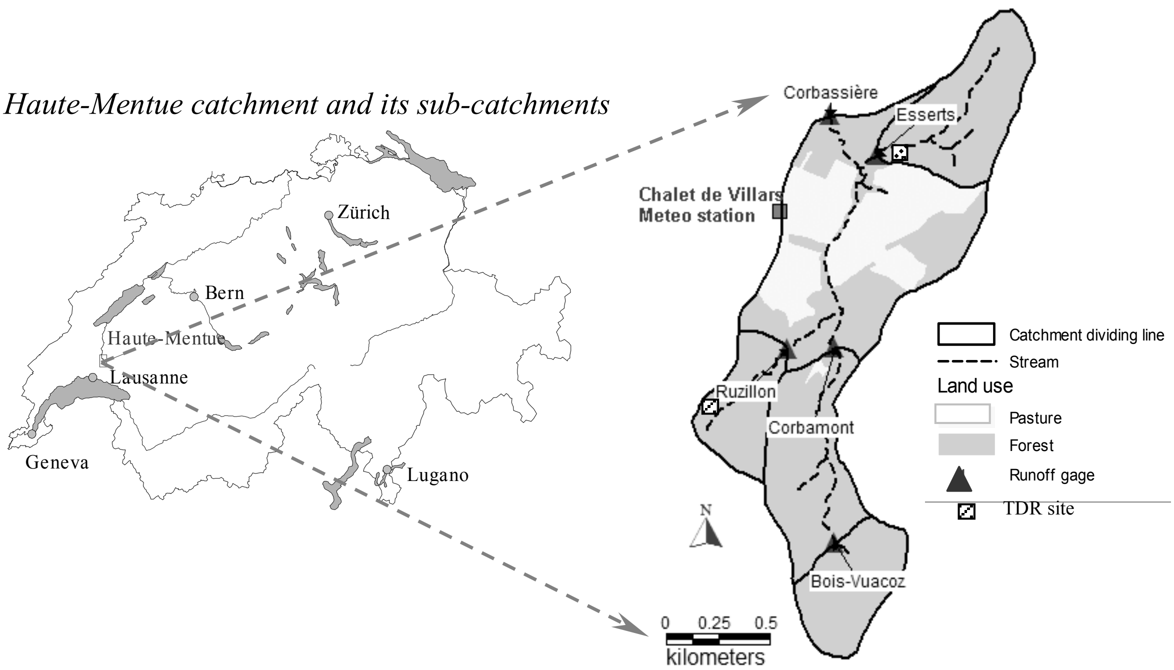

Fig. 1 Haute-Mentue catchment and its subcatchments: geographical localization and field instrumentation.

Environmental tracing and chemical mixing model definition

Flood hydrographs were separated into three components based on concentrations of two chemical tracers: calcium and silica. Definition of the three end-members has been done by using all the samples collected on the Haute-Mentue catchment during 1998–2002 (Joerin *et al.*, 2002). In this work, the model 3 of Joerin (2000) was used: the rainwater and soil water definitions were constant for all considered periods and for all the catchments while the chemical definition of the groundwater was considered unique for each catchment and it was defined by the calcium and silica concentrations measured in the stream water at low discharges (Table 1). The AIDH model of Joerin *et al.* (2002) was used in order to separate the hydrograph into its three components and although we considered the uncertainty of the chemical definition of the end-members, only the median of the resulting hydrograph separations was used for further analysis.

Table 1 Chemical definition of the end-members for Ruzillon and Esserts subcatchments.

End -members	Ruzillon		Esserts	
	Ca (µeq L^{-1})	SiO_2 (mg L^{-1})	Ca (µeq L^{-1})	SiO_2 (mg L^{-1})
Groundwater	3000	10.75	2450	11
Soil water	450	7	450	7
Rain water	70	0.1	70	0.1

Time Domain Reflectometry (TDR)

The TDR equipment was installed on two different sites in order to monitor the soil water content variation with depth and along typical hillslopes on the Haute-Mentue catchment. The two sites were chosen to represent the main hydrogeological conditions of the study catchments:

(a) Ruzillon site: morainic deposits with gentle slopes and clayey soil conditions;
(b) Esserts site: molassic deposits with steeper slopes and more permeable soil conditions.

The position of the two sites is indicated in Fig. 1. For each site, three plots were intensively equipped and named “Near-Stream”—within 2 m of the stream, “Mid-Slope”—7 m away from the streams and “Upper-Slope”—12 m on the hillslope away from the stream. While the average length of the hillslopes is about 80 m, the three sites have been chosen within the 20 m band from the stream in order to monitor the soil regime within the potential active contributing areas. The measuring configuration was possible through the multiplexing facility of the TDR equipment. The TDR system included a cable tester Tektronix 1502 B commanded by a Campbell Scientific data-logger (CR10 and CR21X types), four multiplexors (SMX50 type) and several pairs of rods. The rods (10-cm in length) were inserted vertically into the soils at different depths ranging between 0 and 75 cm. TDR measurements were obtained automatically with an hourly time step. In order to estimate the soil water content (θ) from the soil relative dielectric constant (ε_r) we used the Topp formula (Topp *et al.*, 1980). Two intensive field campaigns were organized during 2002–2003 in order to install the TDR systems and to monitor the soil moisture at the two sites, Ruzillon and Esserts, but only results from the 2002-year are presented here.

RESULTS

Environmental tracing

Environmental tracing has allowed identification of the typical hydrological response of two head Haute-Mentue subcatchments (Ruzillon and Esserts) during dry and wet antecedent conditions (Fig. 2). Different hydrological behaviours were observed for the two head catchments. Ruzillon subcatchment, mainly covered by morainic

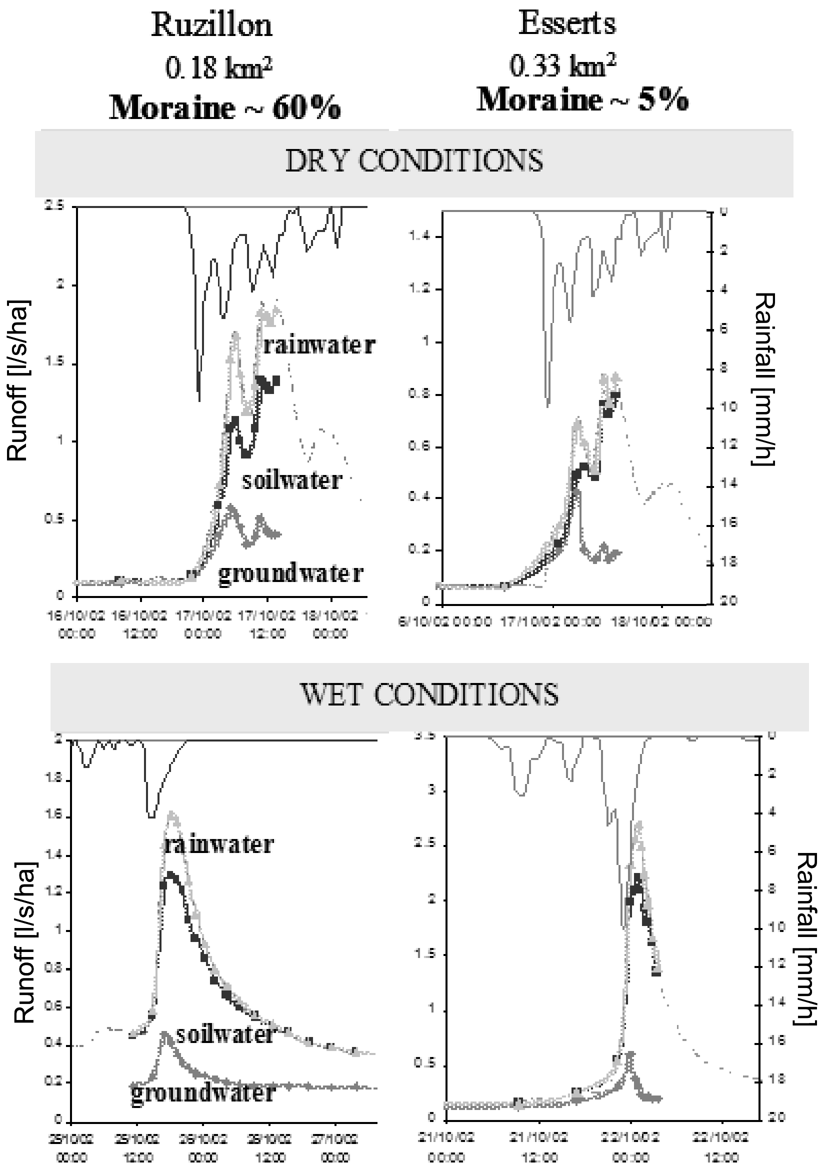

Fig. 2 Environmental tracing results for Ruzillon and Esserts subcatchments.

deposits, reacts more quickly to the rainfall input. The soil contribution is rapidly increasing, becoming the most important flow component even soon after dry antecedent periods (Fig. 2, upper left). Esserts catchment, covered almost entirely by molassic deposits, shows a slow increase of the soil contribution after dry antecedent periods, the groundwater being for part of time the most important flow component (Fig. 2, upper right). The hydrological behaviour seems different for the two catchments during dry antecedent conditions and this is related to the geological properties. In wet periods both catchments have similar reaction (Fig. 2, lower left and right), differences being related to local characteristics of the rainfall event rather than to the geological characteristics. A special case is represented by dry antecedent conditions and high rainfall intensities, when for all Haute-Mentue subcatchments, stream flows are formed essentially by rainwater and groundwater (Fig. 3). The present results complete and confirm those obtained by Iorgulescu (1997) and Joerin (2000). It seems that one major factor able to explain the main characteristics of the hydrological behaviour of the two head catchments would be the geological one. The lithology (morainic or molassic) influenced the soil texture characteristics, and this will further influence the state of the initial soil moisture conditions before a given rainfall–runoff event. In order to validate this hypothesis, a new experiment has been envisaged and finally conducted on two chosen sites with different lithological characteristics: one in Ruzillon catchment, in a region covered by morainic deposits and the second in Esserts catchment, where molassic formations are predominant.

Soil water regime

The soil water regimes for the two experimental sites (Ruzillon and Esserts) were studied with the help of the TDR set-up. Soil moisture changes have been computed at

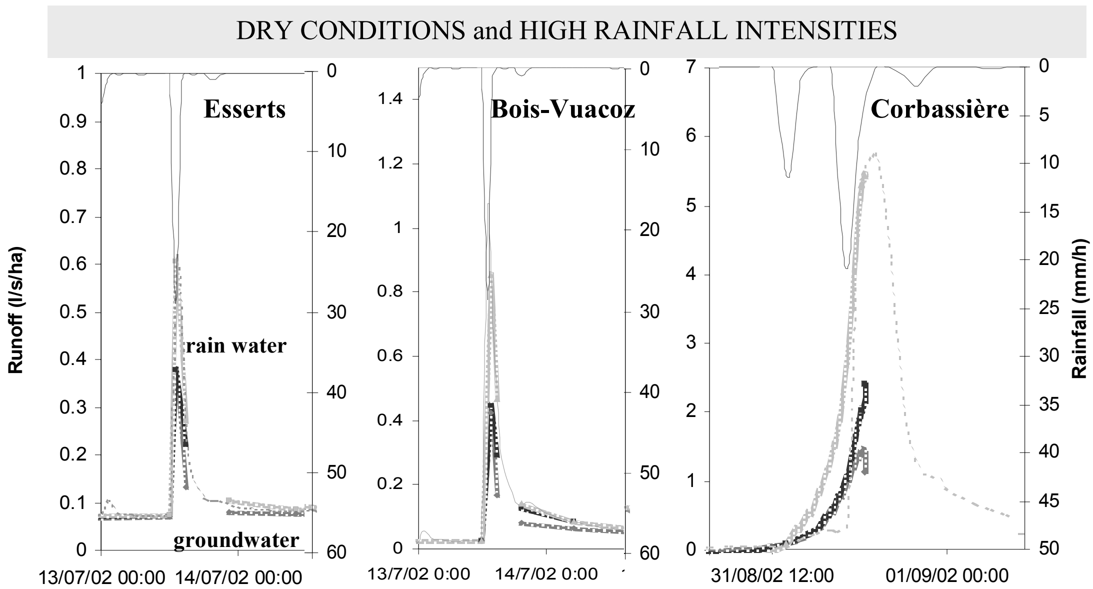

Fig. 3 Environmental tracing results for three Haute-Mentue subcatchments under dry conditions and high rainfall intensities.

different depths and for different rainfall–runoff events with different antecedent conditions and rainfall intensities. Several events during the 2002-year were chosen to reflect the main meteorological context in which representative hydrological processes take place. For this analysis we used only data coming from the "Mid-Slope" plot but detailed analysis including the three sites can be found in Balin (2004). Four cases have been defined as a function of the dry antecedent condition (defined by the ARI index—total amount of rainfall within the last 10 days previous a considered event) and the hourly rainfall intensity (Imax):

(a) DRY (ARI < 30 mm) and LOW (Imax < 7 mm h^{-1});
(b) DRY (ARI < 30 mm) and HIGH (Imax > 7 mm h^{-1});
(c) WET (ARI > 30 mm) and LOW (Imax < 7 mm h^{-1});
(d) WET (ARI > 30 mm) and HIGH (Imax > 7 mm h^{-1}).

Fig. 4 shows that for Ruzillon catchment during dry conditions, infiltration occurs only in superficial horizons (Fig. 4, upper left). During wet conditions rapid infiltration occurs which determines groundwater rise (Fig. 4, lower left) and if rainfall continues the entire soil profile reaches saturation and determines flows over saturated areas (Fig. 4, lower right). Under dry conditions and high rainfall intensities, saturation occurs at the interface between the organic and the mineral soil profile (Fig. 4, upper right). Fig. 5 shows that for Esserts catchment, during both dry and wet conditions, only vertical infiltration occurs. During wet conditions and under high rainfall intensities groundwater rises slowly and approaches the deepest soil horizons (Fig. 5, lower right).

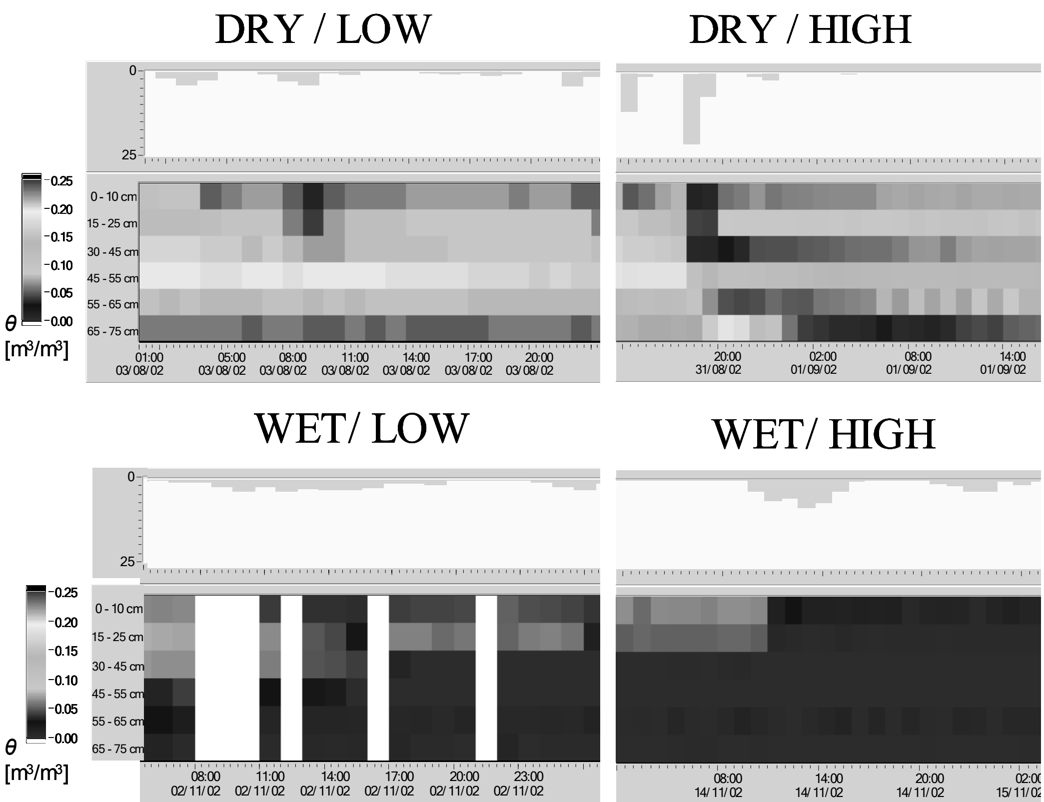

Fig. 4 Ruzillon site: soil moisture monitoring during several rainfall events through dry and wet antecedent conditions.

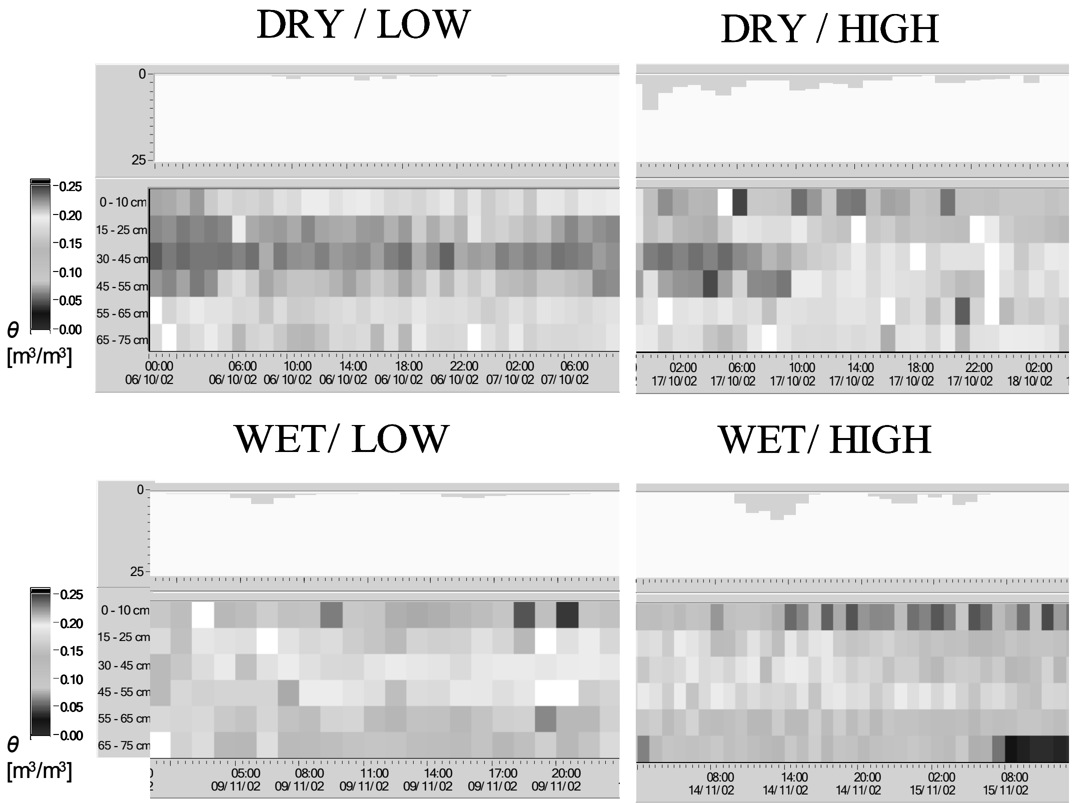

Fig. 5 Esserts site: soil moisture monitoring during several rainfall events through dry and wet antecedent conditions.

CONCEPTUAL MODEL OF THE HAUTE-MENTUE CATCHMENT

Two different approaches have been considered in order to identify the hydrological behaviour of the Haute-Mentue catchment. Association of the environmental tracing and the soil moisture monitoring allowed development of a general conceptual model for the Ruzillon and Esserts head subcatchments. It is difficult to consider that one single type of hydrological processes or mechanisms would be responsible for flood generation. Several processes seem to occur as a function of the meteorological conditions (rainfall amount, intensity and duration, evapotranspiration) and catchment physical factors (soil textures and initial soil storage deficits, vegetation). The main hydrological processes that explain a certain flood event change with time during a single rainfall event as the catchment conditions change. Comparisons between the representative processes at the two sites underline the role of the main geological properties of the two catchments: morainic deposits and soils with various textural changes for Ruzillon and molassic altered sandstone deposits with soils having uniform texture for Esserts catchment. It may be considered that:

(a) Ruzillon head-catchment has a general "Dunnian" behaviour (Dunne, 1978) with gentle hillslopes that saturate quickly and generate return flow and saturation overland flow during wet conditions and temporary perched lateral flow (interflow/funnelled flow) during intensive storm events in dry antecedent conditions.

(b) Esserts head-catchment has typical “Hewlettian“ behaviour (Hewlett & Hibbert, 1967) with steeper slopes and permeable soils with a high infiltration capacity that favours infiltration even during wet conditions and high rainfall intensity.

CONCLUSIONS

Environmental tracing and soil moisture monitoring by means of TDR allowed improvement of the knowledge concerning the hydrological behaviour of two Haute-Mentue head subcatchments. Environmental tracing enabled the observation that their behaviour under dry conditions is related to the initial soil moisture content while under wet conditions their behaviour is similar, with an important contribution from the soil water to the total flow. Differences that might appear in the behaviour of the two catchments are more obvious in transition periods and are related to the characteristics of the infiltration process that further determines the groundwater recharge and groundwater level rise. Both techniques showed that during wet periods, groundwater rise is the main mechanism that contributes to the floods. This process generates saturated overland flow when it reaches the soil surface. The differences between the two head catchments consist in different spatial extension of the “contributing” areas. For Ruzillon catchment, this process characterizes large areas while for Esserts catchment, contributing areas are generally limited to regions close to the stream. Given the nature of the main processes that explain the hydrological behaviour of these two catchments, it was considered, for further modelling purposes, that TOPMODEL could be a reasonable choice to model their hydrological response.

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