Investigating the role of geology in the hydrological response of Mediterranean catchments prone to flash-floods: regional modelling study and process understanding

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Investigating the role of geology in the hydrological response of Mediterranean catchments prone to flash-floods: regional modelling study and process understanding

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Abstract

In this study, a regional distributed hydrological model is used to perform long-term and flash-flood event simulations, over the Cévennes-Vivarais region (south of France). The objective is to improve our understanding on the role played by geology on the hydrological processes of catchments during two past flash-flood events. This modelling work is based on Vannier et al. ("Regional estimation of catchment-scale soil properties by means of streamflow recession analysis for use in distributed hydrological models", *Hydrological Processes*, 2014), where streamflow recessions are analysed to estimate the thickness and hydraulic conductivity of weathered rock layers, depending on the geological nature of catchments. Weathered rock layers are thus implemented into the hydrological model CVN-p, and the contribution of these layers is assessed during flash-flood events simulations as well as during inter-event periods. The model is used without any calibration, to test hypotheses on the active hydrological processes. The results point out two different hydrological behaviours, depending on the geology: on crystalline rocks (granite and gneiss), the addition of a weathered rock layer considerably improves the simulated discharges, during flash-flood events as well as during recession periods, and makes the model able to remarkably reproduce the observed

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streamflow dynamics. For other geologies (schists especially), the benefits are real, but not sufficient to properly simulate the observed streamflow dynamics. These results probably underline the existence of poorly known processes (flow paths, non-linear spilling process) associated with the planar structure of schisty rocks. On a methodological point of view, this study proposes a simple way to account for the additional storage associated with each geological entity, through the addition of a weathered porous rock layer situated below the traditionally-considered upper soil horizons, and shows its applicability and benefits for the simulation of flash flood events at the regional scale.

Keywords: hydrological modelling, process understanding, flash-floods, geology, regional modelling

1. Introduction

In the field of catchment hydrology, many efforts are made to better understand the climate and landscape controls on the water cycle and catchments response dynamics. This thirst of knowledge is largely related to the most challenging problem that has driven the hydrologic community researches for the last decade: predicting the response of ungauged catchments. This challenge, conceptualized within the PUB initiative (Sivapalan *et al.*, 2003), has resulted in a large amount of recent hydrological studies, as reviewed by Hrachowitz *et al.* (2013), focusing on crucial questions such as process understanding (Tetzlaff *et al.*, 2007; Blume *et al.*, 2008, for example), catchments classification (Sawicz *et al.*, 2011,

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among many), uncertainty analyses (McMillan *et al.*, 2010, e.g.), model parameter transferability (Oudin *et al.*, 2010, e.g.) or emerging observation techniques (Selker *et al.*, 2006). Even if progress still need to be made to reach the ambitious target defined in the PUB initiative, significant advances have been made in the field of regionalisation methods (Parajka *et al.*, 2005; Oudin *et al.*, 2008; Parajka *et al.*, 2013; Salinas *et al.*, 2013, e.g.) and emerging modelling approaches (Fenicia *et al.*, 2008a,b; Savenije, 2010; Clark *et al.*, 2011).

Among the dominant factors driving the hydrological behaviour of catchments, geology is regularly cited as an important one (Yadav *et al.*, 2007; Tetzlaff *et al.*, 2007; Oudin *et al.*, 2010, e.g.). At the catchment scale, geology affects the governing hydrological processes through many ways, such as (for example): i) groundwater flow paths direct implication on the transit time distribution of water within catchments (Sayama & McDonnell, 2009; Rinaldo *et al.*, 2011); ii) the nature of the interface between soil horizons and bedrock determining the formation of preferential flows that governs the quick response during flood events (Weiler & Naef, 2003; Weiler & McDonnell, 2007); iii) bedrock permeability strongly impacting the water balance at the catchment scale (Tromp-van Meerveld *et al.*, 2007). More generally, we consider that geology is directly linked to the catchments water storage capacity, which has been shown to be of primary importance in the water cycle dynamics (Sayama *et al.*, 2011; Tetzlaff *et al.*, 2011; McNamara *et al.*, 2011) and which strongly influences the antecedent wetness conditions that acts as a threshold on the response of catchments during flood events (Troch *et al.*, 2003; Latron & Gallart, 2008; Zehe *et al.*, 2010).

To better understand the role played by landscape characteristics in the hydrological behaviour of catchments, distributed hydrological modelling appears as a very relevant tool (Vivoni *et al.*, 2007; Noto *et al.*, 2008; Anquetin *et al.*, 2010; Braud *et al.*, 2010; Nester *et al.*, 2011; Garambois *et al.*, 2015). As mentioned by Parajka *et al.* (2013), besides all the efforts recently made to better estimate and regionalize model parameters, there is a real need for improving the model structures to better understand and reproduce the active hydrological processes. In that way, recent developments made around flexible, data-driven and evolutive modelling approaches (Fenicia *et al.*, 2011; Kavetski & Fenicia, 2011; Gharari *et al.*, 2014) appear as very promising.

In the work presented here, we pursue the multiple working hypotheses approach advocated by Clark *et al.* (2011). The modelling process followed here consists in a "Try - Fail - Learn - Repeat" iterative methodology used for testing hydrological functioning hypotheses, and making the best use of what data can teach (Fenicia *et al.*, 2008a). The objective of this distributed hydrological modelling study is to better assess the role played by geology in the different hydrological behaviours observed in the Cevennes-Vivarais region (Mediterranean area), located in the south of France. The catchments of this region are prone to flash-floods, which represent the most descructive hazard in the mediterranean region (Gaume *et al.*, 2009). Consequently, the hydrological response of the Cevennes-Vivarais catchments to flood events have long been observed, within the Cevennes-Vivarais Hydro-Meteorological Observatory[1] (Boudevillain *et al.*, 2011), and subject of many hydrological modelling studies (Le Lay & Saulnier, 2007; Bonnifait *et al.*, 2009; Garambois *et al.*, 2013, e.g.). Several works aiming

[1] `http://www.ohmcv.fr`

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at developping and assessing forecast tools and flash-flood warning systems also focus on the Cevennes-Vivarais region (Bouilloud *et al.*, 2010; Vincendon *et al.*, 2010; Alfieri *et al.*, 2011), or on neighbouring french mediterranean regions like the Var department, hit by massive floods in June 2010 (Javelle *et al.*, 2014; Caseri *et al.*, 2015). However, the purpose of the current work significantly diverges from forecast-oriented studies, in the sense that it is governed by the understanding of unknown processes, instead of the will to obtain the best results as possible.

Recently, the FloodScale reasearch project[2] (Braud *et al.*, 2014), which is a contribution to the international HyMeX program[3], has been federating the french hydrologic community on research questions related to the understanding and simulation of the hydrological processes leading to flash floods in mediterranean catchments. Here, we use the CVN-p process-oriented distributed model, deriving from CVN (Manus *et al.*, 2009), set-up over the entire Cevennes-Vivarais region, and accounting for evapotranspiration and vegetation-related processes to perform continuous simulations. This study follows the works of Vannier *et al.* (2014), who analysed observed streamflow recession curves and derived catchment-scale aquifer effective thicknesses and hydraulic conductivity, for the different geological entities of the region, using the approach proposed by Brutsaert & Nieber (1977). Here a weathered porous rock layer is added in the model, to fill the lack of water storage capacity identified when considering soil horizons only (Roux *et al.*, 2011; Vannier *et al.*, 2014; Garambois *et al.*, 2015).

The paper is organized as follows. We first describe the model used in this

[2] `http://floodscale.irstea.fr`
[3] `http://www.hymex.org`

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study and, in section 3, how the CVN-p hydrological model is set-up over the study area. In the fourth section we present the results of the simulations performed with and without the addition of the weathered porous rock layer, and we evaluate the model performances obtained for year 2008, with a focus on two flood-events that occured during the autumn. Subsequently, we discuss the results obtained and the observed spatial differences in the model performances, in link with the geology of catchments ('Discussion' section). The final section consists of brief conclusions and of some perspectives for future developments on this subject.

2. Model description

The model used in this study is the CVN-p hydrological model. The CVN-p model is an evolution of the event-based rainfall-runoff model CVN (Manus *et al.*, 2009). Several processes have been implemented in the model so that it can run long-term continuous simulations.

2.1. Structure and processes represented

The CVN-p model was built within the LIQUID hydrological modelling platform (Viallet *et al.*, 2006; Branger *et al.*, 2010), which is a framework providing users the possibility to assemble hydrologic modules together, each one solving a physical process. In its early version, CVN was an event-based model, representing two main processes: the vertical water transfer through soils, and the routing of the generated runoff along the hydrographic network (Manus *et al.*, 2009).

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For the regional simulation purposes, the model evolved to perform continuous simulations. Root extraction, vegetation growth, interception and evapotranspiration processes were added, in order to simulate a realistic water balance and get a dynamic evolution of soil wetness. The box-type structure of the model CVN-p, with the implemented modules and their inter-connexions is given and compared to the previous CVN version in Fig.1. A detailed description of the different hydrological modules coupled within the continuous CVN-p model is presented in Appendix A.

The model is forced with two spatialised variables : precipitation and reference evapotranspiration (ET_0). Precipitation is necessarily liquid (the model does not account for snow accumulation nor melting). Forcings are interpolated over the model mesh using weighted averages by a dedicated module (INPUT).

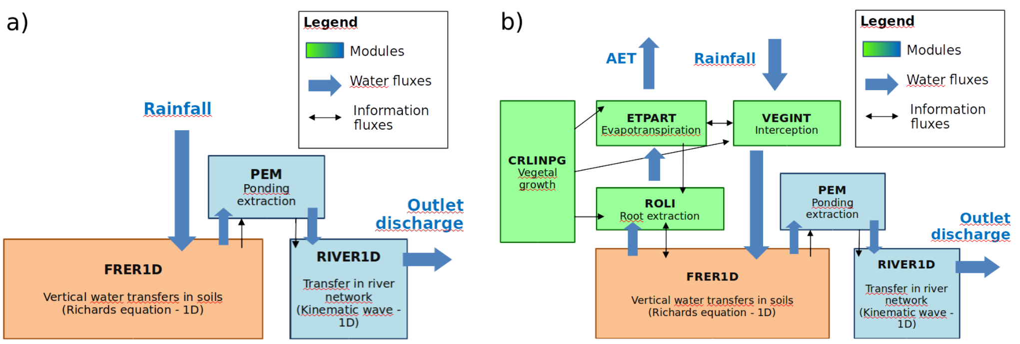

Figure 1: Structure of the event-based model CVN (Manus *et al.*, 2009; Anquetin *et al.*, 2010; Braud *et al.*, 2010) (a) and the continuous model CVN-p used in this study (b). The modules are coloured according to the type of process: brown for the soil compartiment, blue for runoff and river flow, and green for the vegetation-related processes.

2.2. Spatial discretization

The CVN-p model spatial discretization is based on the Representative Elementary Watershed approach (REW) (Reggiani *et al.*, 1998, 1999) later adapted by Dehotin & Braud (2008) who proposed the "hydrolandscape" concept used here. An hydrolandscape is an elementary hydrological response unit, homogeneous in terms of hydrological processes. In this study, following the approach of Manus *et al.* (2009), we assume that topography and soil typology represent the dominant control processes on the Cevennes-Vivarais region hydrological behaviour. Accordingly, the hydrolandscapes are defined as the crossing of two successive discretization steps: i) first the study domain is splitted into sub-catchments using an automated DEM-based tool (Tarboton, 1997), with a threshold of 0.5 km^2; ii) then a second level of discretization is applied, using a pedological soil map. The dominant vegetation type is finally assigned to each hydrolandscape. The hydrolandscapes are the elementary cells of the soil and vegetation processes solved by the CVN-p model. The river network, where runoff extracted from each hydrolandscape is sent and routed, is extracted from the DEM analysis: each sub-catchment is associated to a river reach.

2.3. Implementation of a weathered rock layer

Vannier *et al.* (2014) proposed a methodology to define catchment-scale - deep - soil properties through the analysis of streamflow recession data, based on the works of Brutsaert & Nieber (1977). They performed this analysis after they lacked information on the physical (thickness) and hydraulic (conductivity) properties of weathered rock layers, which stands below well-described upper-soil horizons (Fig.2a).

The application of the streamflow recession analysis over a sample of catchments, located in the Cevennes-Vivarais region (south of France), highlighted a

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strong link between the dominant geology and the estimated values of the thickness and hydraulic conductivity of these deep horizons (Fig.2b). Values of saturated hydraulic conductivities presented in Fig.2b can be seen as very large, and thus out of the range of standard values of conductivities reported for soils or porous rocks. This is due to the nature of the values characterized by Vannier *et al.* (2014): first, the presence of various poorly-known processes such as macroporosity, rock fracturing, or preferential flow directions, may result in flow conditions that significantlty diverge from the theory, and in addition, these values are representative of catchment-wide integrated processes since they derive from streamflow recession analyses. Consequently, values reported in Fig.2b must rather be considered as "effective" parameters than as actual hydraulic conductivities.

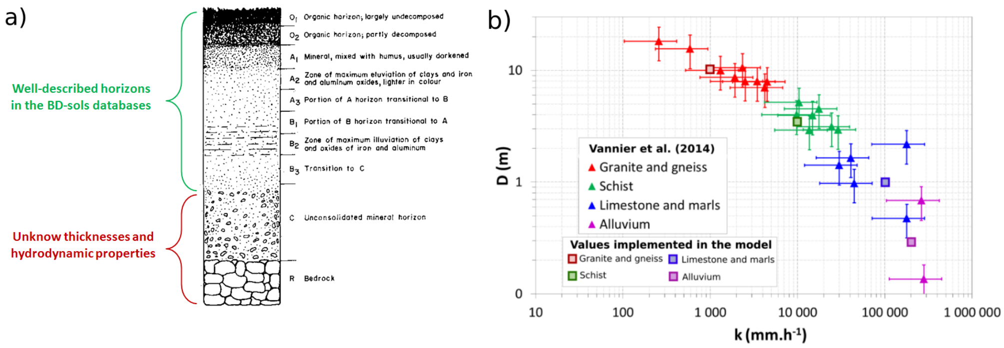

Figure 2: Figures adapted from Vannier *et al.* (2014) : a) Typical pedologic profile, after Kang & Tripathi (1992) and level of description in the Cevennes-Vivarais BD-sols soil databases.b) Depth to bedrock D and lateral hydraulic conductivity k calculated using streamflow recession analysis. The confidence intervals result from the uncertainty in the value of drainable porosity(between 0.05 $m^3.m^{-3}$ and 0.1 $m^3.m^{-3}$). Values implemented (Table 1) have been added to the figure.

In the present paper, we propose to implement deep weatherd rock layers into the CVN-p hydrological model to perform simulations over the Cevennes-Vivarais region. The thickness and hydraulic conductivity of such layers are directly taken

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	Thickness D (m)	Saturated water content	Saturated hydraulic conductivity K_s (mm.h^{-1})
Granite and gneiss	10	0.1	1 000
Schist θ_s (m^3.m^{-3})	3.5	0.1	10 000
Limestone	1	0.1	100 000
Alluvium	0.2	0.1	200 000

Table 1: Chosen values of thickness and saturated hydraulic conductivity of deep weathered rock horizons, according to the dominant geology.

from the results obtained by Vannier *et al.* (2014): an average value of these parameters is considered for each of the four dominant rock types present in the region (Table 1). Implementing additional layers is easy in the CVN-p model, as the FRER1D module can account for different horizons with their own hydraulic properties.

2.4. Boundary conditions

A free gravitary flux condition is used at the bottom of the vertical soil + weathered rock columns, so that water can percolate according to a unitary gradient of charge. The percolation flux is then directly sent into the nearest river reach, similarly to the extracted ponding flux. This free bottom boundary condition of the CVN-p model (here -p stands for "percolation") is one of the main differences with the CVN model used by Manus *et al.* (2009); Anquetin *et al.* (2010); Braud *et al.* (2010), in which a null flux condition was used.

Coupled to the implementation of weathered rock layers, the use of a gravitary bottom flux condition sent into the river network represents a conceptual way to account for a delayed groundwater flow term simulated in the model. The transit-time of water through the entire column depends on its thickness, hydraulic conductivity and wetness state.

3. Regional set-up of the model

3.1. Presentation of the area and available data

The CVN-p model is set-up over the seven largest catchments in the Cevennes-Vivarais region : the Ardèche (2263 km^2) Cèze (1372 km^2) and Gardon (1914 km^2) catchments at their confluence with the Rhône river, the Vidourle at Sommières(650 km^2), the Vistre at its confluence with the Rhony river (493 km^2), the Hérault at Gignac (1410 km^2) and the Tarn at Montbrun (589 km^2) rivers. The location of these catchments is shown on the map in Fig. 3, as well as the geology of the region and the location of the stream gauges.

The Digital Elevation Model (DEM) used for the discretisation procedure is the 25m-resolution DEM provided by the french National Geographic Institute (IGN). Soil data are provided by the BD-sols Ardèche and Languedoc-Roussillon spatial databases (Robbez-Masson *et al.*, 2000). These pedological databases provide information on the dominant soil units (1:250 000 scale), as well as on the physical properties (texture, structure) of the main soil types that compose these units.

Spatial vegetation information required for the computation of interception and evapotranspiration processes derives from the Corine Land Cover (2006) public database. Monthly average values of LAI, crop coefficients, as well as

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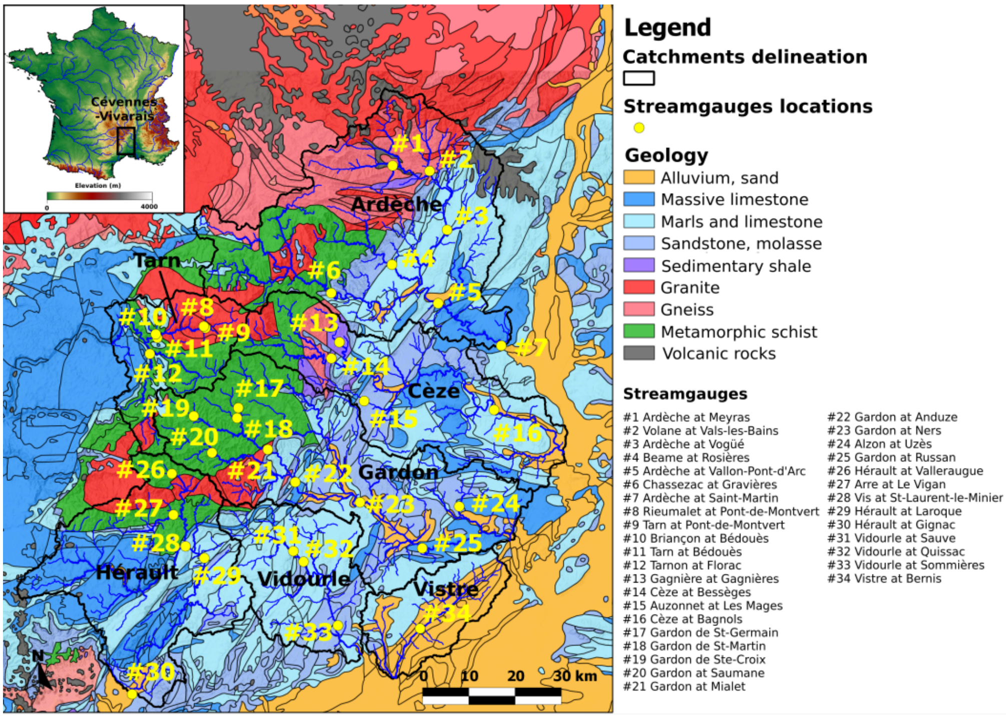

Figure 3: Location of the seven selected catchments, and dominant geology of the Cevennes-Vivarais region (deriving from the 1:1 000 000 french geological map). The location of the streamgauges from which measurements are used in this study is simbolized by yellow points.

root depths of different types of vegetation are extracted from the ECOCLIMAP database (Masson *et al.*, 2003). Geology derives from the 1:1 000 000 scale national geological map[4].

3.2. Forcings

The set-up of the CVN-p model requires different kinds of data. Meteorological forcings are rainfall and reference evapotranspiration ET_0. For inter-events periods, rainfall data is extracted from SAFRAN meteorological reanalyses (Quintana-Seguí *et al.*, 2008; Vidal *et al.*, 2010), whereas for events simulation we

[4]http://www.brgm.fr

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use kriged hourly raingauges measurements. ET_0 is computed on the basis of other meteorological variables provided by SAFRAN (temperature, wind speed, long and short-wave radiation, specific air humidity). The Penman-Monteith formulation (Monteith, 1965) is used, with parameters values chosen according to the Food and Agricultural Organization (FAO) recommandations (Allen *et al.*, 1998).

The input forcing variables are given on spatial grids, with a resolution varying from 8x8 km^2 (SAFRAN meteorological reanalyses) to 1x1 km^2 (hourly kriged rainfall products). The temporal resolution is 1 hour, even if in the case of SAFRAN, rainfall intensities have been shown to be slightly biaised at this temporal resolution (see Vidal *et al.* (2010) for more details).

3.3. Parameters specification

The modelling approach used in this study is based on the testing of hydrological functioning hypotheses, without any calibration of the model. Consequently, parameters values derive from an *a priori* knowledge provided by observations, maps, and available databases. As an example, soil hydraulic properties required within the Brooks & Corey (1964) relationships (FRER1D module) are computed according to the Rawls & Brakensiek (1985) pedotransfer function, using structural and textural information given by the BD-sols databases. Other parameters values can be directly given by databases (Vegetation parameters), or result from regional observations analyses (river geometry, weathered rock horizons properties).

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3.4. Simulations strategy

In this region, rainfall-runoff simulations are performed over the entire 2008 year. The choice of year 2008 was made for two main reasons :

a) Two major rainfall events occured during the autumn : the first one between October 21th and October 23rd, and the second one between October 31th and November 5th. These two events affected different areas, and also differ each other by intensity and duration, as shown in Fig.4: the first event is characterized by a shorter duration (approximately 24 hours) and high rainfall intensities (up to several tens of mm per hour) while the second event lasted for more than one day, with lower rainfall rates.

b) The large availability of discharge data measured by the streamgauges of the region in 2008, as compared to other years. In 2008, almost all of the streamgauges worked correctly, even during flood events.

The whole 2008 year is simulated, split into four periods for which rainfall forcings differ (Table 2). Long-term (i.e. inter-events) simulations are performed with SAFRAN rainfall, while events simulations are forced with hourly kriged rainfall fields. The final state of a long-term simulation (soil wetness, water level in the river) is used as initial state of the following event simulation.

3.5. Evaluation of the simulations

When complete measured hydrographs are available, an evaluation of the model performance through the calculation of four score indices is performed.

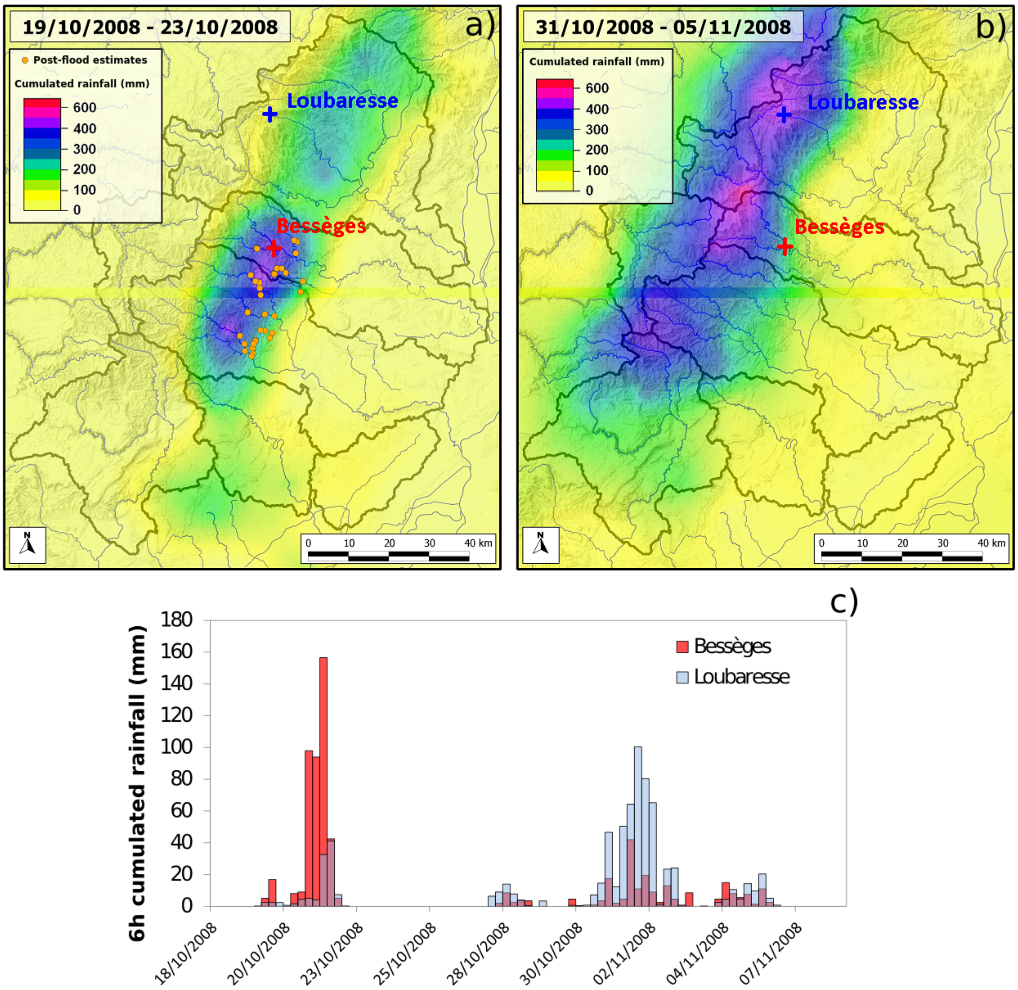

Figure 4: Maps of the cumulated rainfall amounts observed over the Cevennes-Vivarais region during the October 21 - October 23, 2008 event (a) and the October 31 - November 5, 2008 event (b). These maps represent the cumulated rainfall measured on raingauges interpolated through a kriging technique over a 1x1 km^2 resolution grid. The blue and red crosses indicate the location of the Bessèges and Loubaresse raingauges, for which the measured hyetograms are shown in (c).

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Temporal window	**Type of simulation**	**Rainfall forcing**
01/01/2008 - 21/10/2008	Initialisation	SAFRAN
21/10/2008 - 23/10/2008	Event	Kriged rainfall
23/10/2008 - 31/10/2008	Transition	SAFRAN
31/10/2008 - 05/11/2008	Event	Kriged rainfall

Table 2: Simulation table

Nash-Sutcliffe efficiency (Nash & Sutcliffe, 1970) (NSE), Nash-Sutcliffe efficiency of the logarithmic discharge (LNSE), correlation coefficient R^2 and bias indicator PBIAS (Kling & Gupta, 2009) are computed. Along with the tradtional performance indices computation, a deep attention is paid to visual comparison between observed and simulated hydrographs, to evaluate the model ability to reproduce catchments response. Visual comparison is complementary to quantitative evaluation, in a sense that it gives indications on the ability of the model to reproduce flow dynamics, recession rates or flood timing, which are not easily summarised in score indices. In addition, visual evaluation allows the distinction between time periods where the model gives good results, and periods where it is not the case, and thus makes the interpretation of the results easier.

Long-term simulations

In order to assess the role of the added weathered rock layer, same simulations are done with and without weathered rock layer. This evaluation is performed on several catchments of different sizes: three Tarn sub-catchments, essentially composed of granites and gneiss (the Rieumalet, the Tarn at Pont-de-Montvert, and the Tarn at Bedouès, #8, #9 and #11, respectively, in Fig.3); and five Gardon

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sub-catchments, where schists are dominant on the upper part while sedimentary rocks mainly cover the downstream part (Gardon at Saint-Martin, Mialet, Anduze, Ners and Russan, #18, #21, #22, #23 and #25, respectively, in Fig.3). Compared discharge series begin on April 1, 2008 and end on October 21, 2008. In these simulations the three first months are ignored (simulations effectively start on January 1, 2008) in order to avoid initialisation artefacts. Sensitivity tests (not shown here) were performed to assess the average necessary spin-up duration, and a value of three months appeared as enough in the large majority of cases;

Event simulations

The contribution of the implemented weathered rock layer is assessed in the same way during flood events, for the same selected catchments. For each catchment, the considered event is the one which caused the largest observed hydrologic response (highest discharge values).

At the regional scale, the evaluation of the event simulations is performed for a wide range of catchment sizes, for which two types of observations are available:

a) Peak discharge estimated *a posteriori* in 35 catchments, ranging from 1 to 100 km^2, during the post flood investigation of the October 21-23 event. The post flood survey follows the methodology defined by Gaume & Borga (2008);

b) Discharge measurements, available on 34 operationnal streamgauges in the re-

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gion, for catchment sizes ranging from 30 to 2300 km^2. Discharge values derive from automatic water level devices recording at variable timestep. A record is made for each variation of water level larger than a defined threshold (which is specific to each station).

Along with these direct comparison to observations, event simulations results are also compared at the regional scale to CRUPEDIX 10-years return period discharge estimates. Q_{10} is computed according to equation 1, after the CRUPEDIX formula (1980), which is an empirical estimation of the instantaneous 10-years return period peak discharges for catchment size lower than 2000 km^2.

$$Q_{10} = A^{0.8}(P_{d10}/80)^2 C \quad (1)$$

where Q_{10} is the 10-years return period instantaneous peak discharge ($m^3.s^{-1}$); A is the catchment area (km^2); P_{d10} the 10-years return period daily rainfall depth for the considered catchment (mm), and C is a regional coefficient (with a dimension of $[T^{-1}.L^{-0.6}]$), here considered equal to 1.7 (Versini *et al.*, 2010). The estimation of the P_{d10} rainfall for all the considered catchments is based on the grided SAFRAN meteorological reanalyses: an estimation of the 10-years return period daily rainfall is performed for each SAFRAN grid cell according to its statistical distribution. Then the areal rainfall for each catchment is computed through the aggregation of all the values affected to the SAFRAN grid cells contained within the considered catchment, and the use of an Areal Reduction Factor (ARF) (De Michele *et al.*, 2001), with specific coefficient values for the Cevennes-Vivarais region (Ceresetti, 2011). Due to its simplicity, the CRUPEDIX method does not provide a perfectly accurate estimation of the 10-years return period peak discharge. We performed a comparison (not shown here) between CRUPEDIX estimates and data-based 10-years return period peak discharge obtained by fitting annual maxima to a Gumbel distribution, on all streamgauges of the region. It showed a globally fair agreement, despite a tendency of CRUPEDIX to overestimate 10-years return period peak discharges on small catchments (< 200 km^2). Note that a more recent method, named SHYREG (Aubert *et al.*, 2014), has been developed for the estimation of reference peak discharge in mediterranean catchments. But the homogeneous application of the CRUPEDIX method over the whole study area, even on ungauged streams, allows its use as a common reference for the evaluation of regional flood discharges. Consequently, the ratio Q_{max}/Q_{10}, where Q_{max} is the maximum simulated peak discharge, gives a clear indication of the simulated severity of the flood, on each reach of the hydrographic network.

4. Results

4.1. Contribution of the implemented weathered rock layer

The contribution of the implementation of a weathered rock layer in the model is assessed through a comparison between measured discharge and simulated discharge obtained with and without the weathered rock layer. Results are compared and analysed for each geology type. Tables 3 and 4 summarise the scores obtained for each simulation.

4.1.1. Granite and gneiss

On crystalline rock (granite and gneiss) catchments located on the Tarn river, the benefits of including a deep weathered rock layer are clear, whether for event or long-term simulations. For long-term simulations, adding a deep weathered rock horizon significantly increases the Nash-Sutcliffe efficiency and the Nash-Sutcliffe efficiency of the logarithmic discharge (Table 3), which turns from negative to better than 0.7 values on each of the three catchments. R^2 criteria values also improve in all cases. One must notice a slight increase of the PBIAS index values (becoming positive in all cases) when adding the weathered rock layer. For event simulations, results are also improved when adding the deep weathered rock horizon (4): on each of the catchments, the four performance indicators get better values when adding the deep layer. Especially, Nash-Sutcliffe efficiency of the logarithmic discharge and PBIAS index reach satisfying values for non-calibrated event simulations (Table 4).

As an example, Fig.5a compares the measured and the two simulated hydrographs (one with and one without the weathered rock layer) on one of the grantic catchments (Tarn at Pont-de-Montvert, #9) during several months. The visual improvement of the model's behavior when using the weathered rock layer is very significant. The model version in which there is no weathered rock layer produces a noisy discharge signal during long-term simulations, corresponding to a direct response to the precipitation signal. When adding the weathered rock layer, the long-term simulated discharge signal is smoother: the layer acts as a buffer, delaying the hydrologic response in time. This behavior is very similar to the observed response, and the model in this version reproduces very well the streamflow dynamics of the granitic catchment. In Fig.5b, the same comparison during the November, 2008 event is shown. Once again, the visual improvement when using the weathered rock layer is clear. While the simulated volume and peak discharge are overestimated by the unmodified model version, the addition

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of the weathered rock layer brings the simulated hydrograph much closer to the observation. The reason probably stands in the additionnal storage capacity implemented in the model: the added weathered rock layer stores a significant part of the infiltrated water, and releases it progressively. On the other hand, the model without additional layer overreacts to precipitation forcings because of its lack of storage: in this case water quickly percolates and almost instantaneously enters the stream network.

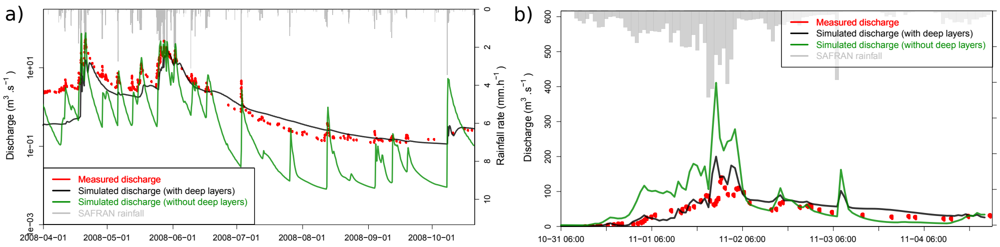

Figure 5: Comparison of measured discharge and discharge simulated by the CVN-p model with and without deep weathered rock layer on a granitic catchment: Tarn in Pont-de-Montvert (67 km^2). a) long-term simulation between April 1, 2008 and October 21, 2008 (discharge scale is logarithmic). b) Event simulation between October 31, 2008 and November 5, 2008.

4.1.2. Metamorphic schists and sedimentary rocks

On the Gardon river catchments, the dominant geology is composed of metamorhic schists on the upper part, and limestone and other sedimentary rocks (marls, sandstone) on the lower part. The long-term simulation results are evaluated in Table 3 and the scores obtained for the October, 2008 event are shown in Table 4. In this case, the benefits of adding a weathered rock layer in the model are not as important as in the case of grantic catchments. Even if almost all of the performance criteria values increase significantly when adding the layer, this is not sufficient to reach what can generally be considered as “good” performance. Especially, Nash-Sutcliffe values computed on discharge and logarithmic discharge

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stay closer from 0 than 1 in most of the case. This is particularly true for the event simulation, for which negative Nash-Sutcliffe eficiencies are obtained. Nevertheless, correlation coefficients R^2 larger than 0.7 are obtained for long-term simulations.

A visual evaluation of the model performances gives indications on the causes of such poor performances. As an example, Fig.6 compares the measured and the two simulated hydrographs on the Gardon at Mialet (220 km^2), which is a schist-dominated catchment. For the long-term simulation (Fig.6a), the implementation of a weathered rock layer reduces the tendancy of the model to simulate frequent variations in the series. This result is similar to the effect observed for granitic catchments, but in this case the smoothing effect due to the weathered rock layer is not sufficient to reproduce satisfyingly the observed discharge series. Similarly, the benefits of adding the layer for simulating flood events are incomplete (Fig.6b). Once again, the implementation of this weatherd rock layer decreases the simulated water volume and peak discharge, but the simulated hydrograph still remains larger than the observed one by order of magnitudes (PBIAS criteria exceeds 400 % on this catchment). Apparently, the added layer does not store enough water in the case of schists and sedimentary rocks.

4.2. Regional simulations of the 2008 events

4.2.1. Cases of the two flood events

The two 2008 flood events differ significantly, although their magnitudes remain approximately similar. The simulated hydrological signature of the two events is shown in Fig.7, where the ratio between simulated peak discharge Q_{max}

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Catchment	Dominant geology	Area (km^2)	NSE		LNSE		PBIAS		R2	
			No WRL	WRL	No WRL	WRL	No WRL	WRL	No WRL	WRL
Rieumalet (Pont-de-Montvert, #8)	Granite	20	-0.49	0.67	-1.29	0.71	19.60	-25.53	0.36	0.72
Tarn (Pont-de-Montvert, #9)	Granite	67	0.44	0.65	0.24	0.88	2.15	-35.69	0.69	0.75
Tarn (Bedouès, #11)	Granite	189	-0.26	0.80	-3.09	0.88	1.14	-2.20	0.64	0.82
Gardon (Saint-Martin, #18)	Schist	30	-4.14	-0.06	0.18	0.49	105.73	21.39	0.44	0.69
Gardon (Mialet, #21)	Schist	220	-0.18	0.63	-0.47	0.52	-6.66	-11.22	0.52	0.76
Gardon (Anduze, #22)	Schist	543	-4.41	0.18	-0.97	0.41	136.11	49.97	0.54	0.77
Gardon (Ners, #23)	Limestone / Schist	1100	-2.14	0.61	-0.12	0.68	88.77	20.43	0.46	0.75
Gardon (Russan, #25)	Limestone / Schist	1520	-2.14	0.51	NA[1]	NA[1]	94.01	35.86	0.64	0.81

[1] Undefined value because of null values in the measured discharge series

Table 3: Performance indices of the simulations performed on 8 catchments of various geologies between January 1, 2008 and October 21, 2008. The first three months are not taken into account in the score calculations, to avoid initialisation artefacts. This table compares the results obtained by simulations performed without adding any weathered rock layer in the model ("No WRL"), and simulations including these weathered rock layer ("WRL").

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Catchment	Dominant geology	Area (km^2)	**NSE**		**LNSE**		**PBIAS**		**R2**	
			No WRL	WRL	No WRL	WRL	No WRL	WRL	No WRL	WRL
Event: 31/10/2008 - 05/11/2008										
Rieumalet (Pont-de-Montvert, #8)	Granite	20	-6.17	0.43	-0.44	0.63	132.63	10.72	0.18	0.59
Tarn (Pont-de-Montvert, #9)	Granite	67	-6.68	0.10	0.28	0.88	117.85	27.84	0.48	0.68
Tarn (Bedouès, #11)	Granite	189	-1.97	0.59	0.22	0.85	108.85	5.28	0.58	0.59
Event: 21/10/2008 - 23/10/2008										
Gardon (Mialet, #21)	Schist	220	-59.76	-25.57	-0.41	0.08	588.51	401.64	0.76	0.90
Gardon (Anduze, #22)	Schist	543	-7.28	-1.69	-1.47	-0.34	290.48	139.86	0.33	0.30
Gardon (Ners, #23)	Limestone / Schist	1100	-22.07	-11.86	-1.41	-0.62	359.58	259.49	0.07	0.17

Table 4: Performance indices of the simulations performed on 6 catchments of various geologies, during two rainfall events of 2008. This table compares the results obtained by simulations performed without adding any weathered rock layer in the model (“No WRL”), and simulations including these weathered rock layer (“WRL”).

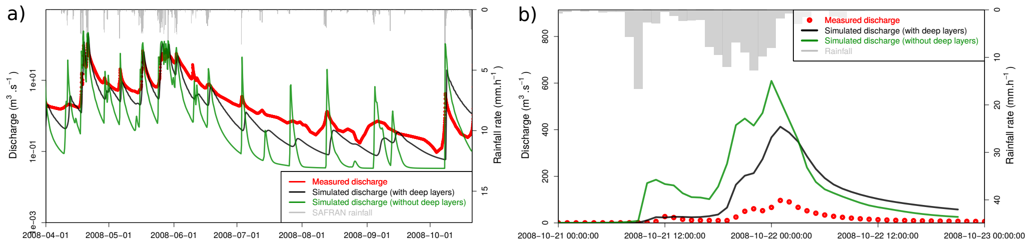

Figure 6: Comparison of measured discharge and discharge simulated by the CVN-p model with and without deep weathered rock layer on a schist catchment: Gardon in Mialet (220 km^2). a) Long-term simulation between April 1, 2008 and October 21, 2008 (discharge scale is logarithmic). b) Event simulation between October 21, 2008 and October 23, 2008.

and 10-years return period CRUPEDIX estimated peak discharge Q_{10} (computed according to equation 1) is presented at the regional scale. Fig.7 highlights the different scales for which the events are the most intense. The October event appears as intense at all scales, from the smallest catchments ($\sim$1 km^2) located where the largest rainfall amounts have been observed, to the largest (Cèze, Gardon, Vidourle catchments, with an area $>$ 500 km^2), as the consequence of a routing effect of the flood. Please note that ratio values computed on small catchments must be considered carefully, because of the known tendency of CRUPEDIX to overestimate 10-years return period peak discharges on catchments smaller than 200 km^2, as mentionned in section 3. On the other hand, the November event is simulated as very intense only at the largest scales (except one small area located in the Ardèche catchment), by accumulation effect.

These differences can be explained by the different natures of streamflow generation processes simulated by the CVN-p model. Fig.8 presents the map of the ratio between surface runoff (i.e. overland flow) and delayed groundwater flow simulated by the CVN-p model for the two events: while massive surface runoff is simulated by the model during the October event, the November event seems to

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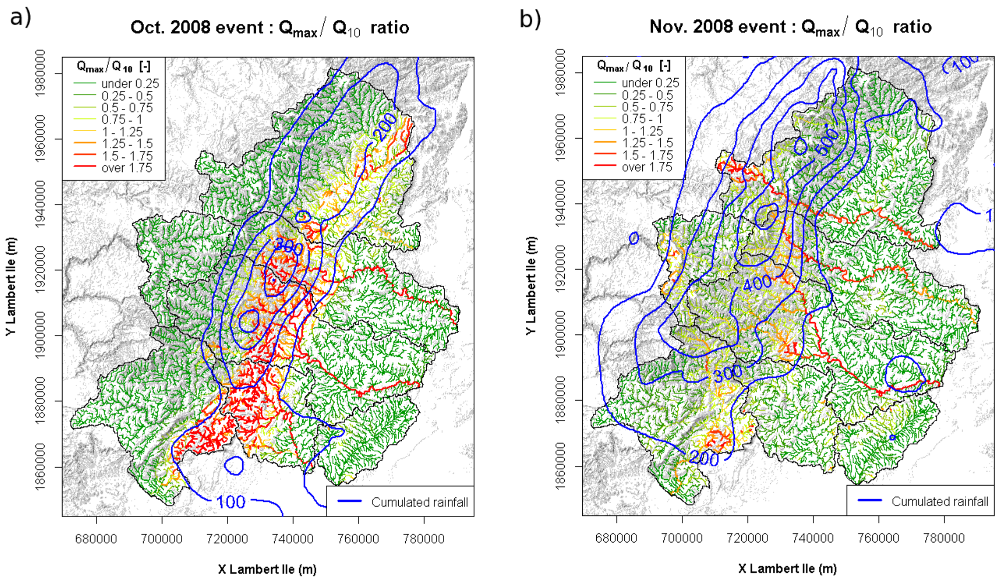

Figure 7: Maps of the ratio between simulated peak discharge Q_{max} and estimated peak discharge Q_{10} of a 10-years return period flood event. The ratio is computed on each river reach. Q10 is estimated according to the CRUPEDIX method (1980). a) October 21 - October 23, 2008 event; (b) October 31 - November 5, 2008 event. The contours of the cumulated kriged rainfall amounts appear in blue.

be associated with groundwater flow essentially. The areas where surface runoff is produced during the October event (Fig.8a) spatially match with the zone of high severity (Q_{max}/Q_{10}>1.5) in Fig.7a. This clearly shows that the simulation of the October event leads to intense surface runoff, responsible of the severity of the flood.

Two reasons probably explain why surface runoff is produced by the model during the October event and much less during the November event:

a) The first stands in the rainfall intensities. Fig.4c shows that the October event, shorter, was associated with larger rainfall intensities than the November event. High rainfall intensities strongly increase the probability of the model to produce infiltration excess overland flow. This is what happens during the simulation of the October event;

b) The second reason is linked to the location of the rainfall, as regard as the soil properties. The largest part of the precipitation of the November event was located on the mountainous area of the Cevennes-Vivarais region (western part of the catchments). This area is mainly covered by forest, with a steep terrain and permeable soils located on cristalline or metamorphic rocks, whereas the soils encountered in the sedimentary plain area, dominated by agricultural land uses, are found to be much less conductive, as shown by experimental *in situ* infiltration measurements (Desprats *et al.*, 2010). This also explains the tendency of the model to mainly simulate surface runoff on the plain areas affected by the October event, and groundwater flow on the areas affected by the November event.

Results presented in Fig.7 and Fig.8, despite they provide usefull information on the spatio-temporal differences between events and on the corresponding simulated streamflow processes, should be considered with caution because they are only model results. In the folowing sections, those results are compared to observations.

4.2.2. Regional evaluation of the simulations

Small-to-medium scale (1-100 km^2) evaluation: comparison to post-flood survey estimates

Since the October 21 - 23 event caused damages (road cuts, landslides, flooding of several places), a post-flood event survey was thus organized. Peak discharges

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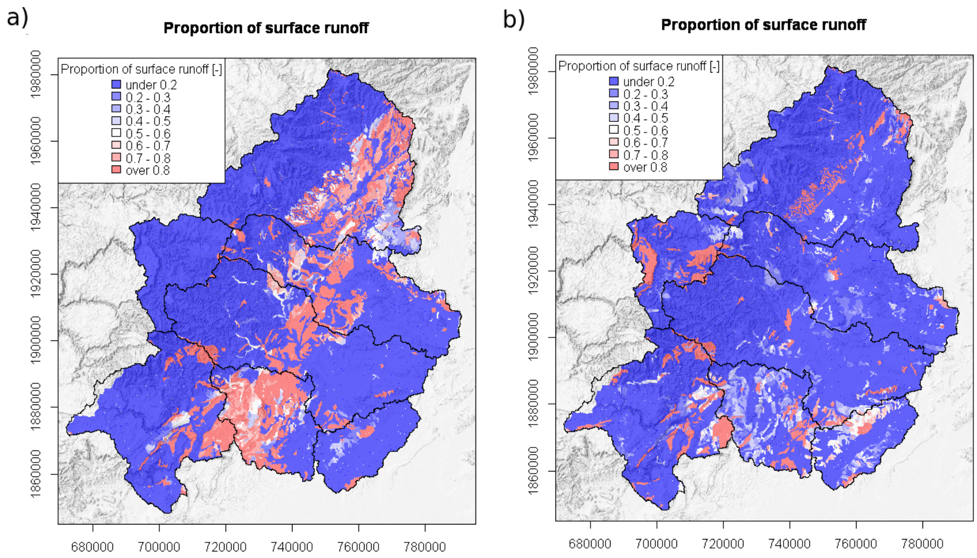

Figure 8: Maps of the ratio between surface runoff and groundwater flow simulated by the CVN-p model. a) October 21 - October 23, 2008 event; (b) October 31 - November 5, 2008 event. The contours of the cumulated kriged rainfall amounts appear in blue.

were estimated in 35 locations according to the methodology described by Gaume & Borga (2008). Fig.9 compares simulated specific peak discharges to post-flood survey estimates. We choose to confront specific peak discharge instead of absolute peak discharge for an enhanced regional overview of the results. A look at fig.9a) and b) shows that the CVN-p model simulates two areas where specifc discharge values are larger than 12 $m^3.s^{-1}.km^{-2}$: a first one at the border between the Gardon and the Ceze catchments, and a second at the southern border between the Gardon and the Vidourle catchments. These two zones correspond to the two most investigated areas during the post-flood event survey, since they were the most affected by the flood. Globally, the spatial coherence between simulated and estimated discharges is relatively good. Zones where post-flood investigations estimated large values of discharge are also reproduced by the model, and conversely zones where discharge values remained low during the flood event are generally not associated with large values of simulated discharges.

Nevertheless, there is no perfect correspondence between simulated discharges and post-flood survey estimates. The scatterplot shown in fig.9c) gives a more precise overview of the relationship existing between simulated values and post-flood survey estimates. It shows the existence of a clear linear correlation between estimations and simulated values (R^2=0.59), even if the spread around the central tendency is non negligible. The reasons of these differences stand both in the model and in the post-flood survey methodology uncertainties. Fig.9c) highlights a particular behaviour of the model: the range of variablity of the CVN-p results (4 to 19 $m^3.s^{-1}.km^{-2}$) is narrower than the range of variabilty of the post-flood survey estimates (1 to 26 $m^3.s^{-1}.km^{-2}$). This characteristic is linked to the tendency of the model to over-estimate small discharge values and to under-estimate large discharge values. A possible reason for this behaviour would stand in the use of hourly kriged rainfall maps with a spatial resolution of 1 km^2: such rainfall fields may spatially (as a result of the interpolation process) and temporally (as a result of the measurements hourly timestep) smooth the actual rainfall intensities.

Medium-to-large scale (30-2000 km^2) evaluation: comparison to streamgauges measurements

Fig.10 presents an evaluation of the simulations for the two flood events. These maps show the calculated value of the three performance criteria previously introduced (NSE, PBIAS and R2), computed at all the gauging sites. On these maps, the size of the circles gives the magnitude of the observed peak discharge, thus indicating the relative importance that must be accorded to the computed score

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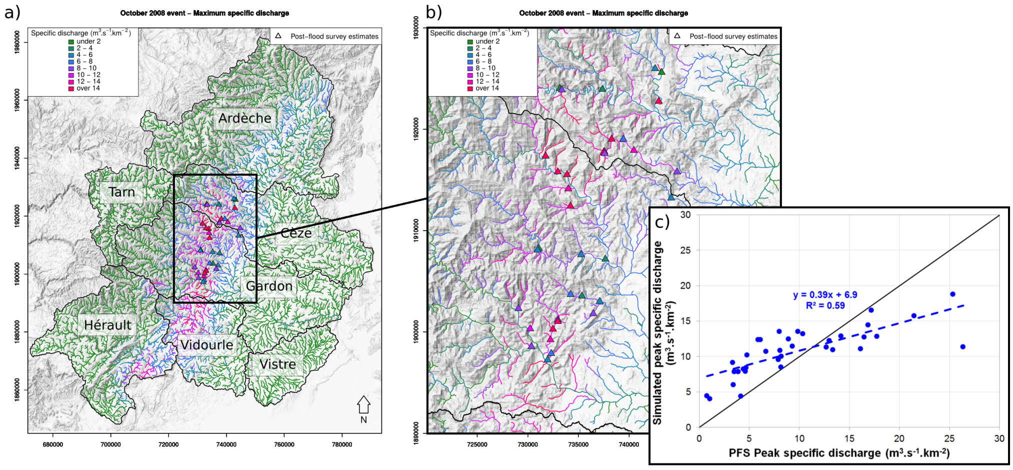

Figure 9: Comparison of the peak specific discharges simulated on each river reach to the peak specific discharge estimated during the post-flood survey, for the October 21 - October 23, 2008 event. River reaches and points denoting the location of the post-flood survey (PFS) estimates are coloured according to the magnitude of the peak specific discharge. a) Map of the regional simulation results; b) Zoom on the locations of post-flood survey estimates; c) Scatter plot of the results.

at this location.

Fig.10 clearly indicates very distinct performances obtained by the model, depending on the considered catchment. On the Ardèche and the Tarn catchments, the model provides fair results (for a non-calibrated model) in terms of Nash-Sutcliffe Efficiencies for both events (note that the October event did not affect strongly the Tarn river), with positive NSE, with a score larger than 0.4 on most of the gauging locations. By contrast, the results obtained on the other catchments (Cèze, Gardon, Vistre, Vidourle, Hérault) are poor, with negative values of NSE calculated almost everywhere, for both events.

The maps of the computed PBIAS and R2 scores provide usefull insights for the understanding of the reasons of such distinct behaviours. The scores obtained

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in terms of R2 and PBIAS do not present similar spatial patterns. While the PBIAS scores map is comparable to the NSE scores map, with a clear separation between the good (Tarn and the Ardèche) and the poor (elsewhere) performances obtained, the correlation coefficient R2 does not present a clear spatial pattern. The correlation coefficients calculated for the Tarn and Ardèche catchments do not clearly differ from the values obtained on the other part of the region. This is particularly true for the second event (November), where R2 values are relatively good everywhere, with most of the simulated hydrographs presenting correlations coefficient towards observed hydrographs larger than 0.85. This result indicates the good ability of the CVN-p model to reproduce the flow dynamics of the catchments (i.e. the shape and the timing of the observed floods).

On the other hand, the model does not properly reproduce the observed flood volumes everywhere, as evidenced by the PBIAS score values obtained. For the largest part of the catchments, CVN-p overestimates flood volumes, with computed values of PBIAS larger than +40%. Interestingly, for the Tarn and Ardèche catchments, the simulated volumes are much more realistic, with obtained PBIAS scores lower than 20%, and even negative (underestimation of volumes) at several locations. These spatial patterns of the NSE and PBIAS scores suggest that the model generally overestimates flood volumes while the dynamics of the flood is satisfyingly reproduced (as shown by the R2 scores map).

The most likely interpretation of these results stands in the geological nature of the catchments. As shown in Fig.3, the Ardèche and Tarn catchments include large areas of crystalline rocks (granite and gneiss). This type of rocks is even dominant in the northern part of the Tarn catchment, and on the upper

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(mountainous) part of the Ardèche catchment, where the November 2008 event was the most intense. The results shown in Fig 10 thus confirm and extend those presented in section 4.1. The tendency of the model to perform well on a certain type of geology and not on others is thus confirmed at the regional scale. These results also prove that the performances are not event-dependent: both flood events provide very similar results. We can thus claim that our results only arise from the structure of the hydrological model and from its parametrization, and can consequently be reproduced for other flood events.

5. Discussion

The role of the sub-soil compartment in the streamflow dynamics

The results of section 4.1 suggest the importance of the sub-soil compartment in the long-term dynamics as well as in the flood event response of catchments. Vannier *et al.* (2014) showed the necessity to account for sub-soil (i.e. weathered rock layers) water storage capacity to correctly reproduce the water balance of Cevennes-Vivarais catchments. The direct implementation of a weathered rock layer into the regional rainfall-runoff model CVN-p, with the parametrization proposed by Vannier *et al.* (2014), involves a massive - although unequal - improvement of the model results, both for flood event and long-term simulations.

These findings confirm the need to properly represent the overall water storage capacity of catchments into hydrological models (Sayama *et al.*, 2011). Because of a generalized lack of reliable information on the water retention capacity of rocks that compose the sub-soil compartment, hydrologists often rely on calibration of

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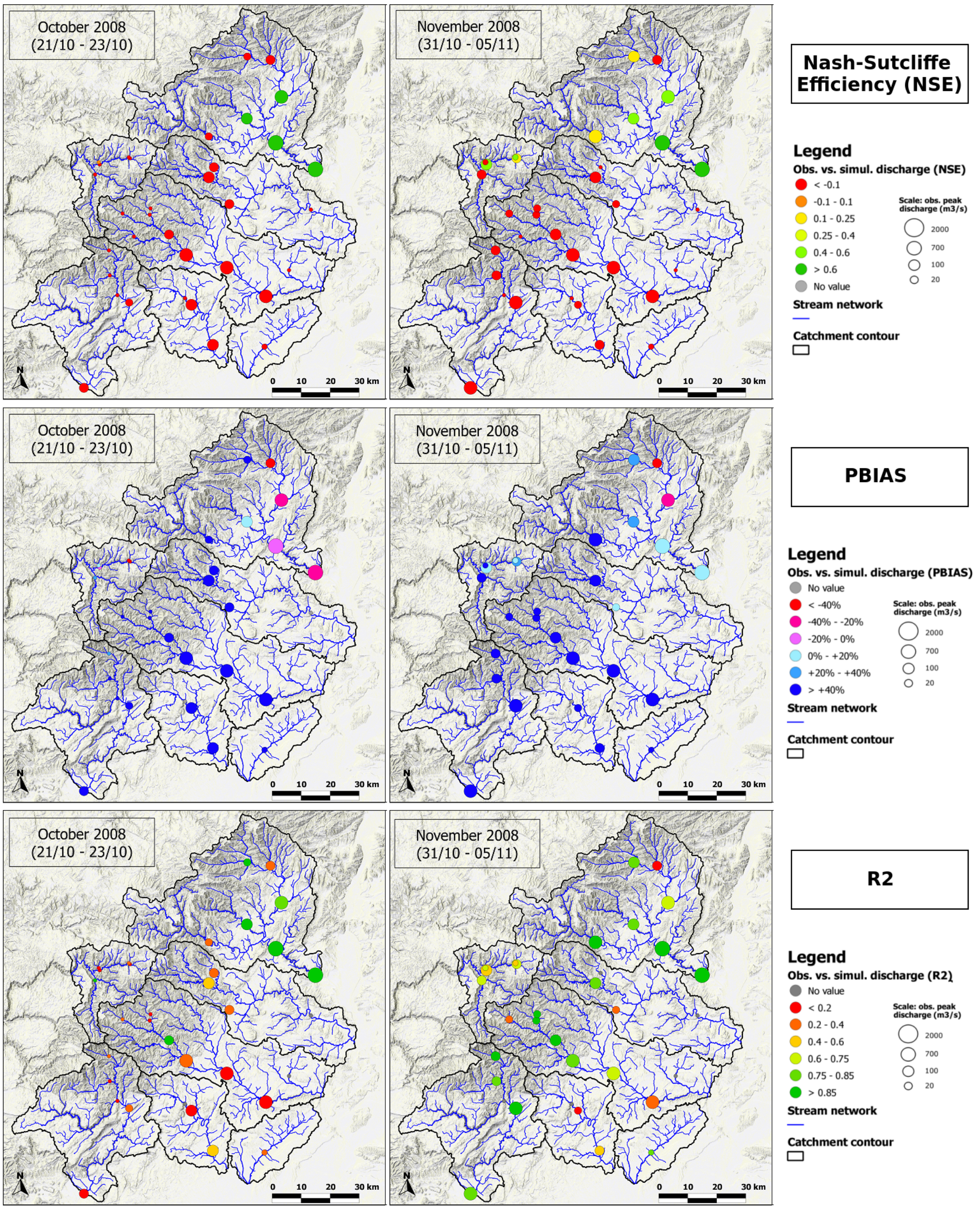

Figure 10: Spatial representation of the performance indices calculated for the simulations of the two flood events of year 2008 in the Cevennes-Vivarais region, using the CVN-p rainfall-runoff model and using the weathered rocks horizons.

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this parameter. Sometimes, models and their water storage capacities are set up using the knowledge provided by soil databases (Manus *et al.*, 2009; Braud *et al.*, 2010, e.g.). Only considering soil horizons can lead to the use of correction coefficients to account for an effective water storage capacity, generally much larger than the soil storage capacity (Roux *et al.*, 2011; Garambois *et al.*, 2015). To face the lack of available data which can be used in process-oriented distributed models, the present study demonstrates the applicability and reliability of the method proposed by Vannier *et al.* (2014) to add a weathered rock layer below upper soil horizons and to characterize it in terms of effective thickness and hydraulic conductivity.

The different hydrological behaviours induced by distinct geologies

The present work shows that in the Cevennes-Vivarais region, geology appears as an important control factor over the hydrological behaviour of catchments. The response of crystalline catchments is properly reproduced by the model, but the results remain perfectible for schist-dominated catchments. Several sensitivity studies (not shown) have been performed on these schist catchments to see if this could have had a positive impact on the simulated streamflow dynamics. The result is that no different parameters combination turned out to provide better simulation results than those presented in this article. This highlights a lack in the model structure more than in the parametrization. It is important to add that the results shown here are not specific to the two events selected. The gardon catchment, for which the CVN-p model overestimates both volume and peak discharge during the October 2008 event, behaves similarly during the November 2008 event (this is not shown here, but results are presented in Vannier (2013)). In

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addition, simulations were performed on another flood event that impacted both the Tarn (crystalline rocks) and the upper Gardon (schists): the 19-20 October 2006 event. Results, not shown here, are almost identical to those discussed in this study. This proves the robustness of the results presented here.

If the model structure is not able to reproduce the storage and draining behaviour of weathered schist rock layers, whatever the thickness and conductivity considered, this means that this geology acts differently than crystalline rocks on the sub-surface flowpaths and thus on the response of the catchments. The potential hydrologic specificity of schist rocks, despite poorly described in litterature, has been suggested by Martin *et al.* (2004) and Maréchal *et al.* (2013), both looking at french mediterranean catchments. In these two studies, the authors observe that schist catchments behave differently from others. Martin *et al.* (2004) assume that the planar structure of schisty rocks represents a preferential sloping direction for the subsurface or groundwater flows and that consequently, depending on the direction of the schist layers regarding the topography, schists can whether accelerate groundwater flows or increase water storage. We believe that this behaviour largely explains the results presented here. Of course, this assumption needs to be confirmed, through other modelling studies as well as complementary observations.

Usefullness of process-oriented and multi-scale regional models

Through this work, we hope to convince hydrologists about the usefullness of regional process-oriented models. Three important features of the modelling approach used here are highlighted:

1. *A regional set-up of the model.* As opposed to most of the modelling works performed in the Cevennes-Vivarais region, focusing on a single catchment, the present study covers the entire region (seven catchments, with an area of several thousands of km^2). This regional approach allows a direct comparison of the simulated streamflow dynamics of catchments which can differ by their physiographic characteristics (such as geology). This inter-catchments comparison, coupled to a classical evaluation of the goodness of the simulations, reveals some important behavioural differences existing between catchments that would have been difficult to detect using a classical catchment-by-catchment modelling approach.

2. *A multiscale modelling strategy.* Another important characteristic of the modelling strategy followed here stands in the wide range of spatial scales covered by CVN-p. The continuity between scales, from the elementary response unit (< 1 km^2) to the outlet of the largest catchments (> 2000 km^2), gives an integrated view of the hydrological response to flood events. It allows a meaningfull multiscale comparison of different flood events and of their magnitude, such as in Fig.7.

3. *An uncalibrated modelling approach.* The absence of calibration is not an end in itself, but is necessary in the purpose of testing hydrological functioning hypotheses. The strength of this approach is illustrated in this study when assessing the contribution of the weathered rock layers in the model performance: the parameters that characterize the weathered rock horizons are not calibrated, the values estimated by Vannier *et al.* (2014) are directly given as input into the model. Through this approach, we found out the adequate

model structure to reproduce the dynamics of crystalline rock catchments and discovered that this structure is not suitable for schist rocks catchments.

6. Conclusions

This work represents a step towards a better understanding of the governing hydrological processes in the mediterranean area, and especially on the role played by geology in catchments prone to flash floods. Through a regional multiscale hydrological modelling approach, focusing both on event and inter-event (long term) simulations, we assess the effect of adding weathered rock layers into the model, with hydraulic properties varying with geology and estimated after the results obtained by Vannier *et al.* (2014). Simulation results highlight the importance of the sub-soil layers and their associated storage capacity in the general streamflow dynamic of catchments, during and between flood events. Results also enhance some behavioural differences between catchments, related to their dominant geology. The addition of sub-soil layers in the CVN-p model largely improves the results, and allows to satisfyingly reproduce the streamflow dynamic and the flood response of crystalline rocks catchments. On other geologies, the improvement is real but still not sufficient to perfectly agree with the observations.

On a methodological point of view, this work proves the reliabilty of uncalibrated, process-oriented modelling studies, especially when set up at a regional scale. Such approaches are very effective to bring out behavioural similarities or differences between neighbouring catchments, or to identify the key hydrological processes over a wide range of spatial and temporal scales. Combined with a multi-criteria evaluation strategy, and proceeding in an iterative way to test hydrological functioning hypotheses, such modeling approaches need to be encouraged and developed.

Further field observations and modelling studies are required to confirm the preliminary results obtained and shown in this work, especially to investigate and better reproduce the groundwater transfers that exist in schists and sedimentary rocks sub-soil layers. We also recommend to use similar modelling appoaches over different regions and under other climatic conditions, to assess the robustness of the proposed methodology.

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Appendix A Details on the CVN-p model structure

A short description of the different hydrological modules coupled within the continuous CVN-p model, which derives from CVN (Manus *et al.*, 2009) is presented as follows:

1. Vertical water transfer through soils : FRER1D. The FRER1D module is able to generate infiltration-excess runoff, as well as saturation excess runoff, even the one caused by perched water tables (non complete saturation of the soil profile), since different soil horizons (with different hydraulic properties) can be described in the model. Relationships between hydraulic conductivity, water content and soil pressure are provided by the Brooks & Corey (1964) model. The FRER1D module is an implementation in the LIQUID platform of the non-iterative Richards' equation (Richards, 1931) solution proposed by Ross (2003). The Ross methodology to compute one-dimensionnal water transfer in soils was assessed by Varado *et al.* (2006b). A new version of the numerical method, accounting for root extraction process by means of the introduction of sink terms in the Richards' equation, was developped and assessed by Varado *et al.* (2006a). Crevoisier *et al.* (2009) highlighted the stability and robustness of the Ross (2003) solution, and showed its superiority towards traditional iterative resolution methods, such as those used in commercial tools (Simunek *et al.*, 1999). Even if the Richards equation resolution in hydrological model is often presented as a "physically-based" description of water transfer in soils, we believe this is a common misconception. Many works have shown that the validity of the Richards equations to describe flow motion is most of the time restricted to laboratory conditions, with homogeneous porous material subject

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to a gradient of charge. In natural conditions, various poorly known processes, such as rock fracturing or macroporosity, make the actual flow conditions significantly differ from Richards theory (Villholth & Jensen, 1991). Therfore, the use of Richards equations solver in hydrological models, like the FRER1D module, should rather be considered as a conceptual representation of the actual processes than as a "physically-based" resolution system.

2. Extraction of ponding and runoff generation: PEM. This module takes as input the ponding depth (runoff) produced by FRER1D, and sends it - instantaneously - to the closest river reach. Since the river network is finely described, this instantaneous transfer of runoff into the river does not imply an unrealistic reduction of the total water transfer time through the catchment. The spatial discretization is based on elementary watersheds with area that does not exceed 0.5 km^2. Considering a runoff velocity of 1 m/s before it reaches the river network, this hypothesis always leads to neglect less than 30 minutes of water transfer time.

3. Water transfer in the river network : RIVER1D. RIVER1D module computes the routing of water along the river network. It is based on the solution of the one-dimensionnal kinematic wave equation (Branger *et al.*, 2010).

4. Vegetation and evapotranspiration modules : ROLI, VEGINT, CRLINPG, ETPART. This set of modules compute the interception and water uptake from vegetation. Note that despite the addition of the modules, CVN-p is not a fully coupled water-vegetation model, in the sense that it does neither solve the vegetation growth nor the energy balance of the system. A reference evap-

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otranspiration (ET_0) is used as a forcing, and modulated by crop coefficients, depending on the vegetation (CRLINPG module). The growth of plants is prescriped by means of a dynamic evolution of the Leaf Area Index (LAI), as monthly average values (CRLINPG). VEGINT computes the fraction of water intercepted by plants during rainfall events (this fraction being subsequently available for direct evaporation) (Noilhan & Planton, 1989), while ETPART computes both potential vegetation transpiration and potential evaporation on soil, using a partition coefficient depending on LAI and a Beer-Lambert law (Huygen *et al.*, 1997). ROLI computes the actual amount of water extracted by roots in the soil according to the potential transpiration and the available water content (Li *et al.*, 2001). The root extraction computed by ROLI is a sink term in the Richards equation solved by FRER1D.