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

4 Olivier Vannier^{a,*}, Sandrine Anquetin^{a,b}, Isabelle Braud^c

5 ^a *Université Grenoble Alpes, LTHE, Grenoble Cedex 9, France*

6 ^b *CNRS, LTHE, Grenoble Cedex 9, France*

7 ^c *IRSTEA, UR HHLY (Hydrology-Hydraulics), Villeurbanne Cedex, France*

8 **Abstract**

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

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,

*Corresponding author

Email address: oliviervannier@gmail.com (Olivier Vannier)

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).

55

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).

72

To better understand the role played by landscape characteristics in the hy-

drological 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 evolu-
tive 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 ap-
proach advocated by Clark *et al.* (2011). The modelling process followed here
consists in a "Try - Fail - Learn - Repeat" iterative methodology used for test-
ing 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 hy-
drological 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 destructive 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 Observatory¹ (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>

at developing 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 project² (Braud *et al.*, 2014), which is a contribution to the international HyMeX program³, 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>

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 occurred 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).

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 compartment, 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 km²; 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.

175

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).

183

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

186 strong link between the dominant geology and the estimated values of the thick-
187 ness and hydraulic conductivity of these deep horizons (Fig.2b). Values of sat-
188 urated hydraulic conductivities presented in Fig.2b can be seen as very large,
189 and thus out of the range of standard values of conductivities reported for soils
190 or porous rocks. This is due to the nature of the values characterized by Van-
191 nier *et al.* (2014): first, the presence of various poorly-known processes such as
192 macroporosity, rock fracturing, or preferential flow directions, may result in flow
193 conditions that significantly diverge from the theory, and in addition, these val-
194 ues are representative of catchment-wide integrated processes since they derive
195 from streamflow recession analyses. Consequently, values reported in Fig.2b must
196 rather be considered as “effective” parameters than as actual hydraulic conduc-
197 tivities.

198

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 $0.05 \text{ m}^3 \cdot \text{m}^{-3}$ and $0.1 \text{ m}^3 \cdot \text{m}^{-3}$). Values implemented (Table 1) have been added to the figure.

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

	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 km²) Cèze (1372 km²) and Gardon (1914 km²) catchments at their confluence with the Rhône river, the Vidourle at Sommières (650 km²), the Vistre at its confluence with the Rhony river (493 km²), the Hérault at Gignac (1410 km²) and the Tarn at Montbrun (589 km²) 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

Figure 3: Location of the seven selected catchments, and dominant geology of the Cévennes-Vivaraïs 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.

244 root depths of different types of vegetation are extracted from the ECOCLIMAP
245 database (Masson *et al.*, 2003). Geology derives from the 1:1 000 000 scale na-
246 tional geological map⁴.

247

248 3.2. Forcings

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

⁴<http://www.brgm.fr>

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) recommendations (Allen *et al.*, 1998).

The input forcing variables are given on spatial grids, with a resolution varying from $8 \times 8 \text{ km}^2$ (SAFRAN meteorological reanalyses) to $1 \times 1 \text{ km}^2$ (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 biased 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).

277 3.4. *Simulations strategy*

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

280

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

288

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

292

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

298

299 3.5. *Evaluation of the simulations*

300 When complete measured hydrographs are available, an evaluation of the
301 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 $1 \times 1 \text{ km}^2$ 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).

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

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

313

314 *Long-term simulations*

315

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

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;

330

331 *Event simulations*

332

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).

337

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:

340

a) Peak discharge estimated *a posteriori* in 35 catchments, ranging from 1 to 100 km², during the post flood investigation of the October 21-23 event. The post flood survey follows the methodology defined by Gaume & Borga (2008);

344

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

gion, for catchment sizes ranging from 30 to 2300 km². 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 km².

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

where Q_{10} is the 10-years return period instantaneous peak discharge (m³.s⁻¹); A is the catchment area (km²); 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

369 discharge. We performed a comparison (not shown here) between CRUPEDIX
370 estimates and data-based 10-years return period peak discharge obtained by fit-
371 ting annual maxima to a Gumbel distribution, on all streamgauges of the region.
372 It showed a globally fair agreement, despite a tendency of CRUPEDIX to overes-
373 timate 10-years return period peak discharges on small catchments ($< 200 \text{ km}^2$).
374 Note that a more recent method, named SHYREG (Aubert *et al.*, 2014), has
375 been developed for the estimation of reference peak discharge in mediterranean
376 catchments. But the homogeneous application of the CRUPEDIX method over
377 the whole study area, even on ungauged streams, allows its use as a common
378 reference for the evaluation of regional flood discharges. Consequently, the ratio
379 Q_{max}/Q_{10} , where Q_{max} is the maximum simulated peak discharge, gives a clear
380 indication of the simulated severity of the flood, on each reach of the hydrographic
381 network.

382

383 4. Results

384 4.1. Contribution of the implemented weathered rock layer

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

390 4.1.1. Granite and gneiss

391 On crystalline rock (granite and gneiss) catchments located on the Tarn river,
392 the benefits of including a deep weathered rock layer are clear, whether for event or

393 long-term simulations. For long-term simulations, adding a deep weathered rock
394 horizon significantly increases the Nash-Sutcliffe efficiency and the Nash-Sutcliffe
395 efficiency of the logarithmic discharge (Table 3), which turns from negative to
396 better than 0.7 values on each of the three catchments. R^2 criteria values also
397 improve in all cases. One must notice a slight increase of the PBIAS index values
398 (becoming positive in all cases) when adding the weathered rock layer. For event
399 simulations, results are also improved when adding the deep weathered rock hori-
400 zon (4): on each of the catchments, the four performance indicators get better
401 values when adding the deep layer. Especially, Nash-Sutcliffe efficiency of the
402 logarithmic discharge and PBIAS index reach satisfying values for non-calibrated
403 event simulations (Table 4).

404

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

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 metamorphic 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 granitic 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

stay closer from 0 than 1 in most of the case. This is particularly true for the event simulation, for which negative Nash-Sutcliffe efficiencies 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 km²), which is a schist-dominated catchment. For the long-term simulation (Fig.6a), the implementation of a weathered rock layer reduces the tendency 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}

Catchment	Dominant geology	Area (km ²)	NSE		LNSE		PBIAS		R ²	
			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 (Russian, #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”).

Catchment	Dominant geology	Area (km ²)	NSE		LNSE		PBIAS		R ²	
			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 ($\sim 1 \text{ km}^2$) located where the largest rainfall amounts have been observed, to the largest (Cèze, Gardon, Vidourle catchments, with an area $> 500 \text{ km}^2$), 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 mentioned 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.

474

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

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. Q_{10} 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.

485

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

491 model to produce infiltration excess overland flow. This is what happens dur-
492 ing the simulation of the October event;

493

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

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

510 4.2.2. Regional evaluation of the simulations

511 *Small-to-medium scale (1-100 km²) evaluation: comparison to post-flood sur-*
512 *vey estimates*

513

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

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 specific discharge values are larger than $12 \text{ m}^3 \cdot \text{s}^{-1} \cdot \text{km}^{-2}$: 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 variability of the CVN-p results (4 to 19 $\text{m}^3.\text{s}^{-1}.\text{km}^{-2}$) is narrower than the range of variability of the post-flood survey estimates (1 to 26 $\text{m}^3.\text{s}^{-1}.\text{km}^{-2}$). 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 R^2), 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

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

568 in terms of R^2 and PBIAS do not present similar spatial patterns. While the
569 PBIAS scores map is comparable to the NSE scores map, with a clear separation
570 between the good (Tarn and the Ardèche) and the poor (elsewhere) performances
571 obtained, the correlation coefficient R^2 does not present a clear spatial pattern.
572 The correlation coefficients calculated for the Tarn and Ardèche catchments do
573 not clearly differ from the values obtained on the other part of the region. This is
574 particularly true for the second event (November), where R^2 values are relatively
575 good everywhere, with most of the simulated hydrographs presenting correlations
576 coefficient towards observed hydrographs larger than 0.85. This result indicates
577 the good ability of the CVN-p model to reproduce the flow dynamics of the catch-
578 ments (i.e. the shape and the timing of the observed floods).

579

580 On the other hand, the model does not properly reproduce the observed flood
581 volumes everywhere, as evidenced by the PBIAS score values obtained. For the
582 largest part of the catchments, CVN-p overestimates flood volumes, with com-
583 puted values of PBIAS larger than +40%. Interestingly, for the Tarn and Ardèche
584 catchments, the simulated volumes are much more realistic, with obtained PBIAS
585 scores lower than 20%, and even negative (underestimation of volumes) at several
586 locations. These spatial patterns of the NSE and PBIAS scores suggest that the
587 model generally overestimates flood volumes while the dynamics of the flood is
588 satisfyingly reproduced (as shown by the R^2 scores map).

589

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

(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

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.

619 this parameter. Sometimes, models and their water storage capacities are set up
620 using the knowledge provided by soil databases (Manus *et al.*, 2009; Braud *et al.*,
621 2010, e.g.). Only considering soil horizons can lead to the use of correction coef-
622 ficients to account for an effective water storage capacity, generally much larger
623 than the soil storage capacity (Roux *et al.*, 2011; Garambois *et al.*, 2015). To
624 face the lack of available data which can be used in process-oriented distributed
625 models, the present study demonstrates the applicability and reliability of the
626 method proposed by Vannier *et al.* (2014) to add a weathered rock layer below
627 upper soil horizons and to characterize it in terms of effective thickness and hy-
628 draulic conductivity.

629

630 *The different hydrological behaviours induced by distinct geologies*

631

632 The present work shows that in the Cevennes-Vivarais region, geology appears
633 as an important control factor over the hydrological behaviour of catchments. The
634 response of crystalline catchments is properly reproduced by the model, but the
635 results remain perfectible for schist-dominated catchments. Several sensitivity
636 studies (not shown) have been performed on these schist catchments to see if this
637 could have had a positive impact on the simulated streamflow dynamics. The
638 result is that no different parameters combination turned out to provide better
639 simulation results than those presented in this article. This highlights a lack in
640 the model structure more than in the parametrization. It is important to add
641 that the results shown here are not specific to the two events selected. The gar-
642 don catchment, for which the CVN-p model overestimates both volume and peak
643 discharge during the October 2008 event, behaves similarly during the November
644 2008 event (this is not shown here, but results are presented in Vannier (2013)). In

645 addition, simulations were performed on another flood event that impacted both
646 the Tarn (crystalline rocks) and the upper Gardon (schists): the 19-20 October
647 2006 event. Results, not shown here, are almost identical to those discussed in
648 this study. This proves the robustness of the results presented here.

649

650 If the model structure is not able to reproduce the storage and draining be-
651 haviour of weathered schist rock layers, whatever the thickness and conductivity
652 considered, this means that this geology acts differently than crystalline rocks
653 on the sub-surface flowpaths and thus on the response of the catchments. The
654 potential hydrologic specificity of schist rocks, despite poorly described in litter-
655 ature, has been suggested by Martin *et al.* (2004) and Maréchal *et al.* (2013),
656 both looking at french mediterranean catchments. In these two studies, the au-
657 thors observe that schist catchments behave differently from others. Martin *et al.*
658 (2004) assume that the planar structure of schisty rocks represents a preferential
659 sloping direction for the subsurface or groundwater flows and that consequently,
660 depending on the direction of the schist layers regarding the topography, schists
661 can whether accelerate groundwater flows or increase water storage. We believe
662 that this behaviour largely explains the results presented here. Of course, this
663 assumption needs to be confirmed, through other modelling studies as well as
664 complementary observations.

665

666 *Usefulness of process-oriented and multi-scale regional models*

667

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

671 1. *A regional set-up of the model.* As opposed to most of the modelling works
672 performed in the Cevennes-Vivarais region, focusing on a single catchment,
673 the present study covers the entire region (seven catchments, with an area of
674 several thousands of km²). This regional approach allows a direct comparison
675 of the simulated streamflow dynamics of catchments which can differ by their
676 physiographic characteristics (such as geology). This inter-catchments compar-
677 ison, coupled to a classical evaluation of the goodness of the simulations, re-
678 veals some important behavioural differences existing between catchments that
679 would have been difficult to detect using a classical catchment-by-catchment
680 modelling approach.

681

682 2. *A multiscale modelling strategy.* Another important characteristic of the mod-
683 elling strategy followed here stands in the wide range of spatial scales covered
684 by CVN-p. The continuity between scales, from the elementary response unit
685 ($< 1 \text{ km}^2$) to the outlet of the largest catchments ($> 2000 \text{ km}^2$), gives an
686 integrated view of the hydrological response to flood events. It allows a mean-
687 ingfull multiscale comparison of different flood events and of their magnitude,
688 such as in Fig.7.

689

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

697 model structure to reproduce the dynamics of crystalline rock catchments and
698 discovered that this structure is not suitable for schist rocks catchments.
699

700 6. Conclusions

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

715

716 On a methodological point of view, this work proves the reliability of uncal-
717 ibrated, process-oriented modelling studies, especially when set up at a regional
718 scale. Such approaches are very effective to bring out behavioural similarities or
719 differences between neighbouring catchments, or to identify the key hydrologi-
720 cal processes over a wide range of spatial and temporal scales. Combined with
721 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 approaches over different regions and under other climatic conditions, to assess the robustness of the proposed methodology.

7. Acknowledgements

This work is part of the FloodScale project, which is funded by the French National Research Agency (ANR) under contract n° ANR 2011 BS56 027, which contributes to the HyMeX program. The authors would like to acknowledge Jérémy Chardon, from LTHE, for supplying the 10-years return period quantiles of SAFRAN daily rainfall depths.

References

- ALFIERI, L., SMITH, P. J., Thielen-del POZO, J. & BEVEN, K. J. : A staggered approach to flash flood forecasting – case study in the Cévennes region. *Advances in Geosciences*, 29:13–20, 2011.
- ALLEN, R. G., PEREIRA, L. S., RAES, D. & SMITH, M. : *Crop evapotranspiration - Guidelines for computing crop water requirements*, volume 56. Food and Agriculture Organization of the United Nations (F.A.O.), 1998.

- 745 ANQUETIN, S., BRAUD, I., VANNIER, O., VIALLET, P., BODEVILLAIN, B., CREUTIN, J.-D. &
746 MANUS, C. : Sensitivity of the hydrological response to the variability of rainfall fields and
747 soils for the Gard 2002 flash-flood event. *Journal of Hydrology*, 394(1-2):134–147, 2010.
- 748 AUBERT, Y., ARNAUD, P., RIBSTEIN, P. & FINE, J.-A. : The SHYREG flow method—application
749 to 1605 basins in metropolitan France. *Hydrological Sciences Journal*, 59(5):993–1005, 2014.
- 750 BLUME, T., ZEHE, E., REUSSER, D. E., IROUMÉ, A. & BRONSTERT, A. : Investigation of runoff
751 generation in a pristine, poorly gauged catchment in the Chilean Andes I: A multi-method
752 experimental study. *Hydrological Processes*, 22(18):3661–3675, 2008.
- 753 BONNIFAIT, L., DELRIEU, G., LE LAY, M., BODEVILLAIN, B., MASSON, A., BELLEUDY, P.,
754 GAUME, E. & SAULNIER, G.-M. : Distributed hydrologic and hydraulic modelling with radar
755 rainfall input: Reconstruction of the 8-9 September 2002 catastrophic flood event in the Gard
756 region, France. *Advances in Water Resources*, 32(7):1077–1089, 2009.
- 757 BODEVILLAIN, B., DELRIEU, G., GALABERTIER, B., BONNIFAIT, L., BOUILLAUD, L., KIRSTET-
758 TER, P.-E. & MOSINI, M.-L. : The Cévennes-Vivarais mediterranean hydrometeorological ob-
759 servatory database. *Water Resources Research*, 47(7):W07701, doi:10.1029/2010WR010353,
760 2011.
- 761 BOUILLAUD, L., CHANCIBAUT, K., VINCENDON, B., DUCROCQ, V., HABETS, F., SAULNIER, G.-
762 M., ANQUETIN, S., MARTIN, E. & NOILHAN, J. : Coupling the ISBA land surface model and
763 the TOPMODEL hydrological model for mediterranean flash-flood forecasting: Description,
764 calibration, and validation. *Journal of Hydrometeorology*, 11(2):315–333, 2010.
- 765 BRANGER, F., BRAUD, I., DEBIONNE, S., VIALLET, P., DEHOTIN, J., HENINE, H., NEDELEC, Y.
766 & ANQUETIN, S. : Towards multi-scale integrated hydrological models using the LIQUID®
767 framework. Overview of the concepts and first application examples. *Environmental Modelling*
768 & *Software*, 25(12):1672–1681, 2010.
- 769 BRAUD, I., AYRAL, P.-A., BOUVIER, C., BRANGER, F., DELRIEU, G., LE COZ, J., NORD, G.,
770 VANDERVAERE, J.-P., ANQUETIN, S., ADAMOVIC, M., ANDRIEU, J., BATIOT, C., BODEVIL-
771 LAIN, B., BRUNET, P., CARREAU, J., CONFOLAND, A., DIDON-LESCOT, J.-F., DOMERGUE,
772 J.-M., DOUVINET, J., DRAMAIS, G., FREYDIER, R., GÉRARD, S., HUZA, J., LEBLOIS, E.,
773 LE BOURGEOIS, O., LE BOURSICAUD, R., MARCHAND, P., MARTIN, P., NOTTALE, L., PATRIS,
774 N., RENARD, B., SEIDEL, J.-L., TAUPIN, J.-D., VANNIER, O., VINCENDON, B. & WIJBRANS,
775 A. : Multi-scale hydrometeorological observation and modelling for flash flood understanding.

- 776 *Hydrology and Earth System Sciences*, 18(9):3733–3761, 2014.
- 777 BRAUD, I., ROUX, H., ANQUETIN, S., MAUBOURGUET, M.-M., MANUS, C., VIALLET, P. &
778 DARTUS, D. : The use of distributed hydrological models for the Gard 2002 flash flood event:
779 Analysis of associated hydrological processes. *Journal of Hydrology*, 394(1-2):162–181, 2010.
- 780 BROOKS, R. H. & COREY, A. T. : Hydraulic properties of porous media. *Hydrology Papers*,
781 *Colorado State University*, 1964.
- 782 BRUTSAERT, W. & NIEBER, J. L. : Regionalized drought flow hydrographs from a mature
783 glaciated plateau. *Water Resources Research*, 13(3):637–643, 1977.
- 784 CASERI, A., JAVELLE, P., RAMOS, M. & LEBLOIS, E. : Generating precipitation ensembles for
785 flood alert and risk management. *Journal of Flood Risk Management*, 2015.
- 786 CERESSETTI, D. : *Structure spatio-temporelle des fortes précipitations : application à la région*
787 *Cévennes-Vivarais*. Thèse de doctorat, Université de Grenoble, 2011.
- 788 CLARK, M. P., KAVETSKI, D. & FENICIA, F. : Pursuing the method of multiple work-
789 ing hypotheses for hydrological modeling. *Water Resources Research*, 47(9):W09301,
790 doi:10.1029/2010WR009827, 2011.
- 791 CREVOISIER, D., CHANZY, A. & VOLTZ, M. : Evaluation of the Ross fast solution of Richards'
792 equation in unfavourable conditions for standard finite element methods. *Advances in Water*
793 *Resources*, 32(6):936–947, 2009.
- 794 CRUPEDIX : (la méthode). Fascicule 3 de la Synthèse nationale sur les crues des petits bassins
795 versants (in french). Rapport technique, French Ministry of Agriculture., July 1980.
- 796 DE MICHELE, C., KOTTEGODA, N. T. & ROSSO, R. : The derivation of areal reduction factor
797 of storm rainfall from its scaling properties. *Water Resources Research*, 37(12):3247–3252,
798 2001.
- 799 DEHOTIN, J. & BRAUD, I. : Which spatial discretization for distributed hydrological mod-
800 els? Proposition of a methodology and illustration for medium to large-scale catchments.
801 *Hydrology and Earth System Sciences*, 12(3):769–796, 2008.
- 802 DESPRATS, J.-F., CERDAN, O., KING, C. & MARCHANDISE, A. : Cartographie de la perméabilité
803 des sols pour l'aide à la prévision des crues; cas d'étude sur le Gardon d'Anduze. *La Houille*
804 *Blanche*, 3:32–38, 2010.
- 805 FENICIA, F., KAVETSKI, D. & SAVENIJE, H. H. G. : Elements of a flexible approach for conceptual
806 hydrological modeling: 1. Motivation and theoretical development. *Water Resources Research*,

- 807 47(11):W11510, doi: 10.1029/2010WR010174, 2011.
- 808 FENICIA, F., McDONNELL, J. J. & SAVENIJE, H. H. G. : Learning from model improvement: On
809 the contribution of complementary data to process understanding. *Water Resources Research*,
810 44(6):W06419, doi:10.1029/WR006386, 2008a.
- 811 FENICIA, F., SAVENIJE, H. H. G., MATGEN, P. & PFISTER, L. : Understanding catchment
812 behavior through stepwise model concept improvement. *Water Resources Research*, 44(1):
813 n/a–n/a, 2008b.
- 814 GARAMBOIS, P.-A., ROUX, H., LARNIER, K., CASTAINGS, W. & DARTUS, D. : Characterization
815 of process-oriented hydrologic model behavior with temporal sensitivity analysis for flash
816 floods in Mediterranean catchments. *Hydrology and Earth System Sciences*, 17(6):2305–2322,
817 2013.
- 818 GARAMBOIS, P., ROUX, H., LARNIER, K., LABAT, D. & DARTUS, D. : Characterization of
819 catchment behaviour and rainfall selection for flash flood hydrological model calibration:
820 catchments of the eastern Pyrenees. *Hydrological Sciences Journal*, 60(3):424–447, 2015.
- 821 GAUME, E., BAIN, V., BERNARDARA, P., NEWINGER, O., BARBUC, M., BATEMAN, A.,
822 BLASKOVICOVÁ, L., BLÖSCHL, G., BORGA, M., DUMITRESCU, A., DALIAKOPOULOS, I., GAR-
823 CIA, J., IRIMESCU, A., KOHNOVA, S., KOUTROULIS, A., MARCHI, L., MATREATA, S., MEDINA,
824 V., PRECISO, E., SEMPERE-TORRES, D., STANCALIE, G., SZOLGAY, J., TSANIS, I., VELASCO,
825 D. & VIGLIONE, A. : A compilation of data on European flash floods. *Journal of Hydrology*,
826 367(1-2):70 – 78, 2009.
- 827 GAUME, E. & BORGA, M. : Post-flood field investigations in upland catchments after major
828 flash floods: proposal of a methodology and illustrations. *Journal of Flood Risk Management*,
829 1(4):175–189, 2008.
- 830 GHARARI, S., HRACHOWITZ, M., FENICIA, F., GAO, H. & SAVENIJE, H. H. G. : Using expert
831 knowledge to increase realism in environmental system models can dramatically reduce the
832 need for calibration. *Hydrology and Earth System Sciences*, 18(12):4839–4859, 2014.
- 833 HRACHOWITZ, M., SAVENIJE, H. H. G., BLÖSCHL, G., McDONNELL, J. J., SIVAPALAN, M.,
834 POMEROY, J. W., ARHEIMER, B., BLUME, T., CLARK, M. P., EHRET, U., FENICIA, F.,
835 FREER, J. E., GELFAN, A., GUPTA, H. V., HUGHES, D. A., HUT, R. W., MONTANARI, A.,
836 PANDE, S., TETZLAFF, D., TROCH, P. A., UHLENBROOK, S., WAGENER, T., WINSEMIUS,
837 H. C., WOODS, R. A., ZEHE, E. & CUDENNEC, C. : A decade of Predictions in Ungauged

- Basins (PUB) - a review. *Hydrological Sciences Journal*, 58(6):1–58, 2013.
- HUYGEN, J., VAN DAM, J. C., KROES, J. G. & WESSELING, J. G. : SWAP 2.0: input and output manual. Rapport technique, Wageningen Agricultural University, and DLO-Staring Centrum, Wageningen., 1997.
- JAVELLE, P., DEMARGNE, J., DEFRANCE, D., PANSU, J. & ARNAUD, P. : Evaluating flash-flood warnings at ungauged locations using post-event surveys: a case study with the AIGA warning system. *Hydrological Sciences Journal*, 59(7):1390–1402, 2014.
- KANG, B. & TRIPATHI, B. : *The AFNETA alley farming training manual - Volume 2: Source book for alley farming research*, chapitre Technical paper 1 : soil classification and characterization. Food and Agriculture Organization of the United Nations (F.A.O.), 1992.
- KAVETSKI, D. & FENICIA, F. : Elements of a flexible approach for conceptual hydrological modeling: 2. Application and experimental insights. *Water Resources Research*, 47:W11511, doi: 10.1029/2011WR01748, 2011.
- KLING, H. & GUPTA, H. : On the development of regionalization relationships for lumped watershed models: The impact of ignoring sub-basin scale variability. *Journal of Hydrology*, 373(3-4):337 – 351, 2009.
- LATRON, J. & GALLART, F. : Runoff generation processes in a small Mediterranean research catchment (Vallcebre, Eastern Pyrenees). *Journal of Hydrology*, 358(3-4):206–220, 2008.
- LE LAY, M. & SAULNIER, G.-M. : Exploring the signature of climate and landscape spatial variabilities in flash flood events: Case of the 8-9 September 2002 Cévennes-Vivarais catastrophic event. *Geophysical Research Letters*, 34(13):L13401, doi:10.1029/2007GL029746, 2007.
- LI, K. Y., DE JONG, R. & BOISVERT, J. B. : An exponential root-water-uptake model with water stress compensation. *Journal of Hydrology*, 252(1-4):189–204, 2001.
- MANUS, C., ANQUETIN, S., BRAUD, I., VANDERVAERE, J.-P., CREUTIN, J.-D., VIALLET, P. & GAUME, E. : A modeling approach to assess the hydrological response of small mediterranean catchments to the variability of soil characteristics in a context of extreme events. *Hydrology and Earth System Sciences*, 13(2):79–97, 2009.
- MARÉCHAL, D., AYRAL, P.-A., BAILLY, J.-S., PUECH, C. & SAUVAGNARGUES-LESAGE, S. : Sur l'origine morphologique des écoulements par l'analyse d'observations hydrologiques distribuées. Application à deux bassins versants cévenols (Gard, France). *Géomorphologie : relief, processus, environnement*, 1:47–62, 2013.

- 869 MARTIN, F., MARTIN, C., LAVABRE, J. & FOLTON, N. : Fonctionnement hydrologique des
870 bassins versants de roches métamorphiques : exemple du bassin versant des Maurets (massif
871 des Maures, Var, France). *Études de Géographie Physique*, 31:39–70, 2004.
- 872 MASSON, V., CHAMPEAUX, J.-L., CHAUVIN, F., MERIGUET, C. & LACAZE, R. : A global
873 database of land surface parameters at 1-km resolution in meteorological and climate models.
874 *Journal of Climate*, 16(9):1261–1282, 2003.
- 875 McMILLAN, H., FREER, J., PAPPENBERGER, F., KRUEGER, T. & CLARK, M. : Impacts of
876 uncertain river flow data on rainfall-runoff model calibration and discharge predictions. *Hy-*
877 *drological Processes*, 24(10):1270–1284, 2010.
- 878 McNAMARA, J. P., TETZLAFF, D., BISHOP, K., SOULSBY, C., SEYFRIED, M., PETERS, N. E.,
879 AULENBACH, B. T. & HOOPER, R. : Storage as a Metric of Catchment Comparison. *Hydro-*
880 *logical Processes*, 25(21):3364–3371, 2011.
- 881 MONTEITH, J. L. : Evaporation and environment. In: The State and Movement of Water in
882 Living Organisms. *In the XIXth Symposia of the Society for Experimental Biology (Swansea,*
883 *UK)*, pages 205–234, 1965.
- 884 NASH, J. E. & SUTCLIFFE, J. V. : River flow forecasting through conceptual models part I - A
885 discussion of principles. *Journal of Hydrology*, 10(3):282–290, 1970.
- 886 NESTER, T., KIRNBAUER, R., GUTKNECHT, D. & BLÖSCHL, G. : Climate and catchment controls
887 on the performance of regional flood simulations. *Journal of Hydrology*, 402(3-4):340–356,
888 2011.
- 889 NOILHAN, J. & PLANTON, S. : A simple parameterization of land surface processes for meteo-
890 rological models. *Monthly Weather Review*, 117(3):536–549, 1989.
- 891 NOTO, L., IVANOV, V., BRAS, R. & VIVONI, E. : Effects of initialization on response of a
892 fully-distributed hydrologic model. *Journal of Hydrology*, 352(1-2):107 – 125, 2008.
- 893 OUDIN, L., ANDRÉASSIAN, V., PERRIN, C., MICHEL, C. & LE MOINE, N. : Spatial proxim-
894 ity, physical similarity, regression and ungaged catchments: A comparison of regionaliza-
895 tion approaches based on 913 French catchments. *Water Resources Research*, 44(3):W03413,
896 doi:10.1029/2007WR006240, 2008.
- 897 OUDIN, L., KAY, A., ANDRÉASSIAN, V. & PERRIN, C. : Are seemingly physically similar
898 catchments truly hydrologically similar? *Water Resources Research*, 46(11):n/a–n/a, 2010.
- 899 PARAJKA, J., MERZ, R. & BLÖSCHL, G. : A comparison of regionalisation methods for catchment

- 900 model parameters. *Hydrology and Earth System Sciences*, 9(3):157–171, 2005.
- 901 PARAJKA, J., VIGLIONE, A., ROGGER, M., SALINAS, J. L., SIVAPALAN, M. & BLÖSCHL, G.
902 : Comparative assessment of predictions in ungauged basins - Part 1: Runoff-hydrograph
903 studies. *Hydrology and Earth System Sciences*, 17(5):1783–1795, 2013.
- 904 QUINTANA-SEGUÍ, P., LE MOIGNE, P., DURAND, Y., MARTIN, E., HABETS, F., BAILLON, M.,
905 CANELLAS, C., FRANCHISTEGUY, L. & MOREL, S. : Analysis of near-surface atmospheric
906 variables: Validation of the SAFRAN analysis over France. *Journal of Applied Meteorology*
907 *and Climatology*, 47(1):92–107, 2008.
- 908 RAWLS, W. J. & BRAKENSIEK, D. L. : Prediction of soil water properties for hydrologic modeling.
909 *In Watershed Management in the Eighties*, pages 293–299. Proceedings of a Symposium ASCE
910 (Denver, USA), 1985.
- 911 REGGIANI, P., HASSANIZADEH, S. M., SIVAPALAN, M. & GRAY, W. G. : A unifying framework
912 for watershed thermodynamics: constitutive relationships. *Advances in Water Resources*, 23
913 (1):15–39, 1999.
- 914 REGGIANI, P., SIVAPALAN, M. & HASSANIZADEH, S. M. : A unifying framework for watershed
915 thermodynamics: balance equations for mass, momentum, energy and entropy, and the second
916 law of thermodynamics. *Advances in Water Resources*, 22(4):367–398, 1998.
- 917 RICHARDS, L. A. : Capillary conduction of liquids through porous mediums. *Journal of Applied*
918 *Physics*, 1(5):318–333, 1931.
- 919 RINALDO, A., BEVEN, K., BERTUZZO, E., NICOTINA, L., DAVIES, J., FIORI, A., RUSSO, D. &
920 BOTTER, G. : Catchment travel time distributions and water flow in soils. *Water Resources*
921 *Research*, 47, JUL 20 2011.
- 922 ROBBEZ-MASSON, J. M., BARTHES, J. P., BORNAND, M., FALIPOU, P. & LEGROS, J. P. : Bases
923 de données pédologiques et systèmes d'informations géographiques. L'exemple de la région
924 Languedoc-Roussillon. *Forêt Méditerranéenne*, 21(1):88–98, 2000.
- 925 ROSS, P. J. : Modeling soil water and solute transport - Fast, simplified numerical solutions.
926 *Agronomy Journal*, 95(6):1352–1361, 2003.
- 927 ROUX, H., LABAT, D., GARAMBOIS, P.-A., MAUBOURGUET, M.-M., CHORDA, J. & DARTUS,
928 D. : A physically-based parsimonious hydrological model for flash floods in Mediterranean
929 catchments. *Natural Hazards and Earth System Science*, 11(9):2567–2582, 2011.
- 930 SALINAS, J., LAHA, G., ROGGER, M., PARAJKA, J., VIGLIONE, A., SIVAPALAN, M. & BLÖSCHL,

- 931 G. : Comparative assessment of predictions in ungauged basins - Part 2: Flood and low flow
932 studies. *Hydrology and Earth System Sciences*, 17(7):2637–2652, 2013.
- 933 SAVENIJE, H. H. G. : HESS Opinions "Topography driven conceptual modelling (FLEX-Topo)".
934 *Hydrology and Earth System Sciences*, 14(12):2681–2692, 2010.
- 935 SAWICZ, K., WAGENER, T., SIVAPALAN, M., TROCH, P. A. & CARRILLO, G. : Catchment
936 classification: empirical analysis of hydrologic similarity based on catchment function in the
937 eastern USA. *Hydrology and Earth System Sciences*, 15(9):2895–2911, 2011.
- 938 SAYAMA, T., McDONNELL, J. J., DHAKAL, A. & SULLIVAN, K. : How much water can a
939 watershed store? *Hydrological Processes*, 25(25):3899–3908, 2011.
- 940 SAYAMA, T. & McDONNELL, J. : A new time-space accounting scheme to predict stream water
941 residence time and hydrograph source components at the watershed scale. *Water Resources*
942 *Research*, 45, JUL 1 2009.
- 943 SELKER, J., van de GIESEN, N., WESTHOFF, M., LUXEMBURG, W. & PARLANGE, M. B. : Fiber
944 optics opens window on stream dynamics. *Geophysical Research Letters*, 33(24):n/a–n/a,
945 2006. L24401.
- 946 SIMUNEK, J., SEJNA, M. & van GENUCHTEN, M. T. : *Agronomy Abstracts*, chapitre The
947 HYDRUS-1D and HYDRUS-2D codes for estimating unsaturated soil hydraulic and solutes
948 transport parameters. American Society of Agronomy, 1999.
- 949 SIVAPALAN, M., TAKEUCHI, K., FRANKS, S. W., GUPTA, V. K., KARAMBIRI, H., LAKSHMI, V.,
950 LIANG, X., McDONNELL, J. J., MENDIONDO, E. M., O'CONNELL, P. E., OKI, T., POMEROY,
951 J. W., SCHERTZER, D., UHLENBROOK, S. & ZEHE, E. : IAHS Decade on Predictions in
952 Ungauged Basins (PUB), 2003-2012: Shaping an exciting future for the hydrological sciences.
953 *Hydrological Sciences Journal*, 48(6):857–880, 2003.
- 954 TARBOTON, D. G. : A new method for the determination of flow directions and upslope areas
955 in grid digital elevation models. *Water Resources Research*, 33(2):309–319, 1997.
- 956 TETZLAFF, D., SOULSBY, C., WALDRON, S., MALCOLM, I., BACON, P., DUNN, S., LILLY, A.
957 & YOUNGSON, A. : Conceptualization of runoff processes using a geographical information
958 system and tracers in a nested mesoscale catchment. *Hydrological Processes*, 21(10):1289–
959 1307, 2007.
- 960 TETZLAFF, D., McNAMARA, J. P. & CAREY, S. K. : Measurements and modelling of storage
961 dynamics across scales. *Hydrological Processes*, 25(25):3831–3835, 2011.

- 962 TROCH, P. A., PANICONI, C. & van LOON, E. E. : Hillslope-storage Boussinesq model for subsur-
963 face flow and variable source areas along complex hillslopes: 1. Formulation and characteristic
964 response. *Water Resources Research*, 39(11):1316, doi:10.1029/2002WR001728, 2003.
- 965 Tromp-van MEERVELD, H. J., PETERS, N. E. & McDONNELL, J. J. : Effect of bedrock perme-
966 ability on subsurface stormflow and the water balance of a trenched hillslope at the Panola
967 Mountain Research Watershed, Georgia, USA. *Hydrological Processes*, 21(6):750–769, 2007.
- 968 VANNIER, O. : *Regional modeling of mediterranean floods : contribution to the understanding*
969 *of the dominant hydrological processes. PhD thesis (in french. Thèse de doctorat, Université*
970 *de Grenoble, 2013.*
- 971 VANNIER, O., BRAUD, I. & ANQUETIN, S. : Regional estimation of catchment-scale soil prop-
972 erties by means of streamflow recession analysis for use in distributed hydrological models.
973 *Hydrological Processes*, 28(26):6276–6291, 2014.
- 974 VARADO, N., BRAUD, I. & ROSS, P. J. : Development and assessment of an efficient vadose zone
975 module solving the 1D Richards' equation and including root extraction by plants. *Journal*
976 *of Hydrology*, 323(1-4):258–275, 2006a.
- 977 VARADO, N., BRAUD, I., ROSS, P. J. & HAVERKAMP, R. : Assessment of an efficient numerical
978 solution of the 1D Richards' equation on bare soil. *Journal of Hydrology*, 323(1-4):244–257,
979 2006b.
- 980 VERSINI, P.-A., GAUME, E. & ANDRIEU, H. : Application of a distributed hydrological model to
981 the design of a road inundation warning system for flash flood prone areas. *Natural Hazards*
982 *and Earth System Science*, 10(4):805–817, 2010.
- 983 VIALLET, P., DEBIONNE, S., BRAUD, I., DEHOTIN, J., HAVERKAMP, R., SAADI, Z., ANQUETIN,
984 S., BRANGER, F. & VARADO, N. : Towards multi-scale integrated hydrological models using
985 the LIQUID framework. *In 7th International Conference on Hydroinformatics. Nice, France,*
986 *pages 542–549, 2006.*
- 987 VIDAL, J.-P., MARTIN, E., FRANCHISTÉGUY, L., BAILLON, M. & SOUBEYROUX, J.-M. : A 50-
988 year high-resolution atmospheric reanalysis over France with the Safran system. *International*
989 *Journal of Climatology*, 30(11):1627–1644, 2010.
- 990 VILLHOLTH, K. & JENSEN, K. H. : Field investigations of preferential flow behaviour. *In Hy-*
991 *drological Interactions Between Atmosphere, Soil and Vegetation (Proceedings of the Vienna*
992 *Symposium).*, 1991.

- 993 VINCENDON, B., DUCROCQ, V., SAULNIER, G.-M., BOUILLAUD, L., CHANCIBAUT, K., HABETS,
994 F. & NOILHAN, J. : Benefit of coupling the ISBA land surface model with a TOPMODEL
995 hydrological model version dedicated to Mediterranean flash-floods. *Journal of Hydrology*,
996 394(1-2):256–266, 2010.
- 997 VIVONI, E., ENTEKHABI, D., BRAS, R. & IVANOV, V. : Controls on runoff generation and
998 scale-dependence in a distributed hydrologic model. *Hydrology and Earth System Sciences*,
999 11(5):1683–1701, 2007.
- 1000 WEILER, M. & McDONNELL, J. J. : Conceptualizing lateral preferential flow and flow networks
1001 and simulating the effects on gauged and ungauged hillslopes. *Water Resources Research*, 43
1002 (3):W03403, doi:10.1029/2006WR004867, 2007.
- 1003 WEILER, M. & NAEF, F. : Simulating surface and subsurface initiation of macropore flow.
1004 *Journal of Hydrology*, 273(1-4):139–154, 2003.
- 1005 YADAV, M., WAGENER, T. & GUPTA, H. V. : Regionalization of constraints on expected
1006 watershed response behavior for improved predictions in ungauged basins. *Advances in Water*
1007 *Resources*, 30(8):1756–1774, 2007.
- 1008 ZEHE, E., GRAEFF, T., MORGNER, M., BAUER, A. & BRONSTERT, A. : Plot and field scale soil
1009 moisture dynamics and subsurface wetness control on runoff generation in a headwater in the
1010 Ore Mountains. *Hydrology and Earth System Sciences*, 14(6):873–889, 2010.

1011 **Appendix A Details on the CVN-p model structure**

1012 A short description of the different hydrological modules coupled within the
1013 continuous CVN-p model, which derives from CVN (Manus *et al.*, 2009) is pre-
1014 sented as follows:

1015

1016 1. Vertical water transfer through soils : FRER1D. The FRER1D module is able
1017 to generate infiltration-excess runoff, as well as saturation excess runoff, even
1018 the one caused by perched water tables (non complete saturation of the soil
1019 profile), since different soil horizons (with different hydraulic properties) can be
1020 described in the model. Relationships between hydraulic conductivity, water
1021 content and soil pressure are provided by the Brooks & Corey (1964) model.
1022 The FRER1D module is an implementation in the LIQUID platform of the
1023 non-iterative Richards' equation (Richards, 1931) solution proposed by Ross
1024 (2003). The Ross methodology to compute one-dimensionnal water transfer in
1025 soils was assessed by Varado *et al.* (2006b). A new version of the numerical
1026 method, accounting for root extraction process by means of the introduction of
1027 sink terms in the Richards' equation, was developped and assessed by Varado
1028 *et al.* (2006a). Crevoisier *et al.* (2009) highlighted the stability and robustness
1029 of the Ross (2003) solution, and showed its superiority towards traditional it-
1030 erative resolution methods, such as those used in commercial tools (Simunek
1031 *et al.*, 1999). Even if the Richards equation resolution in hydrological model
1032 is often presented as a “physically-based” description of water transfer in soils,
1033 we believe this is a common misconception. Many works have shown that the
1034 validity of the Richards equations to describe flow motion is most of the time
1035 restricted to laboratory conditions, with homogeneous porous material subject

1036 to a gradient of charge. In natural conditions, various poorly known processes,
1037 such as rock fracturing or macroporosity, make the actual flow conditions sig-
1038 nificantly differ from Richards theory (Villholth & Jensen, 1991). Therefore,
1039 the use of Richards equations solver in hydrological models, like the FRER1D
1040 module, should rather be considered as a conceptual representation of the ac-
1041 tual processes than as a “physically-based” resolution system.

1042

1043 2. Extraction of ponding and runoff generation: PEM. This module takes as
1044 input the ponding depth (runoff) produced by FRER1D, and sends it - in-
1045 stantaneously - to the closest river reach. Since the river network is finely
1046 described, this instantaneous transfer of runoff into the river does not imply
1047 an unrealistic reduction of the total water transfer time through the catch-
1048 ment. The spatial discretization is based on elementary watersheds with area
1049 that does not exceed 0.5 km². Considering a runoff velocity of 1 m/s before it
1050 reaches the river network, this hypothesis always leads to neglect less than 30
1051 minutes of water transfer time.

1052

1053 3. Water transfer in the river network : RIVER1D. RIVER1D module computes
1054 the routing of water along the river network. It is based on the solution of the
1055 one-dimensionnal kinematic wave equation (Branger *et al.*, 2010).

1056

1057 4. Vegetation and evapotranspiration modules : ROLI, VEGINT, CRLINPG,
1058 ETPART. This set of modules compute the interception and water uptake
1059 from vegetation. Note that despite the addition of the modules, CVN-p is not
1060 a fully coupled water-vegetation model, in the sense that it does neither solve
1061 the vegetation growth nor the energy balance of the system. A reference evap-

1062 otranspiration (ET_0) is used as a forcing, and modulated by crop coefficients,
1063 depending on the vegetation (CRLINPG module). The growth of plants is
1064 prescribed by means of a dynamic evolution of the Leaf Area Index (LAI), as
1065 monthly average values (CRLINPG). VEGINT computes the fraction of water
1066 intercepted by plants during rainfall events (this fraction being subsequently
1067 available for direct evaporation) (Noilhan & Planton, 1989), while ETPART
1068 computes both potential vegetation transpiration and potential evaporation on
1069 soil, using a partition coefficient depending on LAI and a Beer-Lambert law
1070 (Huygen *et al.*, 1997). ROLI computes the actual amount of water extracted
1071 by roots in the soil according to the potential transpiration and the available
1072 water content (Li *et al.*, 2001). The root extraction computed by ROLI is a
1073 sink term in the Richards equation solved by FRER1D.

1074