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Discussions

Multi-scale hydrometeorological observation and modelling for flash-flood understanding

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Abstract

This paper presents a coupled observation and modelling strategy aiming at improving the understanding of processes triggering flash floods. This strategy is illustrated for the Mediterranean area using two French catchments (Gard and Ardèche) larger than 2000 km^2. The approach is based on the monitoring of nested spatial scales: (1) the hillslope scale, where processes influencing the runoff generation and its concentration can be tackled; (2) the small to medium catchment scale (1–100 km^2) where the impact of the network structure and of the spatial variability of rainfall, landscape and initial soil moisture can be quantified; (3) the larger scale (100–1000 km^2) where the river routing and flooding processes become important. These observations are part of the HyMeX (Hydrological Cycle in the Mediterranean Experiment) Enhanced Observation Period (EOP) and lasts four years (2012–2015). In terms of hydrological modelling the objective is to set up models at the regional scale, while addressing small and generally ungauged catchments, which is the scale of interest for flooding risk assessment. Top-down and bottom-up approaches are combined and the models are used as "hypothesis testing" tools by coupling model development with data analyses, in order to incrementally evaluate the validity of model hypotheses. The paper first presents the rationale behind the experimental set up and the instrumentation itself. Second, we discuss the associated modelling strategy. Results illustrate the potential of the approach in advancing our understanding of flash flood processes at various scales.

1 Introduction

The Mediterranean area is prone to intense rainfall events triggering flash floods, characterized by very short response times. They sometimes lead to dramatic consequences in terms of casualties and damages: Vaison-la-Romaine (1992), Aude (1999), Gard (2002, 2005) or Draguignan (2010) for French examples in the last twenty years. Flash floods often occur over very short time and spatial scales (Gaume

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et al., 2009; Douvinet and Delahaye, 2010) with a violent sudden onset, high erosive capacities and a rapid rising time. But impacts differ through scales, as shown by the analysis of the 8–9 September 2002 event (Delrieu et al., 2005) in the Gard region (South-eastern France): many casualties occurred in ungauged catchments of less than 20 km^2, and were related to road flooding (Ruin et al., 2008), while the economic damage (mainly in urban zones and road networks) was observed at larger catchment scales (up to 1000 km^2). Therefore, the scales of interest for flash flood studies range from the small catchments of a few km^2 where the risk is high, to the regional scale where the emergency and alert must be organised.

The range of scales for flash flood processes understanding is also very large. The spatial and temporal rainfall variability, landscape characteristics and soil humidity are recognised as important influential factors in flash flood generation (Borga et al., 2010). Flash-flood events are characterized by space and time scales that conventional measurement networks are not always able to sample (Creutin and Borga, 2003; Kirchner, 2006). In the HYDRATE EU project, a significant effort was dedicated to the collection of hydrometerological data on flash floods in Europe (Gaume et al., 2009; Marchi et al., 2010), and to promote a standardized method for post-flood field surveys (Gaume and Borga, 2008; Marchi et al., 2009). Methodologies were proposed to determine the spatial and temporal characteristic scales of the processes leading to flash floods (Sangati et al., 2009; Anquetin et al., 2010; Viglione et al., 2010a, b). Several authors (Borga et al., 2008; Bouilloud et al., 2010) showed that high-resolution space-time rainfall fields provided by weather radars are essential to analyse properly and understand flash floods. Others showed the importance of topography (Norbiato et al., 2009), geology and soils (Anquetin et al., 2010; Braud et al., 2010; Martin, 2010), initial soil moisture (Borga et al., 2007; Le Lay and Saulnier, 2007; Gaume et al., 2009; Tramblay et al., 2010) or the impact of hydraulic routing within the river network (Bonnifait et al., 2009). Depending on the conditions, one or several factors can impact significantly the hydrological response. As a consequence, the predictability of such events remains low. In addition, this predictability is lowered by a high non-linearity in

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the hydrological response related to threshold effects and structured-heterogeneity at all scales (Blöschl and Zehe, 2005).

Then, assessing flash flood susceptibility and further understanding flash flood processes require a multi-scale and cross-combined approach. Furthermore, to progress in flash flood understanding and modelling, it is necessary to better document the active processes through scales, and to transfer the knowledge acquired at a given scale to another scale, the so-called change of scale problem (Blöschl and Sivapalan, 1995; Sivapalan, 2003a). Additionally, to assess the risk everywhere, it is necessary to provide reliable hydrological simulations and predictions in ungauged basins (the PUB problem, see Sivapalan, 2003a; Hrachowitz et al., 2013) and at various scales (from a few km^2 to 1000 km^2). Kirchner (2006) advocates field experiments, specifically designed to address the change of scale problem in order "to get the right answer for the right reasons" (Klemes, 1986; Grayson et al., 1992). The strategy is based on nested catchments, allowing the sampling of spatial heterogeneity at all scales (Sivapalan, 2003b). In addition, the emergence of new measurement tools (no-contact discharge gauging, geophysics, etc.), automatic sensors (soil moisture, limnimeters, geochemistry samplers) and high-resolution data such as remote sensing (weather radar, lidar DEM (Light Detection and Ranging Digital Elevation Model), satellite images) offers new perspectives in catchment monitoring. The nested sub-catchment sampling strategy is promoted in the US within the CUASHI initiative (Reed et al., 2006) and was also implemented within the AMMA project (Lebel et al., 2009).

This study builds on these recommendations and contributes to the HyMeX international scientific program (Drobinski et al., 2013). HyMeX seeks to improve the understanding of the water cycle, with emphasis on hydrometeorological natural hazards, by monitoring and modelling the Mediterranean atmosphere-land-ocean coupled system and its variability, from the event to the seasonal and interannual temporal scales, over one decade (2010–2020) and in the context of global change. The experimental part of HyMeX covers a ten-year Long Observation Period (LOP, 2010–2020), a four-year Enhanced Observation Period (EOP, 2011–2014) and Special

Observation Periods (SOPs) during which extra monitoring staff and devices can be quickly deployed in case of an extreme event forecast (see Ducrocq et al. (2013) for details about the autumn 2012 SOP).

The study mainly contributes to HyMeX EOP and is conducted in the framework of the FloodScale project (http://floodscale.irstea.fr/) focused on the monitoring, understanding and modelling of flash floods in the Mediterranean context. The two main scientific questions are: (1) how can we document the variability of active hydrological processes between and during flash floods from the hillslope scale to the regional scale? (2) How can we describe and simulate the corresponding processes at the various scales? To address these questions, the study relies on the collection of new data on flash flood and hydrological processes at all scales and their corresponding hydrological modelling. The novelty of the approach is that the experimental set up covers the regional scale (two catchments of about 2000 km^2), while monitoring nested sub-catchments representative of the variability of landscape conditions in the Mediterranean region. The multi-scale approach allows the documentation of active processes at small scale, and how they aggregate at larger scales (Fig. 1). The four-year duration of the experiment gives more chance to capture significant events. The length of the experiment and the setting of continuous measurements allow the documentation of the "normal" catchment behaviour, as well as the "extreme" behaviour in order to capture potential threshold effects and/or abrupt changes in catchment functioning. Long term time series from operational networks are also collected and analysed to get information about hydrological processes over longer time scales (LOP). Finally, innovative monitoring strategy for flash floods, relying on recent progress in instrumentation and sensors is proposed. Data analysis and models are combined in an iterative way (Fig. 2) to increase our process understanding and modelling capability. Progress in these directions is likely to increase our ability to improve social preparedness and warning to flash floods.

This paper presents the multi-scale observation strategy for two large Mediterranean catchments in France (Sect. 2) and the associated modelling approach (Sect. 3). Then the potential of this strategy is illustrated using first data analysis and modelling results (Sect. 4) before drawing conclusions and discussing perspectives (Sect. 5).

2 The multi-scale observation set up

2.1 Introduction

The experimental set up focuses on two pilot-sites in France: the Gard and the Ardèche catchments (Fig. 3), which belong to the existing Cévennes-Vivarais Mediterranean Hydrometeorological Observatory (OHM-CV) network (Boudevillain et al., 2011).

The observation strategy relies on nested-catchments instrumentation covering the following spatial scales (Fig. 1): (1) the hillslope scale, where process influencing the runoff generation and its concentration can be tackled; (2) the small to medium catchment scale (1–100 km^2) where the impact of network structure and of the spatial variability of rainfall, landscape and initial soil moisture can be quantified; (3) the larger scale (100–1000 km^2) where the river routing and flooding processes become important. Innovative observations (enhanced weather radar, disdrometer networks, stream gauging using non-contact techniques, dense limnimeters networks, very high resolution remote sensing data, Lidar DEMs...) complement the traditional measurements (rain gauges, water level, soil moisture, etc). The set-up also favours the combination of various measurements on the same hillslopes/catchments (soil moisture, infiltration tests, geophysics, geochemistry, geomorphological and vegetation surveys, stream gauging and river discharge monitoring) in order to enhance the potential for understanding the active processes during and between floods.

In the following, we successively describe, for the various scales, the scientific questions addressed by the experiments (see also Fig. 1) and the experimental set up itself. Data collected on alert during floods are also described.

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2.2 Experimental set up at the hillslope scale

Hillslope is recognised as the appropriate scale to assess flow-generating processes. Recent papers show that, in a context with sub-surface dominant flow, the long term monitoring of various hillslopes can lead to the emergence of new concepts such as the "fill and spill" mechanisms, underlying the role of bedrock micro-topography on runoff initiation, connexion and propagation (Tromp-van Meerveld and McDonnell, 2006; Anderson et al., 2009; Graham et al., 2010). Based on such a perceptual model, modelling studies using 3-D models and virtual experiments (Weiler and McDonnell, 2004; Herbst et al., 2006; Fiori et al., 2007; Hopp and McDonnell, 2009; James et al., 2010) were used to assess the major control on the hillslope response (slope, bedrock permeability, soil depth, rainfall depth) or to derive new modelling approaches (e.g. Lehmann et al., 2007, based on percolation theory). The "fill and spill" concept and the associated sub-surface flow was found to apply in other locations in the world (Uchida et al., 2005) and could be relevant for part of the Cévennes-Vivarais region (Cosandey and Didon-Lescot, 1990; Tramblay et al., 2010). Infiltration/runoff field experiments (Ayral, 2005; Marchandise, 2007) and modelling studies (Anquetin et al., 2010; Braud et al., 2010) also raise questions about the imperviousness of the bedrock, which is often assumed in models. Other studies conducted in cultivated areas (mainly vineyards) showed that surface Hortonian runoff may also be a dominant mechanism in the region (Hébrard et al., 2006; Nicolas, 2010). Runoff studies based on rainfall simulations and the analysis of in situ events, showed that a process similar to the "fill and spill" mechanism mentioned above can be encountered at the soil surface, in relation with micro-topography and vegetation (Nicolas, 2010).

In the present study, the experimental set up aims at characterizing the dominant processes during and between floods for different types of Mediterranean hillslopes, the final objective being the definition of a hillslope typology, allowing a spatialization of the results to non-monitored catchments. For this purpose, various hillslopes, typical of the Mediterranean environment in terms of spatial variability in soil depth,

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soil hydraulic properties, pedology, vegetation and geomorphology are selected and instrumented. We also explore the permeability/imperviousness and storage capacity of the underlying altered bedrock. Soil moisture variations and the impact of topography and vegetation on pre-event initial soil moisture are also documented. The instrumented hillslopes are located in three small catchments (Valescure, Tourgueille, Gazel), corresponding to different geologies (Table 1, Fig. 3). Details on instrumentation and protocols are provided below and summarized in Table 1.

2.2.1 Hillslopes monitoring

In the Gard catchments where saturation excess is thought to be dominant, the experimental set up is the following. Several hillslopes are selected according to geology, slope, exposition, vegetation and a transect from the bottom to the top of the slope is instrumented. In each transect, soil water contents is measured continuously at 10 locations and two depths (20 cm and the closest to the altered bedrock) to document the initial water deficit at the beginning of a rain event. In addition, the long-term variation of soil water content is of interest in order to assess topography and vegetation influence on soil moisture redistribution, as well as to document potential soil saturation. The sensors are left in place during one year to monitor the whole hydrological cycle, then dismantled and moved to another hillslope. Four transects have already been instrumented in the Valescure catchment[1] (Figs. 3 and 4a) with different geologies (granite, orthogneiss), expositions (east or west) and slopes (20 to 40°). The fifth transect has just been installed in the Tourgueille catchment (Figs. 3 and 4b) on shaley geology.

When the transect is dismantled, a geomorphology and vegetation survey is performed along the transect using the "landscape segments" method (Filleron, 1995; Morschel, 2006) to document the landscape organisation and its geomorphological

[1]http://mistrals.sedoo.fr/HyMeX/Parameter-search/?editDatsId=878&datsId=878&project_name=HyMeX

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dynamics, in particular water pathways. This method requires intensive field work (pedology pits, vegetation structure identification). A multidimensional, quantitative and spatialized description of the vegetation (Lecompte, 1973) is used with separate observation of horizontal structure, vegetation ground cover and vertical structure (in relation to interception). In addition, the main soil properties are characterized along each transect, in order to assess mean values and spatial variability. Particle size analysis, dry bulk density measurements, infiltrometry (Vandervaere et al., 2000) provide the textural and hydraulic soil properties. Electrical resistivity (Brunet et al., 2010) combined with mechanical perforations is used to characterize the soil depth.

In the Gazel catchment (Ardèche catchment, see location in Fig. 3), where infiltration excess runoff is thought to be the dominant process (e.g. Nicolas, 2010), the experiments focus on the documentation of the soil infiltration capacity and initiation of ponded conditions at the surface. First, ten sites (see location in Fig. 5) with different land uses (2 vineyards, 4 pastures, 1 fallow, 2 small oak woods) are selected. They have been equipped since April 2013 with continuous soil moisture measurements at about 10 cm, 20 cm and 30 to 50 cm depth, in order to document soil saturation. Second, specific field campaigns are conducted to document the spatially distributed soil response times to rainfall: between rainfall onset and soil surface saturation (signature of soil surface properties and initial moisture condition), between soil surface saturation and runoff (signature of surface micro-topography). The idea is to find a way to rank various land uses in terms of infiltration capacity/runoff generation while avoiding long time-consuming infiltration tests based on infiltrometers. For this purpose, a simplified rainfall simulator is proposed. As compared to previous simulator types, the water quantity needed to feed the simulator is reduced and it can be fed with a manual pump. The size of the wetted surface is about 1 m^2 and the rainfall intensity can range from 10 to 160 $mm\,h^{-1}$. Instead of waiting for the permanent regime, the time of ponding is determined visually. An analytical relationship between ponding time and rainfall intensity is used to derive estimates of hydraulic conductivity and sorptivity, according to equations proposed by Boulier and Vauclin (1987). The rainfall simulator

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was tested in 2013 on three fields (see location in Fig. 5) (2 vineyards and one pasture). It will be moved to other fields in the coming years to sample additional land uses. To complement the analysis, fields are monitored for runoff and erosion using devices described in Nicolas (2010) and Grangeon (2012).

2.2.2 Characterization of sub-surface flow and bedrock role

An important issue is also to determine the role of subsurface runoff in flood generation, either by direct contribution to the flood volumes or by drainage of the soils during inter-events, as well as the role of bedrock. The experimental setup combines various measurements (Buttle and McDonald, 2002; Joerin et al., 2005; Tromp-van Meerveld et al., 2007; Kientzler and Naef, 2008; Graham et al., 2010; Burke and Kasahara, 2011): soil moisture probes, piezometers, trench for sub-surface flow collecting, sprinklers or upslope trench for water input; natural or chemical tracers (see Fig. 6). One 10 m^2 plot (P1) was implemented in spring 2012 (see location in Fig. 4a) and was dismantled in 2013 after recording 4 artificial rainfall events and 20 natural ones. This first plot is characterized by a steep slopes (about 40°) and relatively deep soils (about 80 cm). The second one (P2) has been installed in October 2013 in shallower soils (about 50 cm) and lower slope (20°) (Fig. 4a). The protocol was incrementally improved during the first events and is now stabilized as follows. Two rainfall configurations can be applied, a homogeneous rainfall on the plot or a rainfall only at the top of the slope, in either case with a constant intensity. Three piezometers are inserted into the soil and are open only at the bottom to document possible saturation at the soil–bedrock interface. Close to the piezometers, two soil moisture probes and two tensiometers are installed at various depths as indicated in Fig. 6. Electrodes for the monitoring of electrical resistivity during the rainfall event are also installed close to the piezometers. Finally, salt can be injected in a trench at the top of the slope and the electrical conductivity is monitored in the piezometers and/or thanks to electrical resistivity.

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2.2.3 Data analysis and generalization

To analyse water content time series from the transects, inverse modelling based on the Richard's equation is performed in order to retrieve the soil intrinsic soil properties following a method derived from Loew and Mauser (2008) or Wollschläger et al. (2009) (see Le Bourgeois et al., 2012). The results are summarized in terms of spatial statistical distribution of soil characteristics for a given hillslope. These distributions are compared amongst hillslopes. Relationships between the statistical distributions of the hillslope properties and the general features of the landscape such as slope, geomorphology, and vegetation are studied (e.g. Ali et al., 2012a). These landscape features are used to provide a hillslope typology, based on the processing of Very High Resolution Images acquired in the small catchments: 1 m resolution DEM (lidar data) and 0.5 m resolution satellite images (Quickbird and/or Pléiades images), leading to an hillslope typology relating soil moisture dynamics, infiltration capacity, soil hydraulic properties, soil structure and vegetation to more easily measurable quantities (Morschel, 2011). The sub-surface flow field experiments, as well as the electrical resistivity surveys, are analysed to understand water pathways within the top-soil and the underlying altered bedrock in order to derive lateral flow velocity, and test the relevance of the "fill and spill" mechanism. If possible, the altered bedrock storage capacity will be assessed. All the data acquired at the hillslope scale can be used to run detailed models of hillslopes with different underlying functioning hypotheses (e.g. Troch et al., 2003; Weiler and McDonnell, 2004, 2007; Graham and McDonnell, 2010) in order to verify the consistency between the observed and simulated water pathways and fluxes.

2.3 Experimental set up at the small catchment scale

At the small catchment scale, runoff coefficients are generally shown to decrease with increasing catchment size (e.g. Braud et al., 2001; Cerdan et al., 2004). In the recent years, as for hillslope (e.g. Hopp and McDonnell, 2009), the concept of hydrologic connectivity emerges as a unifying framework for further understanding the catchment behaviour through different scales (e.g. Ambroise, 2004; Bracken and Croke, 2007; Lexartza-Artza and Wainwright, 2009). These papers distinguish the structural connectivity (which is static) from the functional connectivity which focuses on the role of various objects in the landscape (e.g. ponds, buffer, change in slopes) in producing runoff, storing water or transferring it (Sivapalan, 2003b). Recent work has shown that dense limnimeter networks combined with very high resolution lidar Digital Elevation Model (DEM) provide valuable insight into the connectivity question for headwater catchments (Maréchal, 2011; Sarrazin, 2012; Maréchal et al., 2012). Various types of reaches (artificialized such as ditches, roads; unchanneled and well-channelled reaches) can be identified with various impacts on flow continuity and velocity.

The objectives of the experimental set up in small to medium catchments (1–100 km^2) are: (1) to document, in small catchments, the transition between hillslopes and network and the role of gullies in order to understand when and where runoff is produced and becomes concentrated; (2) to assess the effect of spatial and temporal variability of rainfall on the distributed hydrological responses in small to medium catchments (1–100 km^2); (3) to compare effects of the intrinsic properties of the sub-catchments (soil properties, land use, geology...), the initial condition (soil moisture) and the spatial and temporal variability of rainfall on the rainfall–runoff relationships at different scales from the hillslope to the medium catchment; (4) to identify the hydrological dominant processes in different medium catchments representative of the landscapes of the Mediterranean region and their characteristic hydrological "signatures" (e.g. Gupta et al., 2008); (5) to provide a map of "hydrological functioning units", also called "hydro-landscapes" (Dehotin and Braud, 2008) or "morphological functioning areas" (Douvinet et al., 2013), combining field observation, high resolution GIS layers, lidar DEM and the hillslope typology mentioned earlier.

The data will be used to set up and assess distributed hydrological models, focusing mainly on lateral flow representation and network connexion (see Sect. 3.2). The

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models will be used in a hypothesis testing framework (Clark et al., 2011; Fenicia et al., 2011) in an iterative way as shown in Fig. 2, allowing a better understanding of active processes. Table 2 presents a synthesis of the experimental set up. It is further detailed below.

2.3.1 Nested discharge measurement network

In the Gard catchment, two small catchments are instrumented: the Valescure catchment, dominated by granite geology and a forest cover (3.9 km^2) with 5 gauges[2], and the Tourgueille catchment dominated with a shaley geology and a forest cover (10 km^2) with 3 gauges[3] (see details in Table 2 and Fig. 4). The Avène catchment (60 km^2), a tributary of the Gardon d'Alès has also been equipped with 3 gauges[4] (Table 2, Fig. 3). The Avène represents other lithologic and topographic conditions, combining karstic and crystalline rocks upstream (wooded areas), thick carbonated deposits, and cultivated areas downstream. The nested sub-catchments allow the separate monitoring of each typical landscape.

In the Ardèche catchment, three nested sub-catchments are gauged: the Gazel catchment (3.4 km^2), the Claduègne catchment (43 km^2) with a water level plus a flow velocity sensor[5]; and the Auzon catchment (116 km^2) with an image-based LS-PIV system (Large Scale-Particle Image Velocimetry, see the details in Sect. 2.4.2).

For all these stations, it is necessary to gauge the river to establish the stage–discharge relationship. Traditional salt dilution, current-meter methods or hydro-

[2] http://mistrals.sedoo.fr/HyMeX/Parameter-search/?editDatsId=986&datsId=986&project_name=HyMeX

[3] http://mistrals.sedoo.fr/HyMeX/Parameter-search/?editDatsId=987&datsId=987&project_name=HyMeX

[4] http://mistrals.sedoo.fr/HyMeX/Parameter-search/?editDatsId=988&datsId=988&project_name=HyMeX

[5] http://mistrals.sedoo.fr/HyMeX/Parameter-search/?editDatsId=993&datsId=993&project_name=HyMeX

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acoustic profilers are used for small streams and low discharge. When discharge is higher, hand-held surface velocity radars (SVR) are used (see Sect. 2.5.3).

2.3.2 Limnimeter networks

The objectives of the limnimeter networks are somehow different in the Valescure and Claduègne catchments. In the Valescure catchment, the limnimeters and thermo-buttons (temperature sensors) are installed in the 0.6 km^2 Cartaou sub-catchment (Fig. 4a), mainly in the intermittent drainage network, with drainage area from 0.01 to 0.3 km^2. The objective is to get a yes/no answer to the question: is there water in the river reach and how long does it last? For the thermo-buttons it is assumed that the water temperature is lower than the air temperature to detect such network activation. The automatic sensors network (time step of 2 min) is complemented by field surveys aiming at mapping the extension of the active drainage network, before, during and after a rainfall event.

In the Claduègne catchment (Fig. 5), the limnimeter network[6] has been set up at a larger scale with 11 limnimeters sampling sub-catchments from 0.17 to 2.2 km^2, with variability in geology and land use. The sensors are installed mainly in headwater sub-catchments where the landscape properties are homogeneous. The river reaches are also intermittent. When possible, controlled sections are chosen to allow the determination of stage–discharge relationships. For an easier interpretation of data, the Claduègne catchment is equipped with the HPiconet[7] dense network of rain gauges (10 gauges see Fig. 5). During autumn 2012 and 2013, the area is also covered with two research radars (Ducrocq et al., 2013, Fig. 5).

[6]http://mistrals.sedoo.fr/HyMeX/Parameter-search/?editDatsId=994&datsId=994&project_name=HyMeX

[7]http://mistrals.sedoo.fr/HyMeX/Parameter-search/?editDatsId=656&datsId=656&project_name=HyMeX

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In all these catchments, Very High Resolution (VHR) lidar DTM and satellite images were acquired to accurately determine water pathways on hillslopes and their connectivity with the drainage network (drainage density, distance from a reach), but also the connectivity between hillslopes and potential network, the drainage network morphology (width, depth, etc...) (e.g. Sarrazin, 2012). Detailed land cover maps are also being derived from Pléiades or Quickbird images.

The collected data are useful to: (1) assess the runoff contribution to the intermittent drainage network; (2) detect emergence of runoff in the head of small-basins; (3) measure the space and time connectivity to the perennial drainage network.

2.3.3 Geochemistry measurements

Many studies have shown the interest of using geochemical analysis for the determination of the origin of water and the water pathways. For instance, inter element ratios including Ba / Sr, Ca / Sr, SiO_2 concentration and $^{87}Sr/^{86}Sr$ isotopic ratios are used for studying the relative contributions of soil water and groundwater to stream water discharge during intense rainfall events (Land et al., 2000; Iwagami et al., 2010). Investigations of the spatial and temporal dynamics of Dissolved Organic Carbon (DOC) (Hope et al., 1997) are used to characterize the dominant runoff processes and origin of water fluxes: rapid runoff, soil water (sub-surface flows), and groundwater components (Casper et al., 2003). In this study, the spatial and temporal variability of the water stable isotopes ($\delta^{18}O$, δD) of the rainfall, stream, soil and ground waters at different time scales (seasonal down to intra-event) are used to: (1) identify the bedrock and soil reservoirs dynamics during base flow conditions; (2) study the evolution of the different reservoir contributions during and after flood events. Samples of soil water, groundwater and stream water are collected on alert before, during and after intense rainfall events in the Valescure catchment (see Sect. 2.5.2 and location of samplers in Fig. 4a). In addition, some gauging stations are equipped with continuous measurements of temperature and water electrical conductivity (CT-Divers, Figs. 4 and

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5), which can also provide interesting information about the partition of runoff into surface, sub-surface and groundwater flow (e.g. Birkinshaw and Webb, 2010).

2.3.4 Documentation of the surface hydraulic properties

A field campaign aiming at documenting the variability of surface hydraulic properties was conducted in May–June 2012 in 17 fields in the Claduègne catchment (Fig. 3 and details in Fig. 7). They were selected from the cross-analysis of pedology, land cover, geology maps following the method of Gonzalez-Sosa et al. (2010). The tested hypothesis is that land use has a major influence on the observed hydraulic properties rather than the soil texture. Two types of infiltration tests were performed: positive head infiltration tests in 40 cm in diameter cylinders (3 replicates) and succion (–20 mm) infiltration tests using mini-disk infiltrometers of 4.5 or 8 cm in diameter (Decagon Devices Inc., Pullman, WA) (0 to 2 replicates). The infiltration tests were complemented with particle size data analysis, including coarse fragments. The infiltration tests are analysed using the Lassabatère et al. (2006) and the Vandervaere et al. (2000) methods to get more robust results. A comparison of in situ estimates and various pedo-transfer functions is scheduled. Special attention is paid to account for coarse fragments (Fies et al., 2002) and the impact of macropores in enhancing hydraulic conductivity close to saturation (e.g. Schwartz et al., 2003; Gonzalez-Sosa et al., 2010).

2.3.5 Data analysis methods

Various approaches are considered for analyzing the spatial and temporal patterns of the hydrological response at the different scales. They have not been implemented yet as data collection is on-going, but the aim is to highlight the main factors controlling the catchment behaviour, and signatures of the rainfall–runoff relationship across scales (Beighley et al., 2005; Gupta et al., 2008; Coopersmith et al., 2012). On the small catchments, rising and falling limbs of limnimeter data, transfer times of runoff will be analysed in relation with rainfall characteristics and initial soil moisture (Sarrazin, 2012).

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Sivapalan (2003b) and McDonnell et al. (2010) point out the interest of travel time distributions that are particularly suited to the analysis of the limnimeter/lidar DTM data. They allow testing hypotheses about connected/unconnected parts of the catchment (Sarrazin, 2012).

For the rainfall/discharge data, several methods, summarizing the catchment behaviour will be implemented such as flow duration curves (Vázquez et al., 2008; Willems, 2009), and recession analysis to derive storage/discharge relationships (Kirchner, 2009). Statistical approaches (Ali et al., 2010, 2012a, b) can relate the hydrological response with explanatory variables that are representative of a scale (rainfall characteristics, lithology, land use, rainfall parameters, initial soil moisture, soil properties, slope). Bayesian networks (Maes et al., 2007) are also being tested for flash flood understanding. They provide data mining procedures that can extract previously unsuspected information or patterns, from large databases. The analysis particularly focuses on identifying whether the relationships between observed factors at one scale are identical at other scales.

The fractal approaches of morphological catchment analysis developed with 50 m DEM (Forriez et al., 2011; Nottale et al., 2012) is being adapted to the lidar DEM, in order to analyse the connectivity and the spatial structure of fractality of basins topography (Martin et al., 2013). The approach also provides invariant descriptors which can be compared between catchments (Forriez et al., 2011).

2.4 Large catchments

At this scale, the observation mainly relies on operational networks and it is complemented by research observations during the EOP (Fig. 3). The main objective at this scale is to improve the spatial and temporal resolution of rainfall fields and to quantify their uncertainty. For discharge measurements, the objective is to improve the estimation of the stage–discharge relationship, especially during high water conditions, using innovative non-intrusive methods, and to quantify the discharge uncertainty and how it propagates into hydrographs or the water balance. Given the high space and

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time variability of rainfall (e.g. Molinié et al., 2012) associated with flash floods, accurate rainfall and discharge data are crucial to improve the process understanding trough data mining, as well as to get accurate input forcing and evaluation data for regional hydrological models (Borga et al., 2008; Bouilloud et al., 2010).

2.4.1 Rainfall estimation

Since 2000, OHM-CV collects, critically analyses and performs rainfall re-analyses with the datasets coming from the operational rain gauge networks operated by Météo-France (MF), Service de Prévision des Crues Grand Delta and Electricité de France (252 hourly gauges complemented with 160 daily rain gauges) and the four MF weather radars located at Nîmes, Bollène, Sembadel and St Nizier (Fig. 3). A radar data processing system called TRADHy has been developed (Delrieu et al., 2009; Bouilloud et al., 2010) with a geostatistical framework for assessing the quality of the radar Quantitative Precipitation Estimations (QPES Kirstetter et al., 2010; Delrieu et al., 2014). Results show that radar QPE quality is good over the entire region of interest in case of deep convection but the "hydrologic visibility" (Pellarin et al., 2002) is rather poor in the mountainous part of the CV region during long-lasting shallow convective events These events are less critical in terms of flash flood generation due to their moderate intensities, but they produce large rainfall amounts (up to 100 mm in a few days, Godart et al., 2011) that increase the initial soil moisture. In order to improve rainfall estimation, enhanced rainfall observation capabilities were deployed during the HyMeX SOP1 (Ducrocq et al., 2013): 2 X-band Doppler-polarimetric radars, 2 non-coherent fast-scanning X-band radars, 23 disdrometers and a number of additional rain gauges networks, which were installed in the mountainous parts of the Ardèche and Gard watersheds (Fig. 3). Most of this additional set-up has been operated during autumn 2013 as well. This allows a unique reinforcement of the operational observation system and the possibility to investigate rainfall variability at the very short spatial and temporal scales relevant for the flash-flood generation processes.

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A rainfall reanalysis prototype was derived for year 2008 (Delrieu et al., 2013a). It relies on 5 min operational radar data and 1 h rain gauges amounts. Rainfall fields are provided at the daily time scale and 1 km^2 resolution grid using kriging interpolation for each single day of the year. For the most significant rain events, two additional products are provided: (1) radar rainfall fields with a 5 min time step at 1 km^2 resolution grid and (2) hourly rainfall amounts combining radar and rain gauges using kriging with external drift (KED) on 1 km^2 resolution grid or hydrological meshes (sub-catchments) from 5 to 300 km^2. An enhanced rainfall reanalysis will be conducted using the autumn 2012 radar data and rain gauges observations (both research and operational) with a finer grid resolution of about 100 m and a 10 min time step for selected watersheds.

For the quantification of rainfall uncertainty, two approaches are considered. The first one relies on a statistical analysis of rainfall errors (1) using raingauge data to establish reference rain amounts for the radar-alone estimates (Kirstetter et al., 2010; Delrieu et al., 2014) and; (2) through a novel approach exploiting the Kriging estimation variances for the rain gauge and radar-rain gauge merging estimates. The radar errors, analysed conditionally with respect to the rain intensity thanks to generalized additive models for location, scale and shape (GAMLSS), are shown to be radar-range and rainfall-type dependent (Delrieu et al., 2014). The KED estimates are shown to be systematically more accurate than the estimates provided by the radars and the rain gauge network considered separately. By comparing the rain gauge ordinary kriging errors and the KED ones, the added value of the radar proved also to be most important for the smallest space-time scales, those of interest for flash-flood generation study. The next step will be the implementation of a stochastic simulator to generate ensembles of plausible rainfall time series derived from the re-analyses and the associated error models, for use as inputs of distributed hydrological models.

The second approach is based on a geostatistical space-time rainfall generator (Leblois and Creutin, 2013), based on the Turning Band Method (Matheron, 1973). The rainfall fields are classified into rainfall classes based on a Kohonen classification. Each class is considered statistically homogeneous what facilitates the study of its properties along agregation (Lepioufle et al., 2012). The rainfall simulator has been adapted to be conditioned on observed rain gauges data to produce several realizations of rainfall fields, respecting the observed values at the rain gauges locations, and reflecting the rainfall uncertainty at the other points (example use in Renard et al., 2011). Typical target resolution is 1 km^2, 1 h. New on-going developments include the generation of rainfall fields in non-homogeneous zones (related to topography in the case of the Cévennes-Vivarais region), based on concomitance of local Kohonen-derived rainfall classes in various sub-regions (Ollagnier, 2013). Resulting region-wide rainfall patterns exhibit a useable concomitance with independent classes of atmospheric synoptic situations.

2.4.2 Discharge measurements

The primary source of information about discharges comes from the hydrological services of different organizations (Fig. 3). This operational network covers only watershed larger than about 50–100 km^2. A major limitation comes from the often poor documentation of the rating curves for high and extreme discharges due to the impracticability of classical gauging techniques during floods. To progress in this topic, LS-PIV stations (Le Coz et al., 2010) were developed and installed over several gauging stations (allowing for cross control of discharge estimation between methods) and at new locations[8] (Fig. 3). In the system described by Le Coz et al. (2010), images were recorded continuously even without floods and water level was recorded within the images. However it was only available during floods as the images were destroyed automatically in the absence of significant event. The system was improved to record independently and continuously the water level with a 5 min time step. Images for LS-PIV analyses are recorded once a specified water level threshold is exceeded. LS-PIV gauging stations provide discharge estimations for high flows far beyond the values

[8]http://mistrals.sedoo.fr/HyMeX/Parameter-search/?editDatsId=996&datsId=996&project_name=HyMeX

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recorded using standard gauging methods and they automatically record all floods occurring by daytime, even the fastest ones. Methods are also developed to exploit non-professional movies of flooding rivers, and a procedure is proposed to volunteers on the FloodScale project web site[9] (Le Boursicaud et al., 2013). LS-PIV and SVR are non-contact techniques providing the flow velocity at the free-surface only, which requires the additional use of an appropriate depth-average to surface velocity ratio in order to compute discharge (see Le Coz et al., 2010, for a discussion of coefficient values). Also, a bathymetry cross-section profile must be determined based on pre- and post-flood surveys and a morphodynamical expertise of the site.

The additional flood discharge gaugings obtained thanks to LS-PIV or SVR (see Sect. 2.5.3) are incorporated into a Bayesian inference framework for establishing stage–discharge relationships and for rigorously estimating the associated uncertainty. A methodology, called BaRatin (Le Coz et al., 2014) and some tools have been developed to analyse stationary rating curves, i.e., assuming that the stage–discharge relationship is stable over the period under consideration. The method can be decomposed into three main steps: (1) determination of hydraulic priors from the hydraulic analysis of the gauging site, possibly complemented by numerical modelling; (2) review and validation of existing stream gaugings. An uncertainty is associated to each of them using conventional and original methods (Le Coz et al., 2012), and is taken into account in the estimation of the rating curve; (3) Bayesian inference and simulation of a set of plausible curves. Up to now, the method has been applied to the Ardèche catchment gauging stations, including all types of existing gaugings and to the research stations operated by the involved research teams, providing the most probable stage–discharge relationship and the associated 95 % uncertainty. Ongoing work deals with the propagation of all the sources of uncertainty in hydrographs. A software implementing the method has been developed and is freely distributed[10].

[9] http://floodscale.irstea.fr/donnees-en/videos-amateurs-de-rivieres-en-crue/videos-amateurs-de-rivieres-en-crue

[10] https://forge.irstea.fr/projects/baratin

2.5 On alert observations

During HyMeX SOP1, three types of on alert observations were performed: manual soil moisture measurements to document its evolution before, during and between events in the Gazel catchments; geochemistry sampling of rainfall, river and soil waters, as well as field survey of gullies activation in the Valescure catchment; and discharge measurements of flooding rivers using SVR in the Ardèche and Gard catchments. The alert relied on the HyMeX Operation Center (see Ducrocq et al., 2013, for details) forecasts. Unfortunately, as shown by Ducrocq et al. (2013), our region of interest was one of the less affected by high rainfall events during 2012 autumn, with maximum daily rainfall of 75–100 mm, whereas values of up to 300 mm day^{-1} were recorded in other areas of the western Mediterranean. Nevertheless, these events allowed the testing of the efficiency of the on-alert protocols and to improve them for the next falls. The detail of the on alert observations performed in 2012 is given below. All the on-alert measurements will be continued in the next falls (2013–2015).

2.5.1 Soil moisture measurements during autumn 2012 SOP

On alert observations of soil moisture were performed at two scales (field and small catchment) during HyMeX SOP 1 (autumn 2012) in the Gazel small catchment (Fig. 7). In the absence of continuous measurements in that catchment (which started only in spring 2013), the objective was to document soil moisture status before, during and after the major rainfall events. Two protocols were set up. The first one relies on random soil moisture measurements (10 to 14 points per field) using a capacitive sensor (Delta *T*, SM 200). Ten sites were sampled (four pastures, four vineyards, one fallow and one bare soil field, see triangles in Fig. 7). Due to time constraints and the difficulty to anticipate well in advance rainfall events, only six dates were sampled (23, 24, 26 September; 10, 25, 26 November).

In the second protocol, six fields located along a transect (corresponding to the installation of a micro-wave link during SOP1) were selected, with increasing altitude

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from site A to F (from about 250 to 525 m) (red diamonds in Fig. 7). Within each field, a 50 m long transect was defined and soil moisture measurements were taken every 2 m using a ThetaProbe unit (Delta-T device). Between 14 September and 5 December 2012, 16 dates were sampled. Details are provided in Huza et al. (2014).

2.5.2 Event monitoring (geochemistry sampling and gullies activation survey)

During 2012 HyMeX SOP1, only three significant events were recorded in the Valescure catchment: 24 September (50 mm), 26 October (115 mm) and 9–10 November (93 mm). The last two events were sampled for geochemical analyses using automatic samplers (see location in Fig. 4a). The samplers have to be launched manually before the beginning of the event. Two automatic 24-bottles samplers sample stream water and rainfall respectively. Ten Tensiometers Tensionic and three PHTC lysimeters are also deployed for soil water sampling. Regular sampling is also performed monthly in 5 stream water points over the Valescure catchment. Measurements concern physico-chemical parameters (pH, electrical conductivity, temperature, Na, Ca, K, Mg, NH_4, F, Ci, NO_3, SO_4, alkalinity $HCO_3^- + CO_3^{2-}$), stable isotopes of the water ($^{18}O/^{16}O$, $^{2}H/^{1}H$), total and dissolved organic carbon (TOC and DOC), trace elements (Li, B, Al, Si, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Rb, Sr, Mo, Cd, Sb, Cs, Ba, La, Ce, Tl, Pb, Th, U). All analyses are performed at the HydroSciences Montpellier analytical platforms.

Field survey complementing the automatic limnimeters and thermo-buttons networks were performed for the 24 September, 26 October and 9–10 November events. A series of maps was produced, showing the active hydrographic network before, during and after each event (see examples in Sect. 4.2).

2.5.3 Stream gauging during floods

When an important event is forecast several teams of two people are sent to the field in order to gauge flooding rivers at pre-selected sections (the operational and research

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stations in Fig. 3, always from a bridge). For the largest sections, the teams are equipped with surface velocimetry radars (SVR) (Fig. 8a), which are used to measure the surface flow velocity, pointing upstream (Fig. 8b) at 13 positions across the section (see Fig. 8c). The water level must also be measured at the time of the measurement. The technique allows measuring surface flow velocities safely and rapidly. Combined with pre- and/or post-event bed geometry surveys, it yields useful streams gauging data for sections not documented otherwise or for discharge values which cannot be measured with standard intrusive methods (Dramais et al., 2013). For the smallest sections, salt dilution methods are used.

3 Modelling strategy

3.1 Introduction

The main objective of the modelling effort is to formalize at best the understanding and knowledge on the main hydrological processes at play, between and during flash floods at various spatial scales and to hierarchically organize, the dominant processes and interactions between them. The modelling strategy adopted thus belongs to a "hypothesis testing" framework, as described by Morin et al. (2006); Zehe et al. (2006) or Clark et al. (2011) (see Fig. 2), rather than to a more operational framework such as flood forecasting. Several modelling approaches are developed and compared, at the scale of small catchments of a few km^2 and at the regional scale on large catchments. The models developed in the study use different assumptions and representations of hydrological processes, following both bottom-up and top-down approaches, as defined by Sivapalan (2003a). Bottom-up approach consists of generalizing at larger scales simplifying assumptions of linearity and/or boundary value problems based on partial differential equations established at small scales. This leads to the identification and calibration of "effective parameters" which are sometimes difficult to link with measurable quantities Sivapalan (2003a), although recent methods combining the

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use of small-scale parameters variability and regionalization techniques were shown to be more efficient in preserving spatial patterns of variability (Samaniego et al., 2010; Douvinet et al., 2013). The top-down approach consists of deriving "emergent properties" (Sivapalan, 2003b) or "functional traits" (McDonnell et al., 2007), from a combination of data analysis and process conceptualization (e.g. Kirchner, 2006), across scales. Approaches based on statistical methods (Ali et al., 2010), or data interpretation by segmentation of the rainfall-discharge time series (Latron et al., 2008; Kirchner, 2009; Willems, 2009; Furusho et al., 2013) can also be used. Both the top-down and bottom-up approaches are complementary and their comparison can help understanding the main drivers of the system functioning.

In agreement with the hypothesis testing framework, most of the models used in our study are developed within modelling frameworks, such as JAMS (Kralisch et al., 2007); LIQUID (Viallet et al., 2006; Branger et al., 2010). These modelling tools allow to build "à la carte" models, and to incrementally assess the impact of changing one hypothesis, either in terms of process representation or in terms of parameter specification. Calibration is also avoided as much as possible, in order to obtain direct links between the simulated processes and the available data (Kirchner, 2006).

A key point in the model application is also the catchment discretization. The latter aims at defining the "functional units", based on the available information at the various scales. Many approaches have been proposed in the literature in terms of spatial discretization (e.g. Wood et al., 1988; Flügel, 1995; Reggiani et al., 1998; Dehotin and Braud, 2008). These "homogeneous" units should reflect the hydrological behaviour: production of infiltration excess runoff, saturation excess (Schmocker-Fackel et al., 2007), storage, transfer or accumulation zones (Lin et al., 2006a, b), surface, subsurface or groundwater flow (Latron and Gallart, 2007; Rogger et al., 2012) and their connectivity (Schmocker-Fackel et al., 2007; Lin, 2010). The approach used in this study is built on those papers and it combines image analysis and field work to derive such functional units.

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3.2 Small catchment modelling

At this scale, the objective of the modelling studies is to build models able to represent the diversity of observed catchment behaviours and to simulate the main processes as evidenced by observations. The models are used here as “hypothesis testing tools” in order to understand the impact of different modelling choices, process representation, parameter specification on the hydrological responses and to retain the hypotheses which are the most in agreement with the observed behaviour and/or synthesis of observation. This is an on-going work and only the principles are given here.

The first modelling approach is built on the CVN model (Anquetin et al., 2010; Braud et al., 2010), developed within the LIQUID modelling framework. It discretizes the landscape into irregular hydro-landscapes (Dehotin and Braud, 2008). Infiltration and water redistribution are modelled using an efficient solution of the Richards equation (Ross, 2003; Varado et al., 2006b) with hydraulic properties described using standard pedo-transfer functions (Rawls and Brakensiek, 1985). The model takes into account the vertical heterogeneity of soil hydraulic properties as described in the available soil data bases. Excess runoff is instantaneously directed towards the closest river reach where water flow is modelled using the kinematic wave equation. Evapotranspiration components have also been added in order to provide continuous simulations (Vannier, 2013). The model will be enriched step by step (e.g. Fenicia et al., 2008) to test the following hypotheses: (1) does the improved description of soil hydraulic properties, as derived from in situ observations improve the realism of model simulations?; (2) does the inclusion of sub-surface flow (Jankowfsky et al., 2013) improve the simulation of inter-event processes and initial conditions before events?; (3) what is the impact of the choice of different spatial discretization/functional units definition on the model results?

A second approach uses the RUICELL model (Douvinet et al., 2013). This cellular automaton assesses, in a bottom-up and step by step approach, the sensitivity of the surface flow dynamics to rainfall intensity, infiltration excess, land use or topography.

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As this model only simulates surface runoff, possible mismatch with observations can be a diagnostic of the importance of sub-surface flow. For the small catchments, the model implements lidar DEM. The model thus allows the mapping of surface flow concentration, taking into account possible soil erosion, threshold effect and provides estimation of peak flow discharges and cumulative runoff amounts, according to the catchment morphology. It can also help in quantifying surface transfer time and possible reinfiltration before reaching a network, in order to determine if this process should be included in the CVN model. Running the model on several catchments with similar input data allows the definition of indices and measures that can be used to compare catchments (Douvinet et al., 2013).

3.3 Regional scale modelling

The specific objective of regional modelling is to represent the main hydrological processes on large territories (several thousands of km^2), and to be able to simulate not only discharge at large catchment outlets, but also the hydrological variables at intermediate scales consistent with flash flood dynamics (mostly a few km^2). This imposes to build distributed hydrological models with simplified process representations as compared to the approach described before (Sect. 3.2), but with a good process representation on sub-catchments of a few km^2. Another difficulty of this modelling task is that we can no longer rely only on experimental catchment data, but have to work with data from the operational observation networks. These operational networks have their own objectives which may differ from our research concerns. For example, the operational discharge stations on our catchments are designed for flood forecasting and thus do not take much care of the accuracy of measurements during inter-event periods. Consequently, analyses of the available rainfall/discharge time series are performed to check the consistency of the rainfall and runoff volumes (behaviour across nested catchments, evolution during the rainy season...) and take into account their uncertainty. In addition, various metrics are computed with the aim of characterizing the spatial and temporal variability of rainfall

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within the catchments (e.g. Zanon et al., 2010). Analytical models (e.g. Viglione et al., 2010a) and/or simple hydrological models may also be considered to better characterize the spatially-variable hydrological response as a function of the spatial rainfall and the measured discharge.

The first implemented approach is a bottom-up approach (Sivapalan, 2003a, 2009; Blöschl, 2006) where hydrological processes are modelled at the scale of small hydrological response units, based on the CVN model presented in the previous section and the iterative approach illustrated in Fig. 2 (Vannier, 2013). The second approach consists of distributing on sub-catchments of a few km^2 the top-down approach presented by Kirchner (2009), where each catchment is considered as a single dynamical system. The model formulation is directly derived from the data analysis, retaining the main features of the sub-grid variability and the dominant processes (Zehe et al., 2006). This model is enriched with an explicit representation of routing in the hydrographic network and is currently being implemented within the JAMS framework. As a third complementary approach, the J2000 model (Krause et al., 2006), implemented in the JAMS platform, is also run in parallel in order to provide insight into the meaning of the parameters identified using the bottom-up approach.

In addition, following the example of Bonnifait et al. (2009), who used the CARIMA hydraulic model with the discharge simulated by n-Topmodel (Saulnier and Le Lay, 2009) and showed that the Gorge of the Gardons and its floodplain were very influential on the hydrograph dynamics downstream, the use of a 1-D hydrodynamic model to represent flow routing in the channel network will also be implemented and coupled to the hydrological models. As the influence of river bed topography and river engineering facilities on flow routing within the river network becomes dominant on the hydrograph dynamics when the catchment reaches a certain size (Brath and Montanari, 2000), we expect an improved simulation of hydrograph dynamics and water heights.

A comparative analysis of the spatial and temporal scales at which the different approaches provide consistent and/or relevant information will be conducted. The objective is to assess which information/results are usable for each approach at

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the various scales. This requires working on the adequate metrics necessary to assess the similarity between model simulations and observations, especially for flash floods where the Nash-Efficiency coefficient, traditionally used, may not be appropriate (Jachner et al., 2007; Gupta et al., 2008; Moussa, 2010). As much as possible, hydrological signatures (Gupta et al., 2008; Willems, 2009; Clark et al., 2011), as derived from the data analysis will be used. A multi-sites and multi-variables evaluation (Varado et al., 2006a; Moussa et al., 2007) will be performed. In addition, the use of uncertain observed data to evaluate and compare several modelling scenario raises significant methodological challenges because model evaluation entails comparing two time series of distributions, as opposed to two times series of values. Innovative comparison schemes will be developed for this purpose, following approaches proposed by the probabilistic forecasting community (e.g. Laio and Tamea, 2007).

4 Results

In this section, we illustrate how the currently available observations and models provide interesting insight into the following questions:

1. What is the temporal variability of soil moisture during autumn 2012 SOP and is the variability consistent across scales?

2. What are the active hydrological processes at different spatial and temporal scales during the 9–11 November 2012 event?

3. How can we decrease rainfall and discharge estimation uncertainty?

4. Which information about dominant processes at the regional scale can be derived from the combination of data analysis and modelling?

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4.1 What is the temporal variability of soil moisture during autumn 2012 SOP in relation to the hydrological response and is this variability consistent across scales?

Figure 9a shows the time evolution of local soil moisture (one point in transect T2 – see location in Fig. 4a) at depths 20 and 40 cm between 1 September and 5 December 2012. The figure also provides the daily rainfall in the middle of the Valescure catchment, as well as the instantaneous discharge at the catchment outlet. Before mid-October, soil moisture increases rapidly in response to rainfall, but returns to low values (between 10 and 15 %) within 15 days (note that a significant event occurred on 28–30 August (81 mm) which explains the high values at the beginning of the period. After the 26 October event (115 mm), the soil moisture still decreases after the rainfall event but remains higher than about 25 %. The cumulative rainfall since the beginning of the SOP (including the 28–30 August and 26 October events) reaches about 400 mm. The discharge time series follows the same temporal pattern as soil moisture, with much significant response once the soil remains wet, accompanied with a larger base flow (about 50–100 $\mathrm{L\,s^{-1}}$). However, the maximum peak discharge registered during SOP1 is moderate (2.35 $\mathrm{m^3\,s^{-1}}$) as compared to the maximum value since the beginning of the measurements in 2003 of 12.5 $\mathrm{m^3\,s^{-1}}$, registered on October 2006.

Figure 9b shows the same figure but with soil moisture measured manually at the small catchment scale (Gazel, 3 $\mathrm{km^2}$). At each date, the soil moisture data is the average of the 6 transects × 25 measurements/transect (red squares) or the average of all the random manual measurements performed within the 10 fields (see locations in Fig. 7). Soil moisture is low at the start of SOP1 (about 12 %), increased rapidly after the first rainfall events to reach values around 25–30 %. There is no measurement available to see to which value it dries down. At the end of the period, values larger than 30 % are reached. In terms of discharge, the Gazel river is almost dry until the end of October (less than 1 $\mathrm{L\,s^{-1}}$). The 26 October event only moderately affects this

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catchment, but the discharge increases to about $10\,\mathrm{L\,s^{-1}}$. It is necessary to wait until the 9–10 November event (65 mm at Le Pradel) to measure a significant response in the river, with discharge reaching $1\,\mathrm{m^3\,s^{-1}}$. After this event, a base flow of about $10\,\mathrm{L\,s^{-1}}$ remains into the river. The next event (26–27 November) only brings 43 mm of rainfall in the Gazel catchment. But this is sufficient to trigger a response similar to that of the previous event with less rainfall. Huza et al. (2013) show that, after the catchment soil moisture reaches a threshold of about 22 %, a significant response, with larger runoff coefficient, is obtained. This threshold is very close to the 25 % observed locally in the Valescure catchment.

Figure 10 shows maps of the Soil Wetness Index (SWI) over the South-East France domain from September to November 2012, as calculated operationally by Météo-France from outputs of the SAFRAN-ISBA-MODCOU hydro-meteorological chain (Habets et al., 2008). A SWI of zero means dry soils, whereas a SWI equal to one means saturated soils. Figure 9c shows the discharge at the main outlets of the Gard and Ardèche catchments for the same period. Figure 10a to c shows that, in the Gard and Ardèche catchments, the soils are very dry during September, and remain dry on 25 October, without significant discharge at their outlets (Fig. 9c). The 26 October event significantly wets the soils in the upper part of the catchments (Fig. 10d), but the downstream part remains unsaturated, with lower values of the SWI in the Gard. A quick discharge increase is observed at both outlets after this event (Fig. 9c). The response is larger for the Ardèche catchment than for the Gard, associated with a higher SWI. The subsequent events, and especially the 9–10 November event (Fig. 10e), lead to full saturation of the two catchments. The soils remain saturated during the whole November month (Fig. 10f). The catchment response to the last two events is very quick. As for the Valescure and Gazel catchments, the response to the 9–10 November event is larger, although the rainfall amount is lower or similar: 68.5 (resp. 63.1) mm for the 25–26 October event and 67.5 (resp. 50.7) mm for the 9–10 November events in the Ardèche (resp. the Gard) catchments. Nevertheless, low maximum peak discharges are recorded, as compared to historical values in both

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catchments (maximum peak discharge at the Ardèche at Sauze St-Martin recorded at about 4500 $m^3 s^{-1}$, and maximum daily discharge of 2510 $m^3 s^{-1}$).

Figures 9 and 10 show that, at the three scales (local, small catchment, regional scale), similar behaviours are observed with a progressive wetting of the catchments during the SOP, until saturated conditions are reached after 27 October in the Valescure catchment, and 9–10 November in the Gazel and at the regional scale. Once saturated conditions are reached, the response in terms of discharge is quicker and larger, even if the rainfall amounts are not so important. There is therefore a high consistency of the relationship between soil moisture variations and catchment response at the three scales. Our study catchments were not affected by very high rainfall events in 2012, so the observations conducted in the next falls will provide more data to confirm if the results obtained in 2012 can be generalized.

4.2 What are the active hydrological processes at different spatial and temporal scales during the 9–11 November 2012 event?

In this section, we illustrate how the data collected at the various spatial scales can be used to derive information about active processes during the rainfall event which occurred on 9–11 November 2012. The rainfall amount was 93 mm in the Valescure catchment, 100 mm in the Tourgueille catchment and the rainfall recorded in the Claduègne catchment varies betweem 63 mm (Le Pradel) and 82 mm (Berzème) (see also Fig. 9). For this event, we examine the results provided by the geochemistry sampling in the Valescure catchment, the limnimeters networks (Valescure and Claduègne catchments), as well as the discharge response at all scales.

Figure 11 shows the simultaneous behaviour of the electrical conductivity (EC), isotopic composition δ^{18}O, Ca, Al and TOC concentration of the streamwater in the Valescure catchment (3.9 km^2) during the 9–10 November 2012 flood event. The runoff decomposition between "old" water (i.e. pre-existing water) and "new" water (i.e. rainfall water) is based on the assumption that the streamwater is a mixing between: (1) rainwater and, (2) the isotopically and chemically constant base flow constituted by deep water (groundwater and/or weathered area water) characterized at the onset of the event. By using EC and Ca, new water (EC = 28 $\mu S\,cm^{-1}$, Ca = 0.8 $mg\,L^{-1}$) is found to be between 36 and 56 % of the runoff at the peak. For another event (26–27 October 2012), $\delta^{18}O$ led to a 35 % contribution of new water at the peak flow. Terrigenous elements such as Al and TOC could also help assessing the contribution of the different layers of the soil to the flood. This first result must be refined by (1) accounting for the soil water isotopic or chemical composition, which is now monitored before the beginning of each event; (2) applying a 3-component mixing, including rainfall water, the soil water and the deep water; (3) considering a larger range of events, to relate the contribution with the magnitude of the floods; (4) relating both the old and new water proportions to the understanding of the real processes of both surface and sub-surface flow. This will be achieved by combining geochemical data with physically-based hydro-dynamical models.

For the same event, Fig. 12 shows the river network extension four days before, during, and nine days after the event, as obtained from the limnimeters network and field survey in the Cartaou catchment (Valescure sub-catchment). The maximum extent of the active hydrographic network observed on 10 November 2012 is quite comparable to those of the first two episodes of the autumn (24 September and 26 October, not shown). We however note a significant extension of the active network before and especially after the event. This observation is consistent with the soil moisture level in the catchment reaching around 30 % after the 26 October event and remaining high since then (see Fig. 9a).

Figure 13 shows the limnimeter response to the same event for the Claduègne catchment. The rainfall presents a slight altitudinal gradient with larger rainfall at higher altitude, but a good synchronization in the intensities. The catchment was probably not fully saturated at the beginning of the event, as shown by the absence of reactions to the first rainfall peak at points *sg1*, *mi4* and *sj3*, which only respond to the second peak (Fig. 13c–e). Some points react very quickly to rainfall such as *sj2* which corresponds to badlands and is prone to Horton runoff (Fig. 13e), and to a lesser extent *bz1* on basaltic scoria (Fig. 13c). Some limnimeters do not react at all (e.g. *sg2*, Fig. 13e). The response appears quite differentiated according to the lithology and possibly land use. In terms of scale, the response is quite similar and synchronous for the three largest catchments (Fig. 13b), explained by high velocity in the river network (2 to 2.5 $m s^{-1}$ measured at the Claduègne outlet around the peak), but with longer recessions for the largest catchments. The analysis of more events will be necessary to confirm the role of lithology and/or land use on the sub-catchments characteristics.

Figure 14a provides the cumulative rainfall for the event duration (9–10 November) using an ordinary kriging of the rainfall gauges. Although smoothed as compared to radar data, it illustrates the large spatial variability of the cumulative rainfall amount. The response in terms of specific discharges is quite different across scales in the Ardèche (Fig. 14b) and Gard (Fig. 14c) catchments. In the Gard, the maximum peak discharge decreases with increasing catchment size, which also reflects the lower cumulative rainfall amount, when moving downstream. In the Ardèche catchment, the maximum specific peak discharge is of the same order of magnitude for a large range of catchments sizes (from 3.4 to about 600 km^2 with the exception of #3 catchment). There is a link between maximum specific peak discharge and the cumulative rainfall (e.g. in the smallest catchments #1, #2, #11) but also #4 which has been affected by a large cell with cumulative rainfall larger than 90–105 mm. The picture is certainly more complex, requiring further analysis, in particular by considering the impact of rainfall intensity, which will be possible when accurate radar rainfall estimates are available.

The first results presented in this section show that, for the selected event, subsurface flow processes, initial soil moisture as well as lithology are important factors explaining the hydrological response at small scales. Rainfall variability becomes an important factor when moving to larger scales. The analysis of other events and of the continuous time series will help gaining more insight into the interplay of the various factors on the hydrological response.

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4.3 How efficient are the methods proposed in the study in quantifying/reducing rainfall and discharge uncertainty?

Figure 15 gives an example of hourly estimates together with their uncertainty obtained with the reanalysis methodology exposed in Delrieu et al. (2013b). In this example, the estimation is performed for hydrological meshes of 10 km^2 over the four main Cévennes watersheds (Ardèche, Cèze, Gardons, Vidourle). The top graphs display the estimates obtained with the rain gauge network alone through ordinary kriging (left) and with the radar-rain gauge merging through kriging with external drift (right). In the bottom graphs, the corresponding maps of standard deviations of the estimation error are displayed with much smaller values for the KED estimates, indicative of the added-value of the radar data for the considered space-time scales. These results are very promising and will be used to improve the rainfall field estimates, especially during HyMeX 2012 and 2013 SOPs where additional research radars are available.

Figure 16 illustrates how the additional stream gauging from the on-alert campaign or provided by the continuous LS-PIV system can improve the stage–discharge relationship accuracy for the Volane river, a tributary of the upper Ardèche river (#4 in Fig. 14a). The stage–discharge relationship itself is not very sensitive to the additional gaugings (all the four curves are confounded in Fig. 16), because the station section is very stable and well controlled. The impact of new gaugings is much visible on the corresponding uncertainty. For instance, at 1.5 m the uncertainty is 49 % when only standard gaugings (black points) are considered (grey shading). Although the LS-PIV gaugings (red points) from year 2012 only sampled moderate discharges, their addition in the analysis reduces the uncertainty to 35 % at 1.5 m (pink shading). In October 2013, one very intense event hit this catchment, with a maximum water height of 2.6 m, far beyond the maximum ever gauged. Three SVR on-alert measurements (blue points) were performed around 1.5 m. When these gauging are combined with the standard gaugings, the uncertainty at 1.5 m (blue shading) is 45 %. So although they have a larger error than the SVR gaugings, the numerous LS-PIV gaugings at moderate

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discharge decrease the uncertainty more than the 3 SVR gaugings at high discharge. When all the gaugings are used in the analysis (green shading), the uncertainty at 1.5 m is reduced to 29 %, showing the added value of the two types of non-contact gaugings. This kind of analysis will be performed for the other gauging stations and used to quantify the uncertainty on the discharge time series and hydrological water balance which can be used in the evaluation of the hydrological models.

The results presented in this section illustrate the value of the proposed methods in quantifying and reducing the uncertainty on both rainfall fields and discharge time series for flash floods studies.

4.4 What information about dominant processes at the regional scale can be derived from the combination of data analysis and modelling?

This section illustrates how the iterative approach of Fig. 2, combining observation and modelling, and the bottom-up and top-down approaches are used to enhance the knowledge of dominant active hydrological processes in the study area. In both cases, we use discharge recession analysis from the historical records, which can provide useful information about catchment characteristics or functioning (see the recent review of Troch et al., 2013).

The iterative approach is illustrated using the CVN non-calibrated model, described in Sect. 3. First simulations, based on soil storage capacity derived from available soil data-bases, which only describe the top-soil relevant for agronomic purposes, lead to poor simulation results, as illustrated in Fig. 17 for the Ardèche at Meyras catchment (#3 in Fig. 14a). The model simulation is too much responsive with overestimation of peak discharges and too quick recessions. The specification of the soil water storage capacity of the soil is therefore re-examined, using new data analysis (recession analysis) of available long term discharge series. The objective is to estimate catchment storage capacity and saturated hydraulic conductivity in the weathered bedrock, which are not documented into the existing soil data bases and is a significant source of water storage within the studied catchments (Vannier et al., 2013). Geology is identified as the main driver governing the range of these characteristics (Vannier et al., 2013). Figure 17 shows that the use of this information into the CVN model improves both the long-term and event discharge simulation, even if the peaks are still overestimated and the recession are still too quick. The improvement is very significant when the underlying geology is granite (Vannier, 2013). The simulation results are still improved when the weathered layer is included for shaley geology, but the recessions remain too quick (not shown, see Vannier, 2013).

The CVN model is based on the bottom-up modelling approach. The data-driven method (or top-down approach) is also used to see how they can be complementary. The Kirchner (2009) method is applied to the recession analysis of natural discharge time series of the Ardèche catchment (Adamovic et al., 2014), leading to a simple model of catchment functioning where the discharge at the outlet is assumed to depend only on the catchment storage, and where the parameters of the model are estimated from the data. The method performs much better for catchments with granite geology (Adamovic et al., 2014). The results also show that, in winter, such catchments can be considered as simple dynamical systems and that discharge fluctuations can be assumed to be mainly governed by change in catchment water storage. On the other hand, the results are much poorer during the summer periods where evapotranspiration influence adds complexity to the catchment response (Fig. 17). Figure 17 also shows that both modelling approaches provide quite good results during wet periods. Recessions are somehow better simulated with the Kirchner method, but the peak of the Nov. 2008 event has a delay as compared to observation. On the other hand, the timing of the CVN model is more in agreement with the data.

These results illustrate how the iterative approach of Fig. 2 helps enhancing the knowledge of the catchments functioning at the regional scale and in ungauged catchments in an incremental manner. The combined use of top-down and bottom-up approach is also promising and the next step will be the generalization of comparisons such as the one of Fig. 17. The new data collected thanks to the experimental set up presented in Sect. 2, will provide new times series at different scales, which will be analysed following the same approaches, in order to confirm/infirm and generalize the conclusions drawn from the analysis of historical discharge time series, for instance the importance of geology on the differentiation of the hydrological response in the study area.

5 Conclusions and perspectives

To conclude we hope that the first results presented above demonstrate that the proposed multi-scale approach, combining observation and modelling will allow significant progresses in flash flood understanding and therefore predictability due to the following characteristics:

1. the duration of the observations (four years) which allows the characterization of the standard catchments behaviour and therefore the characterization of exceptional processes which have not yet been observed and are specific to flash floods,

2. the regional spatial coverage of the experimental set up (two large catchments of more than 2000 km^2) and the variability of geology, land uses, soil types which are sampled at small scale that allows an adequate sampling of the variability of responses

3. a significant effort dedicated to the documentation of the soil water storage which has been shown to be able to explain exceptional behaviours (see for instance Rogger et al., 2012),

4. the variety of scales and of instrumental techniques (continuous, on-alert, VHR imagery, etc.) deployed in two regional catchments, which allows the simultaneous documentation of various aspects of the hydrological response,

5. the high resolution of the acquired rainfall fields and the provision of the associated errors bars, as well as the use of the stochastic rainfall generator that

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will allow interesting sensitivity analyses of the hydrological response to the rainfall variability.

The data collection and analysis is still on-going. The SOP1 in autumn 2012 was not rich of exceptional events in our study area, but it allowed the test of the sensors, and of the on-alert protocols, so that we are ready for next autumns. The four-year duration of the experiment will allow the collection of a rich data set on hydrological processes during and between flash floods using both continuous and on-alert observations at various scales. As illustrated in Fig. 2, the combined analysis of observation and simulations in a "hypothesis testing framework" will allow the comparison of different functioning hypotheses in order to better understand the dominant processes during and between floods as well as the impact of differences in landscape characteristics.

As a concluding remark we would like to underline that, although focused on Mediterranean catchments, the multi-scale observation strategy of Fig. 1 and the iterative approach presented in Fig. 2 can be generalized and adapted to other hydro-climatic contexts.

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Table 1. Hillslopes experimental set up.

Instrumented slopes	Valescure (Gard)	Tourgueille (Gard)	Pradel/Gazel (Ardèche)
Slope characteristics	Steep slopes, natural vegetation, granite bedrock	Steep slopes, natural vegetation, shaley bedrock	Moderate slopes, cultivated area (vineyard, pasture), sedimentary clay limestone bedrock
Dominant processes expected	Saturation-excess runoff, sub-surface flow	Saturation-excess runoff, sub-surface flow	Surface flow on cultivated areas, unknown on pastures/forests
Surface runoff measurements	None	None	1 vineyard hillslope studied in Nicolas (2010) Several fields tested with new prototype of rainfall simulator
Soil moisture measurements	20 soil moisture sensors (10 points and 2 depths – 20, 40 cm) during 1 yr on 3 hillslope transects	Same as Valescure on 1 hillslope transect	Continuous soil moisture at 10 (2), 20–25 (2) and 30–40 (1) cm in 2 vineyards, 1 fallow land, 2 pastures, 1 forest since May 2013
Sub-surface flow measurements	2 different fields with natural and artificial events	None	None
Soil topography	1 m Lidar DEM	1 m Lidar DEM	1 m Lidar DEM
Soil hydraulic properties	Infiltrometers	Infiltrometers	Infiltrometers, Beerkan tests
Soil depth/bedrock topography	Perforation method	Perforation method	Perforation method
Geophysical survey	Electrical resistivity	If possible	Not scheduled yet
Landscape segments analysis (pedology)	In detail with field work	General field survey &GIS analysis	General field survey &GIS analysis
Vegetation analysis	In detail with field work &VHR image analysis	Only general survey &VHR image analysis	Only general survey &VHR image analysis

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Table 2. Small to medium catchments monitoring.

Catchments	Valescure	Tourgueille	Avène	Gazel/Claduègne/Auzon
Catchment characteristics	Steep slopes, natural vegetation, granite bedrock	Steep slopes, natural vegetation, shaley bedrock	Upstream wooded areas on karstic and crystalline rocks; downstream cultivated areas on thick carbonated deposits	Moderate slopes, cultivated area (vineyard, pasture), sedimentary clay limestone bedrock
Dominant processes expected	Saturation-excess runoff, sub-surface flow	Saturation-excess runoff, sub-surface flow	Unknown	Surface flow on cultivated areas, unknown on pastures/forests
Raingauges	3 gauges &1 disdrometer	2 gauges &1 disdrometer	3 gauges	HPiconet on Gazel/Claduègne
Discharge gauging stations	0.3, 0.5, 0.6, 0.9, 3.9 km^2	1, 2.5, 10 km^2	10, 21, 60 km^2	3 (Gazel), 43 (Claduègne), 116 (Auzon) km^2
Limnimeter network	5 limnimeters, 18 thermo-buttons &survey of gullies during and after events in the 0.3 km^2 sub-catchment	None	None	11 limnimeters (7 mini-Diver &4 CTDDivers) in the Claduègne catchment
Geochemistry	Sampling of rainfall, soil and groundwater during events &continuous conductivity at the outlet	Continuous temperature &conductivity at the outlet	None	Continuous temperature &conductivity (Gazel, Claduègne) + 4 limnimeters with electrical conductivity and temperature
Infiltration tests	Performed during hillslope monitoring	Collection of existing data	Collection of existing data	17 sampled fields using infiltrometers and Beerkan
DEM	1 m Lidar DEM	1 m Lidar DEM	1 m Lidar DEM	1 m Lidar DEM (Gazel, Claduègne), 25 m DEM (Auzon)
Pedology	Languedoc–Roussillon soil database & landscape segments locally	Languedoc–Roussillon soil database	Languedoc–Roussillon soil database	Ardèche soil database
Vegetation map (summer and winter)	Detailed land use map based on Pléiades images	Detailed land use map based on Pléiades images	Detailed land use map based on Pléiades images	Detailed land use map based on Quickbird images (Gazel, Claduègne); Landsat images (Auzon)

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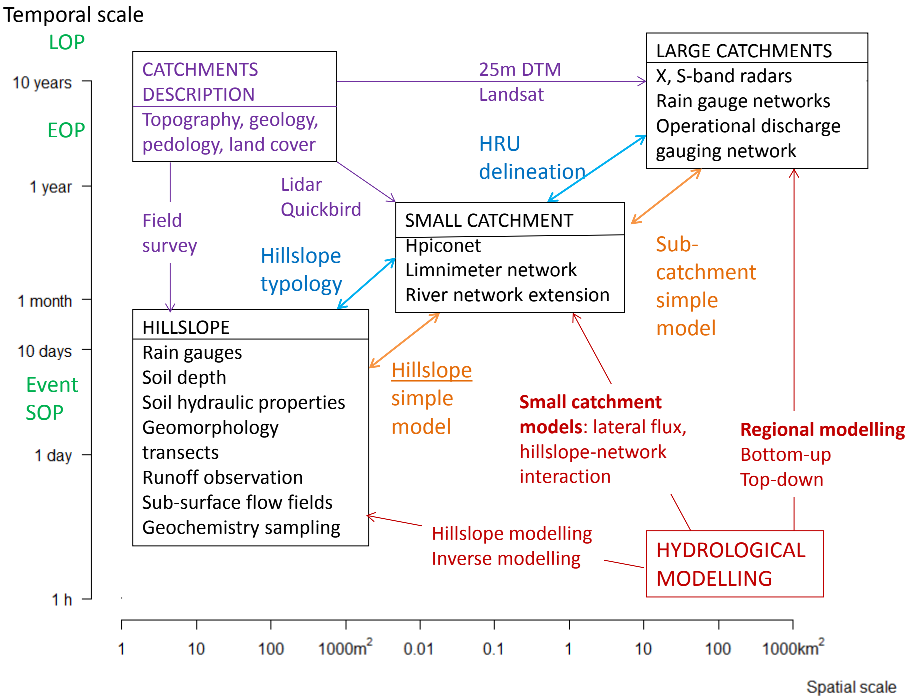

Fig. 1. Diagram showing the characteristic spatial scales of the processes considered in the study (black, diagonal) and the associated typical observation time scales; the required data characterizing the catchments physical properties at each scale (purple, top left); the modelling approaches (red, bottom right). Interactions between scales and how the change of scale problem is addressed are shown with the blue arrows for the model meshing and orange arrows for the processes representation. HRU means Hydrological Response Unit.

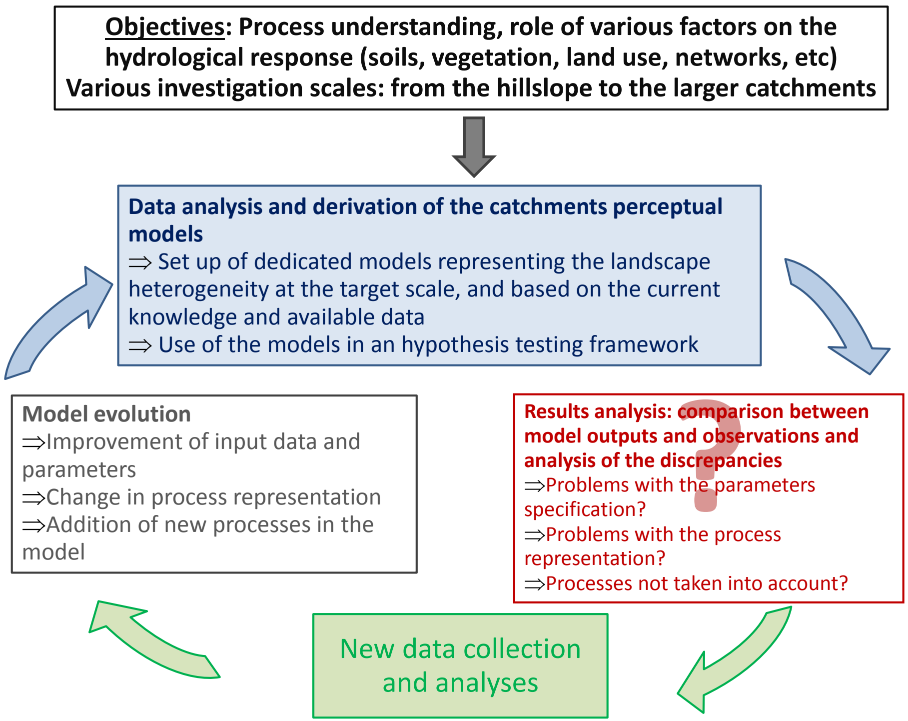

Fig. 2. Proposed iterative approach between observation and modelling to progress in process understanding and their modelling capability.

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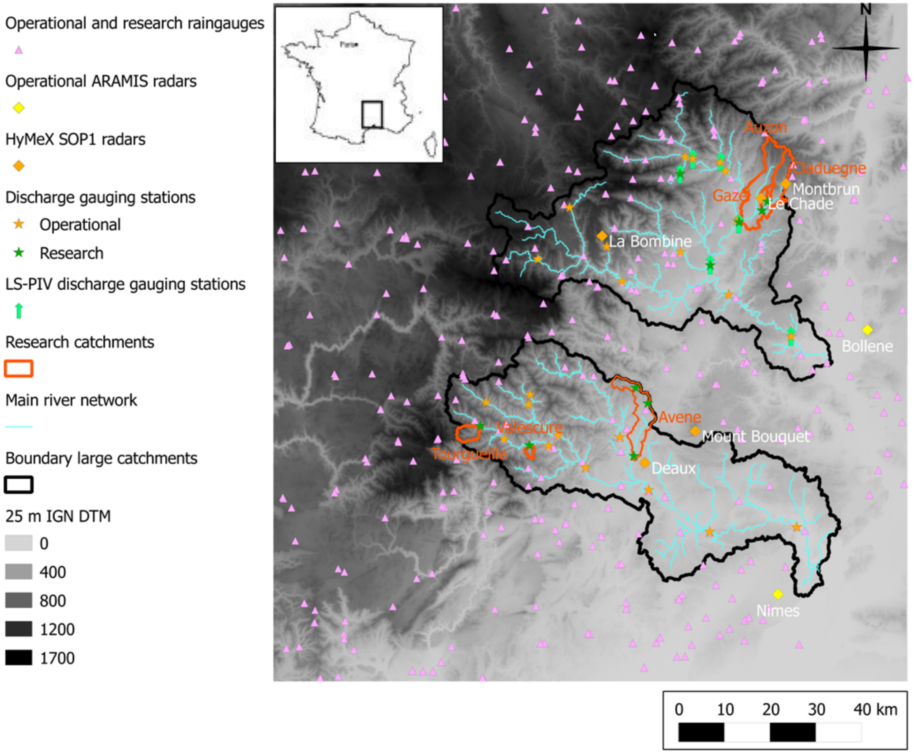

Fig. 3. Location and elevation map of the study area. The two main studied catchments: Gard (2062 km^2) and Ardèche (2388 km^2) appear in bold black. The small research catchments are shown with orange boundaries. The figure also shows the operational rain gauge network, the operational and research meteorological radar network, as well as the operational and research (standard and LS-PIV) discharge gauging stations.

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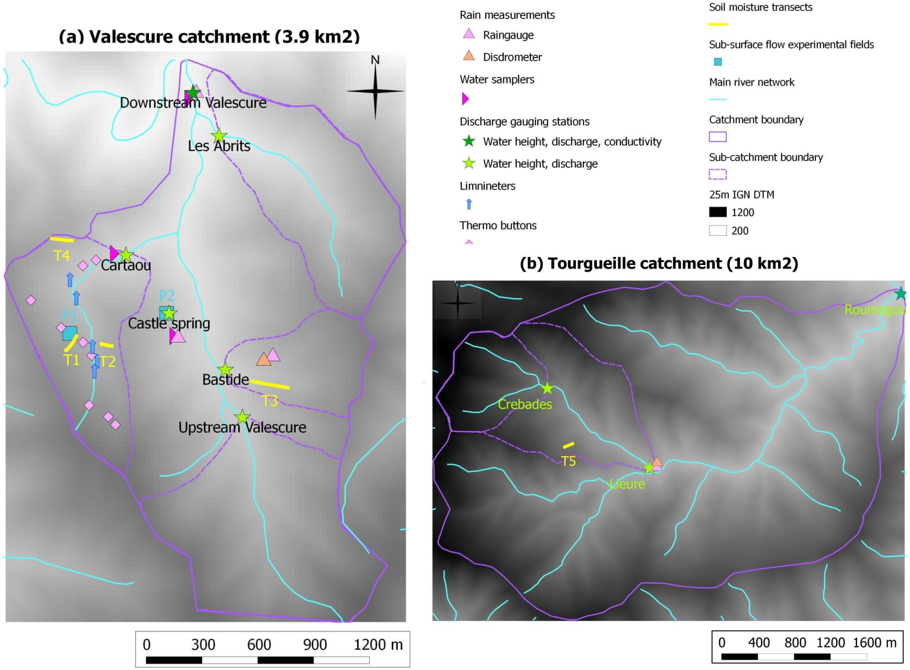

Fig. 4. Elevation map and instrumentation of **(a)** the Valescure catchment (3.9 km^2); **(b)** the Tourgueille catchment (10 km^2) in the Gard catchment.

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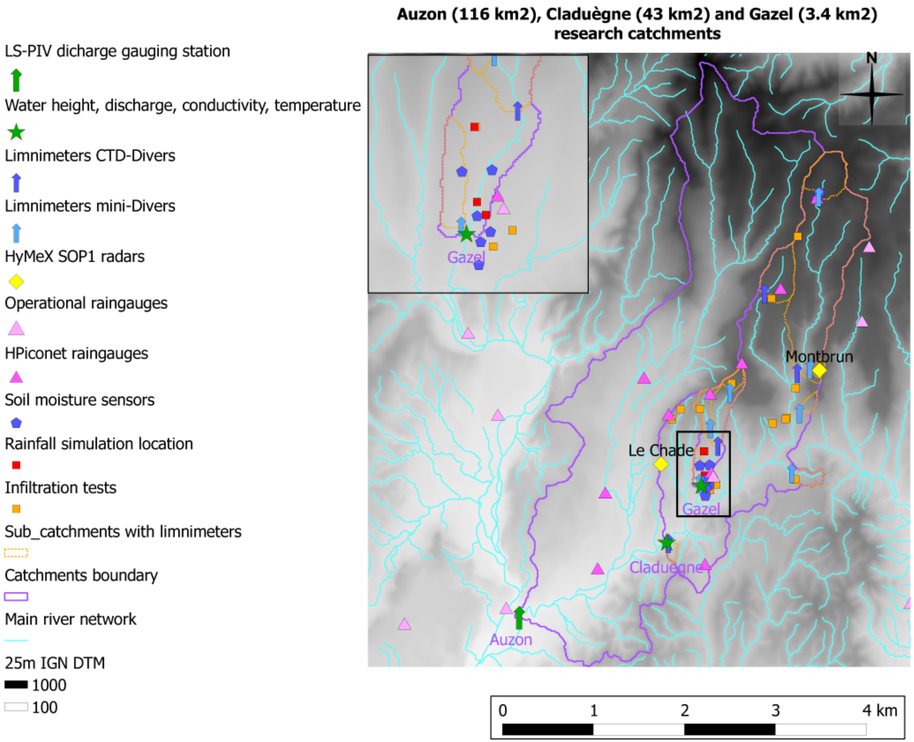

Fig. 5. Elevation map and instrumentation of the Gazel (3 km^2), Claduègne (43 km^2), Auzon (116 km^2) catchments in the Ardèche catchment. The black rectangle shows the position of the zoom provided at the top left of the figure.

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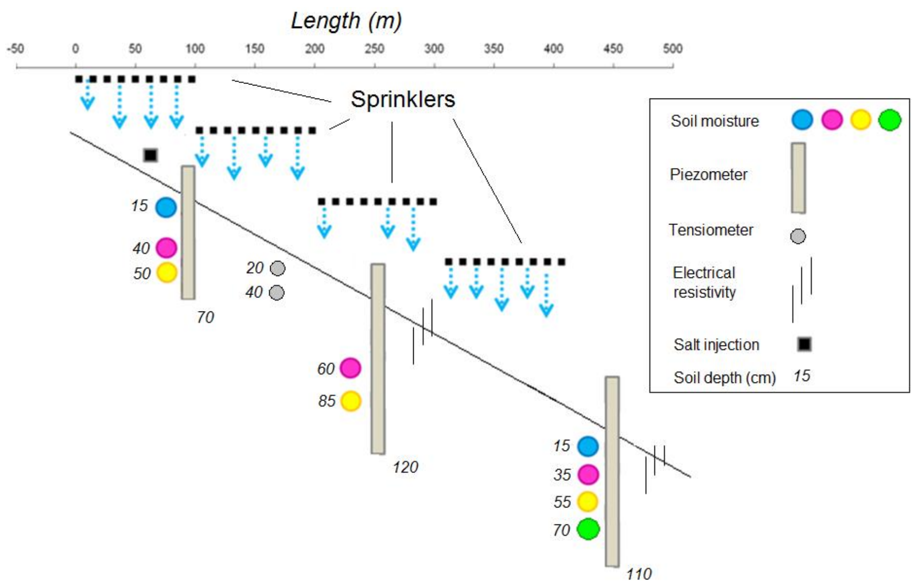

Fig. 6. Scheme of the experimental set up in the 10 m^2 plot for sub-surface flow and bedrock permeability study based on artificial and natural rainfall events. The device combines soil moisture probes, piezometers, tensiometers, electrodes for electrical resistivity, salt injection in order to characterize both vertical and lateral flows in the soil.

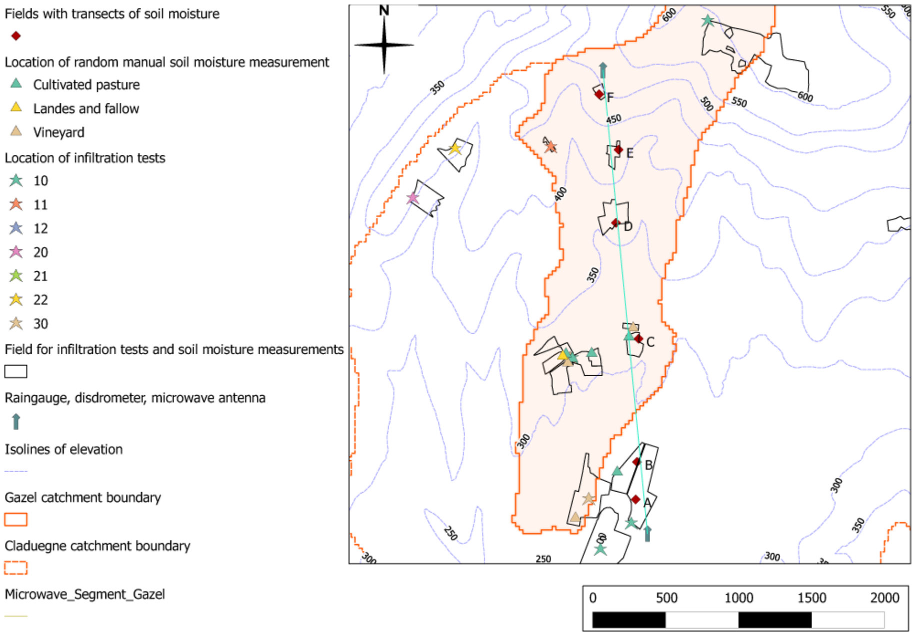

Fig. 7. Location of soil moisture measurements during SOP1 in the Gazel catchment. Detail of the location and land use of the infiltration tests is also visible.

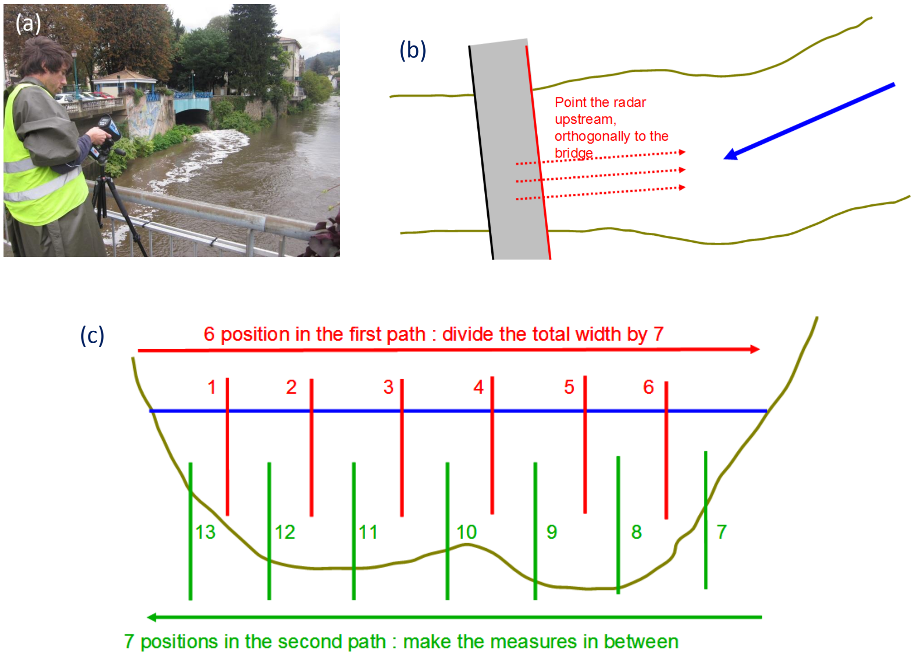

Fig. 8. (a) Photo of a measurement performed with a surface velocimetry radar (SVR); **(b)** position of the measurement transect relative to the bridge; **(c)** location of the positions within the section where measurements are carried out.

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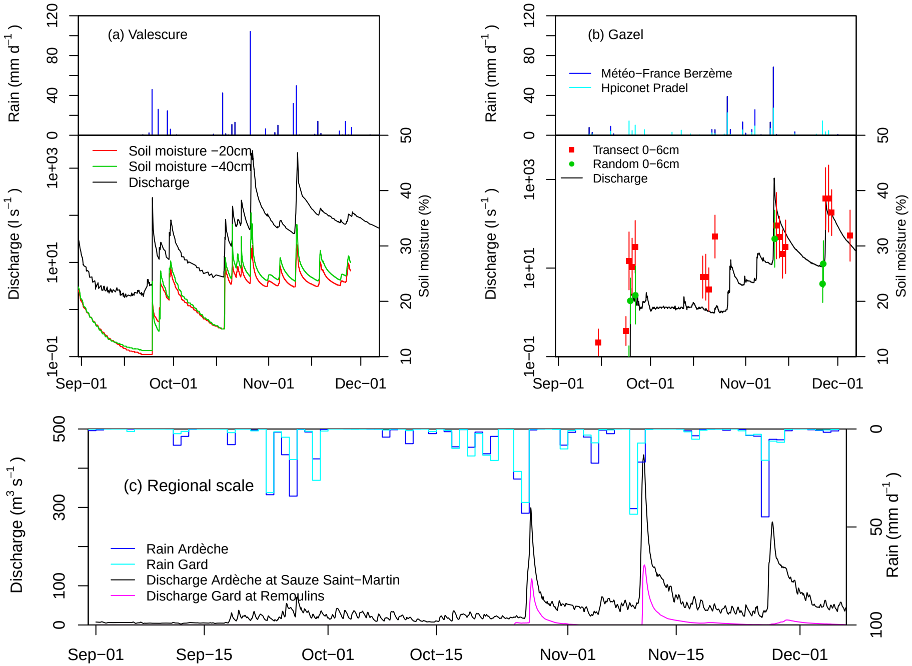

Fig. 9. (a) Daily rainfall at the Castle spring rain gauge (top panel), variable time step discharge (black) and local soil water content at 20 (red) and 40 (green) cm depths in one site of Transect T2 in the Valescure catchment during autumn 2012. **(b)** Daily rainfall at two stations Berzème and Le Pradel (top panel), hourly discharge (black) and manual soil moisture performed along six transects (red) or randomly (green) in the Gazel catchment. **(c)** Average daily catchment rainfall from the SAFRAN reanalysis for the Ardèche and Gard catchments (top) and corresponding hourly discharge at the catchments outlets.

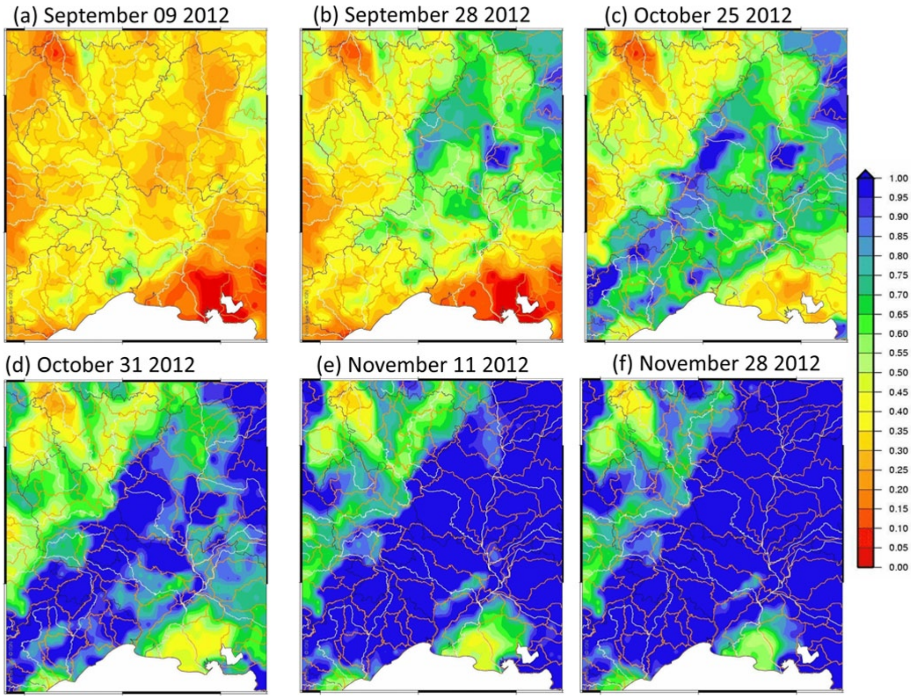

Fig. 10. Maps of the Soil Wetness Index (SWI) derived from the SAFRAN-ISBA-MODCOU chain for 6 dates during autumn 2012. A SWI of zero means dry soils and a SWI of one saturated soils. Catchments boundaries appear in brown and main rivers in white.

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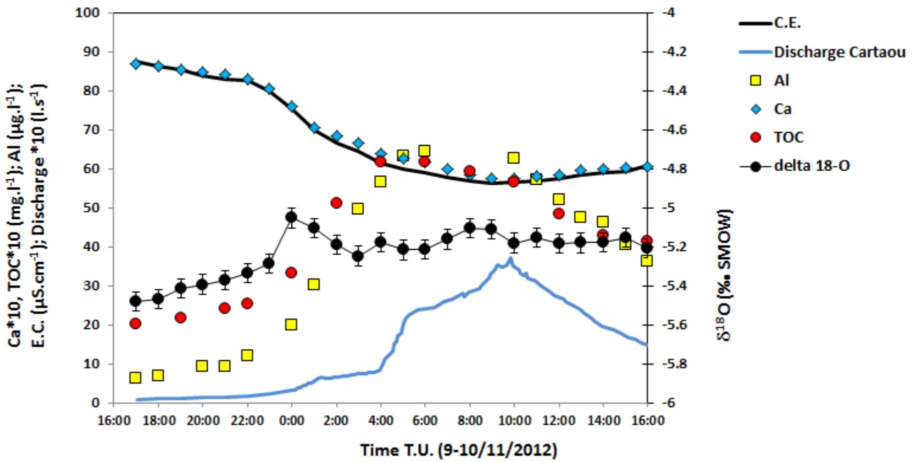

Fig. 11. (Left) Time evolution of the Valescure streamwater electrical conductivity (E.C.), Calcium (Ca), Aluminum (Al), Total Organic Carbon (TOC) and Cartaou subsystem discharge during the 9–10 November 2012 flood. (Right) Valescure streamwater isotopic composition (δ^{18}O)).

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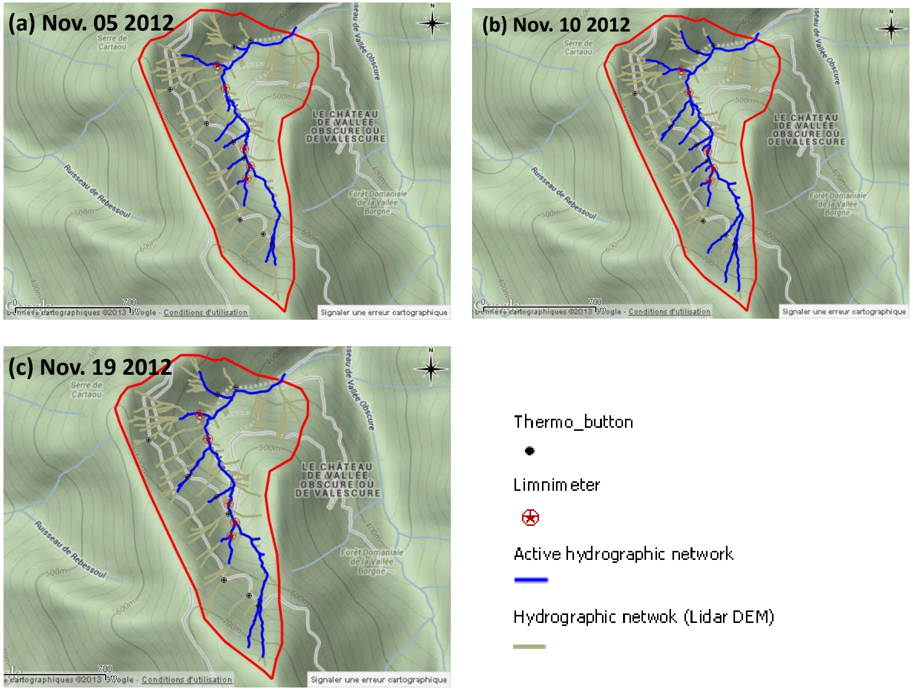

Fig. 12. Mapping of the active hydrographic network within the Cartaou sub-catchment four days before **(a)**, during **(b)**, and nine days **(c)** after the 9–10 November 2012 event. Stars show the location of the limnimeters and the black points that of the thermo-buttons. The blue lines show the active hydrographic network at the various dates and the brown lines the "potential" river network as derived from a Lidar DEM analysis.

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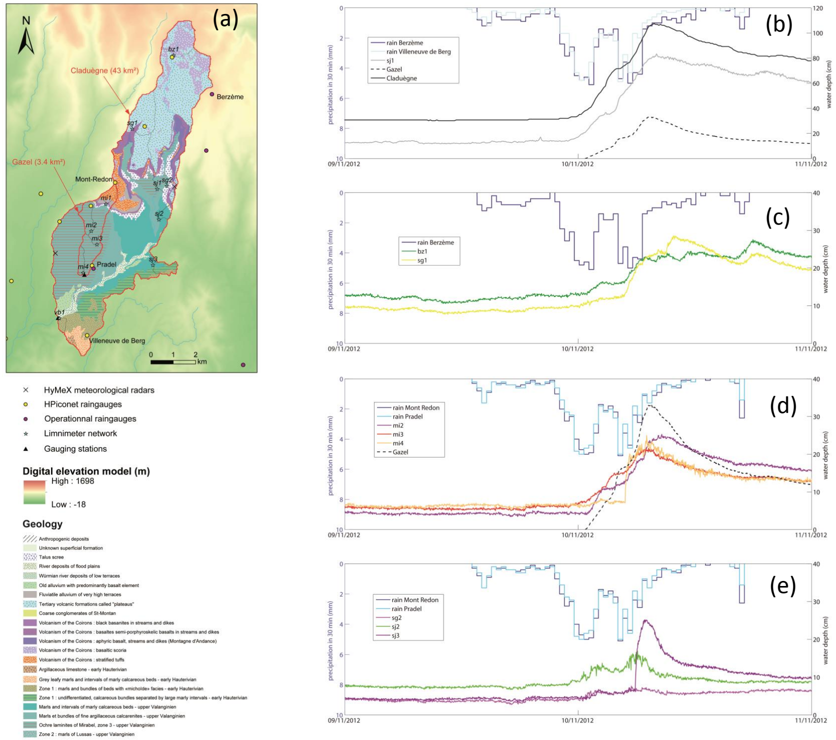

Fig. 13. Water level from the limnimeters network of the Claduègne catchment for the 9–11 November 2012 event. The location of the various limnimeters is shown in **(a)** which also provides the geology map from BRGM. On the right, the various panels present several groups of limnimeters and the associated representative rain gauges: **(a)** the three largest sub-catchments: Gazel, *sj1*, Claduègne (3.4, 12.3, 43 km^2); **(b)** two headwater sub-catchments *bz1* and *sg1* on basalt geology; **(c)** four sub-catchments in the Gazel: *mi2* and *mi4* on marl-calcareous geology, *mi3* and Gazel with a mix of marl-calcareous and basalt geology; **(d)** three sub-catchments with different geologies: *sj2* with regosoils, *sj3* with marls and *sg2* with basalt and forest.

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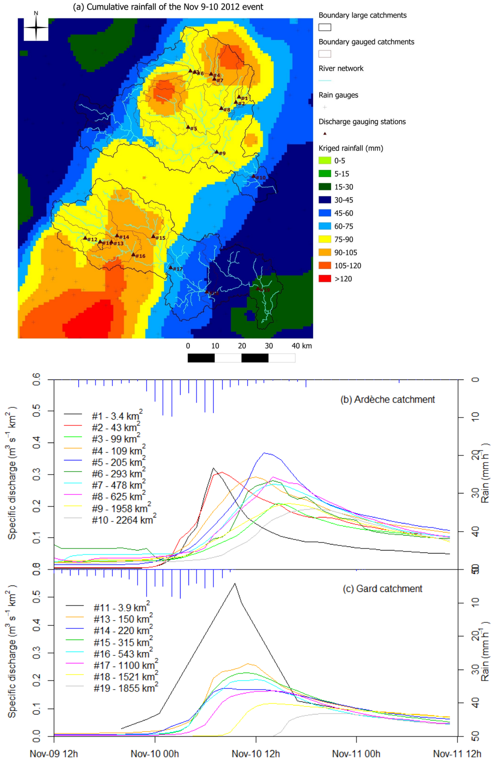

Fig. 14. (a) Cumulative rainfall for the 9–10 November 2012 event obtained by kriging of the rain gauges. Corresponding specific discharge for the same event in sub-catchments of **(b)** the Ardèche catchment and **(c)** the Gard catchment. The hourly rainfall data from a rain gauge in the Claduègne catchment **(b)** and the Valescure catchment **(c)** are also provided as illustration of the rainfall intensity. The boundaries of the sub-catchments and location of the gauging stations are shown in **(a)**.

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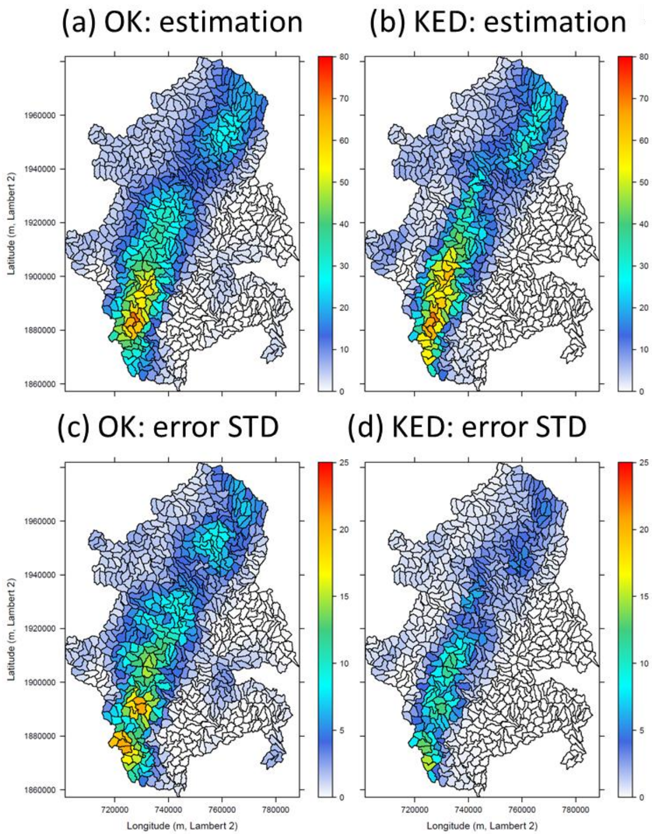

Fig. 15. Ordinary kriging estimates from the rain gauge network (left) and kriging with external drift estimates from radar-rain gauge merging (right) for the 21 October 2008 between 21:00 and 22:00 UTC. The top graphs display the hourly rain amounts (mm) and the bottom graphs the corresponding error standard deviations (mm). The results are provided for an hydrological mesh of 10 km^2.

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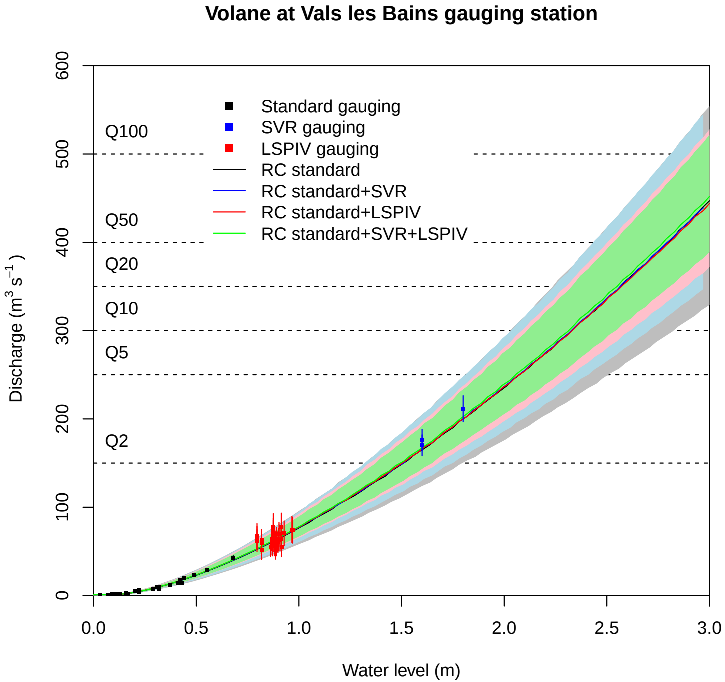

Fig. 16. Illustration of the error reduction in discharge estimation when on-alert SVR (blue points) and LS-PIV (red points) stream gaugings for high flow are added to standard gaugings (black points) in the stage-discharge estimation. The error bars correspond to errors of 5 % for standard gaugings, 7 % for SVR gaugings and 20 % for LS-PIV gaugings. The lines are the Rating Curve (RC) computed using the BaRatin software and the shaded colors correspond to the 95 % uncertainty bounds when standard gaugings only (grey), standard + SVR (blue), standard + LS-PIV (pink), standard + SVR + LS-PIV (green) gaugings are included in the RC computation.

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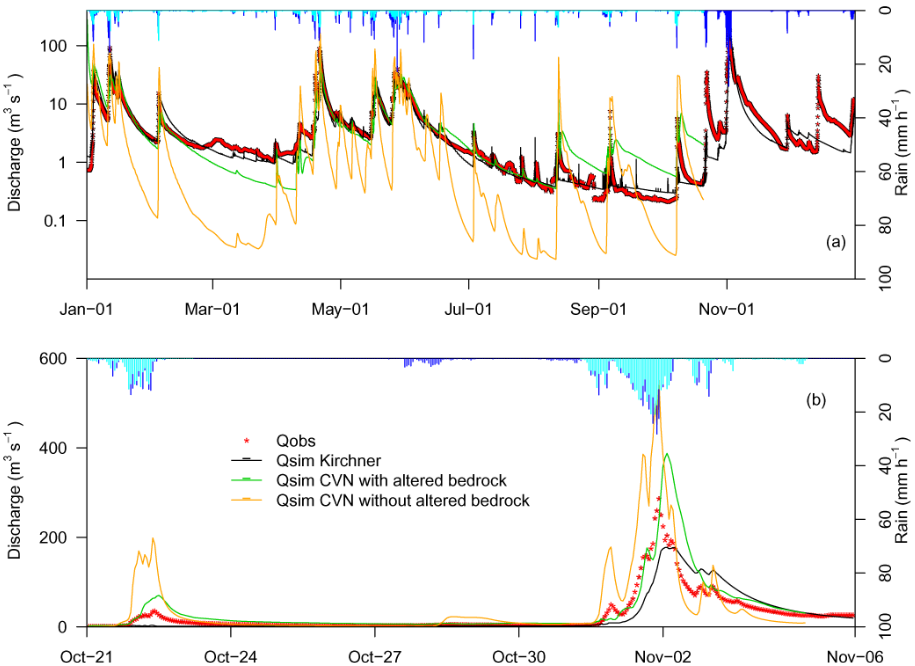

Fig. 17. Simulated and observed discharge (red points) from 1 January to 31 December 2008 for the Ardèche at Meyras gauging station (98 km^2). The simulations correspond to the CVN model with and without taking into account the altered bedrock layer (green and orange respectively), and the use of the Kirchner (2009) modelling approach (black). This graph is provided in log scale for the discharge in **(a)** for year 2008 and the rainfall corresponds to an hourly local gauge (dark blue) and SAFRAN reanalysis (light blue). **(b)** provides a zoom (in linear scale) for the period 20 October–6 November 2008 with two significant events. The rainfall corresponds to an hourly local gauge (dark blue) and hourly kriged estimates (light blue).