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Advances in flash floods understanding and modelling derived from the FloodScale project in South-East France

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Abstract. The Mediterranean area is prone to intense rainfall events triggering flash floods, characterized by very short response times that sometimes lead to dramatic consequences in terms of casualties and damages. These events can affect large territories, but their impact may be very local in catchments that are generally ungauged. These events remain difficult to predict and the processes leading to their generation still need to be clarified. The HyMeX initiative (Hydrological Cycle in the Mediterranean Experiment, 2010-2020) aims at increasing our understanding of the water cycle in the Mediterranean basin, in particular in terms of extreme events. In order to better understand processes leading to flash floods, a four-year experiment (2012-2015) was conducted in the Cévennes region (South-East) France as part of the FloodScale project. Both continuous and opportunistic measurements during floods were conducted in two large catchments (Ardèche and Gard rivers) with nested instrumentation from the hillslopes to catchments of about 1, 10, 100 to 1000 km² covering contrasted geology and land use. Continuous measurements include distributed rainfall, stream water level, discharge, water temperature and conductivity and soil moisture measurements. Opportunistic measurements include surface soil moisture and geochemistry sampling during events and gauging of floods using non-contact methods: portable radars to measure surface water velocity or image sequence analysis using LS-PIV (Large Scale Particle Image Velocimetry). During the period 2012-2014, and in particular during autumn 2014, several intense events affected the catchments and provided very rich data sets. Data collection was complemented with modelling activity aiming at simulating observed processes. The modelling strategy was setup through a wide range of scales, in order to test hypotheses about physical processes at the smallest scales, and aggregated functioning hypothesis at the largest scales. During the project, a focus was also put on the improvement of rainfall fields characterization both in terms of spatial and temporal variability and in terms of uncertainty quantification. Rainfall reanalyses combining radar and rain gauges were developed. Rainfall simulation using a stochastic generator was also performed. Another effort was dedicated to the improvement of discharge estimation during floods and the quantification of streamflow uncertainties using Bayesian techniques. The paper summarizes the main results gained from the observations and the subsequent modelling activity in terms of flash flood process understanding at the various scales. It concludes on how the new acquired knowledge can be used for prevention and management of flash floods.

1 Introduction

The Mediterranean area is prone to intense rainfall events triggering flash floods, characterized by very short response times that sometimes lead to dramatic consequences in terms of casualties and damages as shown by Gaume et al. [1] for Europe. Recent examples in France include the events in Nîmes (1988), Vaison-la-Romaine (1992), Aude (1999), Gard (2002, 2005), Draguignan (2010), Alpes-Maritimes (2015) or the series of events that affected the south-east of France in 2014. Flash floods often occur over very short time and spatial

scales [1-2] with a sudden onset and a rapid rising time. These events can affect large territories, but their impact may be very local in catchments that are generally ungauged. As an example, the analysis of the 8-9 September 2002 event in the Gard region (France) showed that many casualties occurred in less than 20 km² catchments that were ungauged [3]. Larger catchments (up to 1000 km²) suffered important economic damage (urban zones and main transportation network). Several studies and projects have addressed the questions of processes triggering flash floods. They showed that the spatial and temporal rainfall variability, landscape

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characteristics and soil humidity are influential factors on flash flood generation but their respective role still remains unclear [4] and the predictability of such events remains low due to high non-linearity in the hydrological response related to threshold effects and structured-heterogeneity at all scales. In addition, flash floods are difficult to monitor using operational rain gauge and discharge networks and a high spatial and temporal resolution is required [5]. Indeed, gauging flash-flooding rivers with classical techniques remains a challenge due to practical and security reasons and the difficulty to be at the right place at the right moment. Weather radar data proved to be valuable for characterizing the space and time variability of rainfall [6], although the radar signal interpretation is more difficult in complex terrain and/or over urbanized areas, which are the most prone to such events.

To progress in flash flood understanding and modelling, it is necessary to progress on two fundamental questions in hydrology [7]: 1/ the change of scale problem or how to transfer knowledge acquired at a given scale to another scale; 2/ the prediction in ungauged basin (PUB) problem, in order to assess the risk everywhere over a given region, requiring models able to provide reliable prediction at various scales (from a few km² to 1000 km²). To go into that direction, Kirchner [8] advocated for field experiments, specifically designed to advance the science of hydrology and address the change of scale problem in order “to get the right answer for the right reasons” The strategy is based on experiments on nested catchments, allowing the sampling of spatial heterogeneity at all scales. These recommendations formed the basis of the experimental and modelling strategies set up in the framework of the FloodScale project [2], aiming at increasing flash flood understanding and simulation.

In this paper, we first (section 2) present the observation and modelling strategy set up during the FloodScale project [2] that contributed to the HyMeX (Hydrological cycle in the Mediterranean Experiment) [9]. The observation strategy combines a four year multi-scale data collection in two meso-scale catchments in south-east France with opportunistic measurements during the autumn season, when flash floods are more likely to occur. The modelling strategy follows the suggestion of Clark et al. [10] where models are used for process understanding and hypotheses testing. In section 3, we highlight the main findings derived from the observations and data analysis in terms of major active processes during flash floods and their space and time variability. In section 4, we present innovative methods to gauge rivers during flash floods and to improve the rainfall fields’ description as well as methods for quantifying rainfall fields and discharge uncertainty. In section 5, we show how the knowledge derived from observation can be incorporated into models for hypothesis testing. This is conducted at various spatial scales from small to regional scales catchments. Finally, in section 6, we highlight how the knowledge acquired during the project can be useful for operational services and can contribute to improve models used in operational forecasting.

2 Observation and modelling strategies

2.1 Observation strategy

The observation was focused on two meso-scale catchments located in south-east France (Gard and Ardèche catchments) (Figure 1), with a multi-scale observation strategy including both continuous measurements during four years (Enhanced Observation Period – EOP) and opportunistic measurements during the four autumn seasons of 2012 to 2015.

Three scales were considered for data collection: 1/ the hillslope scale for process understanding; 2/ the small to medium-sized catchment scale (1-100 km²) to document the change of scale and the spatial variability of landscape characteristics and processes; 3/ the regional scale (100-2000 km²) that is the scale of interest for flash flood warning and management (Figure 2).

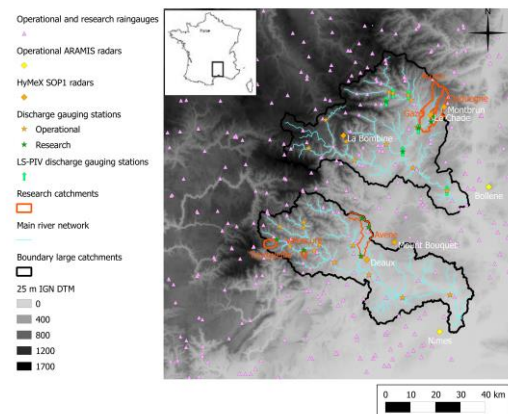


Figure 1: Location and elevation map of the study area. The two main studied catchments: Gard (2062 km²) and Ardèche (2388 km²) appear in bold black. The small research catchments are shown with orange boundaries (from [2])

At the hillslope scale, the experimental set up aimed 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 transposition of the results to non-monitored catchments. For this purpose, various hillslopes, typical of the Mediterranean environment in terms of spatial variability of soil depth, soil hydraulic properties, pedology, vegetation and geomorphology were selected and instrumented. The instrumented hillslopes were located in three small catchments (Valescure, Tourgueille, Gazel, see locations in Figure 1), corresponding to different geologies: granite, schist, marl and limestones respectively (see details in [2] and in Section 3).

The small to medium sized catchments appear in orange in Figure 1. They were chosen to document various geologies: granite, schist, marls, limestones and basalt, and land use: forest and agricultural areas. To document the landscape spatial variability, high resolution information was acquired to document topography (1 m Digital Elevation Model (DTM) from LiDaR measurements); land use (5 to 10 m resolution

land use maps derived from Quickbird or Pleiades images); as well as collection of existing data about geology and pedology (1/ 250 000 resolution). In those catchments, nested water level, discharge and soil moisture measurement networks were set up, documenting as much as possible, homogeneous sub-catchments in terms of geology and land use. This was associated with the collection of high resolution rainfall data. Soil hydraulic properties were also documented from the collection of existing data base or the set-up of dedicated field campaigns (see details in [2] and [11]).

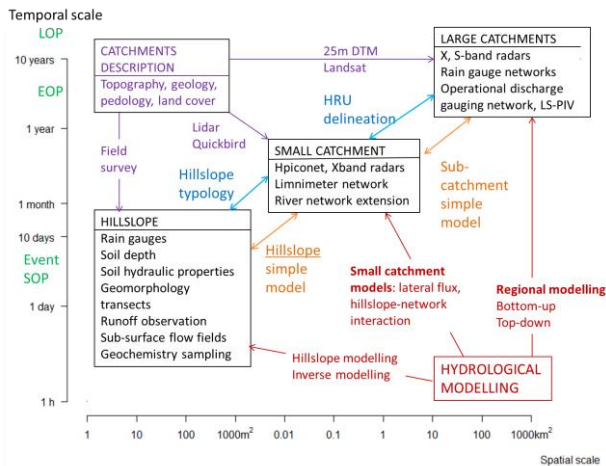


Figure 2: Diagram showing the characteristic spatial scales of the processes considered in the study (black, diagonal) and the associated typical observation time scales; the required data characterizing the catchments physical properties at each scale (purple, top left); the modelling approaches (red, 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. (taken from [2])

At the regional scale, the focus was mainly on the collection of operational rainfall and discharge data. Nevertheless, during HyMeX first Special Observation Period (SOP1) [12] and EOP periods, research radars were deployed in the Gard and Ardèche catchments to refine the rainfall estimation. In addition, the Claduègne catchment in Ardèche (see location in Figure 1) was equipped with a high density of rain gauges (Hpiconet^a network composed of 19 to 21 gauges in about 100 km² with a 1-5 minute time step). In the Ardèche catchment, a network of Large Scale Particule Image Velocimetry (LS-PIV) stations [13] was also set up to continuously monitor discharge in particular during high flows.

The opportunistic measurements included the sampling of flood events for geochemistry analysis, gauging of flooding rivers, soil moisture measurements, field observations of runoff. The deployment of teams in the field was possible thanks to a continuous analysis of weather forecasts available on the HyMeX SOP website by on-duty scientist staff and the availability of real time

information on the <http://sop.hymex.org> web site. This included meteorological forecasts provided by Météo-France, real time rain gauges and radar rainfall observations and reanalysis of soil moisture state over the area of interest. Adopting this EOP strategy for flash-flood observations was very relevant. Indeed, autumn 2012 that corresponded to the first HyMeX SOP [12] did not led to significant events in those catchments whereas during autumn 2014, about 10 significant events hit the Cévennes-Vivarais region, amongst which several concerned our studied catchments. As an illustration, about 45 river gaugings during high floods were performed in the Ardèche catchment in 2014. The strategy of EOP aiming at reinforcing research observatory and operational observations during four years for flash-floods was thus a very successful proof-of-concept for such rare events over specific Mediterranean watersheds.

2.2 Modelling strategy

The modelling strategy is detailed in Braud et al. [2] and relies on an iterative process where models are used, as much as possible, without calibration in order to apply the hypothesis testing framework and be able to relate model parameters with physical hypotheses. The iterative process includes the following steps:

- 1/ A first modelling approach is built from existing knowledge and data and from first hypotheses about dominant processes;
- 2/ The model results are compared with observations and the analysis focuses on discrepancies that can be due to problems in model forcing data; parameters specification; process representation or missing processes;
- 3/ New data are collected or additional analyses are performed to understand the discrepancies;
- 4/ A new version of the model is set up and new hypotheses are tested;
- 5/ The process is continued until sufficient agreement between model and observation is obtained.

This strategy was applied at the various documented scales in order to progress in process understanding and simulation. The results are illustrated in Section 5.

3 Main results from the hillslope and small scale catchments observation and modelling

The experimental set-up at the hillslope and small to medium catchment scale was designed to address the following questions:

- 1/ What is the storage capacity of soils in the studied area?
- 2/ In which conditions do we observe sub-surface lateral flow or direct surface runoff and can we quantify the speed of sub-surface lateral flow?
- 3/ What is the respective part of surface, sub-surface and deeper layers flow in the discharge at the outlet of the catchments?

^a<http://mistrals.sedoo.fr/?editDatsId=656&datsId=656&projectname=HyMeX&q=hpiconet>

- 4/ Is the impact of land use larger than the impact of soil texture on soil surface hydraulic properties?
- 5/ What is the impact of active river network extension on the efficiency of the hydrological response?
- 6/ What is the respective role of rainfall, soil moisture, geology, land use variability on the hydrological response?

The effort of the past four year was mainly dedicated to data acquisition, data validation and data provision to the HyMeX data base^b. A complete analysis of the whole data set has not yet been achieved. Nevertheless, the results obtained up to now already provide interesting insight into some of the questions listed above. They are briefly reviewed below.

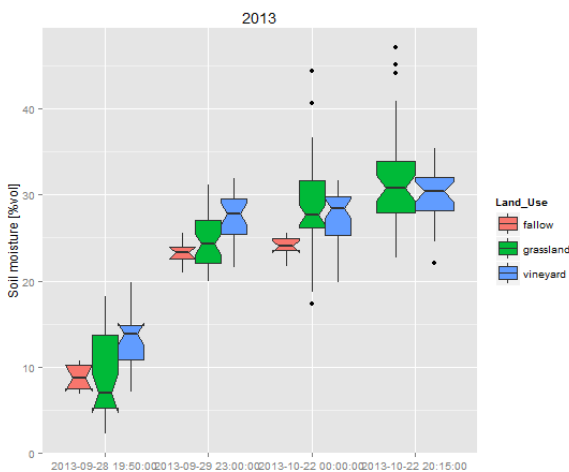


Figure 3: Average of 0-5 cm depth soil moisture for several events in 2013 and different land uses in the Claduègne sub-catchment.

In the agricultural area of the Ardèche catchment, flow was thought to be mainly due to surface runoff and related to land use. Field observations showed that near saturated hydraulic conductivity was low due to high clay contents and that infiltration excess runoff was initiated in less permeable areas (including the crest) with saturated areas progressively connected to the hydrographic network. Soil moisture sensors (Decagon 10HS) installed in various land uses between 10 and 50 cm depth showed that, during rainfall events, only the top soil (30 cm) was affected by significant change in soil moisture. The differences between fields also appeared larger than the differences between different land uses (Figure 3). Hydraulic properties of the soil surface were characterized in situ using a new device called “saturometer” which allows the quantification of the time needed to reach saturation under artificial rainfall [14]. Results show a lower hydraulic conductivity in vineyards than in grassland sites, but a time to saturation longer due to a lower initial soil moisture in vineyards, which can be explained by a higher evaporation within the 0-5 cm top layer between events, not visible at 10 cm depth. Data

^b <http://mistrals.sedoo.fr/HyMeX/>

analysis will be continued and complemented with modelling in order to analyze more deeply the complex interplay between initial conditions, land use and rainfall.

In the forested area of the Gard catchment, runoff was thought to be dominated by sub-surface flow and questions had been raised about the soil storage capacity and imperviousness of the underlying weathered horizons. The experimental set up was mainly devoted to study those questions.

Six transects in granite (Valescure) and schist (Tourgueille) were instrumented with soil moisture sensors (ten locations) with 2 depths at each site. The continuous measurement lasted about one hydrological year at each site. Soil hydraulic conductivity was characterized using disk infiltrometers [15]. Soil depth was measured from direct pedological pits or a method based on the analysis of electrical resistivity (ERT) signal along the transects. This allowed the determination of the statistical distribution of soil hydraulic conductivity, soil water retention and soil depth for each transect. Although the intra-transect spatial variability is quite large, the inter-transect distribution appears quite stable (Figure 4). For soil depth, the average is around 30 cm, and the spatial variability in this area can be considered as following a log-normal distribution, with parameters -1.14 and 0.72 respectively for the mean and the standard deviation of the soil depth logarithm. Soil moisture data were analyzed to derive the soil retention and hydraulic conductivity curves for the surface horizon, but also the deeper horizon using the HYDRUS-1D software and an inverse modelling technique detailed in [16]. The method reveals, consistently with in situ measurements, high value of hydraulic conductivity in the top horizon (several hundreds of mm hr⁻¹), but more interestingly, also large values of hydraulic conductivity towards deeper soil horizons.

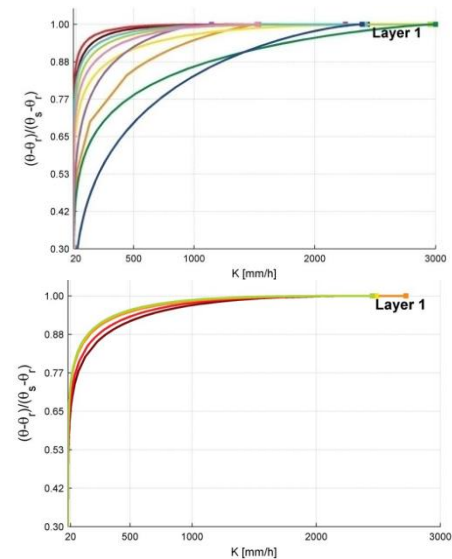


Figure 4: Top: Hydraulic conductivity curves of the top horizon at transect 1 in Valescure Bottom: Hydraulic conductivity curves derived from median parameter of the top horizon for each transects 1 to 5.

The same kind of observations was also conducted on “infiltration fields” of about 10 m² with natural and artificial rainfall. This allows to document the hydrological response from normal to extreme conditions. The sites were equipped with soil moisture sensors, piezometers, tensiometers, and electrode lines to perform multi-temporal resistivity (ERT) surveys (see details in [2]). It was also possible to inject tracers upstream the field and to follow its dispersion using ERT. The example in Figure 5 shows that although rocky horizons are present, fluxes are mainly vertical in the first 2 m of soil. In addition, artificial rainfalls of about 500 mm (100 mm hr⁻¹ in 5 hours) occurring on semi-saturated soil can be completely infiltrated, confirming that infiltration in the weathered horizon is possible and that storage capacity is about twice that of the surface horizon [17].

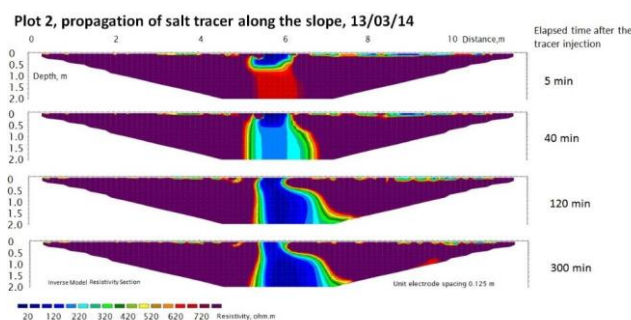


Figure 5: Example of soil resistivity multi-temporal monitoring after salt injection.

Geochemistry sampling performed during some rainfall and flood events allowed to go towards a quantification of the fraction of water coming from the surface and sub-surface. A large panel of elements including physico-chemistry, trace elements, stable water isotopes and organic carbon were analyzed. During floods, Ca, Sr and electrical conductivity analyses show a contribution of about 60-80% of rain water to the peak, and only 20-40% of pre-existing water. However, at the scale of the event, these proportions are inverted.

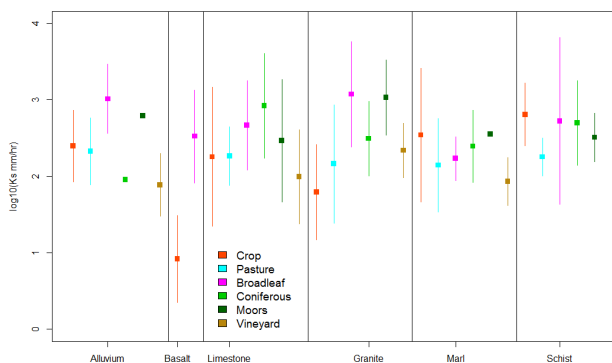


Figure 6: Average and standard deviation of the logarithm of soil surface hydraulic conductivity estimated using all the available data in the Cévennes-Vivarais region, showing that geology and land use are discriminant factors to explain the spatial variability

At the small catchment scale, but also for the whole Cévennes-Vivarais region, a synthesis of infiltration tests

performed by [18] and of the data collected during the project [19] showed that land use and geology were significant controlling factor of surface hydraulic conductivity (significant differences between natural/cultivated and forest/crops and between different geologies, Figure 6) and that pedo-transfer functions, based only on texture or porosity data failed to reproduce the range of observed values.

At the scale of the whole Cévennes-Vivarais area, several studies focused on the analysis of recessions in order to gain insight into catchment characteristics that could be useful for improving flash flood simulation. Vannier et al. [20] showed that soil storage capacity estimated from existing data bases was underestimated, as compared to results obtained from discharge recession analysis. They used this method to derive probable depth and hydraulic conductivity of the weathered bedrock, which was found to be dependent on geology. They also showed that the storage capacity of the weathered layer was much larger than that of the upper soil, described in soil data bases. The results of this large scale analysis are consistent with those of the experiments conducted at the hillslope and small catchment scales, which underlines the interest of the multi-scale approach. The major role of geology in modulating the hydrological response has also been shown.

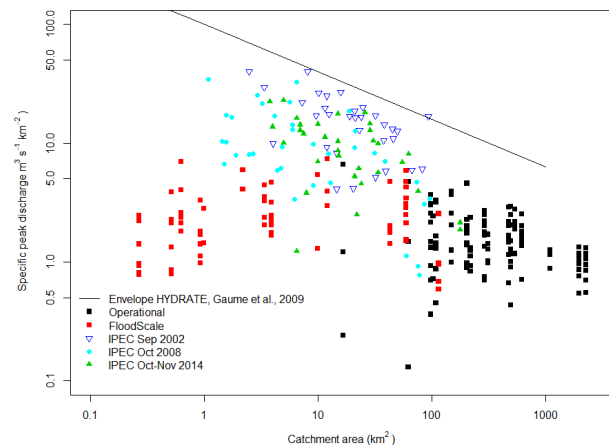


Figure 7: Specific peak discharge as function of catchment area for the operational network in the Gard and Ardèche catchment (black), post-event survey (IPEC) in the region in 2002, 2008 and 2014 (blue and green), and the continuous nested measurement network set up during FloodScale (red points). The black line is the envelope curve proposed by [1].

The nested catchments monitoring strategy also allowed documenting discharge at spatial scales that were seldom sampled by the operational networks, but also by post-event field survey aiming at documenting peak discharge [21] as shown by the red points in Figure 7. The figure shows that the network allowed documenting small spatial scales that were not documented before, even during post-event surveys. No exceptional event was recorded at those scales. Nevertheless values of specific discharge of about 10 m³ s⁻¹ km⁻² were recorded, which is already quite high.

4 Progress in rainfall and high discharge estimation and quantification of their uncertainty

In terms of rainfall, the objective was to progress in rainfall spatial and temporal variability description, as well as in the quantification of uncertainty. A 1 km² -rainfall reanalysis over the Cévennes-Vivarais region (32 000 km²), was produced for the 2007-2014 period and is available on the HyMeX database^c. For the 133 most intense rain events, an hourly rain product based on radar – raingauge merging was produced for two types of geographical supports: 1/ 1-km² raster maps and; 2/ spatial divisions of the main Cévennes watersheds into hydrological meshes of almost constant size in the range of 5 – 300 km². The methods and their comparison to other rainfall products are described in Delrieu et al. [22] and Boudevillain et al. [23], indicating a systematic superiority of the merging method (Kriging with External Drift) over Ordinary Kriging (OK). Additional reanalyses at higher resolution were also conducted using research observation networks. The error model indicates that the added-value of the radar network in terms of Quantitative Precipitation Estimate (QPE) with respect to the hourly raingauge network is larger for localized convection rain events as well as for the smallest space-time scales (Figure 8) which are those of interest for flash-flood prediction in the region.

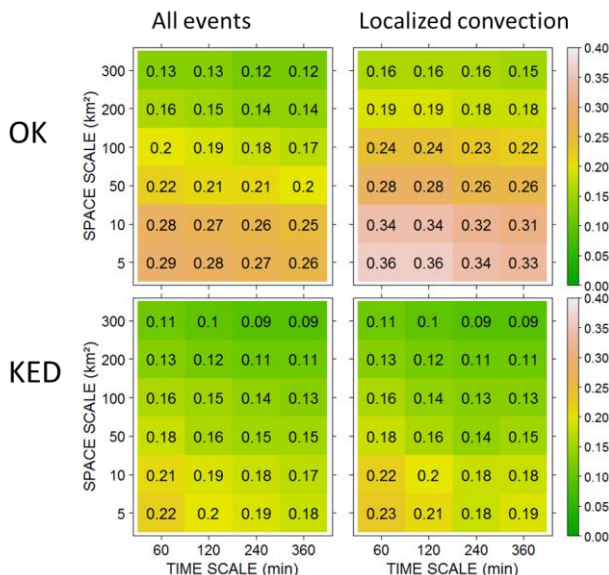


Figure 8: Normalized standard deviation of the rain rate error over a range of spatial and temporal scales using rain gauges alone (ordinary kriging-OK) top) and radar-rain gauge merging (kriging with external drift –KED- bottom) for all studied events (left) and localized convective events (right). Green (resp. pink) values correspond to low (resp. high) errors. The error model was parameterized using a cross validation technique

^chttp://mistrals.sedoo.fr/?editDatsId=1183&datsId=1183&project_name=HyMeX&q=radar

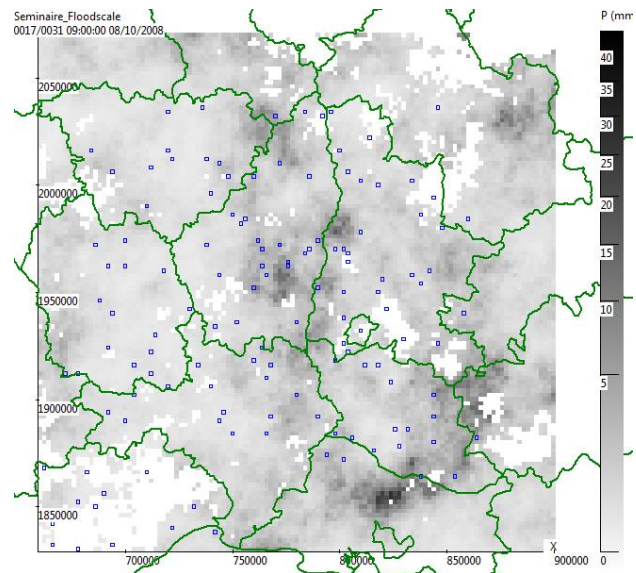


Figure 9: Hourly rainfall field on the Cévennes-Vivarais region conditioned on observed rain gauges (points)

Another way to account for rainfall spatial variability and uncertainty is to use stochastic rainfall simulators. The SAMPO stochastic rainfall simulator [24] was improved 1/ to make a key technical component (a Gibbs Sampler) able to efficiently handle up to ~1500 conditioning data points where available, as broader conditioning chunks make the conditional simulations smoother in both time and space 2/ to be able to simulate rainfall fields in mild non-homogeneous conditions such as the presence of an orographic gradient [25], using gradually variable point distribution parameters - a technique initially tested within the PhD of D. Penot [26]. From this a set of several realizations, conditioned on observations at rain gauges [27], was used to provide plausible rainfall fields in the Cévennes-Vivarais region catchment. An example of such field is provided in Figure 9. More drastic heterogeneity has also been studied, focusing on mosaic simulations where sharply contrasting subdomains are handled separately. This is a technique of primary importance for free (climatological) simulations without conditioning, but results are mixed as far as rainfall reanalysis is concerned.

In terms of discharge estimation of flooding rivers, several non-contact techniques were tested and compared. They allow a safe (for the equipment and the operators) gauging, in conditions when traditional methods are not applicable. This includes the use of fixed video cameras, analyzed using LS-PIV (Large Scale Particle Image Velocimetry) techniques [12, 28] and the use of portable surface velocimetry radars (SVR) [29-30]. Algorithms were also developed to use videos of flooding rivers from the internet for the estimation of discharge, based on the same principles as those used with LS-PIV [31]. In the framework of the Enhanced Observation Period, distributed and multi-scale hydrometry was set up and tested. This includes the setup of dense networks of water level monitoring for catchments ranging from 0.2 to 12 km² [11] allowing discharge measurements at scales much smaller than currently available for flash floods (see Figure 7).

For the establishment of the stage-discharge relationships, a Bayesian framework aiming at including prior knowledge of hydraulic controls and gauging uncertainty was developed [32]. The BaRatin^d software implements the method and is freely available. BaRatin determinates the most probable stage-discharge relationship and the associated uncertainty. The application of BaRatin to the FloodScale stations showed that the added value of the non-contact gaugings is high. First, uncertainties, especially for high discharge where the curves were generally extrapolated, are significantly reduced. Second, the stage-discharge relationship can be established in only a few years of operation. Operational protocols and training sessions have been provided to French operational services and some of them use the tools developed in the project. New developments have been also performed to propagate the stage-discharge uncertainties to hydrographs and water balance components (Figure 10) [33]. This will allow including observation uncertainty in the calibration and evaluation of hydrological models.

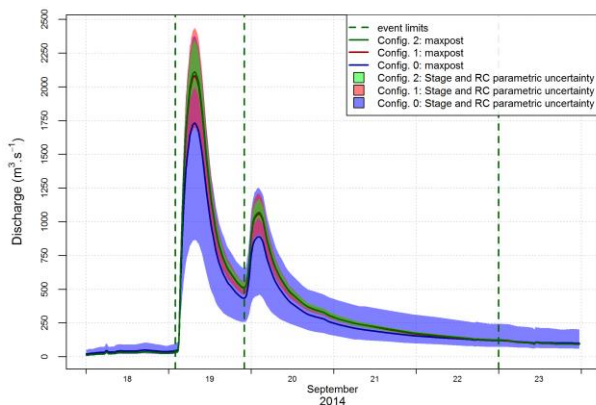


Figure 10: Example of propagation of stage-discharge uncertainty on a measured hydrograph for the flood of November 4 2014 at the Vallon Pont d' Arc gauging station. The colors correspond to uncertainties in the stage-discharge relationship when only a priori hydraulic knowledge (blue – config 0), traditional gauging (pink- config 1) and all gauging including SVR opportunistic measurements (green- config 2) are taken into account

5 Modelling at various scales

At the various scales, the hypotheses testing framework highlighted in section 2.2 was applied. The hillslopes and small catchment scale observations in the granite and schist catchments were used to set up a distributed, event-based model, based on the experimental findings that lateral flow and deep infiltration are the dominant processes in those catchments [34]. It was tested with success on the available rainfall-runoff events on the small Valescure catchment [34] (see also an example in Figure 11). The extension of this model to a medium size catchment (Gardons catchment) also provided satisfactory results.

^d <https://forge.irstea.fr/projects/baratin> and please write to baratin.dev@lists.irstea.fr to register

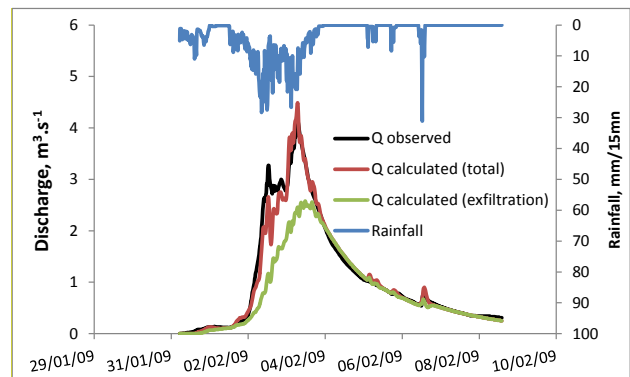


Figure 11: Comparison of the observed discharge with calculated discharge at the event scale. The model either simulates the total discharge and the discharge due to exfiltration of the sub-surface flow, occurring at convergent sub-surface path flows which lead to soil saturation.

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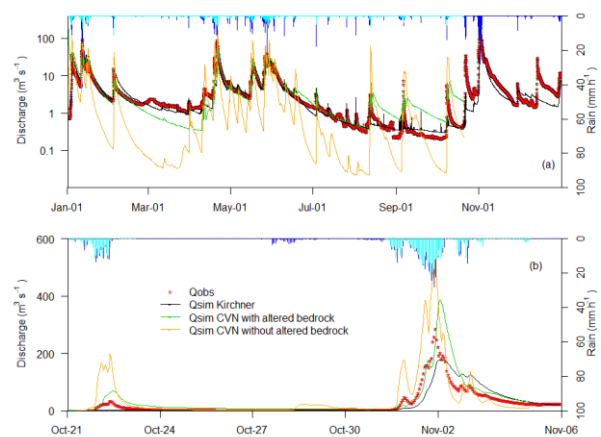


Figure 12: Observed (red points) and simulated discharge at Ardèche at Meyras in 2008 (top) and from October 21 to November 06 2008 (bottom) using the CVN-p (green), the CVN (orange) and the SIMPLEFLOOD (black) models (taken from [2])

At the regional scale, Vannier et al. [35] used the results obtained in [19] about soil water storage to upgrade the CVN model [36], by adding the altered bedrock layer to the soil description in the model (CVP-p). The drainage flow at the bottom of the soil columns was added to the river flow as base flow. They showed improvement in simulated discharge, both at the annual and event scale [35]. The improvement was larger for granite dominated catchments than for schist dominated

catchments. An example is provided in Figure 12 for a granite sub-catchment.

Adamovic et al. [37] and Coussot [38] used discharge recession analysis to characterize the catchment behavior as a simple dynamical system following the approach of Kirchner [39]. They found that such a simple model was applicable to Mediterranean catchments, mainly during low-vegetation periods (when deciduous trees have lost their leaves) and under humid conditions. This led to a simple model (3 parameters), mainly representing rapid sub-surface flow. Adamovic et al. [40] proposed a distributed model, SIMPLEFLOOD, based on this approach, using parameters regionalized according to geology [37, 40]. In the Ardèche catchment, satisfactory performances were obtained for floods and continuous simulations, although discharge was generally underestimated in summer. An example of simulation appears in Figure 12. Adamovic [41] also tested a coupling of the SIMPLEFLOOD model with a 1D hydrodynamic model for flood propagation in the downstream river channel, without significant improvement of discharge estimation in the simulated cases.

6 Synthesis of the main results and interest for operational purposes

The main outcome of the FloodScale project is the unique data set it assembled and the demonstration that the proposed observation strategy mixing continuous measurements over a four-year period and opportunistic measurements during four autumns was adapted to capture flash floods. In addition, effort was made to quantify uncertainty at all levels. All those elements render the collected data set unique given the variety of sampled space and time scales, which are much finer than those captured by operational networks. The project also demonstrated the importance of high quality discharge data, even at low flow, as it was shown that recession data were containing useful information for understanding and simulating flash floods. The whole data set is available for the international research community through the HyMeX data base portal.

In terms of process understanding and innovative measurements, the following points can be highlighted:

- 1/ A method for merging radar and rain gauges data was proposed and validated and error on the estimated rainfall fields was quantified;
- 2/ A method for quantifying rainfall field uncertainty in non-homogeneous areas has also been proposed (use of a stochastic rainfall generator);
- 3/ Various non-contact measurements techniques for flooding discharge have been proposed and validated and are already used in operational services;
- 4/ An objective method for quantifying stage-discharge uncertainty and its propagation to discharge times series has been validated and a

software implementing this method is freely available;

- 5/ Geology was highlighted as an important factor in modulating the hydrological response and the soil water storage, with the necessity to include storage capacity of the weathered soil horizons in the modelling;
- 6/ Lateral sub-surface flow must be taken into account even when surface runoff is important;
- 7/ The iterative modelling strategy mixing observation and modelling for hypothesis testing proved to be successful and allowed building simulation models that are consistent with observations.

There is still work to do to fully exploit the collected data sets, but some results can already be useful for operational services. These data sets can serve as reference for the evaluation of research or operational models. Rainfall field can also be useful for the evaluation of satellite products or the evaluation of rainfall simulated by meteorological models.

Lessons learnt about soil water storage and its modulation by the geology, as well as the results in terms of surface hydraulic conductivity can be directly incorporated into forecasting models. The simulation models developed during the project can form the basis for simplified versions that could be used in the next generation of forecasting models.

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