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Precipitation, soil moisture and runoff
variability in a small river catchment
(Ardèche, France) during HyMeX Special
Observation Period 1

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Abstract

Flash flooding is a potentially destructive natural hazard known to occur in the Cévennes-Vivarais region in southern France. HyMeX (Hydrological Cycle in the Mediterranean Experiment) is an international program focused on understanding the hydrological cycle in the Mediterranean basin. Soil moisture is known to be a useful indicator of catchment response, however, establishing a meaningful estimation of soil moisture at the catchment level can be difficult due to its high variability in space and time.

In a small gauged catchment in the Cévennes-Vivarais region in southern France, a series of manual soil moisture measurements was taken from September to December 2012 at both the field and catchment scale during the Special Observation Period 1 (SOP1) as part of the HyMeX program. Six plots were selected along a trajectory of a microwave link installed in the catchment and were chosen to represent different elevations in the catchment. Within each field plot, surface soil moisture was measured along a 50 m transect at 2 m intervals. This allowed the study of changes in within-field variability as well as between-field variability in response to precipitation events and during the drying out phase.

Several precipitation events occurred over this autumn 2012 period which caused a significant wetting-up of the catchment, allow-

23 ing the study of soil moisture processes over a wide range of wetness
24 conditions. The influence of antecedent catchment conditions (soil
25 moisture) on rainfall-runoff dynamics is demonstrated through the
26 comparison of storm hydrographs for the various events. Dry catch-
27 ment conditions result in minimal response in event flow, whereas large
28 precipitation events occurring during wetter conditions produce much
29 stronger responses in event flow. This further confirms the importance
30 of quantifying catchment initial conditions to enhance the prediction
31 of flash flood occurrences.

32 Keywords: initial soil moisture, small catchments, HyMeX, runoff gener-
33 ation, temporal stability, soil moisture spatial variability

1 Introduction

Orographic precipitation and intense convective systems are common in the Mediterranean region. They can potentially lead to flash floods, creating significant environmental and socio-economic impacts. Prediction of these systems is a challenge due to the complex interaction between oceanic, atmospheric, and hydrological processes (*Ducrocq et al.*, 2010). The Hydrological cycle in Mediterranean Experiment (HyMeX) is an international initiative launched in 2007 aiming at a better understanding of the hydrological cycle and processes in the Mediterranean basin (*Drobinski et al.*, 2013; *Ducrocq et al.*, 2013). One of the focuses includes high impact weather events involving heavy precipitation and flash flooding.

The Mediterranean region is characterized by a hydrological cycle bringing long dry summers where drought often occurs, and wet fall and winter periods (*Drobinski et al.*, 2013). Typical to this highly variable hydrological cycle is the occurrence of heavy precipitation causing flash flooding and floods (*Gaume et al.*, 2004; *Delrieu et al.*, 2005; *Borga et al.*, 2007; *Gaume et al.*, 2009). The FloodScale project, which is centered around the Cévennes-Vivarais region in southern France, contributes to the HYMEX initiative and aims to deepen the understanding of flash flood occurrences and the contributing hydrological processes.

54

55 Soil moisture conditions are of particular importance for predicting hydro-
56 logical processes because they can influence the relative proportion of rainfall
57 input among the possible overland and subsurface pathways (*Massari et al.*,
58 2013). Root zone soil moisture has been shown to influence the dynamics of
59 evapotranspiration and drainage processes (*Albertson and Kiely*, 2000) lead-
60 ing to impacts on the partitioning of latent and sensible heat exchanges to
61 the atmosphere. Furthermore, the antecedent soil moisture conditions of a
62 catchment have been shown in previous studies to be very influential in pre-
63 dicting flood occurrence (*De Michele and Salvadori*, 2002; *Norbiato et al.*,
64 2009; *Sangati et al.*, 2009; *Tramblay et al.*, 2010), also specific for Mediter-
65 ranean regions (*Massari et al.*, 2013; *Aronica and Candela*, 2004).

66

67 Obtaining representative catchment scale soil moisture measurements,
68 even in small catchments, can be difficult given the dynamic spatial and
69 temporal behaviour of soil moisture (*Teuling and Troch*, 2005; *Brocca et al.*,
70 2009a). Previous studies have shown the influence of topographical features
71 (*Famiglietti et al.*, 1998; *Brocca et al.*, 2007) and soil properties (*Teuling and*
72 *Troch*, 2005) on soil moisture values found at the field scale. In a theoretical
73 study done by *Albertson and Montaldo* (2003), the temporal dynamics of soil
74 moisture were explored in the context of the relative influences of parameters

75 such as soil, vegetation, precipitation, topography, and initial soil moisture.
76 All parameters were shown to influence the temporal and spatial dynamics
77 of soil moisture, proving that obtaining accurate soil moisture conditions at
78 the catchment scale for use in flood prediction can be difficult.

79

80 Despite soil moisture being highly variable at small scales, soil moisture
81 fields have been known to display temporal stability. This concept was first
82 introduced by *Vachaud et al.* (1985) who noticed that, although soil moisture
83 variability can be quite high, deviations from the spatial mean show a strong
84 temporal persistence. *Chen* (2006) introduced the term rank stability to de-
85 scribe the temporal stability of soil moisture. In a review on soil moisture
86 observation studies, *Vanderlinden et al.* (2012) show that rank stability in
87 soil moisture has been observed under a wide range of conditions; at different
88 spatial scales, different temporal scales, and for different soil and vegetation
89 types, although *Martínez et al.* (2013) showed that a relation exists between
90 rank stability and climate and soil properties. From this concept, it follows
91 that a limited number of point measurements might be sufficient to infer
92 areal or catchment mean values for soil moisture (*Teuling et al.*, 2006; *Brocca*
93 *et al.*, 2012).

94

95 In addition to in-situ measurements, which are accurate but mainly ap-

106 plicable at smaller scales (*Brocca et al.*, 2013), remote sensing data are an
107 important source to map large scale soil moisture fields. This is achieved
108 through various widely used satellite products, such as Advanced SCAT-
109 terometer, ASCAT (*Bartalis et al.*, 2007), the Soil Moisture and Ocean Salin-
110 ity Satellite SMOS (*Kerr*, 2007), Advanced Microwave Scanning Radiometer
111 for Earth observation, AMSR-E (*Owe et al.*, 2008), and the Microwave Imag-
112 ing Radiometer with Aperture Synthesis, MIRAS (*Kerr et al.*, 2010). The
113 soil moisture data obtained through these sensors are applied in the field of
114 hydrology for multiple purposes including but not limited to weather anal-
115 yses and forecasting. Since remote sensing soil moisture products are still
116 under development (see e.g. *Wagner et al.* (2013)), ground measurements
are of high importance for the validation of remote sensing products (*Cosh
et al.*, 2004).

109

110 In order to improve the understanding of the rainfall-runoff dynamics of
111 small Mediterranean catchments, a field measurement campaign was set up
112 during the HyMeX Special Observation Period (SOP1), which spans from the
113 period of 14 September 2012 to 5 December 2012. SOP1 is a short period
114 spanning the seasonal scale where an increased number of hydrological obser-
115 vations occur in specific catchments. During this period, in situ soil moisture
116 measurements were conducted in a structured way at various scales. These

117 data have been compared to precipitation data from several sources, and soil
118 moisture satellite data. This study has the following research objectives; (i)
119 quantify the temporal and spatial soil moisture variability at the field (or
120 transect) scale and catchment scale; (ii) determine whether regional-scale
121 soil moisture measurements can be used for prediction of field-scale hydro-
122 logical processes; (iii) study the influence of spatio-temporal variability of
123 precipitation on that of soil moisture; (iv) quantify the relationship between
124 catchment initial conditions (soil moisture) and runoff processes.

125 First, the research area and the field work strategy will be described, followed
126 by a presentation of the results obtained through the collection of environ-
127 mental data. Finally a discussion of the results, along with some perspectives
128 will be given.

129 **2 Data and methods**

130 **2.1 Gazel Catchment**

131 The study site is located in the Ardèche catchment, as seen in Figure 1,
132 which is a mesocale catchment of 2,350 km². In the north eastern part of
133 this catchment two smaller nested sub-catchments are located; the Claduègne
134 and the Gazel, which are 43 km² and 3.4 km² in areas respectively. The field

135 experiments for soil moisture measurements were carried out during the fall
136 2012 SOP1 in the Gazel, a small sub-catchment of the Ardèche with an area
137 of 3.4 km² (Figure 1). The Gazel catchment is characterized by a steep
138 south facing slope in the northern part that becomes more gradual near the
139 southern part of the catchment. The elevation of the upper part of the
140 catchment is roughly 630 m, while the elevation at the catchment outlet is
141 approximately 270 m. The upper part of the catchment is characterized by
142 basalt formations, after which a sharp transition occurs where the lower two
143 thirds is made up of sedimentary limestone rock. The soil types are heavily
144 influenced by the geology of the catchment. Volcanic soils and silty-sandy
145 soils are found in the upper and lower part of the catchment, respectively. In
146 addition, proportions of clay are also found in the soils (see Table 1), and the
147 main land use type is pastures and vineyards. Average annual precipitation is
148 approximately 1030 mm (based on daily rain gauge data operated by Météo-
149 France located at Le Pradel (Figure 1) in the catchment for the period of
150 1958-2000).

151 **2.2 Precipitation**

152 Precipitation data were received from the following sources: radar data from
153 the X-band dual polarization weather radar (spatial and temporal resolution

154 of 75 m and 3 minutes, respectively) located approximately 5 km north east of
155 the Gazel catchment, rain gauges and disdrometers located in the upper and
156 lower part of the catchment, and a microwave link running in a north-south
157 direction (Figure 1). The rain gauge and disdrometer data were received
158 for the whole period that soil moisture measurements were done. For the
159 rain gauge located in the village of Mirabel (upper part of the catchment),
160 only data up to 27 October 2012 were available due to technical issues that
161 persisted until after the field work was completed.

162 Hourly precipitation sums were computed for both the radar and the dis-
163 drometer data. In addition, each soil moisture measurement was attributed
164 a precipitation sum, which was calculated by totalling all rainfall occurring
165 during the interval of the previous and current soil moisture measurement.
166 For soil moisture measurements occurring on non-consecutive days, a maxi-
167 mum of three days leading up to the soil moisture measurement was used as
168 the interval length for accumulating rainfall depth.

169

170 **2.3 Soil moisture data**

171 To evaluate the soil moisture spatial and temporal dynamics, a sampling
172 strategy was designed that allowed for capturing both soil moisture condi-

173 tions at the catchment scale as well as the field-scale with a single handheld
174 instrument. Point volumetric soil moisture measurements were done using a
175 portable three-prong (6 cm rod length) ThetaProbe unit (Delta-T Devices
176 Ltd, Cambridge, UK), which employs the time domain reflectometry (TDR)
177 technique. The uncertainty in limiting measurements to the top 6 cm were
178 compared through side-by-side measurements of five transects with an addi-
179 tional TRIME-PICO 64 TDR-probe (IMKO GmbH, Ettlingen, DE) having
180 a rod length of 16 cm. In Figure 2, it can be seen that the two sensors
181 agree quite well based on the small differences between the sensors. The
182 6 cm ThetaProbe was chosen for the field measurements because of increas-
183 ing stoniness with depth found in many fields, which complicated the use of
184 the TDR with longer rod length.

185

186 Fields were selected to appropriately represent the catchment, while still
187 capturing inter-field variability and the influence of different topographical
188 features. The criteria in selecting the location of the different fields through-
189 out the catchment were the following: two fields should be chosen to be in
190 close proximity of the rain gauge and disdrometers found at the Le Pradel
191 and Mirabel sites (blue arrows in Figure 1). The fields in between should
192 be selected in a way that they are aligned with the path of the microwave
193 link, and be equally spaced between to account for the variation of altitude

194 in the catchment (increasing towards the north). The following factors were
195 taken into consideration when selecting the fields: ability to measure, ease
196 of access, and reduced interference (such as ploughing or tilling of the field).
197 Vineyards were not selected because the soil was dominated by stones, mak-
198 ing it impossible to sample without breaking the sensor. This resulted in all
199 selected fields being pastures and grasslands (see Table 1 for a full description
200 of the fields selected).

201 Within each of the selected six fields, a transect path of 50 m was mea-
202 sured. The location of the transect within the field was chosen in order to
203 capture the spatial heterogeneity of the field. If possible, the transect loca-
204 tion within the field was selected to align with the path of the microwave
205 link. Along the 50 m transects, a measurement was taken at spatial intervals
206 of 2 m and all measurements were done at the same location for each of
207 the measurement days. On each measurement day, all fields were measured
208 within a few hours to minimize the influence of evaporation and drainage
209 processes. The strategy was to select measurements days that aligned with
210 high precipitation events and to capture both pre-event and post-event soil
211 moisture conditions whenever possible. Between the period of 14 September
212 2012 to 5 December 2012, 16 measurement days were completed on the six
213 different transects. This produced approximately 2,500 soil moisture mea-
214 surements.

215

216 In addition to soil moisture field data, satellite soil moisture data from
217 the Advanced Scatterometer (ASCAT) on the meteorological operational
218 (MetOp) platform sensor (*Figa-Saldaña et al.*, 2002) were downloaded from
219 <http://www.esa-soilmoisture-cci.org>. This data is downloaded using the TU-
220 Wien algorithm, more information regarding the algorithm can be found in
221 *Wagner et al.* (1999) and *Naemi et al.* (2009). The coarse spatial (between
222 25-50 km) and temporal resolution (revisit time of 1 day or less over Eu-
223 rope) of this data, as well as its high measurement uncertainties make it a
224 challenge to validate in situ data. The reliability of soil moisture estimates
225 from remote sensing data remains a challenge that *Brocca et al.* (2011) have
226 recently addressed. Correlation coefficients with observed soil moisture data
227 ranging from 0.71 to 0.81, depending on scaling methods, were obtained for
228 the ASCAT sensor over different regions in Europe. The remote sensing data
229 were used for the period of 1 September 2012 to 29 November 2012, and was
230 rescaled as the output provided by the ASCAT sensor is not volumetric soil
231 moisture θ_v .

2.4 Soil moisture analysis

This work includes the study of the temporal and spatial aspects of the volumetric soil moisture field $\theta(x, t)$ as vol %, where both x and t denote the spatial and temporal components of the observations. The subscript i is used to represent a discrete measurement point in space along a transect up to $n = 26$ measurements, and the subscript j is used to distinguish between the different fields being sampled (Transect A through F) up to $m = 6$ fields ($x_{i,j} = \{x_{A,1}, \dots, x_{m,n}\}$).

Each soil moisture measurement day is defined as $t_d = \{t_1, t_2, \dots, t_k\}$ where d refers to the measurement day, with the number of total days being equal to $k = 16$. The volumetric soil moisture at a discrete point along a transect is denoted by $\theta(x_{i,j}, t_d)$, and $\bar{\theta}(x_j, t_d)$ represents the daily transect mean for a particular field. The daily catchment mean will be denoted as $\bar{\theta}_d$.

For each measurement day d , the mean for each of the m fields is computed $\bar{\theta}(x_j, t_d)$ as well as the daily catchment mean $\bar{\theta}_d$:

$$\bar{\theta}(x_j, t_d) = \frac{1}{n} \sum_{i=1}^n \theta(x_{i,j}, t_d), \quad (1)$$

$$\bar{\theta}_d = \frac{1}{m} \sum_{j=1}^m \bar{\theta}(x_j, t_d). \quad (2)$$

250 The standard deviation of the soil moisture observations within the transect
251 $s(\theta(x_j, t_d))$ and the standard deviation of the means among the different
252 transects $s(\theta_d)$ is estimated by:

$$s(\theta(x_j, t_d)) = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\theta(x_{i,j}, t_d) - \bar{\theta}(x_j, t_d))^2}, \quad (3)$$

$$s(\theta_d) = \sqrt{\frac{1}{m-1} \sum_{x=1}^m (\bar{\theta}(x_j, t_d) - \bar{\theta}_d)^2}. \quad (4)$$

254 Using these equations, the relationship between mean soil moisture and its
255 standard deviation can be studied at both the transect scale and the catch-
256 ment scale.

257

258 The mean soil moisture of a transect at a specific time t is estimated
259 through n discrete observations, and the uncertainty of this estimate will
260 decrease as the number of observations increases. The uncertainty of the
261 transect mean can be computed through calculating the standard error of
262 the mean. The validity of this equation applies to spatially uncorrelated ob-
263 servations. Additional measurements were performed during this field work
264 at a scale smaller than 2 m, in which distances ranging from 1 cm up to 2.8 m
265 were measured. Large spatial variability was observed at scales much smaller
266 than 2 m, based on a geostatistical analysis of the data. This implies that
267 the discrete measurements at 2 m intervals along the transect can indeed be

assumed to be spatially independent, which further allows for the application of this equation. The standard error (SE) of the transect mean volumetric soil moisture $\theta(x_j, t_d)$ in this example is given by:

$$SE = \frac{s(\theta(x_j, t_d))}{\sqrt{n}}. \quad (5)$$

Furthermore, the different transects measured can be evaluated in terms of temporal stability. The spatial difference $\delta_{j,d}$ is defined as the difference between the soil moisture transect mean $\bar{\theta}(x_j, t_d)$ and the catchment mean $\bar{\theta}_d$ such that:

$$\delta_{j,d} = \bar{\theta}(x_j, t_d) - \bar{\theta}_d. \quad (6)$$

The temporal mean difference $\bar{\delta}_j$ for every site is then estimated as:

$$\bar{\delta}_j = \frac{1}{k} \sum_{d=1}^k \delta_{j,d}. \quad (7)$$

In order to rank the fields to determine which field is the most stable site in time, the field with the smallest temporal mean difference will be considered as the field that on average best represents the catchment mean soil moisture on a given day. The variability of the temporal mean difference for each field $s(\delta_j)$ can be computed as:

$$s(\delta_j) = \sqrt{\frac{1}{k-1} \sum_{d=1}^k ((\delta_{j,d}) - \bar{\delta}_j)^2}. \quad (8)$$

282 **2.5 Discharge**

283 At the catchment outlet of the Gazel, the water depth is logged every sec-
284 ond and averaged over two minute intervals. This depth is converted into a
285 discharge measurement through a stage-discharge relationship. An optimal
286 stage-discharge relationship is provided through the Baratin tool (*Le Coz*
287 *et al.*, 2013), and subsequent minimum and maximum stage-discharge curves
288 are derived as the 5% and 95% statistical distribution based on Monte Carlo
289 simulations. The difference between the maximum and minimum discharge
290 is used to estimate the error of the discharge measurement.

291

292 The discharge data was aggregated to hourly averages over the period
293 of the field work campaign. To investigate the influence of soil moisture
294 on runoff processes, the hydrograph of selected storm events were analysed.
295 The baseflow was removed through a baseflow separation technique where
296 a minimum flow of 5 consecutive days is computed and turning points are
297 identified. For more details on this technique readers are referred to *Tallak-*
298 *sen and Van Lanen* (2004). To further analyse the hydrograph and to allow
299 for comparison between the events, the runoff ratio (RR) was calculated by
300 dividing the cumulative event discharge by the cumulative precipitation for
301 a particular event.

302

303 **3 Results**

304 **3.1 Precipitation**

305 Precipitation was measured with two disdrometers located in the catchment
306 at a temporal resolution of 30 seconds (blue arrows in Figure 1). An av-
307 erage of the two disdrometers was used to provide a daily catchment mean
308 over the observation period (upper panel of Figure 3). Four events of sig-
309 nificant precipitation occurred throughout the SOP1, in which soil moisture
310 measurements are clustered around days that coincide with these strong pre-
311 cipitation events. Throughout the SOP1, approximately 279 mm of rain was
312 recorded by the two disdrometers located in the catchment, as compared to
313 333 mm as recorded by the co-located rain gauges. The rainfall estimates
314 throughout the period for the lower part of the catchment were 288 mm and
315 333 mm for the disdrometer and rain gauge, respectively. For the upper part
316 of the catchment, the disdrometer recorded 269 mm over the same period.
317 Technical problems occurred at the rain gauge located in the upper part of
318 the catchment, resulting in only the rain gauge located in the lower part of
319 the catchment recording precipitation beyond 27 October 2012. For daily

intensities recorded throughout SOP1 were 53 mm day^{-1} and 57 mm day^{-1} for the disdrometer and rain gauges respectively, both recorded in the lower part of the catchment. If the total precipitation sums as recorded by both the disdrometer and the rain gauges are compared for the four periods where soil moisture measurements were done (see section 3.3), it can be seen that the disdrometer consistently records about 22% less precipitation than the rain gauges. Without having rain gauge data available in the upper part of the catchment for the full observation period, it is unclear if this difference is due to spatial variability of precipitation or related to the measurement technique itself.

The precipitation characteristics of five events are compared in Table 2. Looking at the standard deviation $\text{sd}(P)$ and coefficient of variation $\text{CV}(P)$ of the hourly precipitation measured in the lower and upper part of the catchment, it can be seen that the variability was significantly higher within the catchment in the Event #1 as compared to the other events. More details of this first event can be found in Table 2, where the total precipitation accumulated over the event period was computed for the upper and lower part of the catchment through the following four techniques (Table 2): Rain gauges, disdrometers, X-band dual polarization weather radar, and microwave link (provides a single path-averaged value along the trajectory of the link). Due

341 to the occurrence of hail in the upper part of the catchment, the ice phase
342 precipitation was removed from the total measured precipitation by the dis-
343 drometer near Transect E as seen in Table 3. It can be seen that the different
344 measurement techniques produce a range of precipitation accumulation val-
345 ues, with the highest recorded by the rain gauges (24 mm) and the lowest
346 by the radar (17 mm). This highlights the challenge in obtaining accurate
347 precipitation measurements.

348 **3.2 Soil moisture**

349 **3.2.1 Temporal evolution during SOP1**

350 A wide range of soil moisture conditions was captured during the SOP1, as
351 can be seen in the lower panel of Figure 3. Soil moisture measurements are
352 indicated by the points in the lower panel, the error bars provide information
353 related to the range seen at the individual transects (recall that the catchment
354 mean is an average of the six individual transect fields). At the beginning,
355 very dry conditions are measured with a soil moisture mean of 12.5 vol % first
356 recorded in mid-September. However, by the end of the observation period
357 the catchment has become significantly wetter with a catchment mean soil
358 moisture of 31.9 vol %. A maximum mean soil moisture is seen near the end
359 of November, after the occurrence of a significant rainfall event, for which

360 the catchment mean of 38.5 vol % was measured.

361

362 The difference among the six transects, as shown by the error bars in the
363 lower panel of Figure 3, can be seen to be quite small at the beginning of
364 the observation period when conditions are dry. The size of the error bars
365 increases along with increasing soil moisture. Details on the soil moisture
366 values obtained at the transect scale can be found in Table 1.

367

368 **3.2.2 Temporal variability: catchment and field scale**

369 Soil moisture shows a large temporal variability during the dry-wet transition
370 of SOP1, covering a large soil moisture range. Initial values at the end of sum-
371 mer were close to wilting point, and approached field capacity after repeated
372 precipitation events (Figure 3). In addition, there was also a large variabil-
373 ity of the mean soil moisture between the different transects throughout the
374 SOP. Approximate 95% confidence intervals for the transect means are shown
375 in Figure 5, calculated as two times the standard error assuming spatially
376 independent observations (based on the geostatistical analysis described in
377 section 3.2.3). Overlapping error bars imply that two transect means may
378 not statistically different. This assumption was further tested with the *post*
379 *hoc* Tukey Honestly Significant Difference test (interested readers are referred

380 to *Salkind* (2010)). The Tukey HSD test confirmed the results obtained from
381 comparing the transect means based on overlapping error bars. Visual in-
382 spection shows that on DOY 267, 270, and 334, the variability between the
383 different field means is quite low with all transect means having overlap-
384 ping error bars. This provides an indication of the variability throughout
385 the catchment as being small on those particular days. Interestingly enough,
386 a wide range of soil moisture conditions are seen on those days, with this
387 behaviour occurring in both dry, mid-range, and wet conditions. The length
388 of the error bars on these days provides insight into the variability within
389 the transect. The signal is slightly different at this smaller scale. On DOY
390 267, the error bar length of all transects is quite small, with DOY 270 and
391 334 displaying longer error bars, indicating more variability within the field.
392 It can be concluded that by sampling in a randomly selected field only, the
393 resulting field-scale soil moisture dynamics will not be representative for the
394 catchment scale mean.

395 **3.2.3 Spatial variability: catchment and field scale**

396 The relation between soil moisture variability and mean soil moisture at the
397 catchment and field scale is shown in Figure 6, where standard deviations
398 within-field and between-field along with soil moisture conditions are plotted
399 separately. Both plots are fitted with a linear regression line along with the

400 95% confidence interval lines. A better fit is seen for the between-field vari-
401 ability than within-field, as reflected by many more points falling outside the
402 confidence lines in the former than in the latter. However, it should be noted
403 that given a limited number of fields (6), the between-field variability cannot
404 be confidently implied through the computation of the standard deviation.
405 Nonetheless, using standard deviation as a measure of between-field variabil-
406 ity can still serve to compare between-field variability among the different
407 measurement days. During dry conditions, both variabilities show a small
408 standard deviation of approximately 2 vol %. In humid conditions, between-
409 field variability increases to approximately 3.5 vol % as the soil moisture
410 mean approaches 40 vol %. Within-field variability can be anywhere from
411 2.5 vol % to 7 vol %, with a maximum seen in very wet conditions of 8 vol %.

412

413 Although within-field variability exceeded between-field variability, some
414 evidence was found for the impact of landscape-scale controls on soil mois-
415 ture variability. To explore the existence of spatial structure at the transect
416 scale and the influence of topography (see Table 1 for differences in slope
417 among the transects), two empirical semivariograms (*Goovaerts*, 1997) were
418 computed for Transects A and F (Figure 7). The first semivariogram was
419 based on 101 randomly spaced points ranging from 1 cm to 2.8 m (upper
420 panel of Figure 7), as well as using all measurements collected throughout

the observation period at 2 m intervals (lower panel of Figure 7). Note that
Transect A and F represent end-members for slope and elevation in the Gazel
catchment. The standard deviations are plotted as error bars and based on
the approach shown in the upper panel (101 randomly spaced points), Tran-
sect A shows a larger variability. However, when all points at 2 m spacing are
averaged out for Transect A and F, the latter transect shows a significantly
greater variability as evidenced by the longer error bars. Large variability is
seen at small scales as evidenced by the large nugget in both transects. In
the lower panel, a difference among the transects is seen, with evidence of a
sill in Transect F that is not apparent in Transect A.

3.2.4 Temporal stability of the transects

In Figure 8, the transects have been sorted based on their mean difference
with respect to the spatial mean $\bar{\delta}_j$ in order to investigate the temporal or
rank stability of soil moisture in the Gazel catchment. *Teuling et al.* (2006)
showed that on individual dates the site that on average best represents
the catchment has a low probability of being identified. For that reason, to
identify the site that on average best represents the catchment mean, the
average of the spatial means computed for each of the observation days is
taken. Temporal variability, defined as the standard deviation of the spatial

mean difference $s(\bar{\delta}_j)$, is plotted as error bars. The transect with $\bar{\delta}_j$ closest to zero can be termed as the most rank stable site, and is best for representing the catchment mean.

444

Transect D was found to exhibit the highest rank stability. Not only does this field have the smallest mean difference with respect to the spatial mean, but the variability of this difference on any day was smallest, making this transect likely to be selected based on limited sampling.

3.2.5 Precipitation-induced spatial variability

To further investigate the occurrence of large differences among the transect means (Figure 5), including what hydrological processes may have contributed to these differences, the mean soil moisture observations on DOY 267 and 268 (Event #1) are investigated in more detail along with the precipitation data. On DOY 267 (23rd September 2012), Transects A and E had very similar transect mean soil moisture values (14.8 vol % and 14.2 vol % respectively). However, the following day a large scatter in the field means occurred where Transect A increased up to 32 vol % whereas Transect E increased only up to 23.9 vol %. This implies a difference in volumetric soil moisture of 8.1 vol % between the fields.

460

Looking at the precipitation data, it can be seen that disdrometer, rain gauge, and radar data (microwave data excluded due to only a single path-averaged estimate over the link available rather than values at discrete locations in space) all show higher precipitation occurring near Transect A rather than Transect E (Table 3). This analysis shows that the large spatial variability of precipitation was responsible for the creation of variance in the mean soil moisture among the transects over these two observation days.

Precipitation intensity is also relevant to analyse as it can influence soil moisture due to the occurrence of surface runoff from saturation or infiltration excess processes. The disdrometer recorded a maximum precipitation accumulation over a ten minute period of 34 mm and 21 mm, near Transect A and E, respectively. This is consistent with the accumulated rainfall amounts received in the lower part of the catchment, pointing towards a larger storm occurring at Le Pradel as compared to Mirabel during this time period.

If the difference (Diff) in soil moisture between the two days for Transects A and E is computed, the amount of infiltrated precipitation that is being measured in the top 6 cm on the day after the event can be inferred. *Brocca et al.* (2013) used soil moisture data to estimate 1 day and 4 day rainfall observations with satisfactory results at the basin level. In this study, a dif-

ference of 17.2 vol % (equals 10 mm of rain) and 9.7 vol % (6 mm of rain) was computed for the top 6 cm for Transect A and E, respectively. This preliminary analysis shows that the soil moisture measurements in the top soil only account for approximately half of what was measured as precipitation depth by the precipitation measurement equipment. This further illustrates the fast dynamics of the catchment, and the importance of surface runoff and drainage processes to deeper soil layers in this catchment.

3.2.6 Comparison between in situ and satellite data

A time series of the satellite data and the in situ observations over the SOP1 can be seen in Figure 4. The ASCAT output was rescaled with the in situ data through a linear regression using 14 days (Figure 4). A correlation coefficient of 0.55 was obtained through this approach. During some periods throughout the SOP1, there appears to be a small time shift between the two measurements. The time series is plotted on a daily time scale, however some days two measurements were performed followed by none the next day. To avoid gaps in the time series, the second measurement taken in a day was allocated to the following day. This approach could have contributed to the time shift seen between these two data sets. By removing one measurement point where the time difference between the in situ and satellite measurement was

the greatest, the correlation coefficient of the linear regression increases to 0.74. Despite the time shifts, overall the in situ observations agree well with the remote sensing data. Approximately two-thirds of the in situ measurements fall within the measurement uncertainty band of the ASCAT sensor. The spatial resolutions of the satellite and the in situ observations are quite different, hence it is to be expected that the two measurement types will not agree very well. In addition, satellite observations are representative for the top 2-3 cm, whereas the in situ measurements extend to a depth of 6 cm. Nonetheless, both data sets follow a similar signal, proving that the satellite data can be useful tool to fill in gaps of missing in situ data. This is in line with the results of previous studies on ASCAT soil moisture in France (*Albergel et al.*, 2009). However, it should be noted that replacement of in situ data by satellite data remains a challenge due to the need to calibrate satellite data with in situ data.

3.3 Runoff response

Five periods where precipitation occurred during SOP1 are shown in Table 2. Various characteristics are compared for these periods, namely: cumulative precipitation (P sum), standard deviation ($sd(P)$) and coefficient of variation ($CV(P)$) between the hourly precipitation in the upper and lower part

521 of the catchment, cumulative event flow ($Q_{event\ sum}$), runoff ratio (RR), an-
522 tecedent volumetric soil moisture ($\bar{\theta}_d$), post-event volumetric soil moisture
523 ($\bar{\theta}_{d+1}$), and ASCAT antecedent volumetric soil moisture (ASCAT $\bar{\theta}_d$). The
524 base flow has been removed to allow comparison among the different periods.
525 No antecedent or post-event soil moisture are available for Period 5, there-
526 fore, Figure 9 shows the hydrographs for the four periods where soil moisture
527 are available.

528
529 The first two events (Event #1 and #2) show minimal catchment re-
530 sponse, with very low cumulative event flow occurring. In both events, the
531 soil moisture increased significantly the day after the storm, showing that
532 the precipitation input served to replenish the soil moisture storage. The
533 influence of a dry catchment on runoff response is particularly interesting in
534 Event #1, where a significant amount of precipitation fell on the catchment
535 (49 mm), yet hardly any event flow was seen (0.17 mm). If the subsequent
536 events are explored, the catchment displays an entirely different response.
537 In Event #3 and #4, large precipitation amounts occur, resulting in signif-
538 icant rises in event flow. Although no in situ soil moisture measurements
539 were available prior to the last two events, *Massari et al.* (2013) showed that
540 this can be overcome by using ASCAT satellite data when no in situ soil
541 moisture measurement is available. By comparing satellite antecedent soil

moisture data with post-event soil moisture, a strong rise following precipitation is seen. By looking at the storm hydrograph, a fast response of event flow to precipitation input during Event #3 and #4 occurred, followed by a slow recession in the days after the storm. A similar signal is seen with the soil moisture measurements, in which a gradual decrease occurred after the precipitation event.

The antecedent soil moisture conditions appear to have a large influence on the occurrence of runoff processes in this catchment. This relationship was further investigated by analysing the runoff ratio for the five precipitation events shown in Table 2. In Figure 10a, the different runoff ratios are plotted against their corresponding re-scaled initial soil moisture from the ASCAT satellite sensor. The error bars for the runoff ratios are based on the error of the discharge as calculated through the difference between the minimum and maximum stage-discharge curves. The error bars for the re-scaled ASCAT initial soil moisture represent the re-scaled measurement error from the satellite. A generally increasing trend is seen where small runoff ratios occur for dry catchment conditions, and large runoff ratios correspond to wetter conditions. It can also be seen that small events are shown to result in very low runoff ratios during both dry and wet conditions. A strongly nonlinear relationship between (soil moisture) storage and runoff behaviour

563 can be hypothesized.

564

565 The event flow rate at the time of soil moisture measurements is also ex-
566 amined in Figure 10b. The error bars indicate the maximum and minimum
567 event flow rates (baseflow removed) due to the uncertainty in the stage-
568 discharge rating curve (derivation described in Section 2.5). The event flow
569 is shown to be quite variable for different soil moisture measurements, which
570 indicates that storm size is an important indicator along with catchment ini-
571 tial conditions. Small precipitation events will not induce a strong response
572 in event flow even during wet conditions. However, the catchment will re-
573 spond strongly to large precipitation events during wet and dry conditions.

574

575 4 Discussion

576 4.1 Methods

577 4.1.1 Soil moisture sensor selection

578 The selection of the soil moisture sensor used in the field determines the
579 depth and sampling volume of the soil throughout this study. By using the
580 portable ThetaProbe unit with a rod length of 6 cm, only the top soil was

581 measured. By looking at differences in soil moisture from two consecutive
582 measurements days in Table 3, it can be seen that approximately 50% of the
583 precipitation occurring between two measurements days (DOY 267 and 268)
584 was measured by this sensor in the top 6 cm. Assuming that surface runoff
585 and drainage processes being important in this catchment, the fact that the
586 soil moisture sensor manages to capture such a significant amount of the
587 precipitation further proves the usefulness of the field data for this study.

588

589 **4.1.2 Field and transect selection**

590 The selection of the fields determined the land use type that was measured,
591 which can influence soil moisture observations. In this study only pastures
592 and grasslands were chosen due to the large number of stones found in other
593 land use types which made it impossible to perform field measurements with
594 the probe. Although all land use types are important for runoff generation,
595 vineyards were not considered in this study due to measurement difficulties.

596

597 A 50 m transect within the field was selected to capture the spatial het-
598 erogeneity of the field, and was chosen in a way to account for the influence
599 of topographical feature and soil properties on soil moisture. Based on previ-
600 ous studies (*Western et al.*, 1998, 2004), soil moisture spatial patterns were

601 found to have correlation lengths between 30-60 m. This suggests that a
602 transect of 50 m is likely too small to fully capture spatial variation at the
603 field scale. Time constraints required that a single transect per field was
604 measured, as opposed to multiple transects in each field. Therefore, it was
605 necessary that the transect was chosen to account for spatial heterogeneities
606 to best represent the field through a single transect. A spacing of 2 m was
607 used in this study between discrete measurements along the transect. The
608 influence of this choice was tested by repeating 101 measurements in two
609 different fields, whereby the distances between discrete measurements were
610 as small as 1 cm. No spatial structure was seen on a scale smaller than 2 m
611 and so it was assumed that the choice of a 2 m spatial resolution did not
612 significantly impact the study.

613

614 **4.2 Temporal variability: catchment and field scale**

615 A summary of the transect scale volumetric soil moisture can be found in
616 Table 1 (initial, final and maximum volumetric soil moisture is shown), in
617 which the highest soil moisture was measured in Transect F. However, Tran-
618 sect C was the wettest field measured at the end of the observation period.
619 This transect has the highest clay content (Table 1), and is the only field in

620 close proximity to a ditch, where the influence of local groundwater on soil
621 moisture is possible.

622

623 **4.3 Spatial variability: catchment and field scale**

624 The between-field and within-field variance was found to be lower at drier
625 catchment conditions than at wetter conditions (Figure 6), which is contrary
626 to what was reported in recent studies, where a convex upward relationship
627 is becoming more prominent (*Famiglietti et al.*, 2008; *Brocca et al.*, 2010;
628 *Rosenbaum et al.*, 2012; *Brocca et al.*, 2012). This may be due to the high
629 infiltrating soils that characterize this catchment. Drainage processes can
630 contribute to the creation of variance on non-homogeneous soils (*Albertson*
631 *and Montaldo*, 2003), which is likely the case in this study due to the high
632 infiltrating soils that would increase the dynamics of this variance creation.

633

634 To test the influence of micro-topographical features on the variability
635 within the field, two empirical semivariograms were computed for Transects
636 A and F where small scale variability (measurement distances less than 2 m)
637 and the variability at the 2 m interval spacing selected for this study were
638 investigated (Figure 7). A much larger variability is seen in the upper panel

where 101 randomly spaced points were measured, as opposed to the lower panel, where averages of all measurements at 2 m spacings throughout the observation period was done. Differences in the semivariograms are seen which may be linked to topography among other factors such as soil properties. In the lower panel, the existence of a spatial structure at point distances greater than 30 m is seen in the field characterized by a large slope (Transect F). Large nuggets are found in both fields, indicating large variability at small scales. Both findings agree with *Brocca et al.* (2007), who stated difficulty in identifying a correlation lengths in flat areas.

4.4 Temporal stability of the transects

Transect D was shown to be the most rank stable site in the catchment, suggesting that this field would be the optimal site to sample if the catchment mean was to be approximated based on measurements in a single field. Transect D is characterized by the average topographical properties of all the fields (Table 1) in terms of slope, elevation and soil properties. In addition, this transect is found in the middle part of the catchment suggesting an average value for upslope drainage area. This is consistent with *Brocca et al.* (2009b), who found that sites which are most representative are "located in

658 areas reflecting average topography characteristics, in terms of elevation and
659 slope”. This suggests that the best transects for monitoring catchment mean
660 conditions can be selected a priori based on field characteristics.

661

662 **4.5 Precipitation-induced spatial variability**

663 The large local spatial variability of rainfall seen during the event beginning
664 on 23rd September 2012 (Event #1) is an influencing factor on the variabil-
665 ity of the soil moisture mean between the different fields, as evidenced by
666 the large difference in soil moisture measured at Transect A (lower) and E
667 (upper) of the catchment following the event (Table 3). However, this pre-
668 cipitation event was also shown to be characterized by some hail in the upper
669 part of the catchment. The ice phase precipitation was removed from the
670 disdrometer data located in this part of the catchment. The estimate of
671 amount of hail or duration remains difficult making the rain gauge the refer-
672 ence for precipitation (liquid water plus melted solid water) during this event.

673

674 **4.5.1 Satellite data instead of in situ data**

675 Capturing pre-event soil moisture measurements for short-term observation
676 can be a challenge, especially if reliance on accurate weather predictions days

in advance is required to reach the field site. Long-term options can include the installation of a fixed sensor beneath the soil surface, however, the installation process is intrusive and creates non-natural soil conditions enhancing preferential flow paths. This can lead to inaccurate estimations of catchment scale soil moisture when point measurements are used for upscaling. For a short term observation period, such as in this study, in addition to the desire to measure multiple locations, a portable unit was considered as the optimal solution.

The lack of pre-event in situ soil moisture measurements would normally limit the analysis of antecedent soil moisture and catchment response. Given the good agreement between the satellite and in situ soil moisture measured in this study, the gaps in pre-event in situ soil moisture data can be overcome by using satellite data to infer antecedent catchment scale soil moisture.

4.6 Catchment response to soil moisture

The effect of antecedent catchment soil moisture conditions on runoff processes was found to be significant in this catchment. By exploring the hydrographs of four selected events during the observation period (Figure 9), a

link between catchment response and wetness conditions could be made. A comparison between the first two events (Event #1 and #2) and the last two events (Event #3 and #4) shows strong rises in event flow following precipitation occurring only for Event #3 and #4. The runoff ratios for Event #1 and #3 show a difference of two orders of magnitude despite only approximately 20% more precipitation occurring in the latter as compared to the former event. This relatively small difference in precipitation amount as compared to runoff ratio, suggests that the antecedent soil moisture conditions strongly influence in the occurrence of storm runoff. In literature, several studies have shown the relation between antecedent soil moisture and runoff ratio (among others *Castillo et al. (2003)*; *Massari et al. (2013)*), but also the classical Curve Number method links antecedent soil moisture conditions with the runoff ratio (*Ponce and Hawkins, 1996*). *Massari et al. (2013)*, who performed a rainfall-runoff modelling study using varying sources of initial soil moisture data, including satellite, in situ, modelled, and constant input data, showed poor model performance when a constant initial soil moisture was used. *Norbiato et al. (2009)* made a link between larger runoff ratios occurring at higher antecedent soil moisture conditions in catchments characterized by an average sub-surface storage capacity (not an excessively small or large groundwater storage). Both studies show the importance of accurately estimating the initial soil moisture conditions for flood studies.

717

718 The relationship between catchment initial conditions and runoff ratio
719 shows an increasing trend with wetness conditions (Figure 10a), where runoff
720 is likely to occur above approximately 22 vol %. Given that runoff ratio is not
721 a physical quantity in itself, more information regarding the spatial character-
722 istics of precipitation during storm events and pre-event in situ soil moisture
723 observations would be useful to further analyse this hypothesis. In addition,
724 it is important to note that the upper and lower part of the catchment do not
725 respond similarly to precipitation input due to differences in geology. This
726 was reflected in differences in water level observations (not shown).

727

728 **5 Conclusion**

729 In this study, an attempt was made to capture spatial and temporal variabil-
730 ity of soil moisture with structured field measurements, and to compare these
731 measurements with different data sources (e.g. precipitation from different
732 sources, and soil moisture products from remote sensing techniques).

733 The spatial variability in soil moisture was seen to increase with wetness
734 conditions, at both the catchment and transect scale. Within-field variabil-
735 ity was found to be greater than between-field variability. A variation in

736 the nugget of the empirical semivariograms from the different transects sug-
737 gested the influence of micro-topographical features and soil properties on
738 spatial soil moisture variability. Large variability is seen even at very small
739 distances within the transects, making estimations of a correlation length
740 difficult. Topographical features (slope) may enhance spatial structure at
741 distances greater than 30 m within a transect as evidenced by a sill, however,
742 more measurements should be done to confirm the consistency of this finding.

743

744 Temporal stability in soil moisture conditions has been observed in the in
745 situ measurements. One particular transect exhibited the largest rank stabil-
746 ity of all the six fields. This transect can be characterized as displaying aver-
747 age values for upslope drainage area, elevation, slope and soil properties, as
748 compared to the other fields in this study. This indicates that if the selection
749 of a representative site is desired for catchment mean soil moisture estima-
750 tion, sites displaying average characteristics should be considered. However,
751 it was also shown that the spatial characteristics of rainfall influence the
752 spatial variability of soil moisture within the catchment. Differences of soil
753 moisture between two fields increased from less than 1 vol % to greater than
754 8 vol % following the occurrence of a highly spatially variable precipitation
755 event. This highlights the importance of obtaining high spatial-resolution
756 and reliable rainfall measurements even at the small catchment scale. When

757 a limited number of soil moisture measurements is considered as catchment
758 representative, the spatial variability of precipitation events should be taken
759 into account.

760 .

761 Comparison of the in situ soil moisture measurements with the ASCAT
762 soil moisture product lead to a correlation coefficient of 0.55. In general the
763 data agreed well and followed a similar signal, even though both techniques
764 have different spatial resolutions and a different measuring depth (6 cm for
765 in situ measurements versus 2-3 cm for the satellite product). The results
766 showed that there is large potential for satellite data to complement in situ
767 data.

768 Runoff response was shown to be highly dependent on antecedent soil
769 moisture conditions. Runoff ratios varied by two orders of magnitude with
770 a difference of precipitation input of less than 20% between two events. The
771 strong influence of initial soil moisture conditions on runoff generation fur-
772 ther underlines the importance of antecedent catchment conditions for flood
773 prediction at the catchment scale. In the absence of in situ soil moisture
774 data, satellite data can be a good indicator for catchment conditions.

775

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Table 1: Summary of the transect mean in situ volumetric soil moisture (vol %) over the fall 2012 SOP, along with limited topographical and soil properties, as well as land use for each of the transects measured. Initial, final and maximum mean in situ volumetric soil moisture is shown for each of the transects as Initial θ_v , Final θ_v and Max θ_v , respectively.

Transect	Slope (-)	Porosity (-)	% Sand	% Silt	% Clay	Initial θ_v	Final θ_v	Max θ_v	Land Use
A	0.006	0.55	43	12	45	12.57	30.68	36.69	pasture
B	0.133	0.53	47	18	36	13.50	27.59	36.13	pasture
C	0.059	0.66	35	19	46	16.09	35.34	38.64	grassland
D	0.120	0.59	44	20	36	14.68	33.63	36.52	grassland
E	0.130	0.59	42	16	42	14.23	32.42	42.74	grassland
F	0.230	0.62	46	17	38	14.51	31.47	43.22	grassland

Table 2: Comparison of five precipitation events during the fall 2012 SOP. P Sum represents the total accumulated hourly precipitation as measured by the disdrometers over the event period. Standard deviation and coefficient of variation, denoted by $sd(P)$ and $CV(P)$, of the precipitation data measured at the Le Pradel and Mirabel locations. Q_{event} Sum represents the flow discharged over the event period, with pre-event discharge denoted as Q_i . The runoff ratio (RR) is calculated by dividing Q_{event} Sum by P Sum. The volumetric soil moisture prior to the precipitation event for in situ and satellite sources are represented by θ_i and ASCAT θ_i , respectively. The post-event in situ volumetric soil moisture data is denoted by θ_{i+1} . Dates include: 23-28 September (Event #1), 19-22 October (Event #2), 9-17 November (Event #3), 22 November-1 December (Event #4), and 23-31 October (Event #5).

Characteristic	Units	Event #1	Event #2	Event #3	Event #4	Event #5
P Sum	mm	49	8	63	45	47
$sd(P)$	mm	0.04	0.002	0.002	0.005	0.006
$CV(P)$	-	0.13	0.03	0.005	0.02	0.02
Q_{event} Sum	mm	0.17	0.0079	21.17	18.85	0.39
Q_i	l s^{-1}	0.44	0.78	14.3	13.1	0.97
RR	-	0.0035	0.0012	0.29	0.38	0.011
θ_i	vol %	14	23	-	-	-
θ_{i+1}	vol %	27	31	34	39	-
ASCAT θ_i	vol %	16	23	22	24	27

Table 3: Influence of spatial variability of precipitation on volumetric soil moisture variability among Transect A and E during Event #1. Hourly accumulated precipitation amounts from the rain gauge (Gauge), disdrometer (DSD), radar (Radar) and microwave link (Link) are shown. P calc denotes the precipitation estimate using the differences of in situ soil moisture measurements from the 23rd (2309) and 24th (2409) September 2012 over the top 6 cm.

Transect	Soil Moisture (vol %)				Precipitation (mm)				Max Int (mm 10 min ⁻¹)
	2309	2409	Diff	P calc	DSD	Gauge	Radar	Link	P int
A	14.8	32.0	17.2	10	24	30	23	-	34
E	14.2	23.9	9.7	6	15	18	11	-	21
Catchment					20	24	17	19	

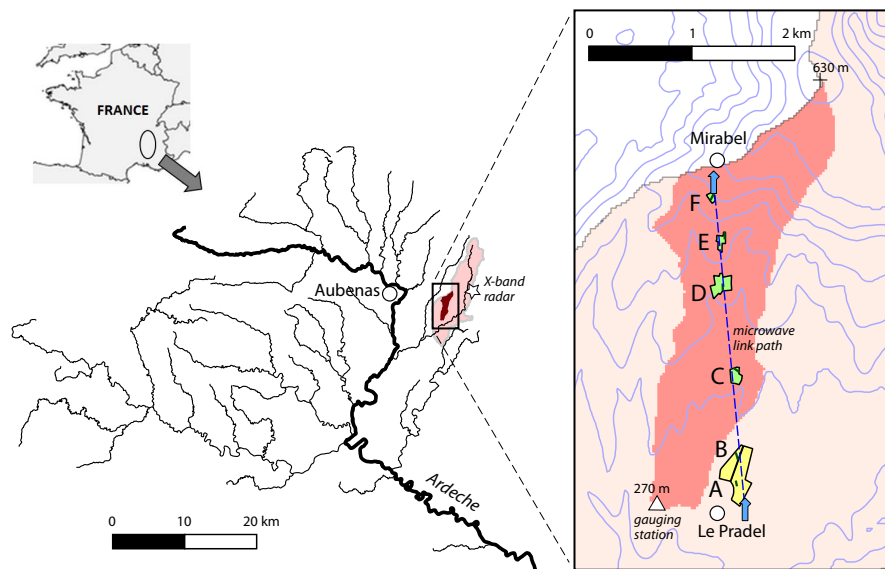


Figure 1: Map of the Ardèche catchment and the Gazel sub-catchment, including measurements being done over the fall 2012 SOP1 in the Gazel catchment. Blue arrows indicate the locations of the disdrometer, rain gauges, as well as the transmitting and receiving ends of the microwave link. Circles represent the villages of Mirabel and Le Pradel. Letters show the locations of the 50 m transects measured throughout the SOP1, which are found in line with the microwave link path (dotted line). The rain gauge operated by Météo-France is located within 200 m of the lower blue arrow at Le Pradel.

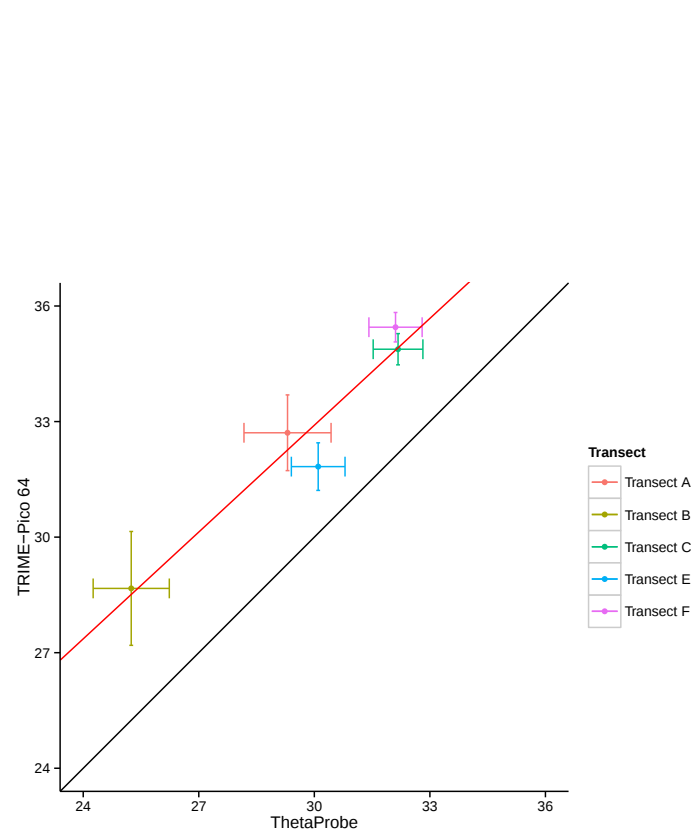


Figure 2: Comparison of volumetric soil moisture transect means on the 14th November 2012 with the ThetaProbe (rod length 6 cm) and TRIME-Pico 64 (rod length 16 cm). Error bar lengths based on the standard error SE of the transect means.

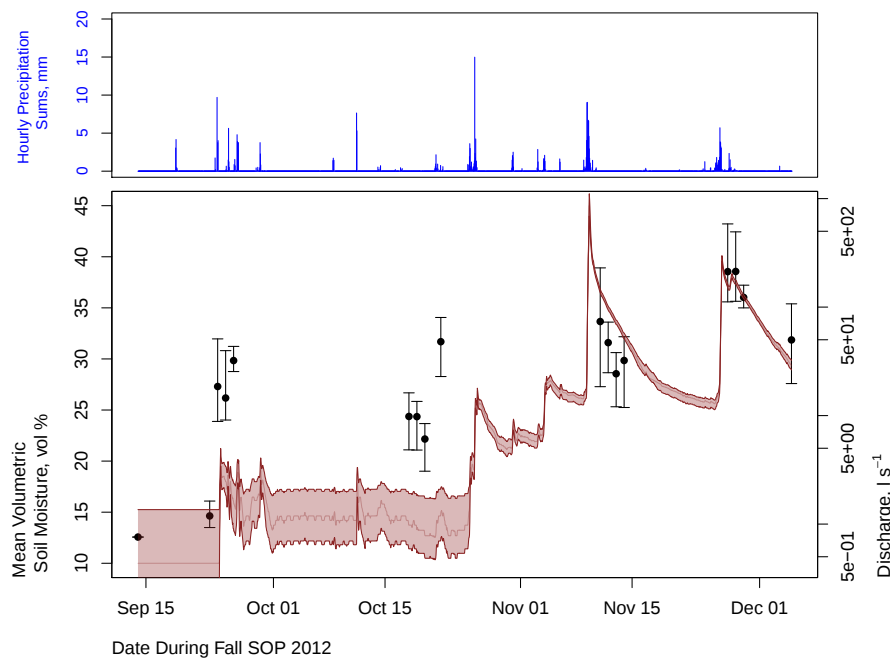


Figure 3: Upper panel: Hourly accumulations for precipitation in mm as estimated by averaging the two disdrometers located in the upper and lower part of the catchment. Lower panel: Mean volumetric in situ soil moisture (vol %) at the catchment scale throughout the SOP. The brown curve shows the discharge in l s^{-1} , with catchment mean volumetric in situ soil moisture measurements (black dots) along with $\pm$ standard deviation as error bars. Four precipitation events are seen on the following dates: 23-28 September (Event #1), 19-22 October (Event #2), 9-17 November (Event #3), and 22 November-1 December (Event #4).

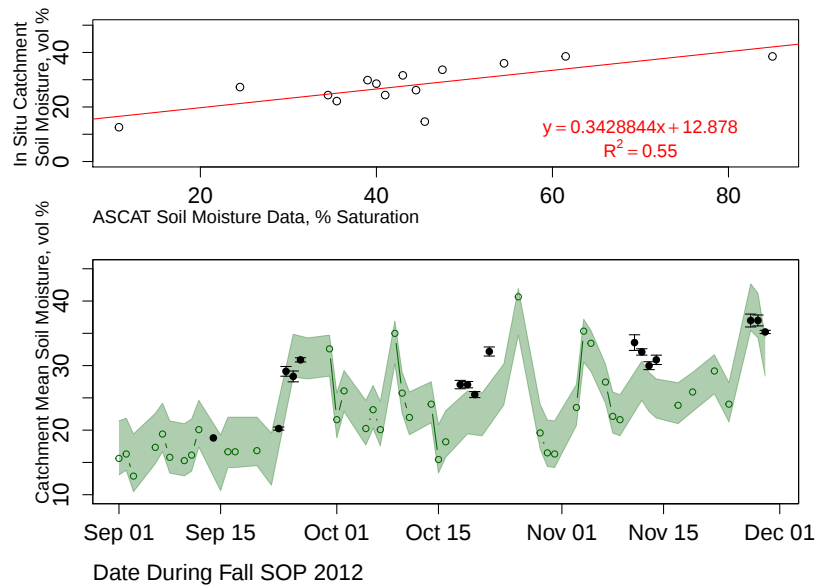


Figure 4: Upper panel: Linear regression of ASCAT satellite observations with in situ volumetric soil moisture measurements (daily catchment means). Lower panel: Time series of ASCAT volumetric soil moisture (open circles) as derived by a linear regression with in situ catchment mean measurements. The error bands (green band) represent the measurement error for the re-scaled ASCAT (*Figa-Saldaña et al.*, 2002) data. Catchment mean in situ volumetric soil moisture measurements (filled circles) with error bars based on $\pm$ the standard deviation are also shown.

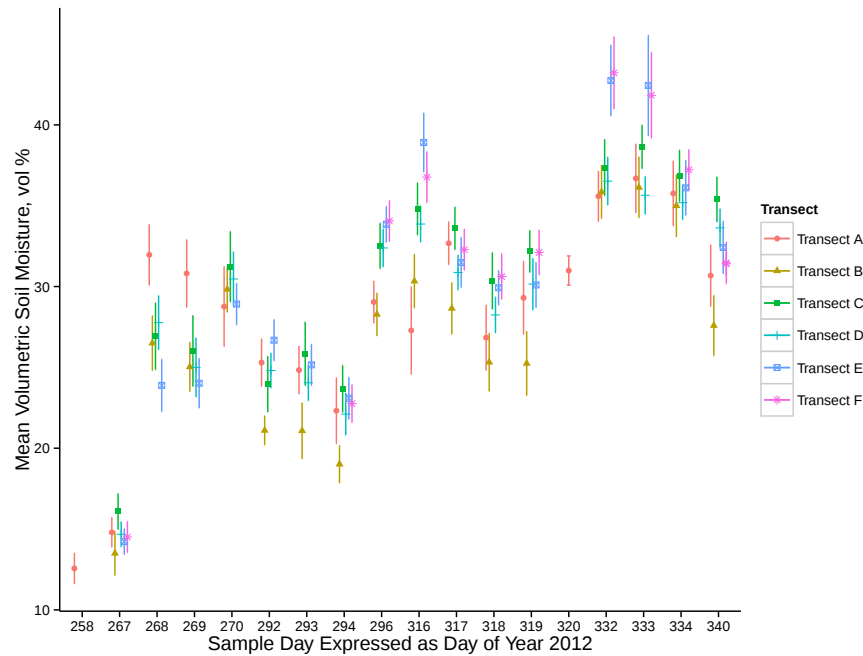


Figure 5: Transect mean volumetric in situ soil moisture for all measurement days as represented by Day of Year (DOY). Error bars indicate 2 times $\pm SE$.

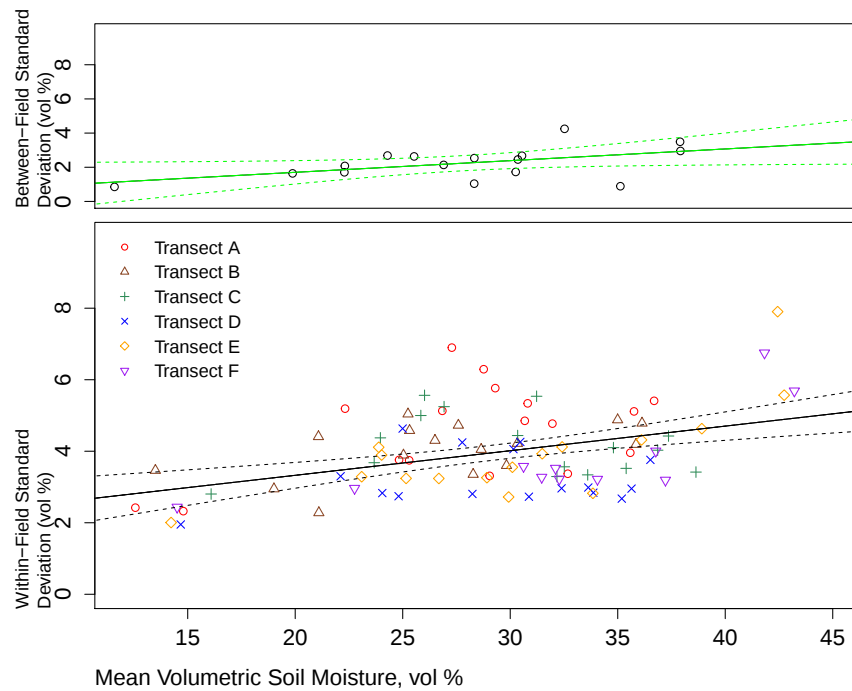


Figure 6: Relationship between mean volumetric in situ soil moisture (vol %) and standard deviation at varying soil moisture conditions. Dotted lines represent a linear fit of the data and solid lines denote the 95% confidence intervals. Upper panel: within-field variability. Lower panel: between-field variability.

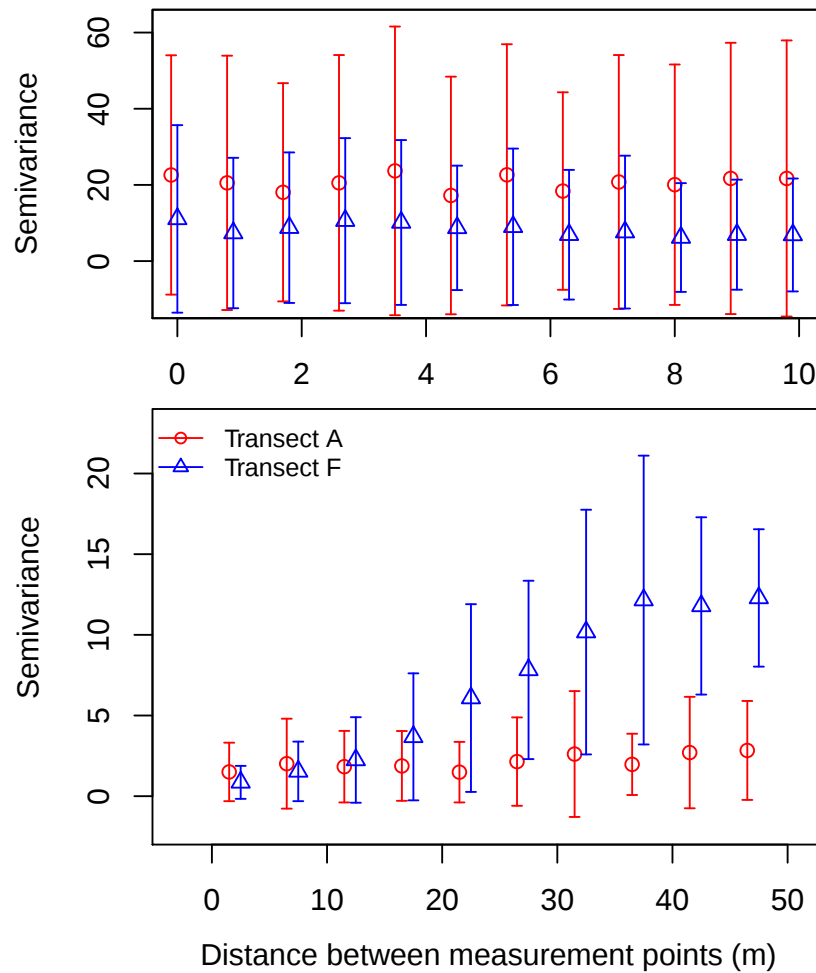


Figure 7: Semi-variogram for Transects A (red circles) and F (blue triangles) with $\pm$ standard deviation as error bars. Upper panel: based on a single measurement day in Transect A and F of 101 randomly spaced intervals, with distances ranging from 1 cm to 2.8 m. A lack of spatial structure at scales smaller than 10 m is seen here. Lower panel: based on all volumetric soil moisture measurement points done during the observation period at a 2 m interval spacing in Transect A and F. The semivariance is seen to be lower here due to averaging out over all measurement days. A clear spatial structure is seen on the average soil moisture conditions for Transect F.

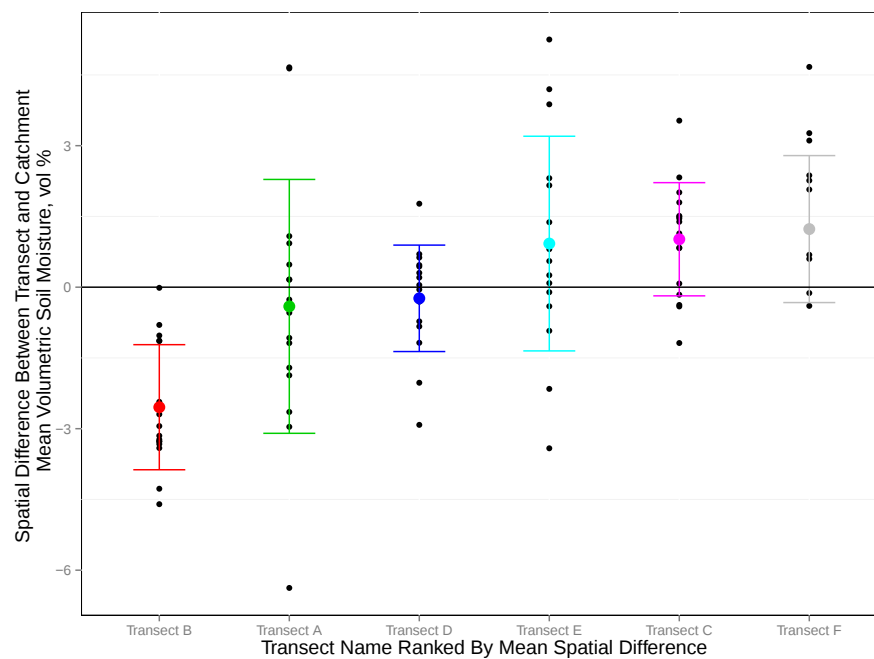


Figure 8: Rank stability plot for the different transect volumetric soil moisture means showing Transect D to be the most temporal stable transect. Black points indicate the spatial difference for each measurement day, the coloured points represent the mean over all measurement days. Error bars correspond to ± 2 times the standard deviation of the spatial differences.

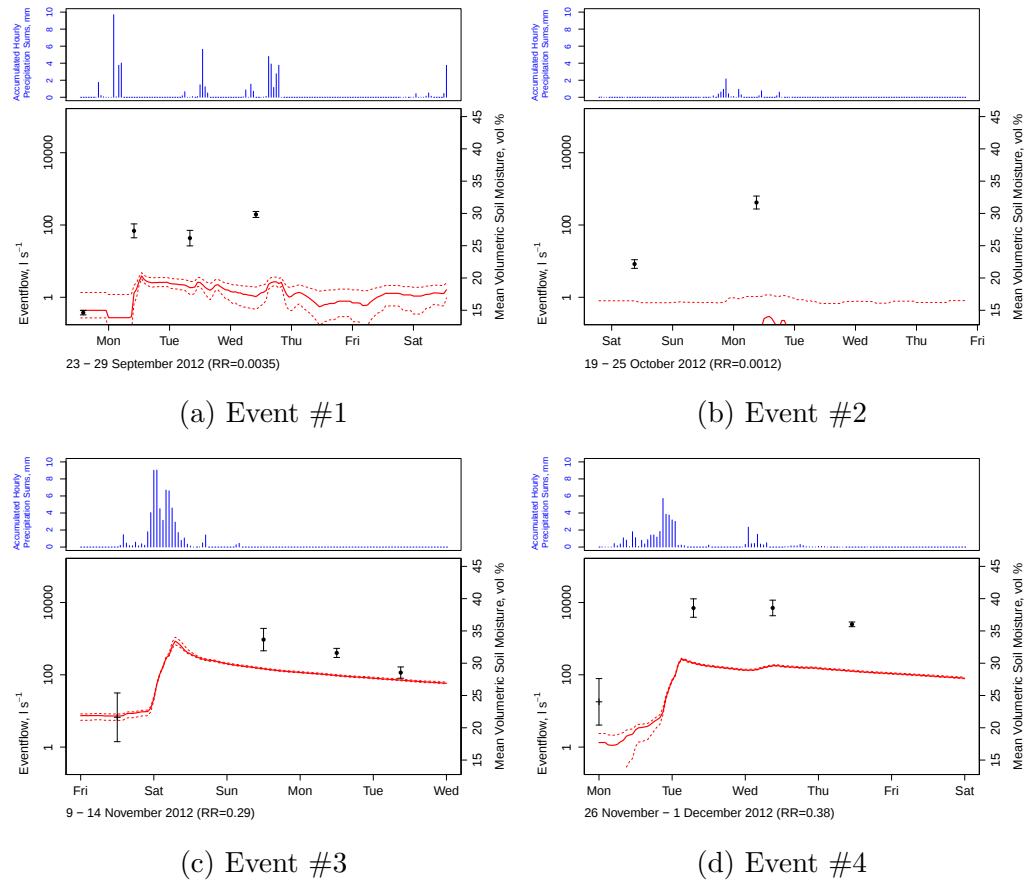


Figure 9: Influence of antecedent soil moisture conditions and precipitation on catchment response during four storm events are shown. Upper panels show hourly precipitation sums in mm as measured by an average of the two disdrometers located in the lower and upper part of the catchment. The lower panels display event flow (baseflow removed) plotted on a log scale as l s^{-1} as a solid red line. Dotted lines indicate the maximum and minimum limits of the discharge based on the error of the stage-discharge curve. The catchment mean volumetric soil moisture is shown in vol % as in situ data (filled circles) and ASCAT data (crosses). RR denotes the runoff ratio.

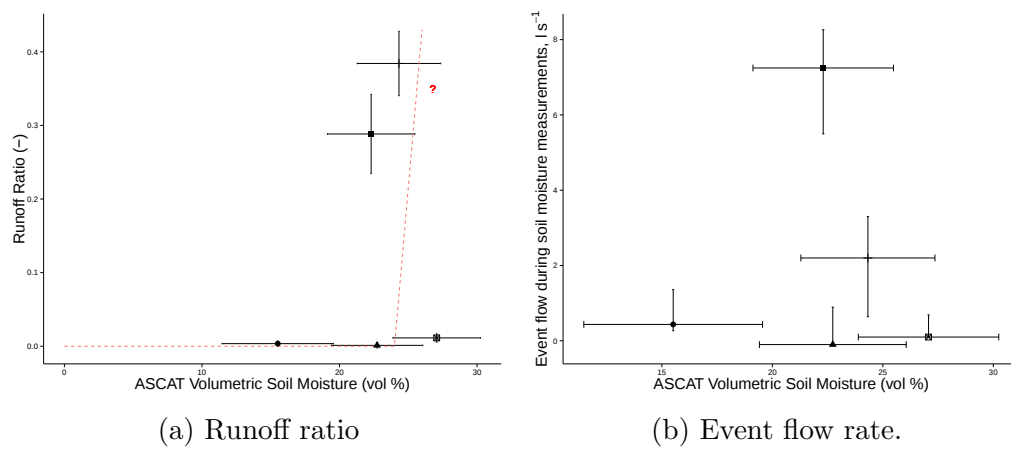


Figure 10: Relationship between runoff ratio (a) and event flow rate in l s^{-1} (b) with initial soil moisture content (source: ASCAT) for five precipitation events during the fall 2012. The different events are represented by the following symbols: diamonds (Event #1, 23-28 September), solid squares (Event #2, 19-22 October), triangles (Event #3, 9-17 November), no symbols (Event #4, 22 November-1 December), and hollow squares (Event #5, 23-31 October).