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Spatio-temporal variability of soil water content on the local scale in a Mediterranean mountain area (Vallcebre, North Eastern Spain). How different spatio-temporal scales reflect mean soil water content

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SUMMARY

As a result of complex human-land interactions and topographic variability, many Mediterranean mountain catchments are covered by agricultural terraces that have locally modified the soil water content dynamic. Understanding these local-scale dynamics helps us grasp better how hydrology behaves on the catchment scale. Thus, this study examined soil water content variability in the upper 30 cm of the soil on a Mediterranean abandoned terrace in north-east Spain. Using a dataset of high spatial (regular grid of 128 automatic TDR probes at 2.5 m intervals) and temporal (20-min time step) resolution, gathered throughout a 84-day period, the spatio-temporal variability of soil water content at the local scale and the way that different spatio-temporal scales reflect the mean soil water content were investigated.

Soil water content spatial variability and its relation to wetness conditions were examined, along with the spatial structuring of the soil water content within the terrace. Then, the ability of single probes and of different combinations of spatial measurements (transects and grids) to provide a good estimate of mean soil water content on the terrace scale was explored by means of temporal stability analyses. Finally, the effect of monitoring frequency on the magnitude of detectable daily soil water content variations was studied.

Results showed that soil water content spatial variability followed a bimodal pattern of increasing absolute variability with increasing soil water content. In addition, a linear trend of decreasing soil water content as the distance from the inner part of the terrace increased was identified. Once this trend was subtracted, resulting semi-variograms suggested that the spatial resolution examined was too high to appreciate spatial structuring in the data. Thus, the spatial pattern should be considered as random. Of all the spatial designs tested, the 10×10 m mesh grid (9 probes) was considered the most suitable option for a good, time-stable estimate of mean soil water content, as no improvement was obtained with the 5×5 m mesh grid (30 probes). Finally, the results of temporal aggregation showed that decreasing the monitoring frequency down to 8 h during wetting-up periods and to 1 day during drying-down ones did not result in a loss of information on daily soil water content variations.

1. Introduction

Both hydrological processes and land atmosphere interactions are strongly controlled by near-surface soil water content and its spatio-temporal variability (e.g. Bárdossy and Lehmann, 1998; Famiglietti et al., 1998; Loague, 1992). The spatial variability of soil water content in the upper soil layer strongly depends on the working scale. This dependence is a common issue when attempts are made to combine information from different spatial scales (Famiglietti et al., 2008; Western and Blöschl, 1999). In addition to precipitation and evaporation dynamics that influence soil water content temporal patterns, soil type, vegetation and topography are expected to control spatial soil water content variability on the catchment scale (Blöschl and Sivapalan, 1995; Brocca et al., 2007). Grayson et al. (1997) distinguished between "local" controls, which operate during dry periods and induce high soil water content spatial variability, and "non-local" controls (such as topography), which are normally present in wet periods and promote low spatial variability. These controlling factors can be more easily

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identified when different locations within a catchment are compared (e.g. Garcia-Estringana et al., 2013; Mohanty and Skaggs, 2001; Williams et al., 2003), especially in areas where soil and vegetation spatial heterogeneities are important, inducing marked differences in soil water content dynamics (Williams et al., 2003).

Even though it is generally recognised that soil water content variability increases with the size of the spatial domain, detailed studies of soil water content at the plot scale still require a great many measurements to achieve good accuracy (Brocca et al., 2009; Famiglietti et al., 2008). A clear picture of soil water content variability at the plot scale is still difficult to achieve because, till now, results have been contradictory, especially because of the numbers of probes required for a robust estimation of the mean soil water content and the dependency of the latter on soil wetness conditions (Brocca et al., 2009; Hupet and Vanclooster, 2002; Jacobs et al., 2004). Calculating the relationship between the spatial variability (in terms of standard deviation, variance or variation coefficient) of soil water content and its mean area value is a common procedure to characterize soil water content variability and its dependency on wetness conditions. Currently, geostatistical and temporal stability analyses are also used, to characterize the spatial structure of soil water content and its persistence in time (Vachaud et al., 1985; Western and Grayson, 1998). Another important question to take into account when studying soil water content at the plot scale is sampling frequency, i.e. the temporal aggregation effect (Robinson et al., 2008). Most of the studies focusing on soil water content dynamics have emphasized the need for good spatial sampling, but have measured the soil water content only at weekly or higher temporal scales (e.g. Brocca et al., 2007; Comegna and Basile, 1994; Hupet and Vanclooster, 2002; Mohanty and Skaggs, 2001; Williams et al., 2009). More recently, technical advances on sensors and data logging systems have made it possible to monitor soil water content at high temporal resolutions (Herkelrath et al., 1991), to schedule irrigation (e.g. Fares and Alva, 2000), to conduct water balance studies (e.g. Vera et al., 2009) and to understand transpiration dynamics (e.g. Ungar et al., 2013). However, information focusing on the effect of temporal aggregation on soil water content is still rather limited. Guber et al. (2008) studied the effect of reducing sampling frequency (from 10 min to 7 days) on the temporal stability of soil water content and on the utility of "representative" locations (Vachaud et al., 1985) for calculating mean soil water content at different depths. Their results showed there was no effect when the sampling frequency was decreased.

When designing an experiment for measuring soil water content, a compromise between the spatial and temporal representativeness of the measurements and the effort needed for the experiment's implementation has to be found. At this stage, two main questions typically arise: (i) How many probes are needed? and (ii) At what time step should soil water content be measured?

To answer these two questions, this paper reports a study of soil water content dynamics on the local scale using data with a high spatial and temporal resolution. The main objective is to analyse the effect of spatial and temporal measuring scales on the estimation of mean areal soil water content and its accuracy.

To attain this objective, this study aims to answer the following questions:

1. What is the spatial variability and temporal dynamics of soil water content on the local scale?
2. What is the most suitable spatial design for measuring soil water content with the minimum number of probes?
3. Which is the most appropriate monitoring frequency for capturing soil water content dynamics accurately?

2. Materials and methods

2.1. Study area

The monitored area is located in the Can Vila catchment, in the Vallcebre research area.

The Vallcebre research area (Latron et al., 2010a) is located on the southern margin of the Pyrenees at the headwaters of the Llobregat river. The area is close to Vallcebre village, 130 km north-east of Barcelona, NE Spain (42°12′N, 1°49′E). The research area was selected in early 1990 to analyse the hydrological consequences of land abandonment, as well as the hydrological and sediment yield behaviour of badlands areas. A complete overview of general hydrological findings in the Vallcebre research area can be found in Latron et al. (2009, 2010a, 2010b); Llorens et al. (2010); Gallart et al. (2010). Results on soil water content dynamics in the area have been recently summarized by Garcia-Estringana et al. (2013).

The Can Vila catchment has an area of 0.56 km^2 and is oriented in an SW–NE direction. Elevations range from 1458 m a.s.l. to 1115 m a.s.l. at the outlet; slope gradients are moderate, with a mean value of 25.6% (Latron and Gallart, 2007). The soils that have developed over red clayey smectite-rich mudrocks are predominantly of silt-loam texture. Topsoils are rich in organic matter and well structured, with high infiltration capacity, although hydraulic conductivity decreases rapidly with depth (Rubio et al., 2008).

Before and during the 19th century, hill-slopes were deforested and terraces, 10–20 m wide, were built for agricultural use over more than 70% of the catchment. During the second half of the 20th century, these were steadily abandoned. As a consequence of terracing, soil thickness ranges from less than 50 cm in the inner part of the terraces to more than 2 or 3 m in their outer part (Rubio et al., 2008). Following land abandonment, spontaneous forestation by *Pinus sylvestris* has occurred (Poyatos et al., 2003) and forest now covers 34% of the catchment. The remainder of the catchment is widely covered by pasture and meadows. Climate is defined as humid Mediterranean and is highly seasonal, leading to periods with a marked water deficit in summer (Latron et al., 2010b). Mean annual temperature at 1260 m a.s.l. is 9.1 °C and long-term (1983–2006) mean annual precipitation is 862 mm (standard deviation, s.d. = 206 mm), with a mean of 90 rainy days per year. The rainiest seasons are autumn and spring. Winter is the season with the least precipitation. In summer, convective storms may provide significant precipitation input. Long-term (1989–2006) mean annual potential evapotranspiration, calculated by the Hargreaves and Samani (1982) method, is 823 (s.d. = 26 mm).

The area monitored is an old abandoned agricultural terrace located in the central part of the Can Vila catchment with a vegetation cover of homogenously distributed mesophile grass. The general slope gradient near the monitored terrace is about 15%. However, due to the terraced topography, the specific gradient of the monitored terrace is lower (9.8%). Soil depths estimated by manual drilling range from less than 1 m in the inner part of the terrace (i.e. close to the margin of the terrace located above) to around 3 m in the outer part. In the first 30 cm, the soil has a silt loam texture with marked textural homogeneity, both lateral and vertical. Bulk density increases with depth from about 0.9 g cm^{-3} in the top layer to 1.6 g cm^{-3} at 50 cm. Organic matter content is high in the top layer (about 10%) and decreases with depth (less than 0.5% at 50 cm) (Rubio et al., 2008). A sampling transect perpendicular to the inner part of the terrace (14 samples at 0–30 cm depth) resulted in mean bulk density of 1.17 ± 0.09 g cm^{-3} and mean organic matter content of 11.2 ± 0.85%, showing the low spatial variability of soil properties in this terrace.