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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Analysis of near-surface soil moisture spatial and temporal dynamics in an experimental catchment in Southern Italy

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Abstract

Management of water resources in basins under Mediterranean climate is based on the knowledge of the complex interaction among rainfall, evapotranspiration, streamflow discharge, and changes in water storage. Understanding the spatial and temporal evolution of such relations is a key issue for obtaining reliable applications of hydrological models. In this study we identified the water dynamics involved in the catchment-scale water balance within a sub-humid area in Southern Italy. To meet this objective, precipitation and evapotranspiration were retrieved through data recorded by a weather station whereas water discharge was monitored at the water reservoir delimited by an earth dam in the outlet of the Alento River 102.5 km^2 catchment. The landuse is dominated by pasture, orchard and grassland and the main terrain attributes have been calculated from a 5 m DEM. Six hillslope transects have been delineated along hillslopes in order to capture soil variability. Surface soil water content has been monitored with a portable TDR device along the aforementioned transects with a spatial interval of 50 m in 10 field campaigns, from October 2004 to January 2005. Mediterranean climate is characterized by dry summers with strong water deficit and wet winters with replenishment of the water reservoir. In the dry season, soil water content has high temporal instability and is mainly influenced by the aspect and tangential curvature. On the other hand during the wet season, near saturation conditions of soil surface are able to diagnose rapid streamflow response since rainfall events generate runoff and subsurface later flow. Soil water content is more stable and shows a significant correlation with the slope and the wetness index.

Keywords: soil water content, topography, water balance, streamflow, catchment scale, water resources.

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1. Introduction

Fresh water is a renewable resource that re-generates continuously through the hydrologic cycle which begins by incoming precipitation and snowfall within a natural watershed. The ever increasing water demand to satisfy multiple uses, including agricultural, industrial, household, recreational and environmental, is already exceeding available supply in many parts of the Mediterranean areas. Nevertheless water management in such regions is characterized by the alternation between wet winters with abundant precipitation inducing water replenishment and very dry summers with exceeding water depletion. Therefore the proper prediction of water budget through hydrologic models is of strategic importance to prevent water deficit in the dry season. Gaining a better understanding on the seasonal interactions of hydrological processes at large scales such as precipitation, evapotranspiration, soil water capacity, deep drainage, runoff and water discharge is the key target for watershed management under Mediterranean climate [16].

The strong seasonal patterns determine quite dramatic changes of soil moisture in the upper soil layer which constitutes a precious indicator of hydrological response over a large-scale study area [18,20,22]. Implementation of a program to monitor surface soil water content must necessarily involve a large number of accurate on-site measurements especially immediately following significant precipitation events in order to capture the response of the study catchment [10,4]. Characterizing spatial and temporal variability of surface soil moisture can be achieved either through airborne remote sensing techniques [13, 12] and through ground-point measurements [9,3]. These two techniques differ on the measurement resolution and support scale: the former attributes "averaged" soil moisture values to footprint scale (usually 800m $\times$ 800m) whereas the latter relies on support size of few centimeters. Therefore airborne images already capture somehow the soil heterogeneity given by the combined interaction of soil, vegetation, and topography. On the other hand point-scale measurements of soil moisture have to be spatially organized in efficient sampling schemes (transects, grids, random fields) in order to closely capture soil heterogeneity [19]. The choice of these two alternative techniques basically depends on financial resources and time scale.

Several studies in scientific literature report the main physical controls that influence soil moisture variability at catchment or hillslope scales [23,5,7]. Whilst the spatial variability of soil hydraulic properties plays a preponderant role, other factors notably contribute in determining the spatio-temporal patterns of soil moisture such as vegetation characteristics, climatic variability within the catchment, topographical properties and land use [17,14,21,15,6,8]. The brief analysis offered in this manuscript represents a preliminary assessment of spatio-temporal variability of near-surface soil moisture using data collected in 10 field campaigns, from October 2004 to January 2005, along experimental transects located in a 102.5 Km^2 watershed under Mediterranean climate. The specific aims of this work are *i*) to capture the seasonal response of soil water content patterns to climate variability and *ii*) to analyze the impact of terrain attributes on soil moisture changes from the dry to the wet season.

2. Materials and methods

2.1. Study location

Fig. 1 illustrates the Alento River basin (Campania Region, Italy) which has a drainage area of about 102.5 km^2. An earth dam at its lower section delimits an artificial lake which functions as a water reservoir for multiple-uses. The 5m-DEM (Digital Elevation Model) permits to infer directly the primary terrain attributes (slope, elevation, aspect, tangential curvature, profile curvature) and indirectly the compound topographic indexes such as the wetness index [2].

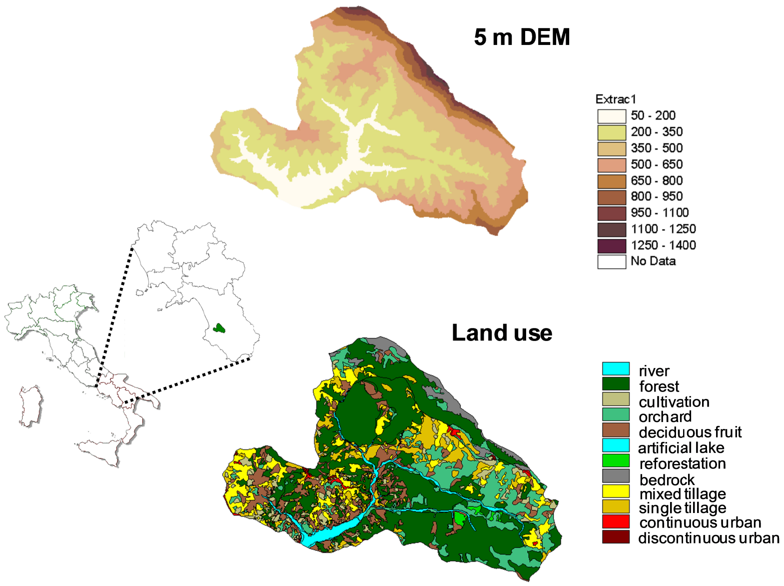

Fig. 1. Geographical location of the experimental watershed with the 5-DEM and Landuse maps.

Bedrock is mainly constituted by an arenaceous-argillitic carbonatic substratum that is scarcely permeable, therefore the rare deep hydraulic circulation events lead to dominant surface and sub-lateral flows during the wet season. The characteristic Flysch of Cilento dominates in this region by generating soils ranging from Vertisols to Mollisols, Inceptisols and Entisols.

The land use map shown in Fig. 1 indicates a heterogeneous situation ranging from extended mostly implanted forests (*Quercus cerris*, *Castanea sativa*, *Eucaliptus camaldulensis* and *Pinus pinaster*), mediterranean macchia (*Crataegus monogina*, *Erica arborea*, *Prunus spinosa*, *Cornus sanguinea*, *Arbutus Unedo*, *Phillyrea latifoglia*, *Myrtus communis*, *Juniperus phoenicea* and *Genista cilentina*), uncultivated grass substratum (*Bromus erectus* and *Brachypodium sylvaticum*) and different agricultural cultivations: vineyards, deciduous fruit, orchard and olive tree.

Mean annual rainfall (R) is about 93 cm/year and mean annual temperature (T) is about 16°C from 1926 to 1988 with significant seasonal disproportion that is typical of Mediterranean climate. The wet and relatively cold season occurs in fall, winter and early spring ranging between October (15.28 cm and 16.8°C) up to April (10.68 cm and 12.1°C) with maximum precipitation of 17.1 cm in December. The dry and hot season extends on the remaining months of the year ranging from May (4.41 cm and 16.9°C) to September (5.17 cm and 20.8°C) with minimum precipitation of 2.21 cm in July (see Fig. 2). The dry season is characterized by prolonged drought events. Snowfall is a rare event in this region since the average temperatures during the wet season rarely decrease below 0°C.

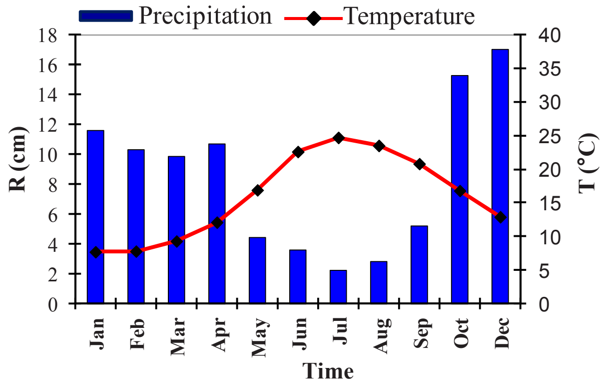

Fig. 2. Monthly climate normals (1926-1988) with total annual amount of rainfall (R) of 106.68 cm and average annual temperature (T) of 15.3°C.

2.2. Measurements

Six hillslope transects have been selected across the major soil-landscape units in order to capture as much as possible spatial heterogeneity [11]. The selected hillslope transects are characterized by slopes ranging from 10% up to 50%. Surface soil properties have been measured on soil samples collected along the hillslope transects with a spatial interval of 50 m. In the same locations, soil water content has been monitored with a portable Time Domain Reflectometer technique (TDR) in 10 field campaigns, from October 2004 to January 2005. The sampling days were established after significant rainfall events. Dielectric constant of the soil was measured with probes 15 cm long, connected to a reflectometer controlled by a palm-size pc. Specific laboratory gravimetric tests were performed to assess the regression equation employed for transforming the dielectric constant on the soil into soil water content.

In close proximity to transect#1, an automatic weather station (40° 22' N, 15°12' E) was installed in June 2004. The station monitored at 15-min interval air temperature, relative humidity, wind speed, and net solar radiation. Precipitation was recorded at 1-min interval and all measurements were acquired at about 2 m height. Reference evapotranspiration (ET_p) was computed with Penman-Monteith equation for FAO56 reference crop [1] during the period of the sampling campaigns.

Daily discharge (Q) at the Alento catchment outlet was retrieved by water balance of the dam reservoir, based on daily storage and volume uptakes data provided by the dam manager.

3. Results and discussion

3.1. Data analysis

To analyze the spatial (defined by the position-counter j) and temporal (defined by the time-counter i) variability of soil moisture values ($\theta_{j,i}$), the following statistical indicators will be employed in this study: standard deviation, σ_i, for each sampling campaign i, to evaluate data dispersion around the spatial mean, ($\theta_{M,i}$):

$$\sigma_i = \sqrt{\sum_{j=1}^{J}\left(\frac{\theta_i - \theta_{M,j}}{J-1}\right)} \tag{1}$$

where J is the total number of sampled locations.
The coefficient of variation, CV_i, for each sampling campaign i, is:

$$CV_i = \frac{\sigma_i}{\theta_{M,i}}100 \tag{2}$$

The Spearman non parametric test for which moisture data time series ($\theta_{j,i}$) are transformed in ranks ($\xi_{j,i}$). This test evaluates the temporal correlation ($r_{s,T}$) between the rank at location j on day i ($\xi_{j,i}$) and the rank at the same location j on the previous day i' ($\xi_{j,i'}$) and is defined as:

$$r_{s,T} = 1 - \left[\frac{6\sum_{j=1}^{J}\left(\xi_{j,i} - \xi_{j,i'}\right)^2}{J\left(J^2 - 1\right)} \right] \tag{3}$$

3.2. Identification of water balance and seasonal patterns of soil moisture

Catchment-scale water balance is simply described by the following equation:

$$R = ET_a + Q + \Delta S + D \tag{4}$$

where ET_a is the actual evapotranspiration, Q is the streamflow discharge, ΔS is the change of soil water storage and D is deep seepage. In this context ET_a, D and ΔS are not measured, therefore we hereby propose a systematic simplification of the watershed-scale water balance, by modifying Eq. *(4)* in this way:

$$R = ET_p + Q + \Delta S_{surf} \tag{5}$$

where D is ignored, ET_a is replaced by ET_p and ΔS is replaced by the surface soil water storage (ΔS_{surf}) with soil depth of 15 cm. We caution that this strong assumption is considered valid only for preliminary observations.

Fig. 3 illustrates daily rainfall and reference evapotranspiration (Fig. 3a - top panel), streamflow discharge (Fig. 3b - central panel) and mean spatial soil moisture values for each sampling campaign (Fig. 3c - bottom panel). During the dry season, we can observe that precipitation events saturate the surface soil without producing streamflow discharge. For example during the time period between the first and second field campaign, sum of rainfall is 9.45 cm, sum of potential evapotranspiration is 3.07, measured soil surface water storage increases by 1.99 cm but sum of streamflow discharge is practically almost null (0.13 cm).

On the other hand the large precipitation events of middle November (sum of R is 13.31 cm) partly relaxed by modest evapotranspiration loss (sum of ET_p is 0.89 cm) generates catchment hydrological response by triggering high streamflow discharge (sum of Q is 1.19 cm) and soil saturation (ΔS_{surf} increases by 3.74 cm).

Moreover it is interesting to observe that during the wet season identified by progressing soil wetting patterns (Fig. 3c), discharge at the outlet produces a quasi-synchronous response to the main rainfall events, implying rapid runoff and sublateral flow processes along the hillslopes of the catchment.

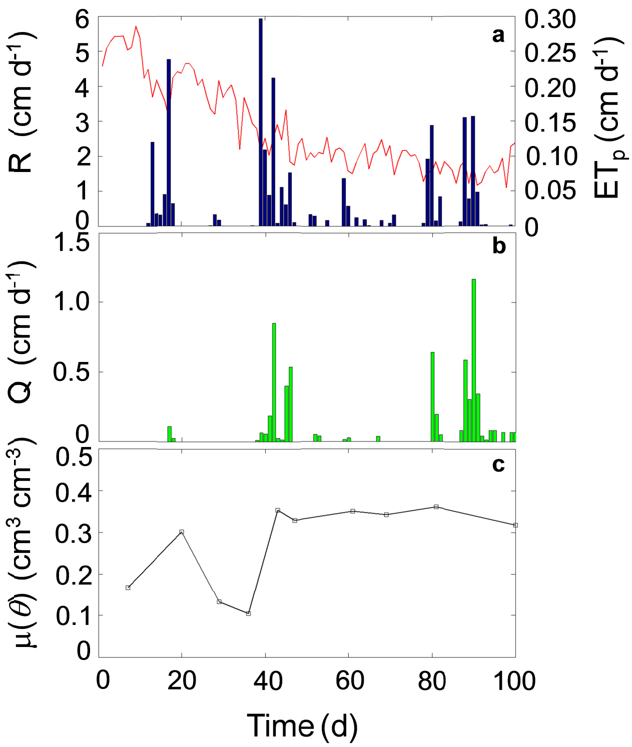

Fig 3. a) Daily values of rainfall (blue bars) and potential evapotranspiration (red line); b) discharge (green bars) recorded at the dam; c) spatial average of soil water content values (black line) as a function of time (first day is October 1 2004 and last day is January 12 2005).

Watershed-scale water balance has been verified in Fig. 4 by comparing the measured sums of ΔS_{surf} that is calculated by multiplying θ_M with the investigated soil depth (15 cm) in each sampling campaign and the estimated ΔS_{surf} ($\sum$(P-ET_p-Q)) that is calculated by inverting Eq. *(5)*. It is clear that estimated ΔS_{surf} -data overestimate the measured ΔS_{surf} -data in wet conditions since the entire soil water storage, infiltration and deep percolation are ignored. However we observe a strong correlation that implicates the proper description of the main hydrologic processes at such scale. In dry conditions, the estimation is already efficient since the aforementioned ignored process plays a weak role.

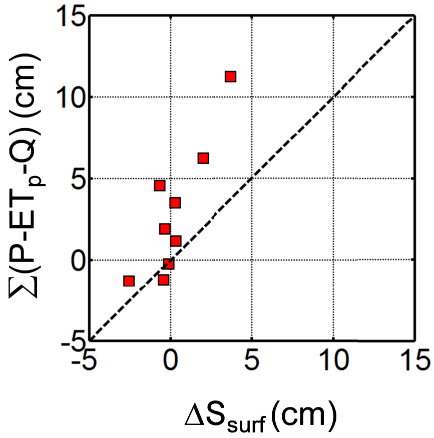

Fig 4. Comparison along the 1:1 line (dashed line) between the sums of measured (ΔS_{surf}) and predicted ($\sum(P\text{-}ET_p\text{-}Q)$) surface soil water storage.

Time stability has been analyzed through Eqs. (1)-(2)-(3). Fig. 5 synthesizes the outcome by showing the Spearman correlation values (rs,T) and coefficient of variation (CV) of the spatial soil moisture values in each soil sampling campaign. Dry season is affected by high temporal instability with low rs,T-values and high CV-values depicted in fluctuating trends. On the contrary, the wet season is characterized by notably high temporal stability with quasi-constant high rs,T-values and low CV-values.

As an example we report in Table 1 the correlation coefficients in the 10 sampling campaigns for transect#4. These values basically confirm the outcome observed in Fig. 5.

Table 1- Matrix of correlation coefficients for the 10 sampling campaigns for transect#4.

date	**07/10/04**	**19/10/04**	**28/10/04**	**03/11/04**	**12/11/04**	**17/11/04**	**02/12/04**	**06/12/04**	**18/12/04**	**12/01/05**
07/10/04	1									
19/10/04	0.50	1								
28/10/04	0.33	0.63	1							
03/11/04	0.51	0.51	0.64	1						
12/11/04	0.53	0.79	0.53	0.53	1					
17/11/04	0.55	0.81	0.56	0.50	0.83	1				
02/12/04	0.62	0.78	0.45	0.66	0.70	0.80	1			
06/12/04	0.72	0.59	0.24	0.46	0.70	0.72	0.64	1		
18/12/04	0.48	0.40	0.16	0.55	0.49	0.54	0.82	0.56	1	
12/01/05	0.62	0.44	0.06	0.25	0.53	0.71	0.57	0.87	0.59	1

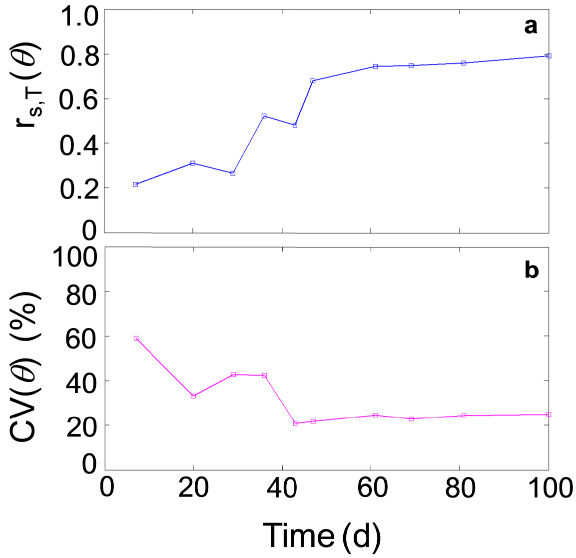

Fig 5. a) Temporal evolution of Spearman's test of soil water content values as a function of time b) coefficient of variations (CV) as a function of time

3.3 Relationship between terrain attributes and soil moisture

In this last section the impact of physical controls on measured near-surface soil moisture has been investigated. Unfortunately vegetation characteristics were ignored for lack of satellite images during the study time period. Therefore only the relation between terrain attributes and soil water content changes is analyzed during the transaction from the dry to the wet season.

Table 2- Correlation coefficients between soil moisture and primary and secondary terrain attributes for transect#4.

date	Elevation	Slope %	Tang. Curv.	Prof. Curv.	Aspect	Wet. Index
07/10/04	0.10	-0.22	-0.37	0.05	-0.33	0.38
19/10/04	-0.50	-0.31	-0.45	-0.14	-0.22	0.46
28/10/04	-0.26	-0.21	-0.35	-0.01	-0.06	0.38
03/11/04	-0.21	-0.44	-0.25	0.13	-0.38	0.33
12/11/04	-0.35	-0.43	-0.34	0.05	-0.02	0.32
17/11/04	-0.08	-0.54	-0.38	-0.30	-0.04	0.61
02/12/04	-0.08	-0.54	-0.24	-0.21	0.13	0.63
06/12/04	-0.08	-0.55	-0.38	-0.21	-0.04	0.40
18/12/04	0.06	-0.59	0.06	-0.13	0.10	0.57
12/01/05	0.19	-0.69	-0.34	-0.29	0.06	0.54

The linear correlation test (rSP) is adopted to verify the relation between the moisture data time series (θj,i) and the primary and secondary terrain attributes in each location j (slope, elevation, aspect, tangential curvature, profile curvature and wetness index). Both correlation coefficients will range between -1 (maximum inverse correlation) and +1 (maximum direct correlation) where the value 0 indicates absence of correlation.

For sake of brevity, Table 2 reports the correlation coefficients only of transect#4. In the dry season, soil water content has high temporal instability and is weakly influenced by the aspect (-0.38<rSP<-0.06) and tangential curvature (-0.45<rSP<-0.25). On the other hand during the wet season soil water content shows significant correlation with the slope (-0.69<rSP<-0.43) and the wetness index (0.32<rSP<0.63). These two topographical properties are highly related to runoff and sub-lateral flow processes.

4. Conclusions

Several recent catchment hydrology field investigations have demonstrated how the understanding and modeling of hydrological processes can be improved by the use of observed space-time patterns of soil water content.

The degree of spatial organization changes seasonally and the organized component of the variation can be predicted using some terrain indices. Topography becomes increasingly important during wet periods, whereas during dry periods soil moisture patterns depend primarily on soil hydraulic properties with little effect from topography.

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