Soil Moisture Monitoring at Different Scales for Rainfall-Runoff Modelling

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Abstract: The soil moisture is a paramount quantity in the study of hydrologic phenomena and soil atmosphere interaction. Because of its high spatial and temporal variability, the soil moisture monitoring scheme was here investigated in view of its application in rainfall-runoff modelling. The results obtained through a "direct" analysis and an "indirect" analysis were found quite similar in terms of contents and useful to address the estimation of soil moisture at the catchment scale. Based on the direct analysis, the soil moisture samples number to get a reliable estimation of soil moisture at catchment scale was defined. The indirect analysis showed that the catchment wetness conditions at the beginning of a storm event can be accurately estimated through the soil moisture observations carried out in a small area.

Keywords: Soil moisture; rainfall-runoff modelling; experimental catchments; antecedent wetness conditions, Soil Conservation Service - Curve Number.

1. INTRODUCTION

Surface soil moisture status is widely recognized as a key parameter in environmental processes because of its control in partitioning the rainfall into runoff and infiltration. For storm rainfall-runoff modeling the knowledge of the wetness conditions at the onset of precipitation is one of the most important aspect mainly for basins in the Mediterranean area [Brocca et al., 2008a]. Because of its high spatio-temporal variability, soil moisture monitoring for large areas is by no means a simple task. In fact, conventional in situ measurements are costly and provide information at only a few selected points, independently by the method used (Time Domain Reflectometry, gravimetric, neutron probes, capacitance probe). Remote sensing techniques, as opposed to point measurements, show promise in assisting hydrologist in describing and measuring surface soil moisture. However, ground-based data are used to assess the accuracy of any remote sensing algorithm being a fundamental component of data analysis. Therefore, the key question for soil moisture monitoring on areas of interest for hydrological applications is how many points must be sampled to estimate a rational mean value. However, intensive field samplings carried out in different climatic regions have shown contrasting results with respect to the main statistical [Brocca et al., 2007a; Famiglietti et al., 2007] and geostatistical [Fitzjohn et al., 1998, Western et al., 2004] properties, to the factors influencing the variability [Grayson et al., 1997; Famiglietti et al., 1998] and, generally, to the entity of soil moisture variability.

In terms of simulation and flood forecasting the interest lies mainly in deriving Antecedent Wetness Conditions (AWC) for rainfall-runoff modelling. Several studies investigated the effect of soil moisture spatial variability on the hydrologic response of a catchment through simulation [Grayson et al., 1995; Merz and Plate, 1997; Bronstert and Bardossy, 1999] and experimental studies [Goodrich et al., 1994; Aubert et al., 2003]. Grayson and Western [1998] suggested that a network of a limited number of moisture sensors could provide reliable estimates of areal mean soil moisture thus addressing the AWC assessment.
Therefore, indicative wetness conditions derived by satellite and/or few point measurements might be sufficient to determine AWC, rather than the use of complex water balance models or detailed spatial measurements [Longobardi et al., 2003]. On this basis, new methodologies for the optimization of the monitoring strategy with indications of representative locations which guarantee information reliability are welcome [Vachaud et al., 1985; Brocca et al., 2008b].

Based on the above insights, this paper addresses two aspects: the optimal sampling and the AWC assessment. For the first one, the optimal soil moisture monitoring scheme, at different scales, has been investigated for rainfall-runoff modelling. In particular, several soil moisture spatial patterns collected in an inland region of Central Italy were investigated through a "direct" method based on statistical and temporal stability analysis. The second aspect has been addressed through an "indirect" analysis based on the estimation of the AWC for rainfall-runoff events occurred in five nested catchments. Because of the lack of significant flood events in the sampling period, the role of soil moisture data was investigated by using observations carried out continuously in an experimental plot included in the smallest catchment. The results of the different analysis were compared and some general findings for soil moisture monitoring at different scales have been derived.

2. METHODS

A monitoring scheme useful to address the soil moisture spatial mean at catchment scale relies on selecting representative observation sites where an optimal number of point measurements have to be carried out. It is well known that more measurement points are required to take account of soil moisture spatial variability at local scale. Therefore, the optimization of the monitoring scheme has been here addressed through a "direct" method based on the investigation of the soil moisture spatial variability at the plot and small catchment scale by using the classical statistical approaches. In particular, the optimal number of measurements to estimate the mean water content in a given area is determined through the relationship between the mean and the coefficient of variation [Famiglietti et al., 2007].

Moreover, the method also includes the temporal stability analysis, such as proposed by Vachaud et al. [1985]. This analysis is based on the parametric test of the relative differences, of which a brief description is reported below. Let $\theta_i$ be the soil moisture at location $i$ at the time $j$, the spatial mean for each sampling is:

$$\overline{\theta} = \frac{1}{N} \sum_{i=1}^{N} \theta_i,$$

where $N$ is the number of measurement points. The relative difference, $\delta_i$, is given by:

$$\delta_i = \frac{\theta_i - \overline{\theta}}{\overline{\theta}}.$$

(2)

The temporal mean of the relative differences for each location, $i$, is given by:

$$\overline{\delta_i} = \frac{1}{M} \sum_{j=1}^{M} \delta_{ij},$$

(3)

where $M$ is the number of measurement campaigns. Obviously, a "representative" location of the mean is characterized by a low value of $\overline{\delta_i}$. Therefore, a regression analysis between the soil moisture values sampled in the most "representative" site having the lowest $\overline{\delta_i}$ value and the catchment-mean moisture would allow to assess the reliability of soil moisture prediction at large scale through local observations.

As far as the AWC assessment is concerned, the capability to use near-surface soil moisture observations carried out in a small experimental plot included in the catchment of interest can be analyzed through an "indirect" method [Brocca et al., 2007b]. For a specific rainfall-runoff event, the AWC determines the amount of rainfall infiltrating into the soil profile and

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hence the surface runoff volume, $R_d$. Considering the Soil Conservation Service - Curve Number (SCS-CN) method for abstraction, $R_d$ is given by:

$$R_d = \frac{(P - F_a)}{P - F_a + S} \quad P \geq F_a$$

where $F_a$ is the initial abstraction, $S$ is the potential maximum retention, and $P$ is the rainfall depth. The quantity $F_a$ is assumed as a fraction of $S$, $F_a = \lambda S$, with $\lambda = 0.2$ as the SCS-CN standard value [Ponce and Hawkins, 1996]. In particular, the parameter $S$ is estimated considering the average dimensionless Curve Number (CN) assessed as a function of land use, hydrological soil group and the AWC. Assuming that the soil/land use characteristics are constant in time, the different values of $S$ from storm to storm are only linked to variations in the AWC. When $R_d$ is known, eq. (4) can be re-written in terms of $S = S_{\text{obs}}$ as:

$$S_{\text{obs}} = \frac{1}{2\lambda} \left(2\lambda P - \lambda R_d + R_a - \sqrt{\lambda R_d^2 - 2\lambda P R_a + 4\lambda P^2 + R_a^2}\right)$$

where $P$ and $R_d$ were derived from the available rainfall-runoff events. Therefore, $S_{\text{obs}}$ is the value to assign to the AWC to obtain the observed $R_d$. Considering the relationship between $S_{\text{obs}}$ and the soil moisture observed in small area it is possible to assess indirectly the reliability of soil moisture prediction at catchment scale through local observations.

3. STUDY AREA

The Niccone stream is a right tributary of the Upper Tiber River and is located in an inland region of Central Italy (Figure 1). The catchment covers an area of $137 \text{ km}^2$ at Mignanella River section (C1) and the elevation ranges between 887 and 249 m above sea level at the outlet, with a mean catchment slope of 25%.

![Figure 1](image)

**Figure 1.** Hydrometeorological network operating in the Niccone catchment. The Colorso experimental plot for continuous soil moisture monitoring and the spot soil moisture measurements sites are also shown.

The catchment is characterized by a Mediterranean climate with average annual precipitation of about 930 mm. In the study area a dense hydrometeorological network has been operating since 1994 with 8 raingauges, 5 hydrometric gauges and 2 meteorological stations (see Figure 1). The data are recorded every 30 minutes and refer to instantaneous values except...
for precipitation depth. As it can be seen by Figure 1, the hydrometric stations allow to analyse the hydrological behaviour of five nested catchments. Table 1 shows the main characteristic of each subcatchment including the soil/land use characteristics and the CN values for intermediate wetness conditions, $CN_{II}$. In particular, for the soil the percentage of clay and pelitic units is only reported because it affects significantly the watershed CN representing a relative measure of retention of storm water at catchment scale.

**Table 1. Main characteristics of the five nested study catchments.**

<table>
<thead>
<tr>
<th>ID</th>
<th>Area (km$^2$)</th>
<th>Mean slope (%)</th>
<th>River length (km)</th>
<th>Clay and pelitic units (%)</th>
<th>Woodland</th>
<th>Crop land</th>
<th>Range land</th>
<th>Pasture</th>
<th>Urban</th>
<th>$CN_{II}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>137</td>
<td>25</td>
<td>18.1</td>
<td>15.0</td>
<td>55.0</td>
<td>32.0</td>
<td>10.0</td>
<td>2.7</td>
<td>0.3</td>
<td>77.9</td>
</tr>
<tr>
<td>C2</td>
<td>104</td>
<td>25</td>
<td>13.4</td>
<td>10.6</td>
<td>55.5</td>
<td>30.6</td>
<td>10.4</td>
<td>3.1</td>
<td>0.4</td>
<td>77.1</td>
</tr>
<tr>
<td>C3</td>
<td>57</td>
<td>24</td>
<td>12.8</td>
<td>6.2</td>
<td>57.7</td>
<td>29.6</td>
<td>7.4</td>
<td>5.1</td>
<td>0.3</td>
<td>74.8</td>
</tr>
<tr>
<td>C4</td>
<td>35</td>
<td>25</td>
<td>6.9</td>
<td>7.6</td>
<td>57.6</td>
<td>27.3</td>
<td>8.6</td>
<td>6.0</td>
<td>0.5</td>
<td>74.0</td>
</tr>
<tr>
<td>C5</td>
<td>13</td>
<td>28</td>
<td>5.4</td>
<td>1.3</td>
<td>71.0</td>
<td>17.9</td>
<td>0.0</td>
<td>10.9</td>
<td>0.1</td>
<td>72.9</td>
</tr>
</tbody>
</table>

4. DATASET

The near-surface volumetric soil moisture measurements (0-15 cm) were carried out on 7 sites, named $SM_{i=1,2,...,7}$, located inside the Vallaccia catchment (C3), having a drainage area of nearly 60 km$^2$. For each site thirty spot measurements were collected on a regular grid with a resolution of 10 m using a two-wire connector-type Time Domain Reflectometer (TDR). The measurements were repeated weekly for 35 times in a period of one year from November 2006 to November 2007 except for the summer due to soil hardness.

Inside Vallaccia catchment there is an experimental plot of nearly 1 ha where soil moisture measurements are carried out automatically with the same time step as of the hydrometeorological stations. The plot is covered by grass (permanent pasture) and the soil texture is sandy loam to a depth of 0.3 m and silty loam to a depth of 1.5 m. Six soil moisture probes, based on the Frequency Domain Reflectometry (FDR) technique, continuously measure soil moisture in the soil column at 10 cm, 20 cm and 40 cm, providing at each depth the volumetric soil moisture for a layer thickness of 10 cm. The soil moisture data set selected for this study covers the period from September 2002 to January 2006 except that from July to September 2003 and from September to November 2005, due to drawbacks in the acquisition. The average of the values measured by the six sensors buried at 10 cm depth was assumed as the 'observed' near-surface soil moisture.

Fifteen rainfall-runoff events were selected for this study and their main characteristics are summarized in Table 2 along with the 'observed' near-surface soil moisture at the beginning of each event.

5. RESULTS AND DISCUSSIONS

As mentioned before, the analysis on the soil moisture monitoring was addressed through two methodologies: the "direct" method applied to the dataset of soil moisture spot measurements, and the "indirect" one that makes use of rainfall-runoff data along with the continuous soil moisture data of the experimental plot.

5.1 "Direct" method

Observations in 1 year of soil moisture consist of 35 campaigns at 7 sites (area of 3000 m$^2$) where for each one 30 spot measurements have been collected for a total of 7350 measurements. Figure 2 shows the temporal pattern of the field-mean soil moisture for each site and clearly shows that the seven patterns are very similar and strongly linked to rainfall. Through this dataset, the spatial and temporal soil moisture variability was investigated considering the Coefficient of Variation (CV) computed in space and in time. For each site the spatial CV was found fairly low (~0.10). On the contrary, the temporal CV considerably
increased and it was found nearly three times the corresponding value obtained for the spatial one. As can be expected, the spatial CV increased up to 0.20 for the whole dataset, representing an area of ~60 km².

Table 2. Main characteristics of the selected rainfall-runoff events for the 5 study catchments. The rainfall depth for the largest catchment (C1) and the initial soil moisture ‘observed’ at the experimental plot, \( \theta_i \), are also reported.

<table>
<thead>
<tr>
<th>Date</th>
<th>Rainfall depth (mm)</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>( \theta_i ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 17, 2002</td>
<td>19.7</td>
<td>4.67</td>
<td>6.54</td>
<td>2.60</td>
<td>3.47</td>
<td>1.53</td>
<td>35.95</td>
</tr>
<tr>
<td>Dec 28, 2002</td>
<td>10.7</td>
<td>1.11</td>
<td>0.94</td>
<td>0.87</td>
<td>0.74</td>
<td>0.84</td>
<td>36.03</td>
</tr>
<tr>
<td>Dec 31, 2002</td>
<td>18.9</td>
<td>3.93</td>
<td>3.85</td>
<td>2.73</td>
<td>1.94</td>
<td>1.45</td>
<td>35.54</td>
</tr>
<tr>
<td>Nov 27, 2003</td>
<td>29.3</td>
<td>3.05</td>
<td>2.88</td>
<td>2.25</td>
<td>1.65</td>
<td>1.51</td>
<td>33.88</td>
</tr>
<tr>
<td>Feb 19, 2004</td>
<td>30.4</td>
<td>1.98</td>
<td>1.75</td>
<td>1.92</td>
<td>0.98</td>
<td>2.17</td>
<td>30.60</td>
</tr>
<tr>
<td>Feb 22, 2004</td>
<td>19.1</td>
<td>3.65</td>
<td>3.60</td>
<td>2.08</td>
<td>3.42</td>
<td>1.74</td>
<td>37.90</td>
</tr>
<tr>
<td>Feb 26, 2004</td>
<td>28.5</td>
<td>12.43</td>
<td>10.74</td>
<td>7.96</td>
<td>10.72</td>
<td>5.22</td>
<td>38.18</td>
</tr>
<tr>
<td>Mar 7, 2004</td>
<td>19.3</td>
<td>5.60</td>
<td>4.58</td>
<td>2.92</td>
<td>2.52</td>
<td>2.00</td>
<td>35.76</td>
</tr>
<tr>
<td>Apr 17, 2004</td>
<td>16.7</td>
<td>1.89</td>
<td>1.24</td>
<td>1.54</td>
<td>0.77</td>
<td>0.49</td>
<td>35.10</td>
</tr>
<tr>
<td>Apr 19, 2004</td>
<td>20.9</td>
<td>8.16</td>
<td>6.32</td>
<td>4.94</td>
<td>7.16</td>
<td>8.11</td>
<td>38.31</td>
</tr>
<tr>
<td>Apr 11, 2005</td>
<td>25.3</td>
<td>4.39</td>
<td>4.35</td>
<td>3.27</td>
<td>3.29</td>
<td>3.75</td>
<td>35.83</td>
</tr>
<tr>
<td>Apr 16, 2005</td>
<td>28.0</td>
<td>4.50</td>
<td>4.17</td>
<td>3.43</td>
<td>3.06</td>
<td>4.00</td>
<td>33.99</td>
</tr>
<tr>
<td>Dec 3, 2005</td>
<td>19.5</td>
<td>5.12</td>
<td>5.19</td>
<td>3.16</td>
<td>3.33</td>
<td>4.37</td>
<td>39.73</td>
</tr>
<tr>
<td>Dec 6, 2005</td>
<td>17.7</td>
<td>6.68</td>
<td>7.05</td>
<td>4.93</td>
<td>4.40</td>
<td>4.23</td>
<td>40.49</td>
</tr>
<tr>
<td>Dec 9, 2005</td>
<td>25.6</td>
<td>7.72</td>
<td>9.01</td>
<td>6.60</td>
<td>7.10</td>
<td>7.62</td>
<td>38.92</td>
</tr>
</tbody>
</table>

Figure 2. Temporal pattern of the field-mean soil moisture collected in the 7 sites.

Assuming the relationship between the field-mean soil moisture and the CV to be represented by an exponential law, it is possible to quantify the Number of Required Samples (NRS) in relation to the field-mean soil moisture and to the confidence level (for more details see Brocca et al., [2007a]). Figure 3a shows the NRS to obtain a value of the field-mean soil moisture within an error less than ±2%, at a 95% confidence level, for all investigated sites.

Figure 3. Number of soil moisture samples required to capture the field-mean soil moisture at 95% confidence level for: a) an absolute error of ±2 % and for different mean values; b) for the mean value requiring the maximum sampling and for different errors.

Similarly with other previous investigations [Famiglietti et al., 2007], the results show that for our study area the highest NRS is needed under almost dry conditions. In particular, to
assess accurately the field-mean soil moisture more resources are needed for SM7 and SM3 sites with a maximum NRS of 15 and 12, respectively. In Figure 3b, NRS is plotted against the absolute error for field-mean soil moisture value requiring the maximum sampling. For an accuracy ±4%, which is the value actually expected with remote sensing techniques, only from 1 to 4 measurements point are needed.

To investigate the NRS to obtain the catchment-mean soil moisture, the temporal stability analysis was conducted. In particular, the catchment-mean soil moisture is here assumed as the mean value of the whole dataset. Figure 4 shows the rank ordered mean relative difference, $\delta$, with the standard deviation (vertical bar). As it can be seen, both the site SM1 and SM5 can be considered representative of the catchment-mean soil moisture as the corresponding $\delta$ was found nearly zero. Considering a single site, the determination coefficient ($R^2$) and the Root Mean Square Error (RMSE) were computed considering the linear regression between the catchment-mean soil moisture and the mean value obtained from different number of measurement points randomly selected in the SM1 site. As it can be seen in the inset of Figure 4 an accuracy of nearly 1% and a very high $R^2$ equal to 0.98 was obtained with 15 measurement points. Increasing the sample size the accuracy improves slightly.

![Figure 4](image)

**Figure 4.** Rank ordered mean relative difference, $\delta$, where error bars indicate ±1 standard deviation. The inset shows the Root Mean Square Error (RMSE) and the determination coefficient ($R^2$) between the catchment-mean soil moisture and the field-mean value obtained for site SM1 varying the number of point measurements.

### 5.2 "Indirect" method

The previous analysis has allowed to establish the number of measurements carried out on a representative site to get a reliable catchment-mean soil moisture. In this section, the relation between the soil moisture 'observed' at the experimental plot in the Colorso sub-basin and the AWC at the Niccone catchment scale is investigated. At the purpose, for each nested catchment the $S_{obs}$ values were computed for the selected events and then normalized, in order to obtain a value between 0 and 1. In particular, the normalized $S_{obs}$, $\hat{S}_{obs}$, was given by:

$$\hat{S}_{obs} = 1 - \left( S_{obs} - 0.2S_{CN(I)} \right) / \left( 1.2S_{CN(III)} - 0.2S_{CN(I)} \right)$$  \hspace{1cm} (6)

where $S_{CN(I)}$ and $S_{CN(III)}$ are the $S$ values corresponding to dry and wet Antecedent Moisture Conditions (AMC) as in the classical SCS-CN method. The $\hat{S}_{obs}$ was related to the 'observed' saturation degree, $\theta_e$, given by the well-known relationship:

$$\theta_e = (\theta - \theta_c) / (\theta - \theta_w)$$  \hspace{1cm} (7)
where $\theta_r$ and $\theta_s$ are the residual and saturated soil moisture, fixed as the minimum and maximum 'observed' values. Through eqs. (6) and (7) both quantities are varying between 0 and 1 and can be directly compared.

Figure 5a shows the $S_{obs}$-$\theta$ relationship for all nested catchments. As it can be seen, the 'observed' saturation degree can be considered fairly accurate to address the catchment AWC. In particular, the regression performance decreases with increasing catchment area (see Figure 5b) but it can be still considered reliable for the largest catchment (137 km$^2$), with $R^2$ equal to 0.71. Considering a threshold value of 0.8 for the $R^2$ value, the 'observed' saturation degree in the plot can be considered appropriate to estimate AWC for catchments draining an area up to ~60 km$^2$. However, this result can be affected by the lumped approach used for relating rainfall and runoff depth. In fact, increasing the drainage area the spatial pattern of AWC, soil/land use characteristics, and rainfall becomes more and more significant in runoff generation.

It has to be noted that, for all catchments, the reliability of the 'observed' saturation degree for the AWC estimation was always better than other indicators commonly used for the AWC assessment, as the Antecedent Precipitation Index (API) or the BaseFlow Index (BFI) (not shown here for sake of brevity). Moreover, eq. (6) allows to take into account the variability of $S$ from one catchment to another through the variability in the soil/land use characteristics as can be inferred from the CN$\text{II}$ values (Table 1).

![Figure 5](image.png)

**Figure 5.** a) 'Observed' normalized potential maximum retention for the study catchments versus the 'observed' saturation degree, $\theta$. b) Root Mean Square Error (RMSE) and determination coefficient ($R^2$) for the previous relationship and for each catchment.

6. CONCLUSIONS

Based on the analysis and the results reported in this study the soil moisture monitoring scheme for inland regions of Mediterranean area can be addressed. In particular: 1) the field-mean and catchment-mean soil moisture can be estimated with a good accuracy by a limited number of measurements, 2) soil moisture measurements carried out in a small area seem to be sufficient to obtain the wetness conditions of a catchment that can be effectively used for rainfall-runoff modelling. This aspect might have significant implications for flood prediction and forecasting and will be investigated in our future study. Finally, the widespread application of the SCS-CN method and the temporal stability of soil moisture observed in different studies make, in principle, the method proposed here reliable in other physiographic regions. However, a more detailed analysis is necessary to corroborate this insight.

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