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Antecedent Wetness Conditions Estimation through ERS Scatterometer Data

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ABSTRACT: Soil moisture is widely recognized as a key parameter in environmental processes, including meteorology, hydrology, agriculture and climate changes. From a hydrologic point of view, soil moisture controls the partitioning of rainfall into runoff and infiltration. In particular, the estimation of the Antecedent Wetness Conditions (AWC) is one of the most important issues for storm rainfall-runoff modeling. To this end, the potential of scatterometer on board of ERS satellites has been investigated for an inland region of Italy where the Upper Tiber is located. The satellite soil moisture data used in this study are taken from the ERS/METOP Soil Moisture archive located at http://www.ipf.tuwien.ac.at/radar/ers-scat/home.htm. First, the Scatterometer-derived Soil Wetness Index (SSWI) data were compared with two soil moisture data sets acquired in an experimental catchment located in the study area with two different methodologies. Then, the reliability of the SSWI to estimate the AWC of a catchment were analyzed through the relationship between the SSWI and the soil potential maximum retention parameter, *S*, of the Soil Conservation Service-Curve Number (SCS-CN) method for abstraction. At the purpose, several storm events observed in three catchments from 1992 to 2005 were selected. The performance of the SSWI for *S* estimation was also compared with two Antecedent Precipitation Indices (API) and the Base Flow Index (BFI). The *S* values obtained by the observed direct runoff volume and rainfall depth were used as benchmark. Results obtained in this study demonstrate the reliability of the SSWI for the wetness condition estimation both at the plot and catchment scale.

INTRODUCTION

Soil moisture is a critical boundary condition in the interaction between land surface and atmosphere. Information of distributed soil moisture at large scale with reasonable temporal and spatial resolution is required for improving hydrologic and climatic modeling and prediction (Western *et al.*, 2002; Brocca *et al.*, 2007).

As regards rainfall-runoff modeling, some authors argued that the Antecedent Wetness Conditions (AWC) of a catchment are the most important factor to determine the outcome of an event prediction (Stephenson and Freeze, 1974; De Michele and Salvadori, 2002; Aronica and Candela, 2004; Brocca *et al.*, 2008a). In addition, the assimilation of remotely sensed (Houser *et al.*, 1998; Pawels *et al.*, 2001; Scipal *et al.*, 2005; Berg and Mulroy, 2006) and ground-based (Aubert *et al.*, 2003; Anctil *et al.*, 2004; Chainian *et al.*, 2005; Brocca *et al.*, 2008b) soil moisture measurements in rainfall-runoff models was found to greatly improve flood prediction and forecasting.

However, the estimation of the near-surface soil moisture over large areas through the classical point measurement techniques (TDR, gravimetric, neutron probes, capacitance probe) is very difficult to obtain because much expensive and time consuming. In the last twenty years, the use of satellite sensors has been investigated to overcome this problem. Out of these, radar microwave sensors, not influenced by solar illumination and cloud cover, are particularly appealing for soil moisture retrieval due to the strong variation of the dielectric constant of soil with volumetric soil moisture. However, scattering from land surface also depends on other factors. In fact, reliable retrieval techniques have to take account of the confounding effects of surface roughness, vegetation, topography and soil texture. In the literature, many studies have used Synthetic Aperture Radars (SAR) to estimate near surface soil moisture owing to its high spatial resolution (<50 m), but for bare soil surfaces (Baghdadi *et al.*, 2007). Moreover, despite the great effort in the developments of SAR systems, actually they neither provide the data necessary for routine application nor are truly optimized for soil moisture retrieval. At the same time, significant progress has been made using coarse-resolution microwave radiometers and scatterometers (Lacava *et al.*, 2005;

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Wagner *et al*., 2007). The advantage of these systems compared to SAR was in their multidimensional and multi-temporal observation capabilities, that is multiple frequencies and polarizations in the case of microwave radiometers and multiple-viewing capabilities in the case of scatterometers. These capabilities allow to better take into account of the confounding effects of vegetation and surface roughness, which are inherent in both active and passive microwave observations. In particular, data from the ERS scatterometer have been used to derive a global validated long term soil moisture data set (Scipal *et al*., 2002). The accuracy of the Scatterometer derived Soil Wetness Index (SSWI), assessed using over 45000 measurements worldwide, was found to be around 0.054 m^3m^{-3} for the 0–1m layer for temperate and tropical climatic regions. Moreover, Scipal *et al.* (2005) investigated the relationship between runoff and the SSWI for the Zambezi river in South-East Africa showing that differences in runoff could, to some extent, be explained by the SSWI anomalies. Assimilating the SSWI into a conceptual hydrologic model at regional scale for 320 Austrian catchments, Parajka *et al.* (2006) concluded that, for regions with small topographic variability and low vegetation, the scatterometer data does not improve the daily runoff simulations but does provide more consistent soil moisture estimates.

On these basis, the main aim of the paper is to assess the reliability of SSWI for flood prediction in an inland region of Central Italy. The SSWI data were compared with two near-surface soil moisture data sets acquired in an experimental catchment (Vallaccia catchment) located in the investigated region. Then, the potential of the SSWI for the wetness conditions assessment was investigated for three catchments of the Upper Tiber river through several rainfall-runoff events occurred in the period 1992–2005. Specifically, the performances of the SSWI in the estimation of the AWC of the catchment were compared with two Antecedent Precipitation Indices (API) and a Base Flow Index (BFI), that are usually employed at the purpose in the hydrological practice.

SOIL MOISTURE RETRIEVAL FROM ERS SCATTEROMETER DATA

Soil moisture data used in this study are taken from the ERS/METOP Soil Moisture archive located at http://www.ipf.tuwien.ac.at/radar/ers-scat/home.htm (Scipal *et al*., 2002). The archive is based on ERS Scatterometer data and comprises global surface soil moisture data and indicators of root zone soil moisture sampled at ten-day intervals. The archive is periodically updated, the surface soil moisture data until May 2007 were used for this study.

Scatterometers are active microwave sensors with a coarse spatial and a high temporal resolution. To retrieve soil moisture information, scatterometers onboard of the European Remote Sensing Satellites ERS-1 and ERS-2 were used. The ERS scatterometer operates at 5.3 GHz (C-band) with vertical polarization, collecting backscatter measurements over an incidence angle ranging from 18° to 57° by using three sideways looking antennae. The sensor achieves global coverage within 3–4 days and each beam provides measurements of radar backscatter for overlapping 50 km resolution cells with a 25 km grid spacing.

Since the 1970's several methods have been developed to retrieve soil moisture from microwave remote sensing data. The largest potential for applicative purposes is held by the "change detection" approaches which have been successfully used to retrieve soil moisture for both active (Wagner *et al*., 1999; Moran *et al*., 2000) and passive sensors (deRidder, 2000). Although more complex theoretical or semi empirical approaches are often preferred for retrieval purposes, the ones based on change detection are attractive for global applications because comprehensive pre-knowledge of surface characteristics is not required.

Retrieval of soil moisture for the ERS/METOP Soil Moisture archive is based on the change detection method developed by Wagner *et al.* (1999). The method fully accounts for the effects of surface roughness, vegetation and heterogeneous land cover. It allows the retrieval of surface soil moisture information equivalent to the degree of saturation in relative units (ranging between 0 and 1). To infer root zone soil moisture a red-noise filtering approach is used. Specifically, the SSWI at time *t* is given by,

$$SSWI(t) = \frac{\sum_i m_s(t_i) e^{-\frac{t-t_i}{T}}}{\sum_i e^{-\frac{t-t_i}{T}}} \quad \ldots (1)$$

where $m_s(t_i)$ is the retrieved surface soil moisture at time t_i of track and T is the time constant of the filter or the characteristic time length. In general, the characteristic time length depends on soil properties, including soil depth and moisture state (Wagner *et al*., 1999). In this study the T value was considered as a calibration parameter (Ceballos *et al*., 2005; Parajka *et al*., 2006).

STUDY AREA

The study area is the Upper Tiber river catchment at Ponte Nuovo (4150 km^2) located in an inland region of Central Italy, along with two sub-catchments, Niccone at Migianella (137 km^2) and Assino at Serrapartucci (165 km^2). The Tiber catchment has a topography mainly hilly with elevation above the mean sea level ranging from 200 to 800 m. The mountain peaks on a large portion of the territory range in elevation from 1000 to 1500 m above the mean sea level (see Figure 1a).

The climate is Mediterranean with mean annual rainfall of ~950 mm and ranging over the region between 650 mm and 1600 mm. Higher monthly rainfall values generally occur during the autumn-winter period. It is this period during which floods, caused by widespread rainfall, normally occur. Mean annual runoff in the last 70 years is 350 mm ranging between 150 mm to 800 mm; the maximum instantaneous discharge is about 1350 m^{3}s^{-1}. Mean annual air temperature is 13.4 °C, with maximum in July and minimum in January. Accordingly, the mean annual potential evapotranspiration, computed by Thornthwaite formula, is about 800 mm.

The Upper Tiber river catchment lithology is mainly characterized by terrigeneous facies and flysch deposits. The soil, overlying practically impervious rocks, is made up of clay and silty silt. The main land use are woods (44.9%) and crops (47.0%), whereas urban areas covers only 3.1% of the territory.

The catchment is monitored through a dense hydro-meteorological network (see Figure 1b) with most of the stations connected to a central unit through a radiolink.

The ERS data for the study area refers at ascending and descending tracks at 9:30 a.m. and 9:30 p.m., respectively. The locations of the centroids of the pixels for our study catchment are presented in Figure 1. Unfortunately over Europe ERS scatterometer operations were often in conflict with Synthetic Aperture Radar (SAR) acquisitions. For this reason only a portion of all possible acquisitions were actually available.

SOIL MOISTURE AND RAINFALL-RUNOFF DATA

In order to analyze the usefulness of the SSWI at small scale, two on-site soil moisture data sets were used. In spring 2002 an experimental plot (10^4 m^2), henceforth denoted as Colorso field, was set up inside the Niccone catchment (see the inset of Figure 2) with six soil moisture probes continuously measuring volumetric soil moisture with Frequency Domain Reflectometry (FDR) at a depth of 10, 20 and 40 cm. The soil moisture data set used in this study cover the period from November 2003 to January 2006, except from September to December, 2004 and from September to November, 2005, due to acquisition drawbacks. The daily average of the measured values by the six sensors at the depth of 10 cm was assumed as the 'observed' moisture for the upper soil layer for the Colorso field.

Furthermore, spot measurements of near-surface volumetric soil moisture (0–15 cm) were carried out by Time Domain Reflectometer (TDR) during the same day in 7 sites located inside the Vallaccia catchment (see Figure 2), henceforth denoted as Vallaccia field, and covering a larger area (~60 km^2). For each site, thirty spot measurements were collected from November 2006 to May 2007 and the mean soil moisture assessed in the area was considered as benchmark. Figure 3 shows the time evolution of the volumetric soil moisture along with daily rainfall for the Colorso and Vallaccia fields.

The analysis on the SSWI reliability at catchment scale has been carried out considering the Upper Tiber catchment at Ponte Nuovo and its two sub-catchments, Niccone and Assino at Migianella and Serrapartucci gauged site, respectively (see Figure 1a). Many isolated rainfall-runoff events (73 events) were selected and their main characteristics in terms of total rainfall, runoff depth and peak discharge are collected and reported in Table 1. The events were selected on the basis of the availability of the scatterometer derived surface soil moisture data, m_s. In particular, a maximum gap of 5 days between the beginning of the event and the last m_s value was allowed with the constraint of negligible rainfall.

SSWI VERSUS FIELD MEASUREMENTS

The comparison of the SSWI with the two ground-based soil moisture data sets was performed varying the parameter T in Eqn. 1 from 1 to 100 days. For both sites the 'observed' soil saturation degree was computed by the volumetric soil moisture observations and assuming as the residual and saturated soil moisture the minimum and maximum 'observed' values.

The SSWI was computed considering the satellite-derived surface soil moisture data of the nearest available pixel, which is the pixel to the north of the Migianella hydrometric section on Niccone river (see Figure 1a). Figure 4 shows the temporal pattern of the SSWI for the two periods when ground-based soil moisture observations were carried out and for four different values of the parameter T.

Table 1: Main Characteristics of the Selected Rainfall-Runoff Events. *P*: Rainfall Depth, *Q*: Direct Runoff Depth, Q_p: Peak Discharge

Tiber River at Ponte Nuovo				*Assino River at Serrapartucci*				*Niccone River at Migianella*			
dd mm yy	*P (mm)*	*Q (mm)*	Q_p (m^3/s)	*dd mm yy*	*P (mm)*	*Q (mm)*	Q_p (m^3/s)	*dd mm yy*	*P (mm)*	*Q (mm)*	Q_p (m^3/s)
20 10 92	42.9	12.6	453.1	25 03 92	28.1	7.6	45.0	30 12 95	59.4	12.1	36.7
16 11 92	37.7	11.2	386.3	05 12 92	40.2	14.3	90.0	02 02 96	26.5	4.6	32.8
16 09 95	47.8	16.1	820.5	0712 92	38.9	13.8	70.3	17 11 96	58.7	18.8	63.1
30 12 95	23.2	0.8	109.7	10 04 93	28.1	3.2	43.9	14 12 96	22.7	6.5	35.5
02 04 96	56.5	13.8	625.4	01 10 93	42.9	5.1	48.1	20 12 96	23.3	5.4	29.2
17 11 96	37.9	7.2	316.6	25 12 93	22.2	4.5	31.2	29 11 97	91.8	42.7	53.2
15 02 97	68.3	18.8	707.2	04 01 94	24.7	5.0	40.9	03 05 98	65.5	23.0	45.5
20 12 97	30.7	5.2	291.2	17 11 96	35.8	7.1	79.1	09 02 99	49.7	22.6	39.9
10 11 98	33.2	9.4	171.8	20 11 96	24.5	4.0	48.7	15 04 99	28.3	8.2	43.7
04 12 98	33.5	3.3	171.8	14 12 96	25.6	3.3	33.4	21 11 99	47.2	13.2	35.1
09 02 99	32.5	6.5	716.8	02 06 97	38.4	10.6	104.9	15 11 00	34.1	11.5	30.3
23 10 99	46.3	10.7	763.8	22 11 97	36.9	7.3	45.0	21 11 00	26.8	6.2	36.7
10 12 99	36.2	3.1	159.9	04 12 98	17.9	4.0	37.5	27 11 03	40.4	10.5	35.9
06 11 00	27.2	4.5	230.7	09 02 99	32.4	2.8	34.3	22 02 04	23.3	7.4	45.5
27 12 00	33.6	5.1	230.7	21 11 99	31.7	6.7	77.1	26 02 04	29.3	1.5	17.5
16 10 04	42.9	19.1	879.2	27 03 00	43.3	13.1	77.7	07 03 04	18.3	1.8	17.2
18 09 05	29.3	2.1	152.0	01 04 00	32.0	5.1	52.0	16 04 04	34.1	14.5	68.2
19 10 05	27.7	1.0	117.3	27 12 00	44.9	10.9	46.5	19 04 04	19.3	4.3	19.0
15 11 05	32.3	3.3	107.2	03 01 01	24.4	2.9	40.9	11 04 05	17.6	0.9	8.3
05 12 05	31.9	4.1	289.8	26 02 04	23.9	6.5	83.4	16 04 05	25.4	9.6	49.5
20 10 92	38.7	13.2	870.7	25 11 05	32.2	10.8	82.0	05 05 04	25.3	2.2	25.8
				03 12 05	26.5	5.9	47.6	26 11 05	28.0	2.3	23.0
				05 12 05	81.6	40.6	195.4	02 12 05	25.4	7.8	38.7
				25 03 92	28.0	5.7	42.9	05 12 05	56.7	40.5	111.6
				05 12 92	25.0	6.0	48.7	09 12 05	20.3	5.4	44.2
								30 12 95	20.3	6.2	43.3
								02 02 96	25.7	7.0	32.1

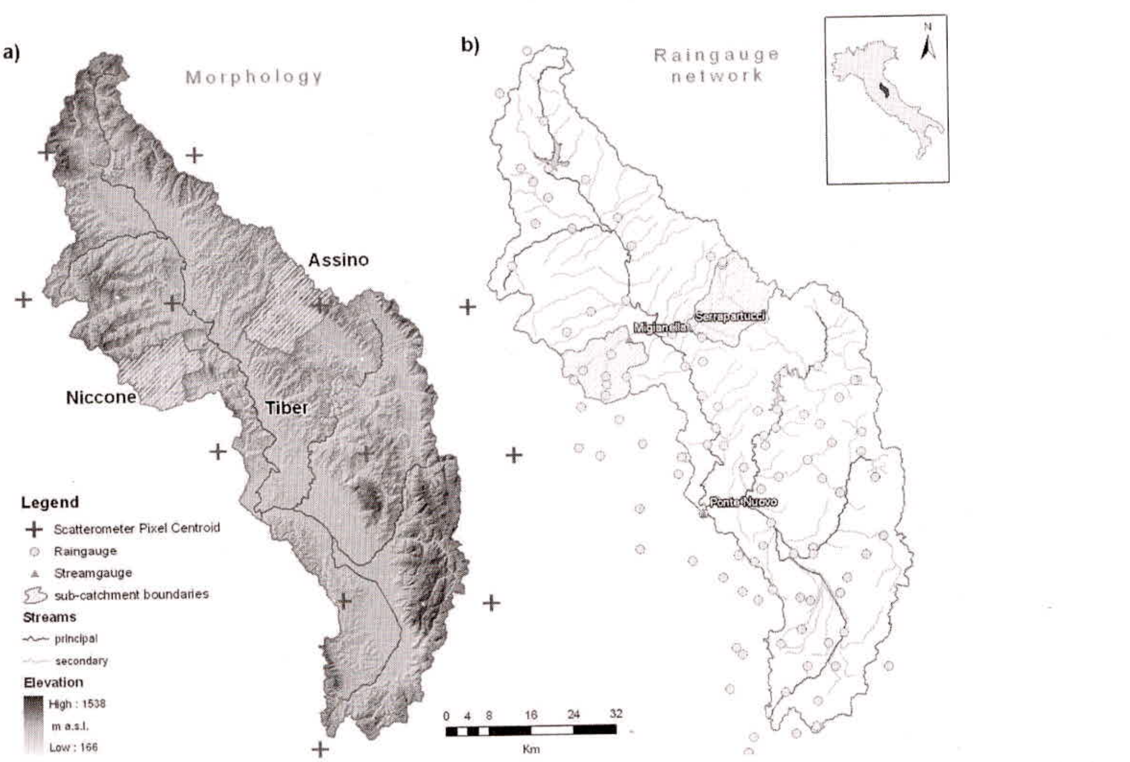

Fig. 1: Upper Tiber River Catchment: (a) Morphology and sub-catchments used in this study. The centroid of the pixels for the scatterometer data is also shown; (b) Drainage network and raingauge stations

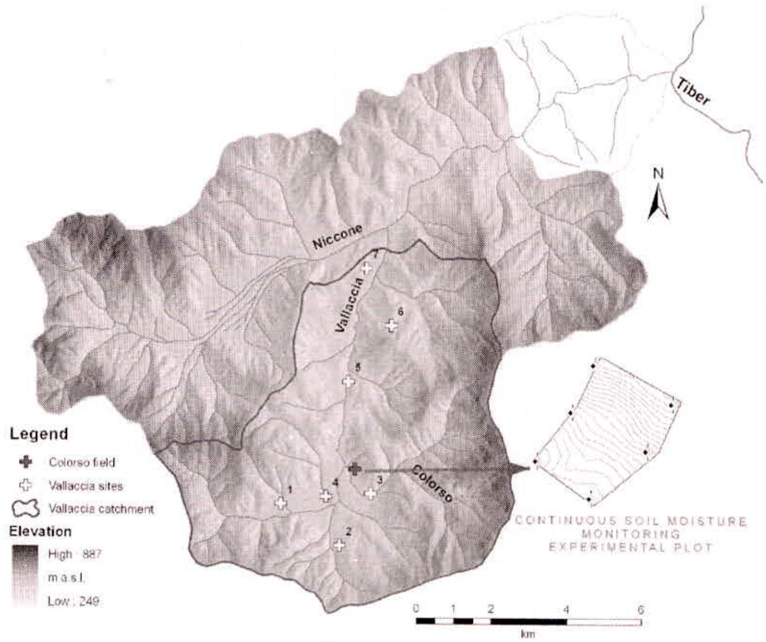

Fig. 2: Niccone river catchment and location of the ground soil moisture measurements

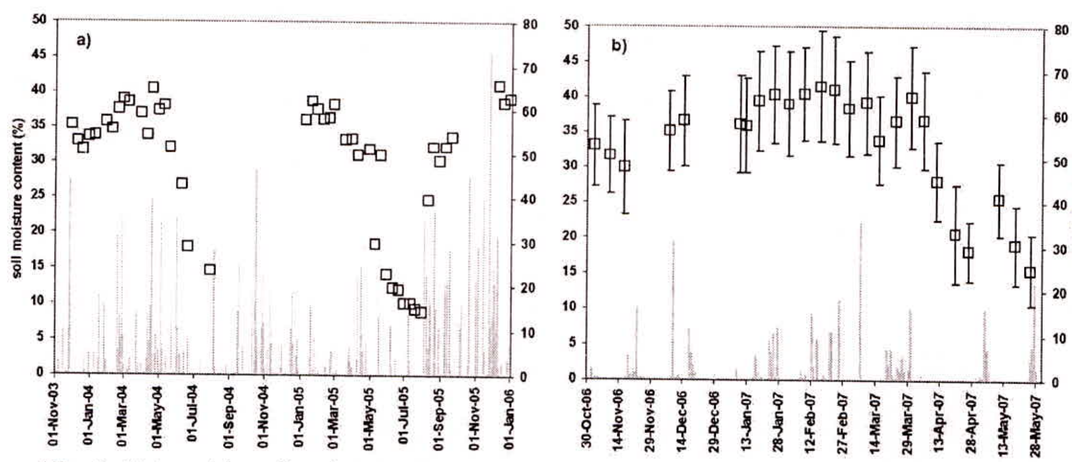

Fig. 3: Volumetric soil moisture and daily rainfall temporal pattern for the: (a) Colorso, and (b) Vallaccia sites. The standard deviation for the Vallaccia site is also shown

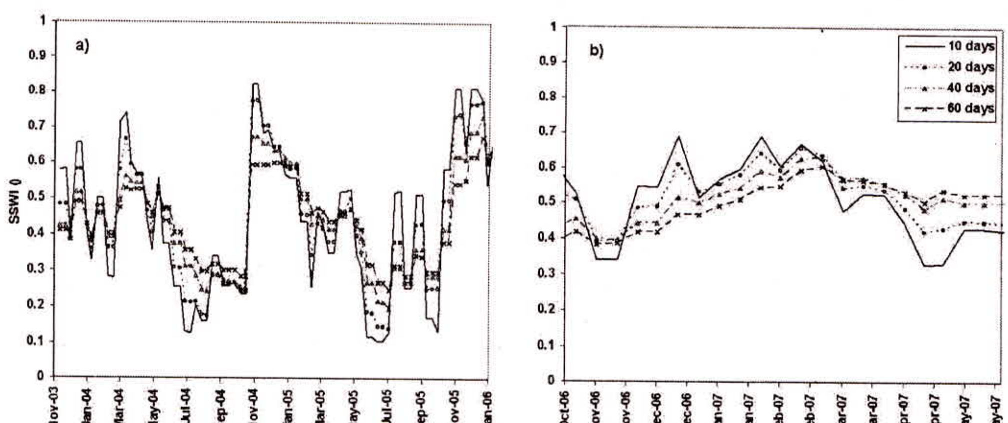

Fig. 4: Temporal pattern of the Scatterometer derived Soil Wetness Index, SSWI, for the pixel nearest to the Niccone catchment for two time periods (see also Figure 3). Four different values for the characteristic time length were considered

Figure 5 shows the correlation coefficient (R) and the Root Mean Square Error (RMSE) of the linear regression between the SSWI and the two ground soil moisture data sets varying the characteristic time length, T. As it can be seen, the characteristic time length value for the Colorso site (40 days) is higher than the standard value of 20 days suggested by Wagner *et al.* (1999), whereas it is in accordance with that obtained by Ceballos *et al.* (2005) for a similar investigation depth (25 cm). A lower value, T = 10 days, was obtained for the Vallaccia site as can be expected by the comparison of the soil type for the 7 sites locations the Colorso site.

Despite the strong difference in the measurement spatial support an high correlation coefficient was obtained for both data sets. This can be ascribed to the temporal stability properties shown by the soil moisture spatial pattern as reported in the literature (Vachaud *et al.*, 1985) and it is also confirmed by the analysis of the temporal pattern of the 7 sites belonging to the Vallaccia data set (not shown for sake of brevity). However, the highest correlation of the Vallaccia site can be linked to a larger spatial support of this soil moisture data set but also to the lower sample size. The scatter plot of the observed versus estimated soil moisture with the optimal value of the T parameter is shown in Figure 6. In general, notwithstanding the SSWI overestimates the lower moisture value, the capability of the ERS scatterometer to retrieve near-surface soil moisture is confirmed by the two data sets here used.

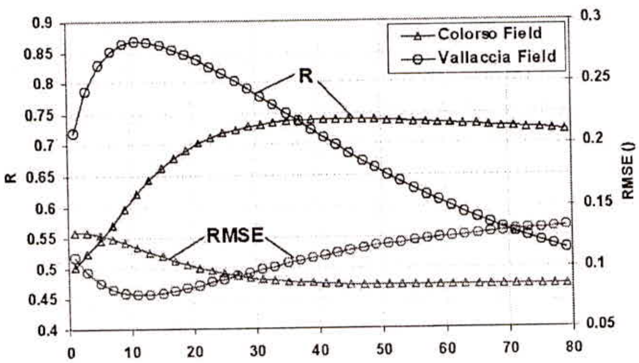

Fig. 5: Correlation coefficient (R) and Root Mean Square Error (RMSE) between the SSWI and the ground-based soil moisture data sets versus the characteristic time length for the Colorso and Vallaccia sites

SSWI Versus Catchment Antecedent Conditions

Following Brocca *et al.* (2008b), in order to estimate the AWC at the catchment scale the potential maximum retention parameter value, S, was determined assuming the knowledge of the direct runoff and rainfall depth and it is denoted henceforth as 'observed' potential maximum retention, S_{obs}. Specifically, S_{obs} is given by,

$$S_{obs} = \frac{1}{2\lambda^2}\left(2\lambda P - \lambda Q + Q - \sqrt{\lambda^2 Q^2 - 2\lambda Q^2 + 4\lambda PQ + Q^2}\right) \quad \ldots (2)$$

where P is the rainfall depth and Q is the runoff depth. The value of λ parameter was set to 0.20 as in the classical SCS-CN method because it does not influence significantly the results.

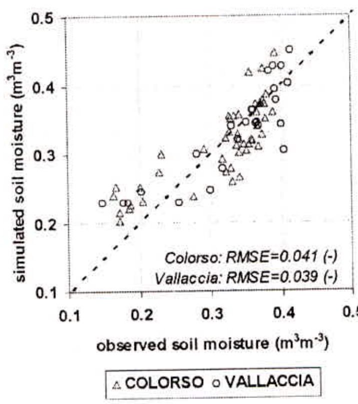

Fig. 6: Observed versus simulated saturation degree for the Colorso and Vallaccia sites by using the calibrated T value

Along with the SSWI, two API indices were considered for the AWC estimation: 1) the total N-day antecedent rainfall depth, API_N, and 2) the API_i index (Brocca *et al.*, 2008a) defined as,

$$API_i = K \cdot API_{i-1} + P_i \quad \ldots (3)$$

where P_i is the rainfall depth for the i^{th} day and K is a daily decay parameter linked to the inverse of the evapotranspiration and estimated by calibration. In the literature the K value at the daily time scale was found ranging between 0.80 and 0.98.

Moreover, since an exponential relationship between the AWC and the discharge was proposed in literature (Troch *et al.*, 1993; Romanowicz *et al.*, 2006), a Base Flow Index (BFI), merely estimated from the natural logarithm of the discharge at the beginning of the rainfall event, was also considered.

The SSWI was obtained by the weighted average, according to the area, of all the pixels included in the catchment. In particular, 12 pixels were used for the Tiber river at Ponte Nuovo (see Figure 1) and only one pixel, the nearest one, for the two sub-catchments Niccone and Assino. As before, the T value was considered as a calibration parameter ranging between 1 and 100.

Considering the whole rainfall-runoff events data set, the four indicators of AWC were fitted to S_{obs} varying the parameter N, K and T for API_N, API_i and the SSWI, respectively. Table 2 shows the results of the regression analysis in terms of R and RMSE for each catchment along with the optimal value of parameters. In particular, the value of the T parameter for the two smallest catchment is nearly the same equal to 80 days, a lower value (45 days) for the larger catchment (Tiber) was obtained. As it can be seen in Table 2, the SSWI performances are always better than the other AWC indicators with a very high correlation coefficient, equal to about –0.90. This suggests that the SSWI could be considered reliable in the estimation of the catchment AWC, too. As in previous analysis, fairly accurate results were obtained with the BFI; whereas the API indices furnished poor achievements (Brocca *et al.*, 2008a; 2008b). In particular, the API_N with $N = 5$, as in the classical formulation of the SCS-CN method, was found not reliable with correlation coefficient less than 0.10. Figure 7 shows the scatter plot of the SSWI against S_{obs} for the three investigated catchments. Considering the best fit, its slope was found similar for the Niccone and Tiber catchment, whereas for the Assino river, owing to the higher variability of the SSWI values, the slope is steeper.

As the API were found poorly representative of AWC, the accuracy of the other two indicators SSWI and BFI in runoff depth estimation has been investigated. Figure 8 shows the cumulative frequency of the absolute error between the observed and estimated runoff depth for the three investigated catchments. In general, when the SSWI was considered, the mean error didn't exceed 20%, whereas for 80% of the selected events the absolute error was found less than 20%, 25% and 30% for the Tiber, Assino and Niccone catchments, respectively (see Figure 8a). Moreover, the highest errors were obtained for the smallest events that are less significative for flood prediction and forecasting purposes. The error on runoff depth estimation was found to increase by adopting the BFI (see Figure 8b). In particular, the mean error was nearly twice ranging between 28% and 42%.

Table 2: Regression performance of the relationship between the 'observed' maximum potential retention and different indicators of antecedent wetness conditions, AWC. For symbols see text

AWC	*Tiber (N = 20, K = 0.99, T = 45)*		*Assino (N = 3, K = 0.99, T = 80)*		*Niccone (N = 11, K = 0.99, T = 78)*	
	RMSE (mm)	*R*	*RMSE (mm)*	*R*	*RMSE (mm)*	*R*
API_N	16.10	–0.24	12.69	–0.29	17.17	–0.51
API_i	13.69	–0.57	12.72	–0.31	16.82	–0.54
BFI	11.60	–0.72	8.15	–0.79	14.10	–0.70
SSWI	6.80	–0.91	6.25	–0.91	9.10	–0.89

CONCLUSIONS

Based on the analysis and the results reported in this study the following conclusions can be drawn.

- The SSWI was found reliable in the soil moisture estimation for the 0–15 cm top layer, which is fundamental in runoff generation for areas of Central Italy.
- For the Colorso data set the value obtained for the SSWI parameter T was found higher ($T = 40$ days) than the standard value used at global scale ($T = 20$ days) as proposed by Wagner *et al.* (1999), but in accordance with the results of Ceballos *et al.* (2005). For the Vallaccia data set, probably due to the soil type differences, a lower value was obtained ($T = 10$ days).

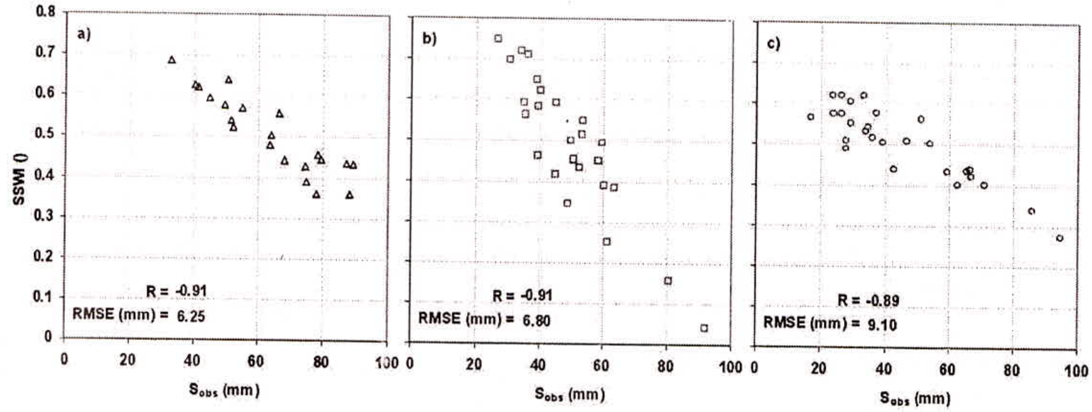

Fig. 7: Observed potential maximum retention, S_{obs}, *versus* Scatterometer derived Soil Wetness Index, SSWI, for: (a) Tiber, (b) Assino, and (c) Niccone catchments

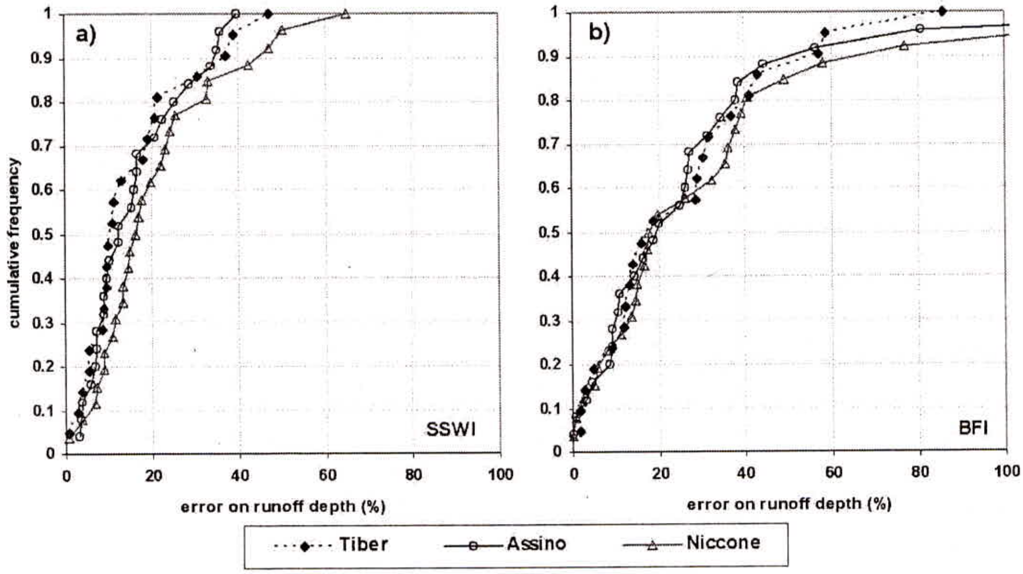

Fig. 8: Cumulative frequency of the absolute error between the observed and estimated runoff depth for the three investigated catchments by using: (a) the Scatterometer derived Soil Wetness Index, SSWI, and (b) the Base Flow Index, BFI

- The AWC for the three investigated catchments, as determined through salient rainfall-runoff events, were found highly correlated with the SSWI, with correlation coefficient of ~0.90. Moreover, the SSWI outperformed the API and BFI indices, that are usually considered in the hydrological practice for the AWC assessment.
- The SCS-CN method for runoff depth estimation based on the use of the SSWI, for the determination of the *S* parameter, was found quite accurate providing a mean absolute error less than 20% for the three investigated catchments.

The good correlations obtained reveals that the scatterometer soil moisture estimates can be confidently used to address the prediction in ungauged basin. However, the analysis should be carried out in other catchments, in order to assess an overall procedure to estimate the SSWI parameter.

Finally, the correlation of the soil moisture observed at the plot scale with the inferred one by satellite data reveals the potential of scatterometer data, particularly considering the higher spatial resolution provided by the successor of ERS scatterometer (Advanced Scatterometer, ASCAT, on board the Meteorological Operational (METOP) platforms). The investigation of the capabilities of current operative passive microwave radiometers such as the Advanced Microwave Scanning Unit (AMSU) onboard of NOAA satellites (Lacava *et al.*, 2005) or the Advanced Microwave Scanning radiometer (AMSR-E) onboard of NASA's Aqua satellite will be the object of future studies.

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REFERENCES

Anctil, F., Michel, C., Perrin, C. and Andreassian, V. (2004). "A soil moisture index as an auxiliary ANN input for stream flow forecasting." *Journal of Hydrology*, 286, 155–167.

Aronica, G and Candela, A. (2004). "A regional methodology for deriving Flood Frequency Curves (FFC) in catchments with uncertain knowledge of soil moisture conditions." *Proc., iEMSs 2004*, University of Osnabrück, Germany, 1147–1183.

Aubert, D., Loumagne, C. and Oudin, L. (2003). "Sequential assimilation of soil moisture and streamflow data in a conceptual rainfall runoff model." *Journal of Hydrology*, 280, 145–161.

Baghdadi, N., Cerdan, O., Zribi, M., Auzet, V., Darboux, F., El Hajj, M. and Kheir, R.B. (2007). "Operational performance of current synthetic aperture radar sensors in mapping soil surface characteristics in agricultural environments: application to hydrological and erosion modelling." *Hydrological Processes,* 22(1), 9–20.

Berg, A.A. and Mulroy, K.A. (2006). "Streamflow predictability in the Saskatchewan/Nelson River basin given macroscale estimates of the initial soil moisture status." *Hydrological Sciences Journal*, 51(4), 642–654.

Brocca, L., Morbidelli, R., Melone, F. and Moramarco, T. (2007). "Soil moisture spatial variability in experimental areas of central Italy." *Journal of Hydrology*, 333(2–4), 356–373.

Brocca, L., Melone, F. and Moramarco, T. (2008a). "On the estimation of antecedent wetness conditions in rainfall-runoff modelling." *Hydrological Processes*, 22, 629–642.

Brocca, L., Melone, F., Moramarco, T. and Singh, V.P. (2008b). "Assimilation of observed soil moisture data in storm rainfall-runoff modelling." *Journal of Hydrologic Engineering*. in press.

Ceballos, A., Scipal, K., Wagner, W. and Martınez-Fernandez, J. (2005). "Validation of ERS Scatterometer-Derived Soil Moisture Data in the Central Part of the Duero Basin, Spain." *Hydrol. Proc.*, 19, 1549–1566.

Chahinian, N., Moussa, R., Andrieux, P. and Voltz, M. (2005). "Comparison of infiltration models to simulate flood events at the field scale." *Journal of Hydrology*, 306, 191–214.

De Michele, C. and Salvadori, G. (2002). "On the derived flood frequency distribution: analytical formulation and the influence of antecedent soil moisture condition." *Journal of Hydrology*, 262, 245–258.

De Ridder, K. (2000). "Quantitative estimate of skin soil moisture with the Special Sensor Microwave/Imager." *Bound-Lay. M.*, 96, 421–432.

Houser, P.R., Shuttleworth, W.J., Famiglietti, J.S., Gupta, H.V., Syed, K.R. and Goodrich, D.C. (1998). "Integration of soil moisture remote sensing and hydrologic. modelling using data assimilation." *Water Resource Research*, 34(12), 3405–3420, doi: 10.1029/1998WR900001.

Lacava, T., Cuomo, V., Di Leo, E.V., Pergola, N., Romano, F. and Tramutoli, V. (2005). "Improving soil wetness variations monitoring from passive microwave satellite data: the case of April 2000 Hungary flood". *Rem. Sens. Environ.*, 96(2), 135–148.

Moran, M.S., Hymer, D.C., Qi, J. and Sano, E.E. (2000) "Soil Moisture Evaluation Using Multi-Temporal Synthetic Aperture Radar (SAR) in Semiarid Rangeland." *Agr. For. Met.*, 105, 69–80.

Pauwels, V.R.N., Hoeben, R., Verhoest, N.E.C. and DeTroch, F.P. (2001). "The importance of the spatial patterns of remotely sensed soil moisture in the improvement of discharge predictions for small scale basins through data assimilation." *Journal of Hydrology*, 251, 88–102.

Parajka, J., Naeimi, V., Bloschl, G., Wagner, W., Merz, R and Scipal, K. (2006). "Assimilating scatterometer soil moisture data into conceptual hydrologic models at regional scale". *Hydrology and Earth System Sciences*, 10, 353–368.

Romanowicz, R.J., Young, P.C. and Beven, K.J. (2006). "Data assimilation and adaptive forecasting of water levels in the river Severn catchment, United Kingdom." *Water Resources Research*, 42, W06407, doi: 10.1029/2005WR004373.

Scipal, K., Scheffler, C. and Wagner, W. (2005). "Soil moisture runoff relation at the catchment scale as observed with coarse resolution microwave remote sensing." *Hydrology and Earth System Sciences*, 2(2), 417–448.

Scipal, K., Wagner, W., Trommler, M. and Naumann, K. (2002) "The Global Soil Moisture Archive 1992–2000 from ERS Scatterometer Data: First Results." *Proc. IGARRS'2002*, Toronto, Canada.

Stephenson, G.R. and Freeze, R.A. (1974). "Mathematical simulation of subsurface flow contributions to snowmelt and runoff, Reynold Ck. Watershed, Idaho." *Water Resources Research*, 10, 289–294.

Troch, P.A., De Troch, F.P. and Brutsaert, W. (1993). "Effective water table depth to describe initial conditions prior to storm rainfall in humid regions." *Water Resources Research*, 29(2), 427–434.

Vachaud, G., Passerat de Silans, A., Balabanis, P. and Vauclin, M. (1985). "Temporal stability of spatially measured soil water probability density function." *Soil Science Society of America Journal*, 49, 822–828.

Wagner, W., Lemoine, G. and Rott, H. (1999). "A Method for Estimating Soil Moisture from ERS Scatterometer and Soil Data." *Remot. Sen. Env.*, 70, 191–207.

Wagner, W., Blöschl, G., Pampaloni, P., Calvet, J.C., Bizzarri, B., Wigneron, J.P. and Kerr, Y. (2007). "Operational readiness of microwave remote sensing of soil moisture for hydrologic applications." *Nordic Hydrology*, 38(1), 1–20.

Western, A.W., Grayson, R.B. and Blöschl, G. (2002). "Scaling of Soil Moisture: A Hydrologic Perspective." *Annual Review of Earth and Planetary Sciences*, 30, 149–180.