Italian Journal of Engineering Geology and Environment
www.ijege.uniroma1.it

PERFORMANCE OF RAINFALL AND SOIL MOISTURE SATELLITE PRODUCTS ON A SMALL CATCHMENT IN CENTRAL ITALY

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EXTENDED ABSTRACT

L'acquisizione di dati meteo-climatici (precipitazioni, temperatura, umidità del suolo, ecc.) può essere impegnativa e le informazioni a disposizione possono non essere rappresentative dell'area di studio (Basist *et alii*, 1994; Millán *et alii*, 2005; Cambi *et alii*, 2010). I dati a terra possono essere utilizzati per validare le stime di precipitazioni e contenuto d'acqua nei primi cinque centimetri di suolo (SSM) derivate da satellite, quest'ultime disponibili a diverse risoluzioni spazio-temporali. A causa dell'estrema variabilità spaziale dell'SSM, specialmente a scala di bacino (Walker *et alii*, 2004; Evett *et alii*, 2006; Rudnick *et alii*, 2015; Ortenzi *et alii*, 2022), la validazione con dati a terra risulta particolarmente complessa. La verifica delle prestazioni dei prodotti satellitari su piccoli bacini idrografici è quindi un problema aperto, in particolare in aree con forti variazioni topografiche e con copertura del suolo eterogenea. Il presente studio si propone di valutare le performance di alcuni prodotti satellitari sul bacino idrografico del T. Tatarena (Italia centrale). Tale bacino, che presenta un'area di circa 32 km2, ha un'altitudine media di 407 m s.l.m. e si imposta prevalentemente su rocce a medio-bassa permeabilità appartenenti alla parte alta della Serie Umbro-Marchigiana (litotipi calcareo-marnosi) e di quella torbiditica Umbro-Romagnola. Il bacino del T. Tatarena è scarsamente antropizzato (0.5% di copertura urbana), con prevalente copertura agricola (72%), seguita da copertura boschiva (26%) e prati (1.5%). Le caratteristiche geomorfologiche e di copertura del suolo rendono il T. Tatarena rappresentativo di molti bacini dell'area appenninica, spesso caratterizzati da eventi di piena improvvisi a seguito di piogge intense. I dati disponibili sul bacino sono riassumibili in:

- n. 3 pluviometri gestiti dal Servizio Idrografico Regionale dell'Umbria, ad elevata risoluzione temporale e spazialmente ben distribuiti;
- n. 2 prodotti pluviometrici satellitari, l'IMERG GPM (Integrated Multi-satellitERetrievals for Global PrecipitationMeasurement, Nasa) e il dataset SM2RAIN (EUMETSAT, European Space Agency, ESA and European Commission projects). Il prodotto IMERG GPM ha una frequenza di campionamento di 30 minuti e una risoluzione spaziale di 0.1° x 0.1° (dati dal 2014). Il dataset SM2RAIN fornisce dati mensili e giornalieri di pioggia con una risoluzione spaziale di 0.1° x 0.1° a partire dal 2007;
- n. 2 prodotti di SSM satellitari, il Copernicus Sentinel-1 SSM1km e il dataset L2_SM_SP (SMAP, Nasa), entrambi con dati sovrapponibili dal 2015.

Per verificare e quantificare le prestazioni dei dati satellitari, rispetto ai dati a terra, sono stati utilizzati sia test statistici che analisi a doppia massa, prendendo in esame il periodo 2015-2021. In assenza di misure al suolo, la qualità dei dati satellitari SSM è stata valutata tramite l'Hydrological Consistency Index (HCI, Paciolla *et alii*, 2020) che valuta la risposta dei dati SSM alle precipitazioni giornaliere.

I risultati delle analisi indicano che la performance dei dati IMERG GPM sul bacino analizzato è migliore di quella SM2RAIN, sia a scala mensile che giornaliera. Tale risultato può essere imputato a alcune limitazioni del prodotto SM2RAIN, quali la sottostima degli eventi piovosi intensi (Brocca *et alii*, 2019). Le prestazioni di IMERG GPM peggiorano spostandosi dalla scala mensile verso la scala oraria. Per quanto riguarda i dati SSM, Copernicus Sentinel-1 SSM1km sembra avere prestazioni migliori rispetto ai prodotti SMAP L2_SM_SP, confermando quanto riportato da Bauer-Marschallinger *et alii* (2019) e Colliander *et alii* (2022). Sebbene l'analisi qui effettuata abbia considerato la risposta dell'SSM alle sole precipitazioni, come evidenziato da Paciolla *et alii* (2020), ulteriori studi sono necessari per considerare anche gli effetti dell'evapotraspirazione nei periodi estivi. Poiché i dati satellitari sono sempre più utilizzati nella modellazione dei processi idrologici a varie scale, la verifica dell'affidabilità di questi prodotti è fondamentale, soprattutto quando vengono utilizzati dalle autorità territoriali e da quelle di protezione civile. Il mantenimento di una rete attiva ed estesa di stazioni di misura nelle aree interne è una delle sfide dei prossimi anni, considerata la loro importanza per la verifica delle prestazioni dei dati satellitari in zone topograficamente complesse. I dati IMERG GPM e quelli Copernicus Sentinel-1 SSM1km sono promettenti per diverse applicazioni e i risultati del presente studio possono supportare ulteriori ricerche per la definizione delle soglie di attivazione del ruscellamento in bacini con caratteristiche simili a quelle del T. Tatarena.

IJEGE, Special Issue 1 (2023): 99-111, DOI: 10.4408/IJEGE.2023-01.S-13
E-ISSN 2035-5688 | ISSN 1825-6635 / ©Author(s)

ABSTRACT

Reliable rainfall and soil moisture data is crucial to investigate hydrogeological processes at the catchment scale (runoff, soil erosion, infiltration, etc.). The present study aims to evaluate the performance of several high-resolution satellite products (IMERG GPM, SM2RAIN, Copernicus Sentinel-1 SSM1km, and SMAP L2_SM_SP) that can support hydrological studies in areas with a lack of ground-based data. The analysis was carried out in a small low permeability catchment in Central Italy (Tatarena basin), equipped with three rain gauge stations. The basin is scarcely anthropized and can be considered representative of many catchments with different soil cover, from forest to farming. The satellite rainfall products were analysed using probability plots, the double mass method, statistical tests and three categorical scores. Satellite soil moisture data were tested with the Hydrological Consistency Index, aiming to verify the consistency between soil moisture satellite data and precipitation. The results show that the IMERG GPM rainfall dataset performs better than SM2RAIN at different time scales. Despite some uncertainties, the Copernicus Sentinel-1 SSM1km proved to be the best-performing soil moisture satellite dataset. Results may be useful for using satellite data to understand runoff processes in poorly instrumented basins.

Keywords: *satellite products, soil moisture, rainfall, small catchment, performance tests*

INTRODUCTION

Availability of meteo-climatic data coupled with geomorphological and land cover information is fundamental for understanding processes such as infiltration, runoff, soil erosion and slope stability (e.g., Dunne *et alii*, 1991; Ng & Shi, 1998; Rahardjo *et alii*, 2001). Acquisition of meteo-climatic data can be challenging and collected information can be not representative of the study area since, as an example, topography significantly affects spatial patterns of rainfall (e.g., Basist *et alii*, 1994; Millán *et alii*, 2005). Quality of ground-based rainfall data depends on the number, spatial distribution, and working period of the rain gauges over a territory (Molini *et alii*, 2009) which are not always available especially in mountain regions (Cambi *et alii*, 2010; Lorenz & Kunstmann, 2012). In many sites of the world, the number of measuring stations is decreasing, because many factors, including accessibility, ease of maintenance, and topographical aspects, affect the choice to install and/or to maintain rain gauges (Liang *et alii*, 2020). Despite these problems, the World Meteorological Organization (WMO) established a minimum density standard for constructing precipitation gauge networks (Wmo, 1976). The range of norms for mountainous regions in Mediterranean areas, for the minimum network, is 100-250 km^2/gauge. In Central Italy (Umbria Region), the number of active rain gauges is 86, with a network distribution of about 100 km^2/gauge (https://www.regione.umbria.it/documents/18/7110267/Stazioni+Umbre/b2a5996d-7e9c-42c5-8f31-be1848ef8b75).

The geomorphological setup deeply affects the acquisition of reliable rainfall data, as it usually occurs in the case of orographically complex regions such as the Umbria Region (Viviroli *et alii*, 2011; Di Matteo *et alii*, 2013; Camera *et alii*, 2017; Di Matteo *et alii*, 2017; Gentilucci *et alii*, 2022). Although rain gauges measurements – when present and spatially well distributed – can be representative for the characterization of catchments, the use of satellite data can improve rainfall estimation in areas with low sensor density.

In the last decades, satellite rainfall products such as SM2RAIN (EUMETSAT, European Space Agency, ESA and European Commission projects) and IMERG GPM (Integrated Multi-satellitE Retrievals for Global Precipitation Measurement, Nasa) have been largely used. Both products are referred to 0.1°x0.1°, with a spatial resolution close to the rain gauge density in Central Italy. Other satellite-derived meteo-climatic data such as the surface soil moisture (SSM) is also available. Checking the accuracy and reliability of SSM data is challenging since the measurements at plots and catchment scales are time-consuming and expensive (e.g., Walker *et alii*, 2004; Evett *et alii*, 2006; Rudnick *et alii*, 2015; Ortenzi *et alii*, 2022). Moreover, the acquisition of spot measurements by on-site probes can be unrepresentative of the water content distribution at the catchment scale, where the interaction of static properties (topography, soil types, geology, etc.) and dynamic processes (vegetation cover and growth, changes of porosity in the first centimetre of soils, etc.) is responsible for the high variability of SSM (Vereecken *et alii*, 2014). Summarizing, satellites provide multiple meteo-climatic variables, that are freely available and useful for understanding hydrological processes occurring on the Earth's surface. In this context, satellite data and are increasingly used in the prediction models at regional scales (Artan *et alii*, 2007; Ciabatta *et alii*, 2016). According to Rossi *et alii* (2017), a complex relationship exists between rain gauge and the satellite rainfall products in different Italian morpho-climatic settings and we expect that this can also affect satellite soil moisture data. Although there have been efforts to implement the global in-situ measurement networks, the number of ground sensors are still limited (Dorigo *et alii*, 2011). Assessing the performance of satellite-derived meteo-climatic estimates on small catchments is an open issue, particularly in topographically and land covers heterogeneous areas.

The present study aims to investigate the reliability of rainfall satellite products at different timescales on a small well-instrumented catchment in Central Italy (Tatarena basin). Moreover, the available satellite SSM data products are compared and discussed using a physics-based index aiming to verify the consistency between soil moisture satellite data and precipitation.

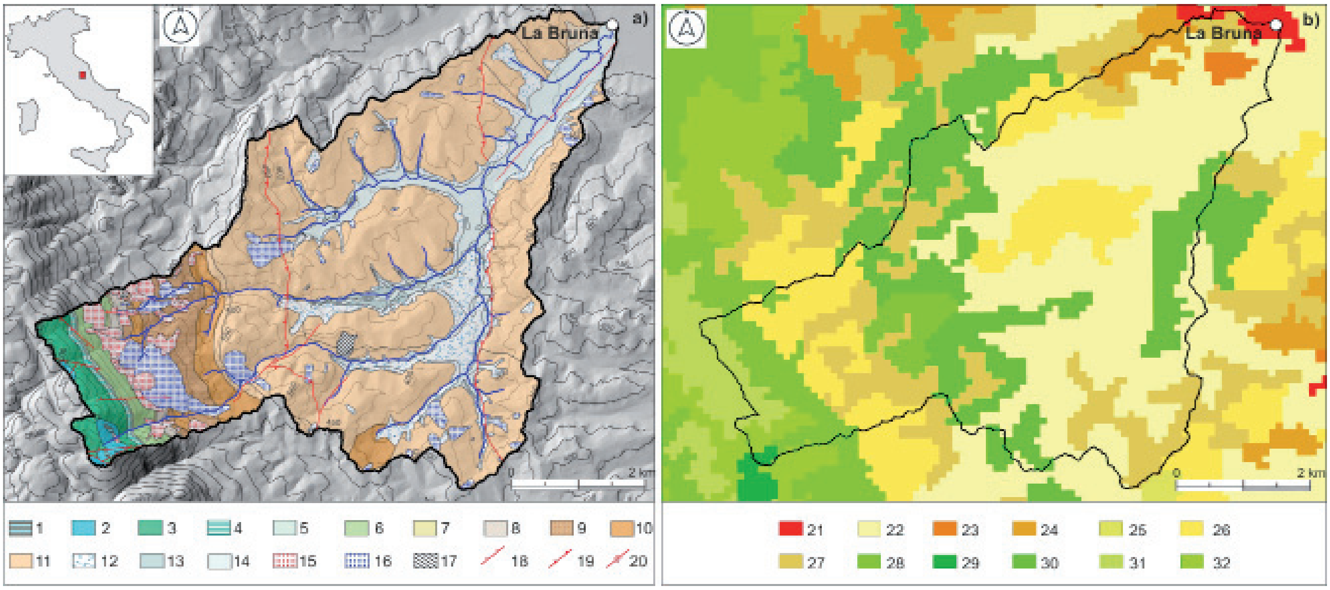

Fig. 1 - a) Geological map of the Tatarena basin and b) land cover map base on Corine Land Cover 2018 (https://land.copernicus.eu/pan-european/corine-land-cover/clc2018) – LEGEND:1) Rosso Ammonitico; 2) Corniola; 3) Maiolica; 4) Marne a Fucoidi; 5) Scaglia Rossa; 7) Scaglia Variegata; 8) Scaglia Cinerea; 9) Bisciaro; 10) Schlier; 11) Umbro-Romagnola turbidite sequence; 12) Eluvial-colluvial deposits; 13) Terraced alluvial deposits; 14) Fluvial-lacustrine deposits; 15) Talus; 16) Landslides; 17) Anthropic deposits; 18) Normal fault; 19) Thrust; 20) Strike-slip fault; 21) Discontinuous urban fabric; 22) Non-irrigated arable land; 23) Vineyards;24) Olive groves;25) Pastures; 26) Complex cultivation patterns; 27) Land principally occupied by agriculture with significant areas of natural vegetation;28) Broad-leaved forest; 29) Coniferous forest; 30) Mixed forest;31) Natural grasslands;32) Transitional woodland shrub

MATERIALS AND METHODS

Geological and geomorphological characteristics

The Tatarena stream is located in Umbria (Central Italy), and its catchment covers an area of approximately 32 km2 with an average altitude of 407 m a.s.l. The catchment is mainly characterized by turbiditic rocks, belonging to the Umbria-Romagnola sequence, with some outcropping of limestone-marly rocks belonging to the Umbria-Marche stratigraphic sequence (western highest elevation part of the basin, Fig. 1a), from Rosso Ammonitico to Schlier formations. Most of the catchment (about 74%) hosts marly rocks (from Scaglia Variegata to Schlier formations), pelitic-arenaceous rocks, and fluvial-lacustrine deposits with low-to-medium permeability. The catchment is characterized by two geomorphological zones based on the digital elevation model imagery (Tinitaly, Tarquini *et alii*, 2007): a western part corresponding to the eastern flank of the Martani mountain (mean elevation of about 800 m a.s.l.) and a hilly central-eastern part with a mean elevation of about 400 m a.s.l.

According to the Corine Land Cover 2018 dataset (Fig. 1b), the Tatarena basin is scarcely anthropized (discontinuous urban fabric occupies 0.5% of the total coverage) with main agricultural activities occupying about 72% of the total catchment extent. In detail, non-irrigated arable land occupies about 40% of the catchment, while vineyards, olive groves, and complex cultivation patterns with significant areas of natural vegetation characterize about 32%. Forests and grasslands occupy the remaining part of the basin's highest part, 26% and 1.5%, respectively.

The geomorphological and land cover characteristics of the Tatarena basin make it prone to rapid floods triggered by high-intensity rainfalls. Over the centuries, the channel of the Tatarena stream has undergone several hydraulic works (e.g., D'Agata, 2015), with river diversions (mainly downstream of La Bruna village) and embankment constructions since the 14th century (Fig. 2).

Hydraulic management is also a very important issue nowadays, as evidenced by recurring work carried out by the Consorzio della Bonificazione Umbra, the authority in charge

Fig. 2 - a) Detail of the embankments close to the La Bruna village, b) location of La Bruna rain gauge

for the hydraulic management of the system. According to the Aree Vulnerate Italiane database (AVI, SICI-IRPI, http://sici.irpi.cnr.it/avi.htm), several floods affected the river network fed by the Tatarena stream between 1860 and 1991 (e.g., CBU 2019). The last documented floods occurred on December 9, 2020, with some flooding about 5 km downstream La Bruna village (https://tuttoggi.info/trevi-tatarena-argine-cannaiola/608565/). This is confirmed by existing national flood zoning maps (ISPRA, 2015; Marchesini *et alii*, 2021).

Meteorological Data

Rain Gauges

The study area is equipped with 3-gauge stations, managed by the Regional Hydrographic Service of Umbria, providing high-resolution rainfall data recorded every minute. This work aggregates the sub-hourly records to hourly, daily, and monthly time scales. Table 1 summarize sensor codes and main characteristics of the gauge stations. The average rainfall in the catchment was obtained using the well-known Thiessen Polygon method. The locations of the stations and their areas of influence are shown in Fig. 3a. The observation of rainfalls at different time scales is useful for analysing the performance of satellite products, focusing on the 2015-2021 period.

Gauge Station	Sensor code	m. a.s.l	Time series
La Bruna	43648	246	2011-present
San Silvestro	12945	383	1992-present
Montemartano	37469	618	2008-present

Tab. 1 - Main characteristics of the rain gauges. The sensor codes are the official used by Regional Hydrographic Service of Umbria

Rainfall satellite data

The Tatarena catchment is covered by two main rainfall products, the IMERG GPM and the SM2RAIN dataset. The IMERG GPM algorithm intercalibrate, merges and interpolates the precipitation estimates GPM satellites, considering both microwave precipitation estimates with microwave-calibrated infrared (IR) and provides a rainfall product with a sampling frequency of 30 minutes and a spatial resolution of about 11 km x 8 km over the catchment. GPM is an international satellite network that provides observation of rain and snow from February 2014. The algorithm also includes monthly data from precipitation gauge analyses (Global Precipitation Climatology Center, GPCC) to produce a significant improvement, e.g., compared to TRMM (Tropical Rainfall Measuring Mission), especially for some regions. IMERG GPM system runs multiple times (two in near-real time), and the algorithm provides the “Final Product” after the calibration with monthly data from rain gauges, occurring, in general, about 3.5 months after the observation month. The Final Product of IMERG GPM dataset is available until September 2021. This product includes multiple variables (e.g., “PrecipitationCal”, “PrecipitationQualityIndex”, “ProbabilityLiquidPrecipitation”, etc.). In particular, the variable “PrecipitationCal” (Precipitation calibrated) is available at yearly, monthly, daily, and 30-minute scales (Huffman *et alii*, 2019). The current version (Version 06, V06) can be downloaded for free from the GPM NASA website (https://disc.gsfc.nasa.gov/) in ASCII or NetCDF4 format.

The SM2RAIN dataset provides monthly and daily satellite cumulated rainfall data derived from soil moisture observation (ASCAT dataset), with a spatial resolution of 0.1° from 2007 and globally. ASCAT soil moisture data record is provided by the EUMESTAT H SAF, which includes MetOp-A, MetOp-B and MetOp-C satellites working on the C-band, and supply soil moisture product (12.5 km spatial resolution) using the TU Wien algorithm (Wagner *et alii*, 2013). To obtain the rainfall data, three other additional variables, taken from the ERA5 dataset, are considered (evaporation, soil temperature, from 0 to 7cm depth, and total rainfall). All information is derived at 36 km spatial resolution and hourly time scale. Moreover, Ground-Based rainfall datasets are also collected and integrated into the computation (Brocca *et alii*, 2019). The SM2RAIN dataset is freely available online (https://zenodo.org/record/6459152#.Y7Lrt3bMJPY).

The grids of IMERG GPM and SM2RAIN, including the Tatarena basin, are shown in Fig. 3a

Soil moisture satellite data

The Tatarena catchment is covered by two main satellite soil moisture products, the SSM1km (Copernicus, ESA) and the L2_SM_SP dataset (SMAP, Nasa). Since 2013 the European Copernicus Project (Copernicus Global Land Service - CGLS) has aimed to provide climate variables (e.g., soil moisture, land surface temperature, water bodies area, etc.) on the earth’s surface with a high spatial-temporal resolution to monitor the involved processes at global scale (Bauer-Marschallinger & Paulik, 2019). In particular, the Sentinel-1 mission consists of two identical C-band Synthetic Aperture Radar (C-SAR) instruments, Sentinel 1A (launched in April 2014) and Sentinel 1B (launched in April 2016). Both satellite spacecraft operate and make observations from the Informetric Wide swath (IW) in VV polarization mode to derive the Copernicus Global Land SSM (Surface Soil Moisture) product.

The Surface Soil Moisture at time t (SSM(t)) is derived from the observed radar backscatter, which is normalized to a common reference observation angle (θr = 40) using the model TU-Wien-Change-Detection (Wagner, 1998). From the long-term backscatter measurements, the wettest (θ0dry(40)) and driest (θ0wet(40)) soil conditions are derived. The relative surface soil moisture is given by Eq.1.

$$SSM(t) = \frac{\theta_{40}(t) - \theta^0_{dry(40)}}{\theta^0_{wet(40)} - \theta^0_{dry(40)}} \quad (1)$$

The SSM1km product describes the soil moisture of the first 50 mm of soil at 1km spatial resolution and with a temporal resolution that ranges from every 3–8 days (since January 2015) and every 1.5–4 days (since October 2016, thanks to Sentinel-1B satellite). The SSM1km dataset (https://land.copernicus.eu/global/products/ssm) provides flag values that mask the non-meaningful pixel; SSM values cannot be correctly detected in extremely dry conditions, frozen soils, snow-covered soils, flooded areas, and slopes higher than 17°. Vegetation influences the C-SAR backscatter measurements; the SSM1km algorithm applies a static vegetation correction that can lead to bias during the vegetation period, especially in areas with high vegetation density. SSM values cannot be retrieved over high-vegetation regions (e.g., tropical forests).

In January 2015, NASA launched the Soil Moisture Active Passive (SMAP) mission, which included an L-band radar (active) and an L-band radiometer (passive). The acquisitions are at a fixed angle of 40°, and the combination of the two datasets aims to acquire high spatial-temporal resolution of surface soil moisture at a global scale (~5 cm depth). Unfortunately, on July 7, 2015, the SMAP radar ceased transmitting. To maintain the acquisition of high-resolution active-passive soil moisture products, the Copernicus Sentinel 1A and Sentinel 1B SAR products (C-band) have been used. Due to the differences in the two observations, the temporal resolution decreased to 12 days (initially was three days). L-band, compared to C-band, can retrieve soil moisture over a much higher range of vegetation conditions. The SMAP radiometer (L-band) is sensitive to surface soil moisture, but the ground resolution is about 40 km; instead, the C-band SAR (Copernicus Sentinel-1A/1B) has a higher spatial resolution than the SMAP radiometer, but the soil moisture retrieval is much more sensitive to surface roughness and vegetation scattering. The L2_SM_SP product is based on the radiometer included in SMAP observations merged with the SAR observations from Sentinel 1A/1B at two different grid resolutions (i.e., ~33km and ~1 km). This process produces soil moisture retrievals at 3 km (validated) and 1 km (experimental) resolution (Das *et alii*, 2019). Each dataset contains two parts:

a) "soil_moisture_am", indicating values obtained when only the SMAP descending orbit is used to find an overlap with Sentinel-1A/1B overpass (+/- 24hrs time difference).

b) "soil_moisture_apm", indicating values obtained when both SMAP descending-ascending combination is used to find an overlap with Sentinel-1A/1B overpass (~ 12 hours).

The grids of SMAP and Sentinel-1 SSM1km, including the Tatarena basin, are shown in Fig. 3b.

Satellite data performance

Some statistical tests are used to check and quantify the performance of satellite data (Tab. 2), such as the Pearson's Correlation Coefficient (CC, Eq.1), Nash-Sutcliffe efficiency (NSE, Eq.2), Root Mean Square Error (RMSE, Eq. 3) and the relative bias (rBias, Eq.4). In addition, three categorical scores (i.e., POD – Probability Of Detection, FAR – False Alarm Ratio, and CSI – Critical Success Index) have been considered (Eqs. 5,6,7) (Moazami & Najafi, 2021; Yu *et alii*, 2021, Yusnaini *et alii*, 2022). To estimate, without ground measurements, the quality of satellite moisture data, the Hydrological Consistency Index was used (Paciolla *et alii*, 2020); the HCI is physics-based and aims to verify the consistency between SSM satellite data and precipitation data by assigning a positive or negative agreement to the record.

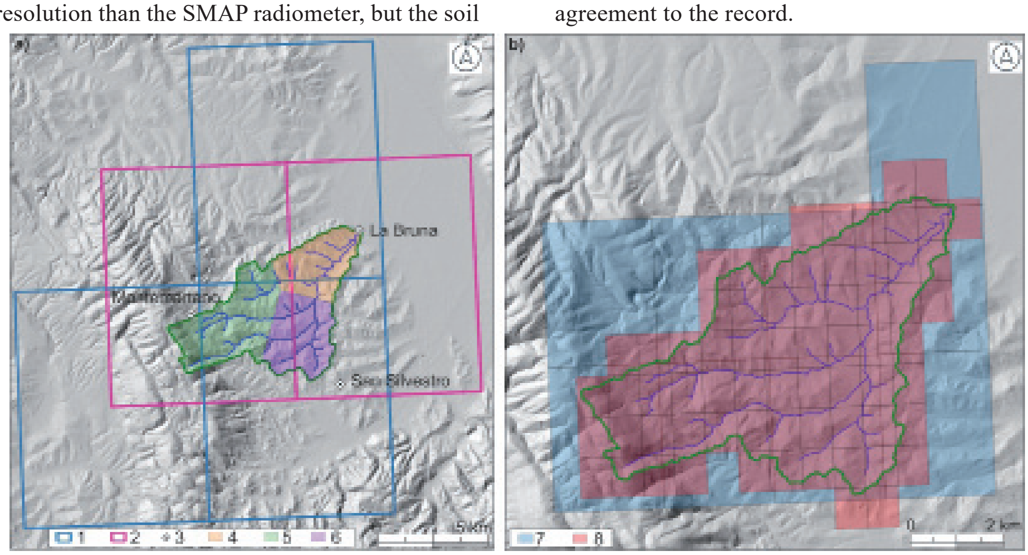

Fig. 3 - a) Grid cells of rainfall satellite data with Thiessen polygons of rain gauges; b) Grid cells of satellite surface soil moisture data b). LEGEND – 1) IMERG GPM; 2) SM2RAIN; 3) Rain gauges; 4) La Bruna rain gauge area; 5) Montemartano rain gauge area; 6) San Silvestro rain gauge area; 7) SMAP L2_SM_SP 3 km; 8) Sentinel-1 SSM1km

The "positive agreement" (A+) is set when:

- soil moisture increased and precipitation occurred between two successive satellite measurements;
- soil moisture decreased and no rainfall occurred between two consecutive satellite measurements;

The "negative agreement" (A-) is set when:

- soil moisture decreased and precipitation occurred between two successive satellite measurements.
- soil moisture increased and no rainfall occurred between two consecutive satellite measurements.
- When the variations of SSM fall in the range of the measurement error the agreement cannot be detected (n/a).

RESULTS

The satellite-based and ground-based meteo-climatic data available for the Tatarena catchment allow us to check the performance and the inter-comparison of the different satellite products.

Rainfall data

Regarding rainfall data, the first step for evaluating the performance of satellite data was plotting the probability distribution of the data value of the different datasets at different time scales. According to CHO et alii (2004), rainfall data generally follow the lognormal and gamma distribution; the latter outperforms in rainy regions. Figure 6 shows the p-p plot for satellite rainfall data (IMERG GPM and SM2RAIN) and ground-based rainfall at the catchment scale as obtained by the Thiessen Polygon method. Several theoretical distributions have been used to characterize monthly, and daily precipitation amounts; the Kolmogorov-Smirnov test (KS) and its Lilliefors modification (e.g., VLCEK & HYTH, 2009) are used to check the distance between the data and the theoretical distributions. The analysis highlighted that all the datasets are gamma distributed at both monthly (Fig. 4a) and daily scales (Fig. 4b), with the best performance for monthly data.

Ground-based and satellite rainfall data have been compared through double-mass analysis (SEARCY *et alii*, 1960). This analysis generally compares the cumulated rainfall data of two rain gauges to highlight abrupt deviations produced by instrument malfunctions and/or relocations. The double-mass method is also helpful in comparing the satellite rainfall data and gauge station observations to check the reliability of satellite observations at different time scales (VERNIMMEN *et alii*, 2012). Figure 5 shows the double mass curve of the ground-based cumulated rainfall at the catchment scale against the satellite estimates (IMERG GPM and SM2RAIN). The analysis of the Tatarena catchment shows that IMERG GPM estimates align along the equality line better than SM2RAIN data at both monthly and daily scales (Figs. 4c, 4d). In other words, at a daily scale, SM2RAIN observations underestimate the rainfall data

n.	Equation	Perfect value
(2)	$CC = \frac{\sum_{i=1}^{n}(G_i - G) * (S_i - S)}{\sqrt{\sum_{i=1}^{n}(G_i - G)^2} * \sqrt{\sum_{i=1}^{n}(S_i - S)^2}}$	1
(3)	$NSE = 1 - \frac{\sum_{i=1}^{n}(S_i - G_i)^2}{\sum_{i=1}^{n}(G_i - G)^2}$	1
(4)	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - G_i)^2}{n}}$	0
(5)	$rBias = \frac{\sum_{i=1}^{n}(S_i - G_i)}{\sum_{i=1}^{n} G_i} * 100$	0
(6)	$POD = \frac{Tp}{(Tp + Fn)}$	1
(7)	$FAR = \frac{Fp}{(Tp + Fp)}$	0
(8)	$CSI = \frac{Tp}{(Tp + Fp + Fn)}$	1

Tab. 2 - Statistical tests and categorical scores to check and quantify the performance of satellite data. Gi = rain gauge observation (L/T); G = mean rain gauge observation (L/T); Si = satellite observation (L/T); S = mean satellite observation (L/T); n = number of observations (-); Tp = number of true positive values (rainfall data are recorded both by satellite and rain gauges); Fn = numbers of false negative values (rainfall data are recorded by rain gauges and not by the satellite); Fp = numbers of false positive values (rainfall data are recorded by the satellite and not by rain gauges)

in several periods. For example, an abrupt deviation from the equality line is observed for a value of the cumulated rainfall of about 450 mm with some other important deviation registered at 2200 mm and 5000 mm (Fig. 4d). In these periods (end of June 2015 and beginning of December 2017 and December 2020) the SM2RAIN underestimates the rainfall data for about ten consecutive days (about 40% lower than ground-based observations). Similar behaviour is also observed for the IMERG GPM but with much smaller deviations so that the points remain on the equality line.

To check the reliability and performance of satellite rainfall data against ground-based sensors measurement, statistical indices and categorical scores were applied at monthly, daily, hourly and 6-hourly scales (DI MATTEO *et alii*, 2021; DUARTE *et alii*, 2022; HOSSEINI-MOGHARI & TANG, 2022). Computation of the performance of hourly and 6-hourly scales satellite rainfall data is carried out only on IMERG GPM data (no hourly SM2RAIN data are available) and, due to the large amount of data to be managed only for 2015. Table 3 summarizes the results of the statistical analysis. As obtained by the double-mass analysis, the IMERG dataset on a monthly and daily scale performs better than the SM2RAIN dataset. In particular, on a daily scale, the CC value for IMERG GPM is 0.90 compared to 0.68 for SM2RAIN. Although the POD values of the two datasets are similar, RMSE, rBias, FAR, and CSI values for IMERG GPM dataset are better than the SM2RAIN. IMERG GPM can be an alternative to observed precipitation at 6-hourly and daily time

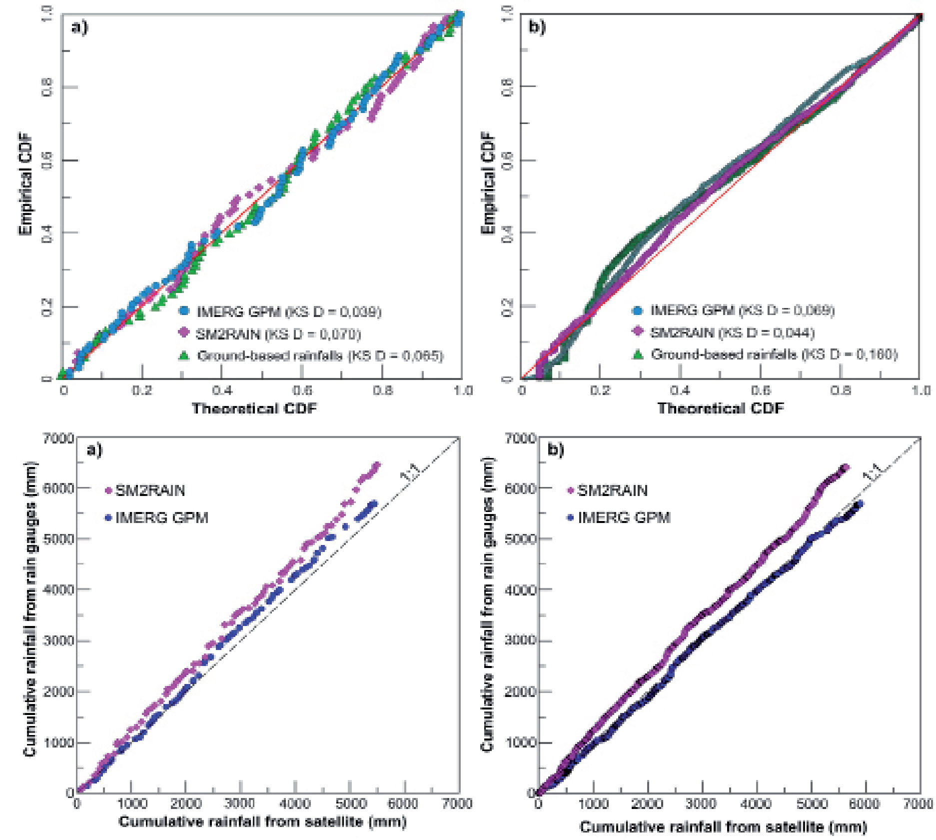

Fig. 4 - p-p plots of monthly (a) and daily (b) rainfall data over the catchment. Double-mass curves for detecting the consistence of satellite rainfall data at monthly (c) and daily (d) time-scales

Performance measure	IMERG (Monthly)	SM2RAIN (Monthly)	IMERG (Daily)	SM2RAIN (Daily)	IMERG (hourly)	IMERG (6-hourly)
CC	0.83	0.82	0.90	0.68	0.29	0.57
NSE	0.66	0.58	0.34	0.43	-1.07	-1.11
RMSE (mm)	29.51	36.54	4.76	5.18	1.22	1.74
rBias (%)	-4.44	-13.32	1.55	-11.42	-0.00	-0.00
POD	-	-	0.84	0.86	0.60	0.67
FAR	-	-	0.40	0.48	0.65	0.56
CSI	-	-	0.54	0.47	0.28	0.36

Tab. 3 - Results of the performance of rainfall satellite products at different time-scales. For the meaning of the performance tests refer to Table 2

scales, therefore particularly useful for describing or modelling basin-scale processes caused by intense and prolonged rainfall.

Soil moisture data

In the Tatarena catchment, the performance of SMAP L2_SM_SP products and Copernicus Sentinel-1 SSM1km product were investigated by using the Hydrological Consistency Inde (HCI), over the 2015-2021 period. The number of acquisitions of Sentinel-1 SSM1km resulted higher than the SMAP ones (706 vs. 518-516). As shown in Fig. 5, satellite SSM products react effectively to rainfall in both Autumn-Winter and Spring-Summer periods. The maximum volumetric water content in the analysed period occurred in Autumn-Winter of 2017-2018 and 2020-2021 (about 0.35 for both SMAP L2_SM_SP products, Figs. 5a, 5b), where the degree of saturation recorded by Sentinel-1 SSM1km was about 95% (the soil was almost saturated, Fig. 5c). Table 4 summarizes the results obtained by means of the application of the HCI index. Overall, the Copernicus Sentinel-1 SSM1km seems to perform better than the SMAP L2_SM_SP products, at least using the HCI index. In detail, about 54% Copernicus Sentinel-1 SSM1km data have a positive agreement (A+) compared to about 26-35% of SMAP products. Anyway, it should be emphasized that the number of n/a values for SMAP products (i.e., variations of SSM fall in the range of the measurement error of 0.04 cm^3/cm^3) is higher than those of Sentinel-1 SSM1km, adding a further issue in comparing satellite products.

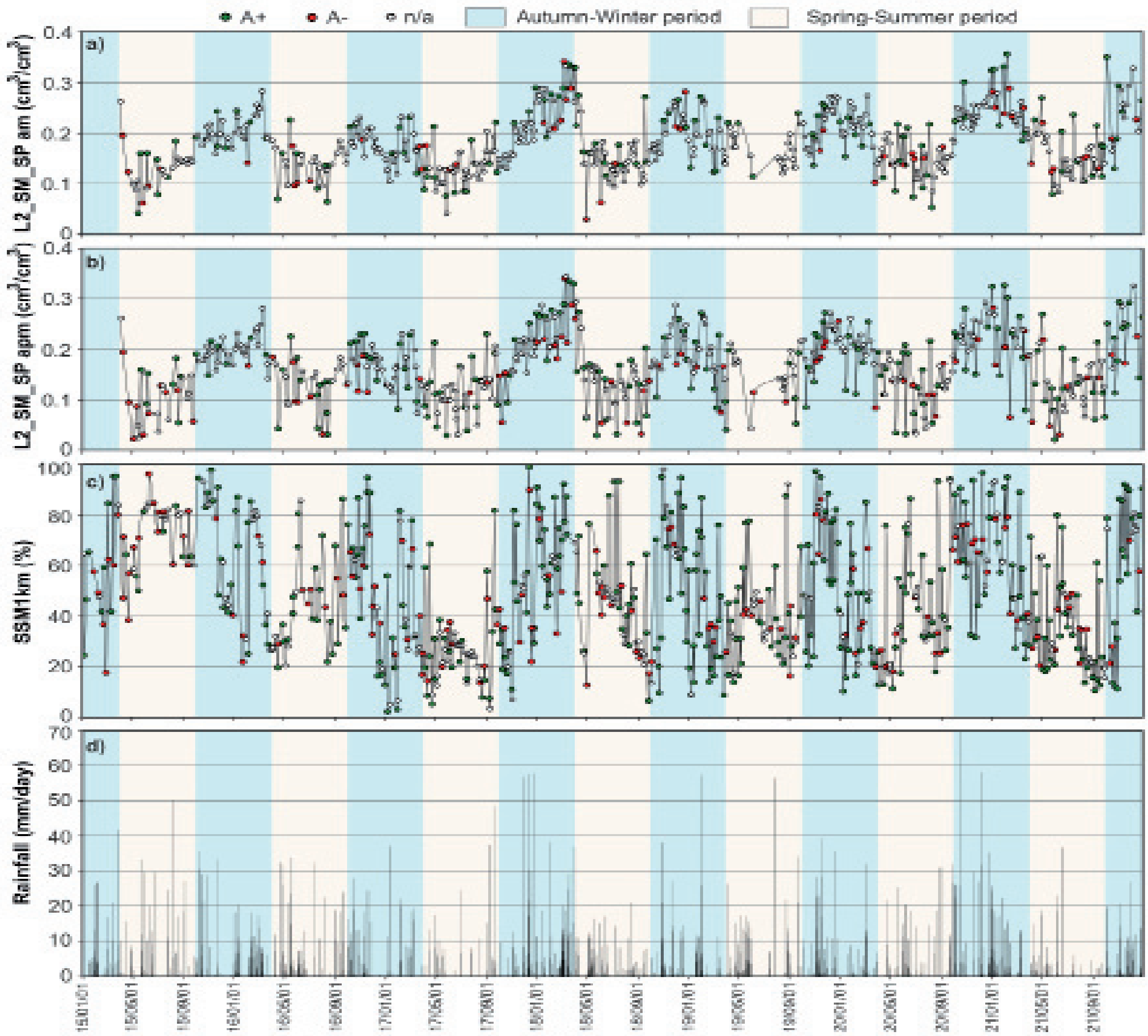

Fig. 5 - HCI analysis of soil moisture datasets for the 2015-2021 period. a) SMAP L2_SM_SP (ascending orbit, am); b) SMAP L2_SM_SP (ascending and descending orbits, am); c) Copernicus Sentinel-1 SSM1km; d) daily ground-based rainfall data at catchment scale

	SSM1km	L2_SM_SP am	L2_SM_SP apm
A+	380	136	181
A-	166	53	83
n/a	160	329	252
% of A+	53.8	26.3	35.1

Tab. 4 - Results of the HCI analysis for the Copernicus Sentinel-1 SSM1km dataset and the two SMAP products (L2_SM_SP am and L2_SM_SP apm)

DISCUSSIONS

The results obtained for the Tatarena basin can be discussed considering other regional studies investigating the reliability and performance of satellite data. Regarding rainfall data, the monthly and daily rainfall distribution agrees with the analysis carried out by Zolina *et alii* (2004) and Vlcek & Hyth (2009). In detail, Zolina *et alii* (2004), using the non-corrected KS test, found that data of about 90% of rain gauges in Europe have a gamma distribution. Vlcek & Hyth (2009), using the modified KS test at a daily scale, concluded that no obvious physical mechanism could explain why the gamma distribution represents the precipitation data. Anyway, Vlcek & Hyth (2009) reported that rainfalls in Central-Northern Italy are gamma-distributed throughout the different seasons by investigating the 1951-2000 period.

The results of the double mass analysis (Fig. 5) agree with that presented by Brocca *et alii* (2019), who reported some limitations of SM2RAIN data record that are similar to those obtained for the Tatarena basin. These limitations include underestimating peak rainfall events, spurious rainfall events due to high-frequency soil moisture fluctuations and estimating liquid rainfall only (snowfall cannot be estimated). Overall, the results of Tatarena catchment confirm that IMERG GPM data record performs better than the SM2RAIN in Central Italy.

As expected, according to Hosseini-Moghari & Tang (2022), the IMERG performance deteriorates with increasing temporal resolution; at an hourly scale, IMERG GPM leads to underestimation of rainfalls as highlighted, for example, by the CC value that approaches zero (see Tab. 2 for the reference perfect value for each test).

Regarding SSM data, evaluating the performance of satellite products is an open problem due to the lack of ground control points helpful in checking the spatial distribution at the catchment scale. It should be noted that direct observations of soil moisture are generally taken at specific locations, and the point-based measurements are not frequently representative of the spatial distribution of SSM, a highly variable parameter in both space and time (Wang & Qu, 2009). Although probes measurements are often used to describe the soil moisture in equipped very small basins or plots (e.g., Penna *et alii*, 2011; Morbidelli *et alii*, 2014; Korres *et alii*, 2015; Di Matteo *et alii*, 2018; Zhou *et alii*, 2019; Di Matteo *et alii*, 2021), most catchments are not equipped with soil moisture probes, or the monitored network is not representative to describe the SSM at the catchment scale. Passive and active microwave remote sensing can be alternatives to in-situ measurements to obtain SSM data at the basin scale. However, data acquisition techniques have some not negligible limitations, which may be more pronounced in some areas than others. As highlighted by many authors (Wang & Qu, 2009; Srivastava, 2017; Ma *et alii*, 2019; Huang *et alii*, 2019; Kim *et alii*, 2020; Peng *et alii*, 2020; Mohseni *et alii*, 2022) the microwave spectrum domain suffers for limitations due to soil roughness and vegetation. The latter attenuates soil emission and adds its contribution to the emitted radiation. Low frequencies observations (L-band) show a better vegetation penetration than C-band (Wang & Qu, 2009). Low-frequency L-band radiometers have penetration depths of approximately 3–5 cm and are sensitive to soil moisture through moderately thick vegetation water content (<5 kg/m^2) (Entekhabi *et alii*, 2010). In this framework, SMAP products (3 km) should perform better in highly vegetated areas than Copernicus Sentinel-1 SSM1km. Unfortunately, as recently reported by Colliander *et alii* (2022), the current reliability of 3km SMAP L2_SM_SP remains relatively low due to uncertainties related to the disaggregation scheme. The results for the Tatarena catchment seem to confirm a lower performance of SMAP L2_SM_SP compared to Copernicus Sentinel-1 SSM1km (see Tab. 4). Since the Tatarena catchment is mainly covered by agricultural lands (72% of the catchment area), C-band can be used to obtain reliable SSM estimates. These findings agree with the evaluation of the performance of the Copernicus Sentinel-1 SSM1km dataset for the Umbria Region recently carried out by Bauer-Marschallinger *et alii* (2019). Although the comparison of in-situ and SSM1km data is not very meaningful, Bauer-Marschallinger *et alii* (2019) reported satisfying results about the SSM1km signal quality over the Umbria Region, especially in non-densely forested area and agricultural lowlands.

The issue of the performance of L-band (SMAP) and C-band (Copernicus Sentinel-1) SSM retrievals is still open. It should be highlighted that our analysis is based on the HCI index that considers only the response of satellite SSM data to daily rainfalls. Further investigations should be carried out also to consider the effect of the actual evapotranspiration, especially in the warmer months, where the vegetation can alter the SSM satellite data (e.g., Paciolla *et alii*, 2020).

The analysis of the performance of both rainfall and SSM satellite products is mandatory before their use in the modelling and understanding of hydrological processes in catchments. Checking the quality of the available and spatially distributed hydrological data is becoming even more important in studying different topics, such as the evaluation of rainfall thresholds inducing shallow landslides (Brunetti *et alii*, 2018; De Vita et alii, 2018), the definition of runoff generation thresholds (e.g., Mirus & Loague, 2013), and the estimation of soil erosion (e.g., Longoni *et alii*, 2016). The knowledge of the event rainfall depth and the antecedent soil moisture content at the catchment scale could help the definition of runoff thresholds, especially in low permeability basins like the Tatarena. Up to now, these thresholds have been defined with promising results on plots or small instrumented basins (Penna *et alii*, 2015; Saffarpour *et alii*, 2016; Scaife *et alii*, 2017; Todisco *et alii*, 2022; Wang *et alii*, 2022), and therefore there is a need for reliable and representative data for describing the phenomena on small-to-medium basins. The results of this work should be considered preparatory to the use of satellite data for the modeling of runoff processes in poorly instrumented catchments, especially where the satellite products can compensate for the lack of soil moisture data.

CONCLUSIONS

The investigation carried out on the Tatarena basin made it possible to assess the reliability of data from various satellite products in a typical inland region of Central Italy.

The following conclusions are to be drawn based on the analysis of ground- and satellite-based rainfall and SSM data for the 2015-2021 period:

1. IMERG GPM products perform better than SM2RAIN, giving promising results also at daily scale.
2. The performance of IMERG GPM seems to deteriorate increasing temporal resolution (e.g., hourly scale).
3. Some peak rainfall events in the SM2RAIN dataset are not detected, although, to a lesser extent, this problem also applies to IMERG GPM.
4. Although no in-situ soil moisture ground control points

are available for the Tatarena catchment, a preliminary analysis indicates that Copernicus Sentinel-1 SSM1km data are more consistent with precipitation data than SMAP products.

Since remote sensing data for meteo-climate purposes are increasingly used in modelling hydrological processes at various scales, checking the reliability of these products is crucial, especially when used by decision-makers and civil protection authorities. Maintaining an active and extensive network of measuring stations in inner regions, where topographical effects influence rainfall estimates, is one of the challenges of the coming years. These data will increase the performance of satellite data with benefits for the temporal-spatial evaluation of precipitation. The capability to sense soil moisture at a high spatial-temporal resolution of Copernicus Sentinel-1 SSM1km is promising for evaluating changes in local hydrology due to rainfall. In this way, the presented findings will support further research in preparation for the definition of runoff thresholds for the Tatarena catchment and for some basins in Central Italy having similar topographic and lithological characteristics.

ACKNOWLEDGMENTS

The Authors wish to thank Dr. Luca Ciabatta of CNR-IRPI of Perugia for the support in downloading satellite soil moisture data.

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Received February 2023 - Accepted March 2023