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The validation of soil moisture satellite products based on hydrological parameters measured in a small basin, Romania

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Abstract: Stated from the idea that soil moisture is correlated with hydrological processes, this study proposed to validated two satellite products: Copernicus Global Land Service's surface soil moisture at 1 km^2 resolution (*SSM* 1 km) and Copernicus Global Land Service soil water index at 1 km^2 resolution (*SWI* 1 km) taking into account a small basin, located in the west part of Romania, Moneasa representative basin (MRB). The analyses were based on a dataset spanning 2016–2021, which included water discharge, precipitation, evapotranspiration, surface soil moisture, and the soil water index. Based on the Pearson test, the results support the idea that soil moisture is the hydro-pedological parameter that can be analysed based on hydrological elements. The results indicated low correlation between soil moisture and precipitation or soil moisture and evapotranspiration at daily time step, but the aggregated values at 10 days can improve the corrections. The *SSM* 1 km has closer correlations with the hydrological parameters (streamflow, runoff) than *SWI* 1 km. The *SWI* 1 km products have the advantage of generating daily values during April–November from each year, but it has a higher degree of error, especially in forested basins (such as MRB). Overall, the findings emphasise the potential of satellite-derived soil moisture products to complement ground-based observations and enhance hydrological studies, particularly in data-scarce basins.

Keywords: hydrological parameters, Pearson test, Romania, satellite products, small basin, soil water index, surface soil moisture

INTRODUCTION

Soil moisture is a multidisciplinary parameter often the subject of research in hydrological and agrometeorological studies (Martinez-Fernandez and Ceballos, 2003; Allen *et al.*, 2011; Montenegro *et al.*, 2019; Mincu and Neculau, 2024; Constantin *et al.*, 2025; Subbarayan *et al.*, 2025; Timilsina *et al.*, 2025). Detailed data for soil moisture are difficult to obtain, especially for large areas, using in-situ measurements. In Romania, soil moisture measurements have been carried out in representative and experimental basins at different depths (from soil surface to more than 1 m depth), every five days (with the gravimetric method) or even daily (with automatic equipment) (Minea, Iliescu and Dedu, 2016; Ortenzi *et al.*, 2024b), but only in few hydrological basins: the Voinesti experimental basin, the Moieciu representative basin and the Moneasa representative basin (MRB) – which is our case study. Another data source for surface soil moisture is International Soil Moisture Network (https://ismn.earth/en/dataviewer; ISMN, 2025), which for Romania includes 20 stations, with soil moisture data starting from 2014 until present, but with gaps caused by different malfunctions of the sensors. In recent years, studies have been enriched based on satellite products, some of them are the Copernicus Global Land Service's surface soil moisture and soil water index.

In Romania, the difficulty of measuring soil moisture and the insufficient number of stations at the country level, do not allow to use this parameter on a large scale in water balance studies or in water management studies. So, the data obtained from satellite products regarding soil moisture, at the level of Romania, but not only, comes to complete and improve hydrological research, and can offer important information regarding the soil during some extreme events.

In Romania, soil moisture data are limited due to complex measurements and few monitoring stations. In contrast, hydrological parameters like water level, temperature, and precipitation are accurately recorded twice daily (at 6:00 a.m. and 6:00 p.m.) and often supplemented by hourly automated data. Such consistency is lacking for evapotranspiration measurements. These remain, one of the most difficult hydro-meteorological parameters to measure, but with the greatest impact on water losses at the level of hydrographic basins, which is directly influenced by the predominant vegetation type. Evapotranspiration is the process that answers the question of how much water is released into the atmosphere from a surface. Weighing lysimeter is the most accurate, sensitive, and direct means of measuring evapotranspiration, which can develop procedures of predicting water use and shows soil-water-plant relations. Actual evapotranspiration represents the total amount of soil evaporation, plant transpiration, and even the evaporation of precipitation retained on the trunk, branches, and leaves of the plant.

The relationship between soil moisture and hydro-meteorological parameters, such as runoff, precipitation and evapotranspiration, has been studied on large basin, but also on small ones where the response time of water runoff and soil moisture to precipitation is faster (Anderton and Chinn, 1978; Schumann *et al*., 2009). Soil moisture is correlated with evapotranspiration and precipitation and significantly influences latent heat flux over land as a result of soil moisture–precipitation reaction (Seneviratne *et al*., 2006). Depending on the soil moisture and the amount of precipitation and evapotranspiration, as well as the characteristics of relief, soil and vegetation, runoff can have a different path from one hydrological event to another. Some authors have shown that there is a strong relationship between directly measured soil moisture and precipitation amounts, especially in semi-arid and semi-humid regions, compared to other climatic zones. The relationship between soil moisture and runoff is not a close one, especially in forested areas with dense vegetation, due to the forest's capacity to retain water in the canopy and branches and to use part of the water in the photosynthesis process.

The purpose of this study is to analyses the relationship between soil moisture and hydro-meteorological parameters, such as precipitation, evapotranspiration and flow, based on satellite products and direct measurements obtained in the Western part of Romania, in Moneasa Representative Basin (MRB). Started from the hypothesis that evapotranspiration (especially from the forest areas) has the role of reducing the discharge, a fact that is also reflected in the soil moisture variation, and on the other hand, the precipitation has the capacity to increase the soil moisture through the water supply of the soil, but also the discharge. The research question addresses whether these hydrological factors explain the variability of soil moisture and support the validation of satellite-derived data. To this end, the novelty of the study lies in its focus on a predominantly forested catchment, enabling a more comprehensive understanding of these interactions.

MATERIALS AND METHODS

STUDY AREA

The MRB is located in the western part of Romania, covers an area of 14.2 km^2 and has an average altitude of 680 m at the Boroaia hydrometric station where soil moisture is monitored (Fig. 1). The upper basin of the Moneasa River extends in the geographical region of the Apuseni Mountains, with altitudes ranging from 375 m to 981 m. The average slope of the basin is 26%, which indicates a rapid runoff, influenced by the general orientation of the slopes (south, southeast, and southwest), that accentuates the slope runoff processes and the melting of the snow, especially during winter and spring months.

From a hydrological point of view, the water flow measured at the Boroaia hydrometric station between 1981 and 2021 has an average value of 0.273 m^3·s^{-1}, ranging from 0.163 m^3·s^{-1} in 1983 to 0.471 m^3·s^{-1} in 1995. After 2000 to present, large variations were observed among the hydrological parameters and low flow values were measured in 2000 and 2002 (annual average flow – 0.25 m^3·s^{-1}), due to the forest evapotranspiration amounts of about 650–850 mm·year^{-1}.

Regarding the climatic regime of MBR, it is moderately continental, specific to hilly areas and medium mountains with predominantly western circulation. The annual precipitation values exceed 1,100 mm·year^{-1} and at monthly level May, June and July have maximum precipitation (over 100 mm·month^{-1}). In the months of December and January, the amounts of precipitation are also high, but they are characterised by snow. Based on the difference between precipitation and evapotranspiration, the MRB has water surplus, except for the year 2000, when evapotranspiration was almost equal to the value of precipitation. Forest evapotranspiration depends on precipitation; the connection between these two can have different direction, one if precipitation is accompanied by days with high cloudiness and low temperatures, then the evapotranspiration values will be decreasing, but if the precipitation episodes are not associated with other atmospheric modifications, then evapotranspiration will be high due to the high-water vapour exposed to atmosphere.

IN-SITU MEASUREMENTS

To analyse the correlation between precipitation, evapotranspiration, flow, and soil moisture in the MRB, direct measurements have been used: flow (m^3·s^{-1}), precipitation (mm), water evaporation (mm), and forest evapotranspiration (mm). Within the MRB, an automatic meteorological station is installed, having a GGI-3000 evaporation pan where daily water evaporation is determined during the period with positive air temperatures, from the end of March until October/November. At the same time, direct soil moisture measurements are made within the MRB, at the Boroaia hydrometric station every 5 days, and at Moneasa hydrometric station every 10 days, but do not capture its spatial variation.

The area covered by vegetation at the level of the upper part of the Moneasa representative basin is almost 99%, so it was necessary to determine the evapotranspiration at the level of the forest. So, in order to obtain daily values of forest evapotranspiration, the evaporation (measured directly) and the forest vegetation coefficient (K_{forest}) were taken into account. For the estimation of the K_{forest} it was considered that the vegetation period is about 240

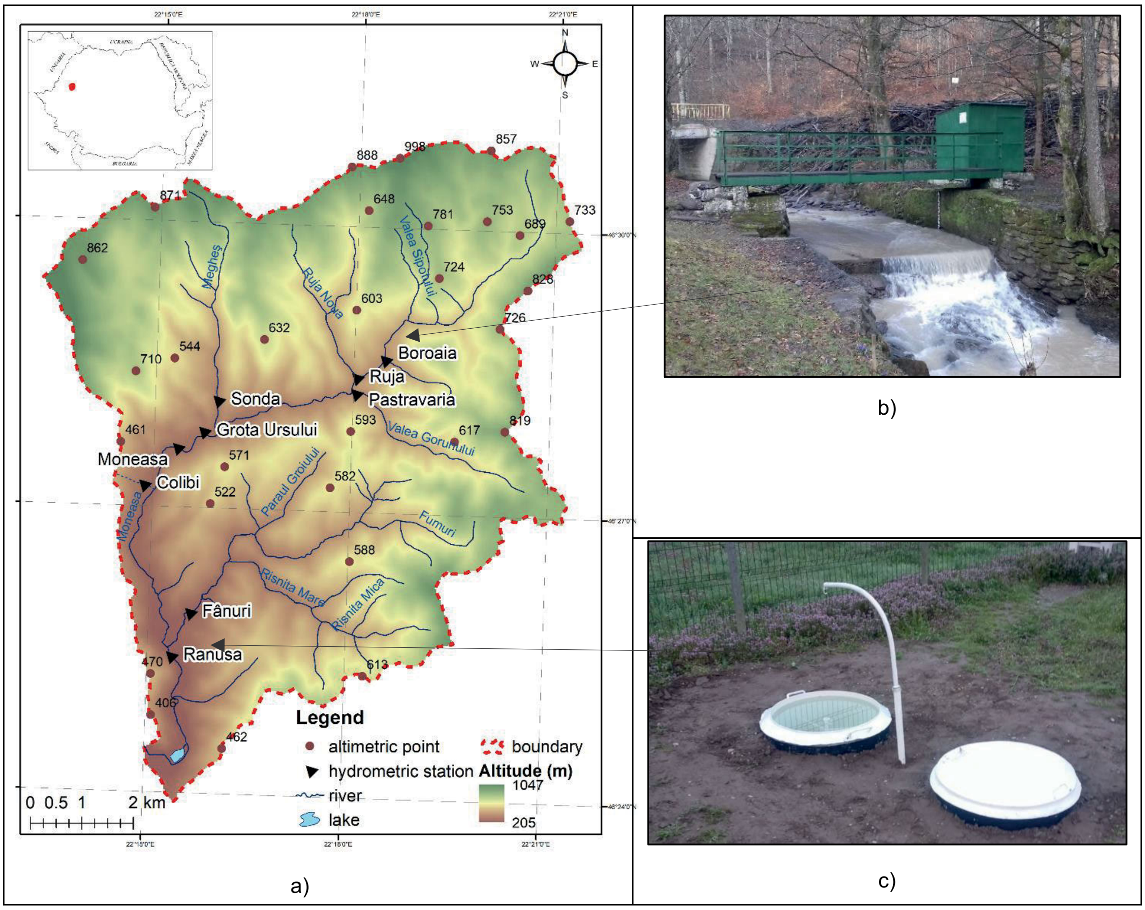

Fig. 1. Moneasa Representative Basin: a) hypsometric map, b) Boroaia hydrometric station, c) Rânuşa evaporation station; source: own elaboration based on information obtained from Moneasa Hydrological Station and Representative Basin

days, the age of the trees is over 20 years, so the vegetation coefficient has an average value of 0.8–0.9. The estimation of forest evapotranspiration was based on the equation:

$$ET_{\text{forest}} = Eo \cdot K_{\text{forest}} \tag{1}$$

where: ET_{forest} = forest evapotranspiration (mm), Eo = evaporation (mm).

SATELLITE PRODUCTS

Compared to other parameters, soil moisture can differ quite a lot from one region to another, strictly dependent on precipitation and evapotranspiration. Thus, for the analysis of this parameter in this study it was decided to use two satellite products that have generated good results in the case of other hilly regions in Romania (Ortenzi *et al.*, 2024a), respectively: surface soil moisture of Copernicus Global Land Service 1 km (*SSM* 1 km), and soil water index of Copernicus Global Land Service 1 km (*SWI* 1 km). The first one, Copernicus Global Land Service's Surface Soil Moisture at 1 km^2 resolution (*SSM* 1 km), provides water degree of saturation (m^3·m^{-3}) estimation every 4–5 days of the top few centimeters of soil (~5 cm) with a spatial resolution of 1 km over Europe. In the same time, *SWI* 1 km estimates soil moisture as the degree of saturation (m^3·m^{-3}) across soil layers at various depths and 1-day temporal resolution. The *SWI* 1 km product is provided for eight *T*-values (2, 5, 10, 15, 20, 40, 60, 100), where $T = L/C$ (L = the reservoir depth, C = the pseudo diffusivity constant). Higher *T*-values correspond to deeper soil layers, assuming constant soil diffusivity (Ceballos *et al.*, 2005). However, because this method does not account for soil texture, the same *T*-value can represent different depths in different soil types (Lange de *et al.*, 2008; Paulik *et al.*, 2014). The *SWI* algorithm cannot be applied in high-altitude permafrost regions, glaciers, ice caps, and deserts, and it must be used carefully in areas with dense forest, like our study area. In this study, the average soil moisture values determined at the level of the Moneasa basin (Boroaia hydrometric station) were analysed.

PEARSON CORRELATION

To establish the correlation between the hydrological parameters and the soil moisture, the Pearson correlation coefficient was applied (in the R application). The dependence of soil moisture on the hydrological parameters was highlighted based on the correlations with different hydrological variables, such as precipitation and forest evapotranspiration (Bauer-Masrchallinge, Paulik and Jacobs, 2022).

The Pearson test is an important statistical parameter and it is widely used in the field of statistics to evaluate the intensity of the link between two linear variables, based on the determination of the Pearson correlation coefficient (r). In Pearson correlation, the p-value is used to determine the statistical significance of the r, also the α value (usually set at 0.05) is a threshold for significance. The correlation is deemed statistically significant if the p-value is less than α.

RESULTS

During the 2016–2021 period, the streamflow was characterised by an average value of 0.269 $m^3 \cdot s^{-1}$ and a maximum value of 5.39 $m^3 \cdot s^{-1}$ (26 Dec 2021). The maximum values could not be justified only by the amounts of precipitation; a large variation of discharge in recent years is the response of the soil moisture and forest evapotranspiration daily variation. During the period 2016–2021, forest evapotranspiration varied between 450 and 530 $mm \cdot year^{-1}$, while the amount of precipitation is twice as high (>1100 $mm \cdot year^{-1}$), with daily maximum values in winter and spring seasons. The MRB is more than 99% forested by deciduous trees, which means that the forest plays an important role in retaining water and using it for photosynthesis. During the summer, the impact of forest evapotranspiration (>6 $mm \cdot day^{-1}$), resulted in a reduction in soil moisture content, which could drop to moderate or very dry conditions (<0.2 $m^3 \cdot m^{-3}$) – Figure 2). The soil moisture values varied between 0.06 and 0.9 $m^3 \cdot m^{-3}$, based on *SSM* 1km, and 0.16 and 0.91 $m^3 \cdot m^{-3}$ based on *SWI* 1 km, and they characterised the study area with very wet soil moisture content (>0.3 $m^3 \cdot m^{-3}$), especially in the spring months.

Also, for the same amount of precipitation, soil moisture and discharge respond differently from one season to another, for example, precipitation of 40–50 $mm \cdot day^{-1}$ ensures soil moisture greater than 0.9 $m^3 \cdot m^{-3}$ in January and February while in September and October the same amount of precipitation result in a soil moisture of <0.5 $m^3 \cdot m^{-3}$.

Results showed that the impact of soil moisture is observed also in the base flow during the period of high level of river (e.g. from January to March), where base flow values are maximised and range between 0.19 and 0.59 $m^3 \cdot s^{-1}$ (in 2016 year), accounting for more than 50% of discharge.

Regarding the correlation between soil moisture satellite products *SSM* 1 km and precipitation, the results present low correlation at daily time step (due to the duration and intensity of precipitation), during the period 2016–2021, correlation coefficient (r) having values from 0.04 to 0.49; the aggregated values at 10 days can improve the corrections, e.g. June (Fig. 3). The *SWI* values

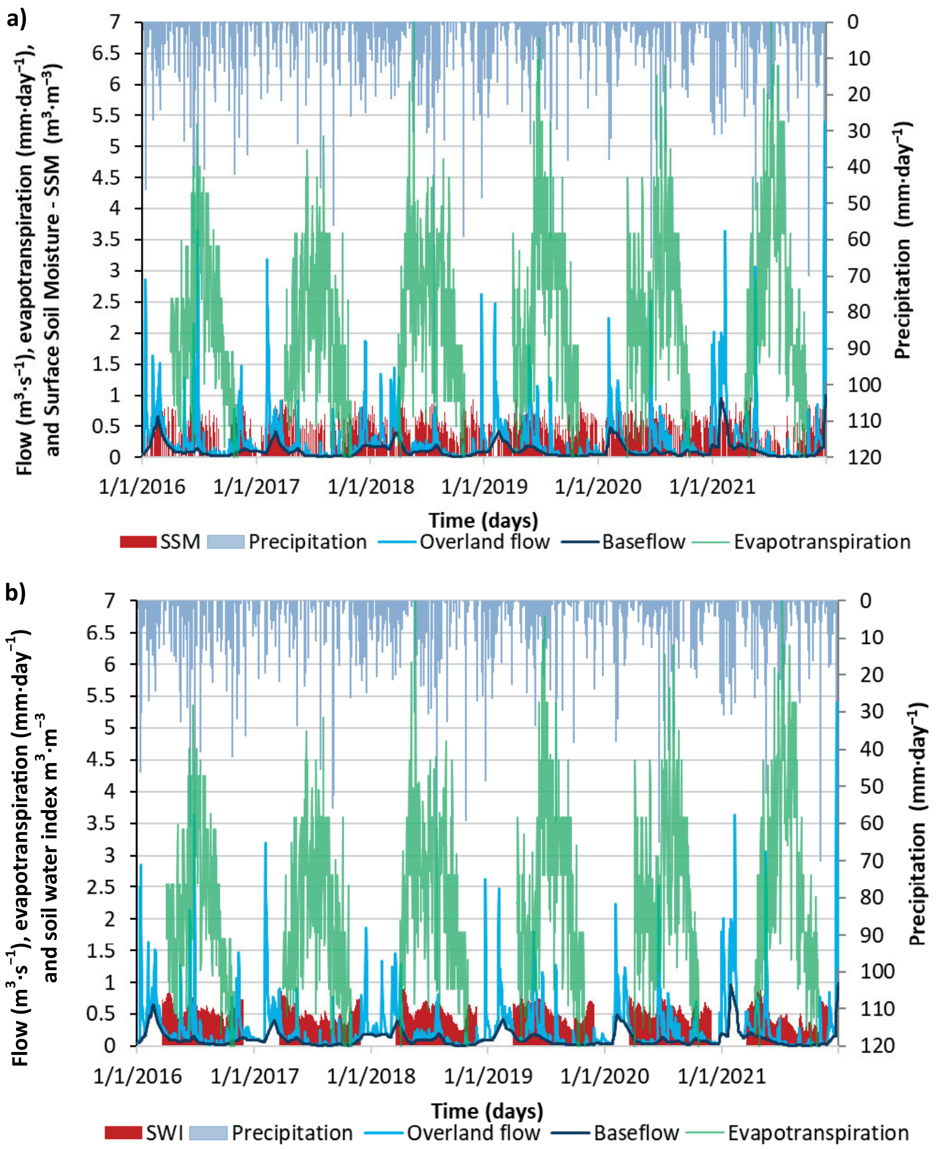

Fig. 2. The daily variation of flow ($m^3 \cdot s^{-1}$), precipitation ($mm \cdot day^{-1}$), forest evapotranspiration ($mm \cdot day^{-1}$), (a) surface soil moisture (*SSM*, $m^3 \cdot m^{-3}$) and (b) soil water index (*SWI*, $m^3 \cdot m^{-3}$) series of data, Boroaia hydrometric station; source: own study

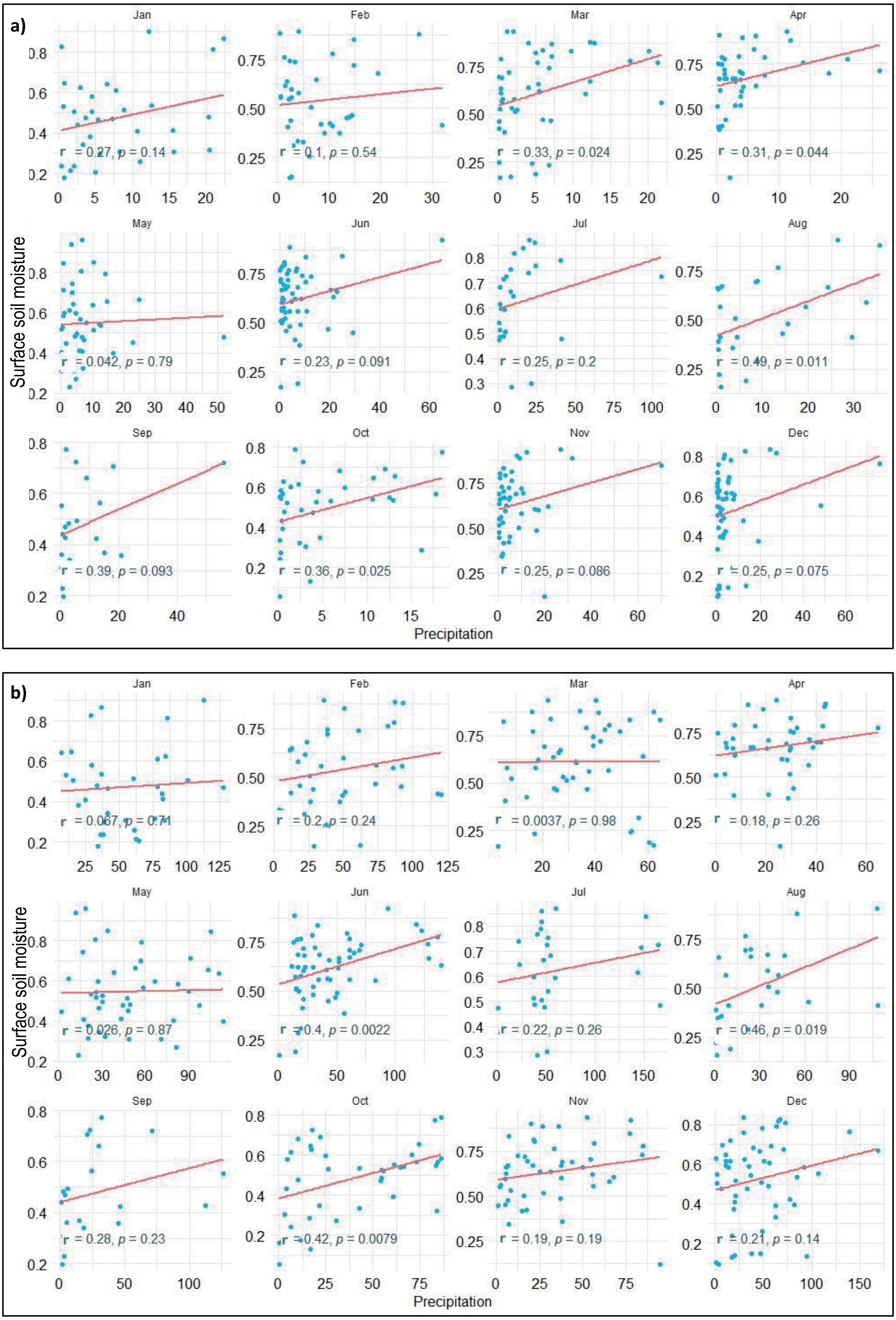

Fig. 3. Linear correlation between surface soil moisture at 1 km^2 resolution (*SSM*, m^3·m^{-3}) and: a) daily precipitation (mm·day^{-1}), b) 10 days precipitation (mm·(10 day)$^{-1}$); r = correlation coefficient, p = significance level; source: own study

correlate better with the precipitation especially at 10 days' time step (r from 0.18 to 0.70), which means that the time response of soil moisture may depend on both, quantity and duration and be seen in days. Between *SSM* 1 km or *SWI* 1 km with forest evapotranspiration a low correlation was obtained ($r < 0.42$) – Table 1.

The correlations are statistically significant especially with daily precipitation data and discharge (p-values > 0.05), but they are less statistically significant during the spring and early summer months (March, May, July) due to rapid atmospheric changes (Figs. 3, 4). According to the r coefficient values and p-values, it is observed that daily precipitation (Fig. 3a), compared to that accumulated over 10 days (Fig. 3b), has a better degree of correlation with the *SSM*, so r values reached 0.5 in May and August; during these months the rainfalls in our study area are short-term and very intense. Also, a good correlation was obtained between soil moisture and specific discharge ($r \leq 0.5$ in different months); during the summer months (June–August), r coefficient varied from 0.45 to 0.57; during the winter months, strong correlation was obtained in January ($r = 0.59$), but low correlation in February and December because of the snow influence (Fig. 4).

Between specific discharge and soil moisture, there is not always a closer correlation, because of the important role that forest evapotranspiration plays, especially during the month of May when the vegetation has the highest degree of development, and during the month of August because of the maximum period of vegetation (Fig. 5).

DISCUSSION

This study aimed to use satellite products because there are no measured soil moisture data at the country level that cover the entire country and they are not obtained at a fine data-time step, due to the difficulty of gravimetric measurements. In this sense, the use of satellite products in hydrological studies has always been a challenge, especially in areas where there are no direct measurements or the series of data are insufficient for the validation.

Regarding the *SSM* 1 km and *SWI* 1 km satellite products, at a daily time step (depending on their availability) for the period 2016–2021, these were compared and analysed by their direct and indirect correlation with the hydrological and meteorological parameters determined within the MBR. The accuracy of satellite soil moisture data is affected by the local characteristics of the analyses area, such as slope, soil roughness, vegetation (Wang *et al.*, 2023). The soil moisture monitoring points (managed by the Romanian Meteorological Administration) in Romania do not cover high hydrographic areas, also the gravimetric measurements from the experimental and representative basins, have an uncertain time step, pentanal or decadal, covering only the annual interval without snow. Both *SSM* 1 km and *SWI* 1 km have been used on a large or small scale in Romania in different studies in which they were compared with measurements from either experimental basin in the Subcarpathian area or from the entire area of the country, covering different altitudinal ranges, land uses and soil types (Ontel *et al.*, 2021; Ortenzi *et al.*, 2024a). Previous results have shown that the two satellite products targeting soil moisture show a close correlation with direct values measured pointwise at depths of 5 cm, the correlation coefficient reaching values of 0.8. According to Onțel *et al.* (2021), *SWI* 1 km has a close and direct correlation (r coefficient of 0.69), with soil moisture data (from the Romanian Meteorological Administration database) from the Oradea station, this one being at 60 km from the MRB. At the same time, low correlation was obtained between *SWI* 1 km and soil moisture data from Chișineu Criș (r coefficient of 0.21), situated at 50 km from the MRB.

Table 1. Coefficient of correlation obtained with Pearson Test, between *SSM* and *SWI* with hydrological parameters (daily values, for each month during the period 2016–2021)

Month	*SSM* 1 km ($m^3 \cdot m^3$) in correlation with				*SWI* 1 km ($m^3 \cdot m^3$) in correlation with			
	P_{daily} (mm)	$P_{10\ days}$ (mm)	ET_{forest} (mm)	q ($m^3 \cdot s^{-1} \cdot km^{-2}$)	P_{daily} (mm)	$P_{10\ days}$ (mm)	ET_{forest} (mm)	q ($m^3 \cdot s^{-1} \cdot km^{-2}$)
January	0.27	0.067	ND	0.59	ND	ND	ND	ND
February	0.1	0.2	ND	0.24	ND	ND	ND	ND
March	0.33	0.00	ND	0.35	0.37	−0.18	ND	0.28
April	0.31	0.18	−0.19	0.30	0.02	0.36	−0.17	0.50
May	0.04	0.03	−0.30	0.08	−0.01	0.32	−0.29	0.41
June	0.23	0.4	−025	0.45	0.11	0.57	−0.02	0.46
July	0.25	0.22	−0.42	0.57	0.081	0.54	−0.1	0.58
August	0.49	0.46	−0.08	0.45	0.18	0.51	−0.12	0.36
September	0.39	0.28	−0.26	0.54	0.02	0.42	−0.08	0.21
October	0.36	0.42	−0.22	0.42	0.2	0.73	−0.16	0.6
November	0.25	0.19	ND	0.06	−0.09	0.33	ND	0.20
December	0.25	0.21	ND	0.18	ND	ND	ND	ND

Explanations: P = daily precipitation, ET_{forest} = daily forest evapotranspiration, q = daily specific flow, *SSM* = daily surface soil moisture, *SWI* = daily soil water index, ND = no data.
Source: own study.

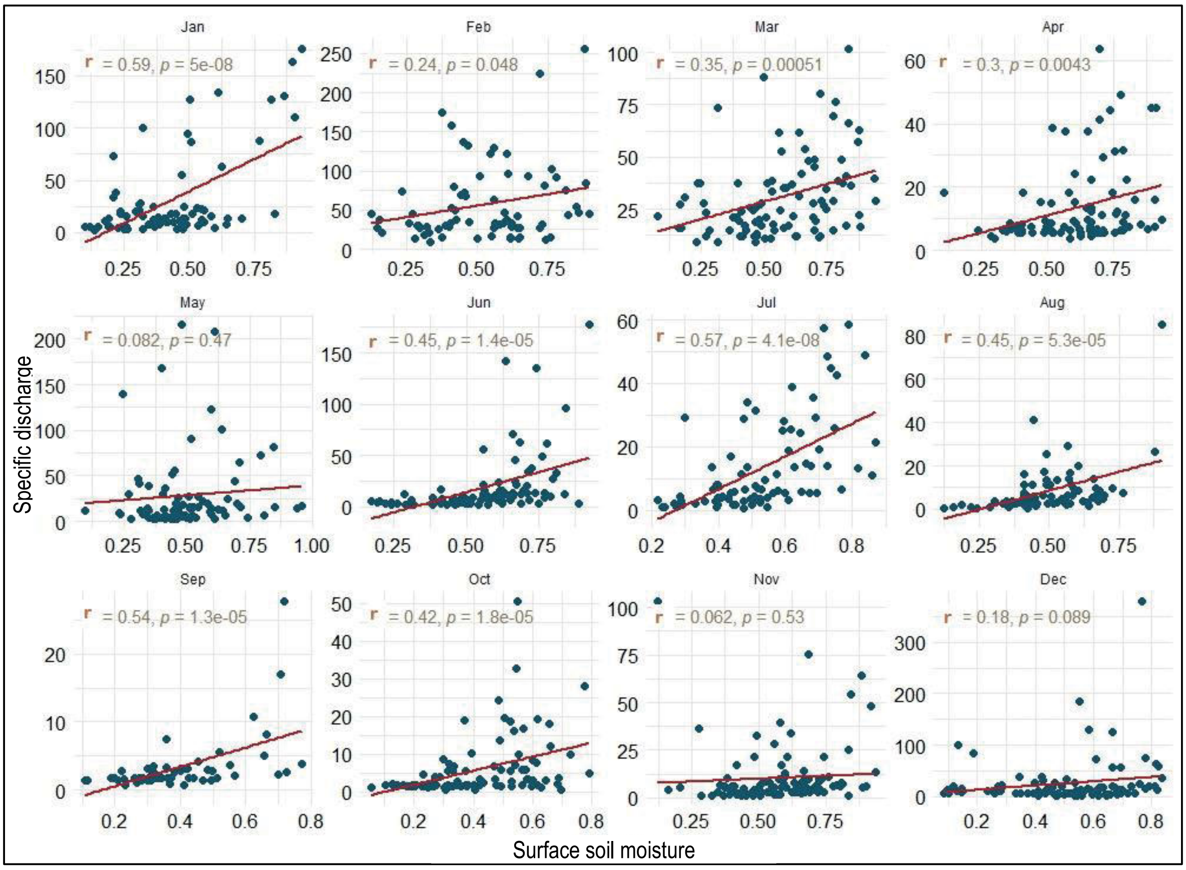

Fig. 4. Linear correlation between surface soil moisture at 1 km^2 resolution (*SSM*, m^3·m^{-3}) and specific discharge (m^3·s^{-1}); *r* and *p* as in Fig. 3; source: own study

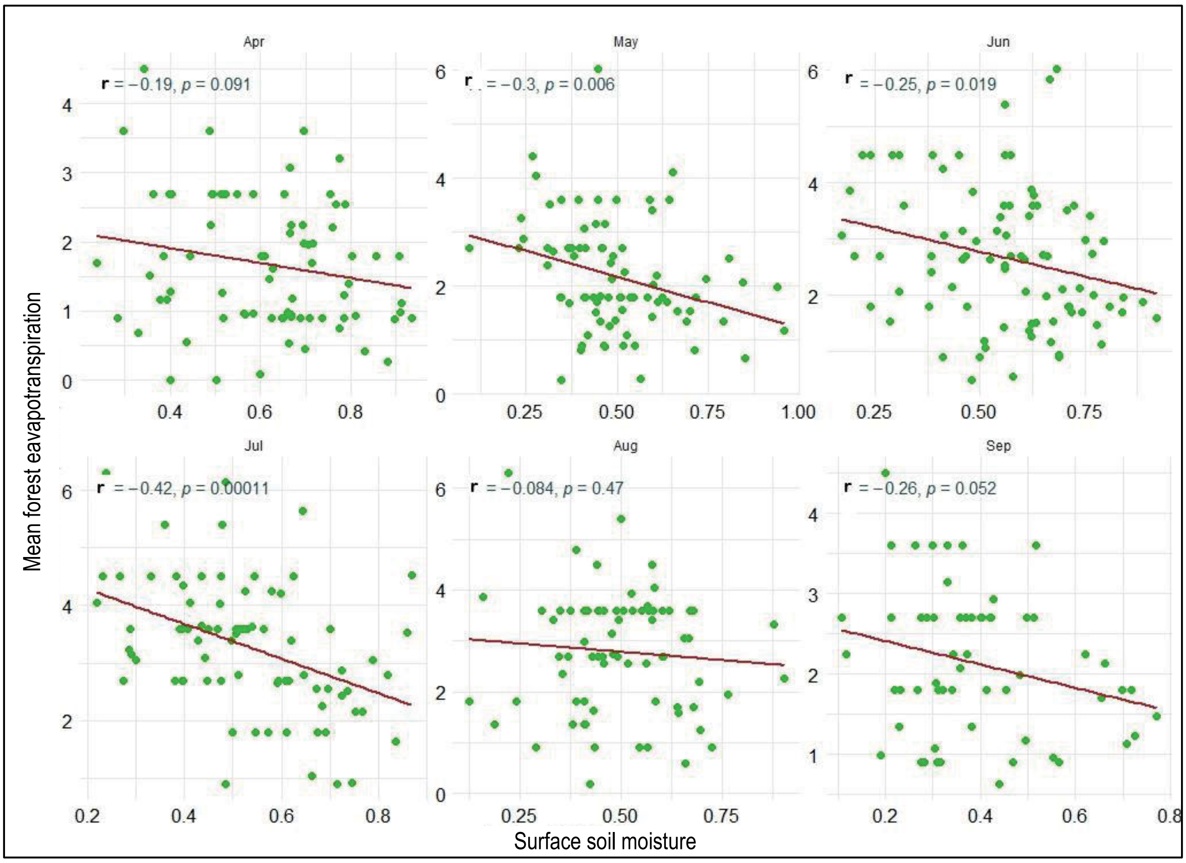

Fig. 5. Linear correlation between surface soil moisture at 1 km^2 resolution (*SSM*, m^3·m^{-3}) and forest evapotranspiration (ET_{forest}, mm·day^{-1}); *r* and *p* as in Fig. 3; source: own study

Our study supports the impact of hydro-meteorological parameters, already described in other studies, on the soil moisture variability. So, for MRB the precipitation is directly correlated with soil moisture (r coefficient of 0.4), especially during the months with lower precipitation values, when the soil is almost dry (<0.2–0.3 $m^3 \cdot m^{-3}$). This idea was sustained also in previous studies, researchers have shown that there is a strong relationship between directly measured soil moisture and precipitation amounts, especially in semi-arid and semi-humid regions, compared to other climatic areas. So, we must take into consideration that, soil moisture-precipitation relation is regional and climatic dependent (Singh *et al.*, 2021), so during dry period strong relationship can be obtained, and during wet period low ones are characteristics.

The results obtain between soil moisture and discharge in MRB, Romania, have also been observed in other international studies made in Italy, Spain or Brazil, where the problem identified referred to the degree of homogeneity that exists at the basin area (Blume, Zehe and Bronstert, 2009). So, studies have shown that soil moisture reached peak fastest along the wettest hillslopes and that in forested basins soil moisture can sustain the baseflow in headwater streams during some rain events and dry period of the year (Brocca, Melone and Moramarco, 2008). Regarding the correlation between soil moisture and evapotranspiration, the negative values of coefficient correlation mean that the evapotranspiration can increases with the increasing soil moisture, but when the soil becomes very wet or saturated with water, then it will no longer be controlled by the soil water reserve, only by meteorological parameters (Wang *et al.*, 2023).

The results obtained in previous studies complement the results of this article, supporting the validity of the *SSM* 1 km product, both based on correlative analyses with other parameters and even with direct measurements made in Romania (Ontel *et al.*, 2021; Ortenzi *et al.*, 2024a).

CONCLUSIONS

Soil moisture is a hydro-pedological parameter that can be analysed and characterised based on hydrological elements: water discharge, precipitation and evapotranspiration. Soil moisture obtained based on satellite products has a very important status in the hydrological analyses of small river basins, providing data at 1 day time step and areas of 1 km^2, and for their validation, data measured in the river basins, such as discharge, precipitation and evapotranspiration, can be used.

1. Soil moisture satellite products had a normal temporal variation, with higher values during the winter and spring months due to the precipitation, and lower values in summer when evapotranspiration values were maximum.
2. Specific discharge was the one that indicated a good correlation with soil moisture. The correlation was improved with the precipitation at 10 days' time step; regarding the soil moisture and forest evapotranspiration, no direct dependence was obtained between the two.
3. Copernicus Global Land Service surface soil moisture at 1 km^2 resolution (*SSM* 1 km) has closer correlations with the hydrological parameters, compared to soil water index at 1 km^2 resolution (*SWI* 1 km).

The results of this study sustain the importance of the *SSM* 1 km and *SWI* 1 km satellite products analyses, in the hydrological studies and perspectives, for small basins.

Therefore, in the future, we propose to expand our research by using soil moisture satellite products, in order to complement the data sets used in hydrological modelling or in water management studies.

CONFLICT OF INTEREST

All authors declare that they have no conflict of interests.

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