Hydrological drought monitoring in the Ebro basin: Standardized Soil Moisture Index

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ABSTRACT

Recent studies have highlighted the escalating frequency and severity of droughts attributed to climate change. Drought stands as a major climate risk; thus, its understanding and study are of utter importance. This phenomenon arises from intricate interactions among the atmosphere, continental surfaces, and water resource management systems, and can lead to substantial socioeconomic impacts.
Following the work of Wilhite and Glantz, droughts can be categorized based on their severity as meteorological, agricultural, hydrological, and socioeconomic [1]. The former three delineate droughts by their physical impacts, while the latter deals with drought in terms of supply and demand dynamics (e.g., energy, food, or potable water shortages).
Meteorological drought is associated to precipitation deficiency periods. If it persists through time, it becomes into an agricultural drought, with soil moisture deficiencies, and a reduction in crop population and yield. The frequency and severity of hydrological droughts are defined typically on a river basin scale, impacting on the surface and sub-surface water resources (i.e., reduced streamflow or inflow to reservoirs, lakes, and ponds).
Various indices have been devised to study droughts, based on variables such as precipitation or vegetation status. However, these indices possess inherent limitations. Vegetation-based drought indices can only be applied once the drought has already caused damage to the vegetation, making them unsuitable for drought forecasting. Conversely, precipitation-based indices rely on in-situ measurements or theoretical models, as remote sensing-derived precipitation data suffer from high uncertainties and coarse resolutions.
Hence, soil moisture emerges as a key element for agricultural monitoring and drought forecasting, offering early indicators of impending drought conditions. Drought indices based on soil moisture data can be derived from L-band (21 cm, 1.4 GHz) radiometers, which provide soil moisture measurements without the problems that accompany precipitation data. With nearly 14 years of historical data since the first L-band radiometer retrieved soil moisture measurements in 2010, the use of soil moisture derived from remote sensing stands as a powerful tool for the upcoming years.
This study introduces the Standardized Soil Moisture Index (SSI), drawing inspiration from the widely used Standardized Precipitation Index (SPI), which shows the deviation from average precipitation. By extending SPI's methodology to soil moisture data, diverse drought types can be monitored based on the selected integration time for SSI. Focusing on the Ebro basin region, situated in the northeastern part of the Iberian Peninsula with a semi-arid climate, our findings underscore SSI12-SSI24 as a robust index for hydrological drought assessment.

1. Introduction

It has been demonstrated that soil moisture (SM) data derived from remote sensing provides knowledge about meteorological droughts [2]. The scope of this work is to prove that SM data derived from remote sensing is also suited for studying hydrological droughts. The frequency and severity of hydrological droughts are increasing due to climate change; thus, tools to monitor them are of utmost importance. Since this type of drought is displayed through deficiencies in the hydrologic system, studies of the SM anomalies (such as in [2]) cannot grasp the status of the hydrological drought. For this reason, we propose the Standardized Soil Moisture Index (SSI) as a candidate to monitor hydrological droughts.

2. Area of Study

The area of interest is the Ebro basin region, located in the northeast of Spain. With the Ebro River being its main drainage system, it is the most extensive basin in Spain. The population density of the area is considerably lower than the Spanish average and presents intensive agriculture at the Ebro Valley. In the upper part of its course, the associated vegetation consists of pastures, oak groves, and plants that require plenty of moisture. In the central depression, the climate is drier and more extreme in temperature. Finally, the climate is Mediterranean once it crosses the Catalan Mediterranean System.

3. Methodology

The SSI is based on the Standardized Precipitation Index (SPI), which purpose is to monitor drought independently of the region's climate. Depending on the time scale chosen (e.g., 3 or 6 months), the SSI can provide information on different types of drought. Namely, SSI6 and bellow can assess meteorological and agricultural droughts, while SSI9 and above are more suited to study hydrological droughts.

Fig. 1: Map of the Ebro basin region [3].

The SSI has been computed using a SM dataset that spans from 2010/06 up to 2024/05. Such dataset has been derived combining SMOS and SMAP with MODIS satellite data. By applying the DISPATCh methodology [4], we obtain daily SM data with a spatial resolution of 1 km. To validate the SSI, precipitation data from the SAIH (*Sistema Automático de Información Hidrológica*) meteorological stations has been used to compute the SPI for the same period, as well as model-derived SPI and SPEI (Standardized Precipitation Evapotranspiration Index) from [5].

4. SSI vs SPI

Due to the precipitation and SM having different behaviors, the SSI and the SPI do not display the same aspects of drought. A comparison between the SSI and SPI can be seen in Fig. 2 for Vinebre (Catalonia) for the integration times of 12 and 24 months. These time series manifest the similarities between the indices. However, the inertia intrinsic to SM makes the SSI less prone to drastic changes and it evolves smoothly with time. Furthermore, Fig. 3 shows the time series and correlation between the SSI12 and the SPI12 generated with in-situ measurements and from the model [5]. The monthly precipitation is also plotted to better understand the behavior of the indices. From Fig. 3, we can clearly see that the remote sensing-derived SSI12 can represent the hydrological drought status, with a high correlation with the in-situ SPI12.

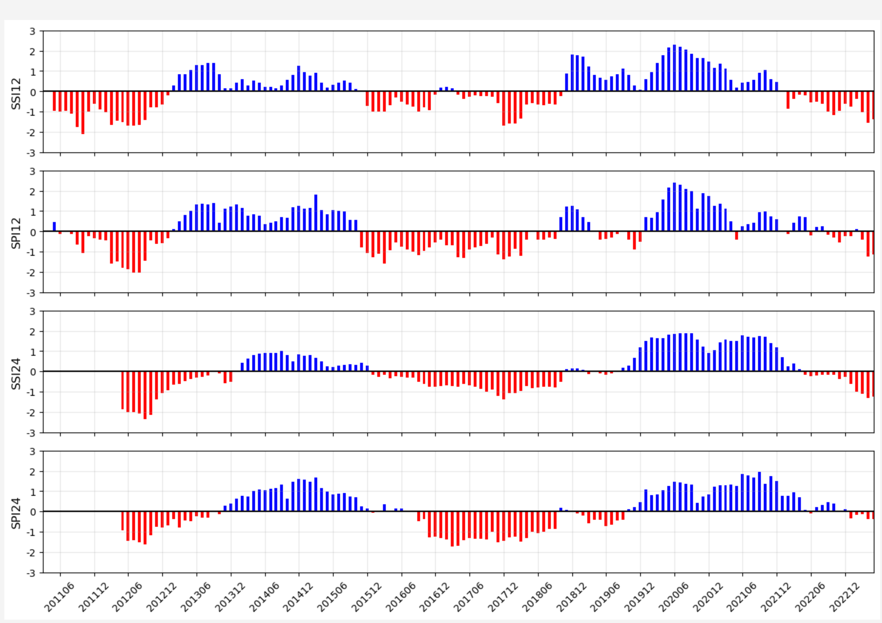

Fig. 2: Time series of SSI vs SPI for Vinebre, with integration times: 12 and 24 months.

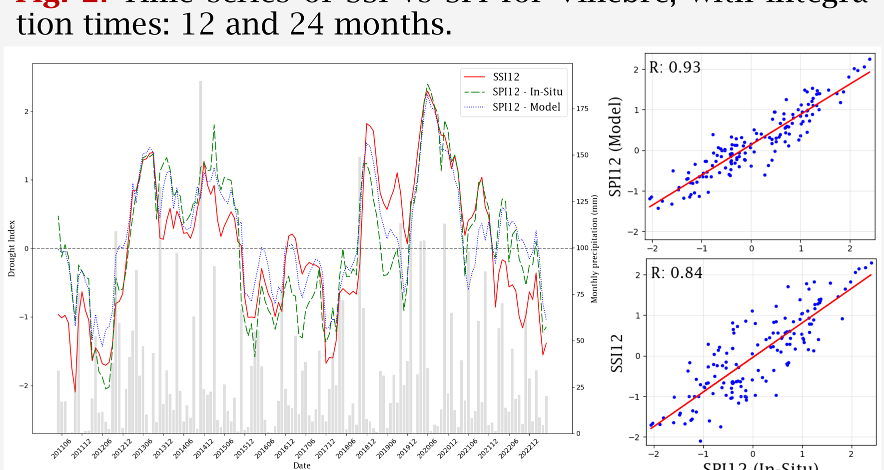

Fig. 3: Time series and correlation between the SSI12 and SPI12 from in-situ and model data at Vinebre.

A more general correlation between the SSI and SPI is shown in Fig. 4, where it compares the different time series of these indices over 235 points inside the Ebro basin region for the period of 2010/06-2024/05.
The decrease in correlation compared with the one found in Fig. 3 can be due to different causes. Firstly, we are comparing two indices that depend on variables of different nature. Namely, the SPI is only affected by precipitation episodes, while the SSI can remain positive during periods of rainfall shortage. Moreover, the stations of SAIH used to compute the SPI are located over different types of areas, where its land cover may differ from bare soil, shrubs or evergreen forests. Also, the resolution of the SSI is of 1 km, making its behavior greatly dependent on the homogeneity of soil and land cover over that area. Thus, these factors differentiates the demeanor between the indices. Finally, the slightly lower correlation for SSI24-SPI24 can be attributed to not having a sufficiently large time series for such integration time.

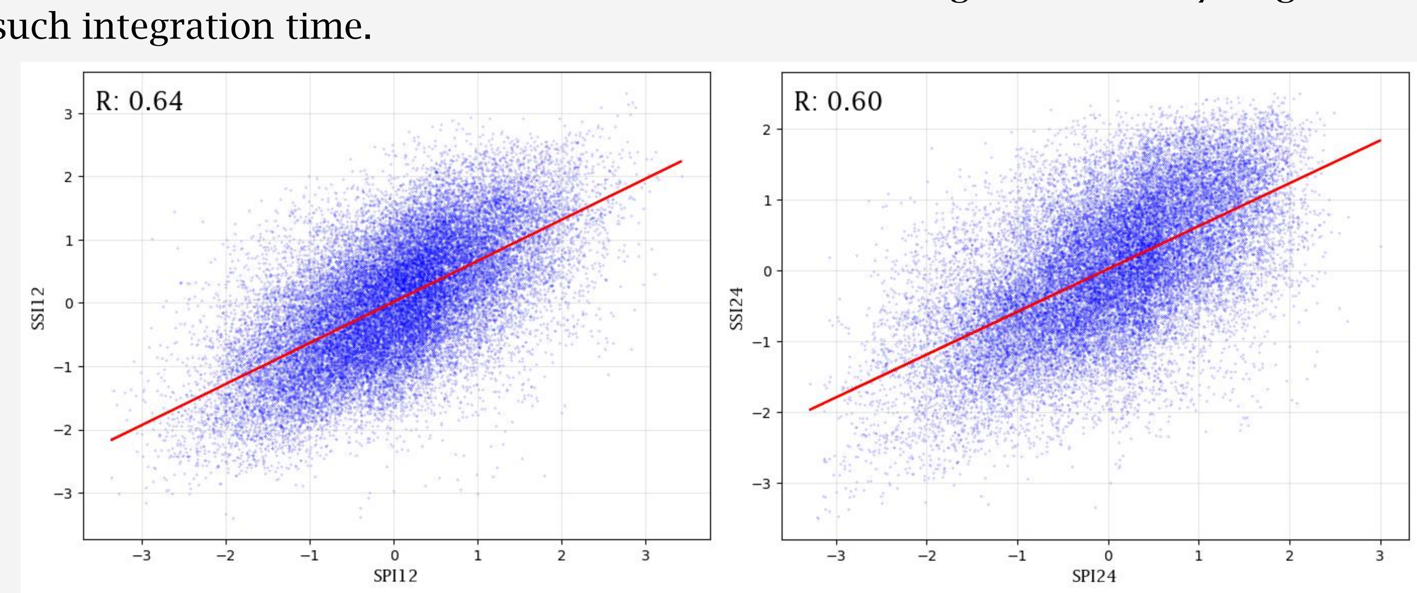

Fig. 4: Correlation between the SSI-SPI for integration times of 12 and 24 months over 235 meteorological stations of SAIH for the period 2010/06-2024/05.

5. SSI for Hydrological Drought

In Fig. 5, the SSI12 for the Ebro basin region is shown for all the historical data acquired through remote sensing. The index shows the hydrological droughts registered in 2011-2012 and 2017-2018. Furthermore, it demonstrates that another hydrological drought took place during 2022-2023, from which we are now recovering.

Another potential aspect of the remote sensed-derived SSI is its spatial coverage and high resolution compared with the typical maps of SPI or SPEI (Fig. 6). The SSI12 map from Fig. 6 displays more detailed information about the drought status than the other model-derived maps. Hence, using SM data derived from remote sensing not only is suited to monitor droughts, but also provides a better coverage and resolution than other variables.

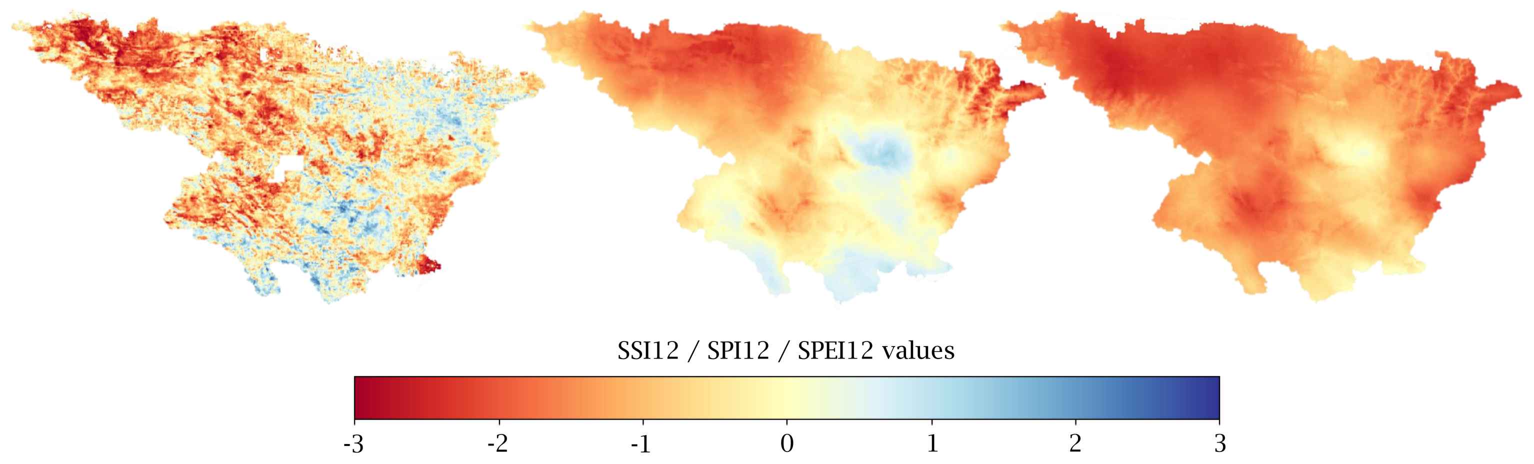

Fig. 6: From left to right: SSI12, SPI12 and SPEI12 for the Ebro basin, March 2023. The SPI and SPEI data have been obtained from [5].

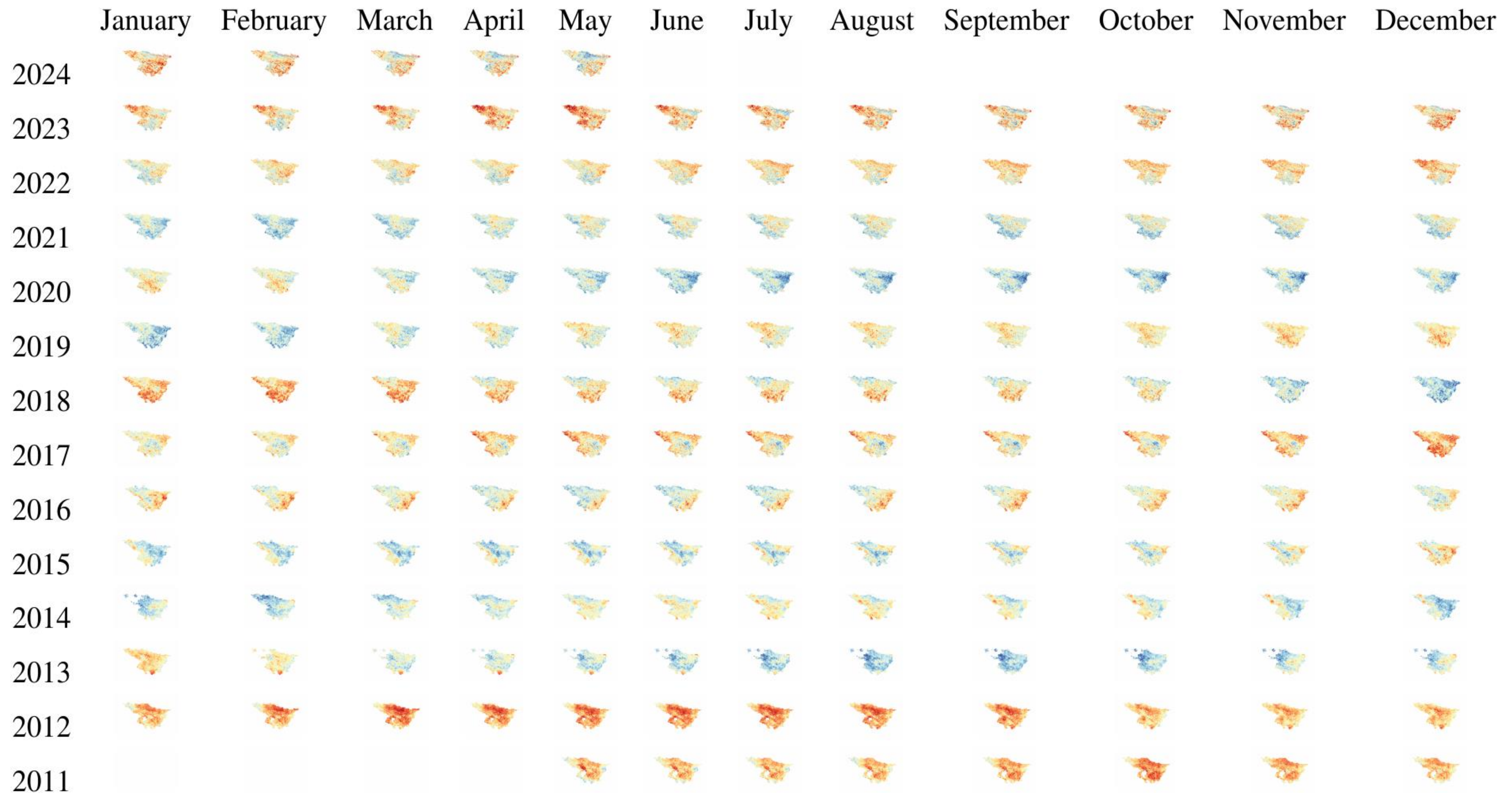

Fig. 5: Historical SSI12 for the Ebro basin region.

6. Conclusions

- The SSI from remote sensing techniques is a powerful tool for drought monitoring, able to display information on different types of drought with high spatial resolution.
- Despite using satellite data to derive soil moisture is still a relatively new technology, reliable results are starting to arise. Furthermore, such methodology will only be more consistent and robust with time. Thus, indices like the SSI or similar will play a key role in the upcoming years.
- For the Ebro basin region, the SSI12 shows that a hydrological drought started at the end of 2022. Due to recent rainfall episodes, we are now recovering from the last hydrological drought.

REFERENCES

[1] Wilhite, D.A. and Glantz, M.H.: "Understanding the Drought Phenomenon: The Role of Definitions". *Water International*, 10(3):111–120, 1985.
[2] Escorihuela, M.J., Quintana, P., Stefan, V., Gaona, J.: "Drought monitoring in the Ebro basin: comparison of Soil Moisture, Vegetation and Evapo-transpiration anomalies". *E0 4 Water* 2020, 16–19 November 2020.
[3] Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente (MAPAMA).
[4] Merlin, O., Escorihuela, M.J., Mayoral, M.A., Hagolle, O., Al Bitar, A., Kerr, Y.: "Self-calibrated evaporation-based disaggregation of SMOS soil moisture: Anevaluation study at 3km and 100m resolution in Catalunya". *Spain Remote SensEnviron.* 130, 25–38, 2013.
[5] Vicente-Serrano S.M., Tomás-Burguera M., Beguería S., Reig-Gracia F., Latorre B., Peña-Gallardo M., Luna Y., Morata A., González-Hidalgo J.C. "A High Resolution Dataset of Drought Indices for Spain". *Data*, 2 (3): 22, 2017.