Journal of Hydrology 522 (2015) 265–273

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A soil water based index as a suitable agricultural drought indicator

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ARTICLE INFO

Article history:
Received 24 September 2014
Received in revised form 18 December 2014
Accepted 20 December 2014
Available online 31 December 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Rao S. Govindaraju, Associate Editor

Keywords:
Soil moisture
Drought
Available water content
Field capacity
Wilting point

SUMMARY

Currently, the availability of soil water databases is increasing worldwide. The presence of a growing number of long-term soil moisture networks around the world and the impressive progress of remote sensing in recent years has allowed the scientific community and, in the very next future, a diverse group of users to obtain precise and frequent soil water measurements. Therefore, it is reasonable to consider soil water observations as a potential approach for monitoring agricultural drought. In the present work, a new approach to define the soil water deficit index (SWDI) is analyzed to use a soil water series for drought monitoring. In addition, simple and accurate methods using a soil moisture series solely to obtain soil water parameters (field capacity and wilting point) needed for calculating the index are evaluated. The application of the SWDI in an agricultural area of Spain presented good results at both daily and weekly time scales when compared to two climatic water deficit indicators (average correlation coefficient, R, 0.6) and to agricultural production. The long-term minimum, the growing season minimum and the 5th percentile of the soil moisture series are good estimators (coefficient of determination, R^2, 0.81) for the wilting point. The minimum of the maximum value of the growing season is the best estimator (R^2, 0.91) for field capacity. The use of these types of tools for drought monitoring can aid the better management of agricultural lands and water resources, mainly under the current scenario of climate uncertainty.

1. Introduction

Not too long ago, soil moisture was a hydrological variable that was difficult to obtain. However, there are currently a variety of reliable and feasible methods to measure soil water content from the point scale to the global scale. The development of very precise measurement techniques, efficient data loggers and data transmission systems enables continuous monitoring. Recently, the impressive progress in remote sensing (Fernández-Prieto et al., 2012; Xu et al., 2014) has allowed the scientific community and, in the very next future, a diverse group of users to obtain precise and frequent soil moisture maps anywhere in the world.

The installation of long-term soil moisture networks around the world provides complete databases with long time series of observations. For example, the Soil Climate Analysis Network (SCAN) throughout the United States of America has more than 200 stations with the soil moisture series starting in the mid-1990s in some cases (Schaefer and Paetzold, 2001). An increasing number of measurement networks are hosted and freely available in the International Soil Moisture Network (Dorigo et al., 2011). Meanwhile, global satellite-based soil moisture data are becoming increasingly available (Rebel et al., 2012). Some research institutions, such as the Vienna University of Technology, provide global multi-satellite-based soil moisture products from the early 1990s (Bartalis et al., 2007; Wagner et al., 1999). The global Soil Moisture Climate Change Initiative (SMCCI project) soil moisture dataset from the European Space Agency has been generated using active and passive microwave spaceborne instruments since 1978 (Dorigo et al., 2014).

Remote sensing approaches for soil moisture monitoring have been investigated since the 1970s (Dickey et al., 1974; Schmugge et al., 1974; Ulaby et al., 1983). Over the last three decades, soil moisture was retrieved from satellite instruments that were not specifically designed for sensing soil moisture. In 2009, the first dedicated soil moisture mission, SMOS (Soil Moisture and Ocean Salinity), was launched (Kerr et al., 2010); the beginning of the second mission, SMAP (Soil Moisture Active Passive), is expected soon (Entekhabi et al., 2010). All these initiatives will soon provide global long-term soil moisture time series.

Among the three categories of drought that are commonly recognized, i.e., meteorological, hydrological and agricultural drought (Mishra and Singh, 2010), agricultural drought has a more direct

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http://dx.doi.org/10.1016/j.jhydrol.2014.12.051
0022-1694/

and immediate impact. An agricultural drought is considered to begin when the soil moisture availability to plants drops to such a level that it adversely affects the crop yield and, hence, agricultural production (Panu and Sharma, 2002). Consequently, drought is a major cause of limited productivity in rainfed agroecosystems throughout the world, accounting for a large proportion of the crop losses and annual yield variations of crops (Boyer, 1982).

Due to its linking-processes condition, soil moisture is placed squarely in the center of the spectrum of drought classifications and drought indicators (Ochsner et al., 2013). However, as Torres et al. (2013) mentioned, most of the drought assessment methods are based on long-term atmospheric data, such as rainfall and temperature, or on precipitation indices, but they typically do not consider site-specific soil properties. This is the case of most of the agricultural drought indices proposed so far. The Crop Moisture Index, CMI (Palmer, 1968) is based on a subset of the calculations required for the Palmer Drought Severity Index, PDSI (Palmer, 1965), which is primarily a meteorological drought index. The CMI originated as a way to calculate the water balance using historic records of precipitation and temperature. The Climatic Moisture Index, while it was first used for forestry applications (Hogg, 1994, 1997), it is essentially another agricultural index, and it is calculated subtracting potential evapotranspiration from precipitation. Narasimhan and Srinivasan (2005), used the Soil Moisture Deficit Index and the Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring, from simulated soil moisture and evapotranspiration derived from the SWAT (Soil and Water Assessment Tool) model. ETDI uses a concept of water stress from the reference crop evapotranspiration and the actual evapotranspiration, both SWAT model outputs. The Agricultural Reference Index for Drought, ARID (Woli et al., 2012), is based on a reference crop, which is actively growing grass that completely covers the soil surface and uses a simple soil water balance. Ceppi et al. (2014) use meteorological forecasts and hydrological modeling to simulate soil moisture as a component of a. real-time agricultural drought forecasting system.

Recently, several agricultural drought indices based on remote sensed products have been proposed. Keshavarz et al. (2014) introduced the Soil Wetness Deficit Index, calculated from the land surface temperature and the NDVI (Normalized Difference Vegetation Index) derived from MODIS satellite. From the same satellite, Li et al. (2014) obtained and compared NDVI anomaly with CMI in order to assess the agricultural drought in the northeast of China. Scaini et al. (2014) used SMOS-derived soil moisture anomalies for drought monitoring assessment.

According to its definition, agricultural drought is identified by a soil water shortage. Therefore, it is reasonable to consider soil moisture observations a suitable approach for agricultural drought monitoring, taking into account, as well, that plant water stress is more strongly related to the relative amount of plant-available water in the soil than to the absolute amount of soil moisture (Allen et al., 1998).

As it was mentioned before, several soil moisture approaches have been used for assessing drought, but soil moisture is usually estimated from hydrological modeling (Dutra et al., 2008; Hogg et al., 2013; Narasimhan and Srinivasan, 2005). However, there have been few attempts to use measurements of soil moisture for drought monitoring. Sridhar et al. (2008) introduced the soil moisture index (SMI), which was subsequently revised by Hunt et al. (2009) and was also used by Mozny et al. (2012). Previously, Porporato et al. (2001) used the concept of static vegetation water stress to analyze the effects of soil moisture deficit on plant conditions and was based not only on soil water limits but also on plant physiological dynamics. Martinez-Fernandez et al. (2005) introduced the concept of the water deficit index (WDI), which is not specifically a drought index but is intended to provide a better understanding of the water availability in the soil and its evolution. Recently, Torres et al. (2013) introduced a method for using long-term measurements of the soil water deficit to compute site-specific drought probability. Most of the mentioned studies are based on the normalization of the actual soil moisture with the available water content (θ_{AWC}) in the root zone using different methodologies.

In the present work, a new approach to define the soil water deficit index (SWDI) is analyzed for using soil moisture as a drought indicator. This new index is calculated using several root zone soil–water content series from an agricultural area in Spain. The index is tested and verified using a simple water deficit indicator and the CMI, as reference indices. Another goal of this research was to study a simple and accurate method using soil series solely to obtain the value of the soil water parameters needed to calculate the index to facilitate their universal use with the increasing availability of soil moisture databases worldwide.

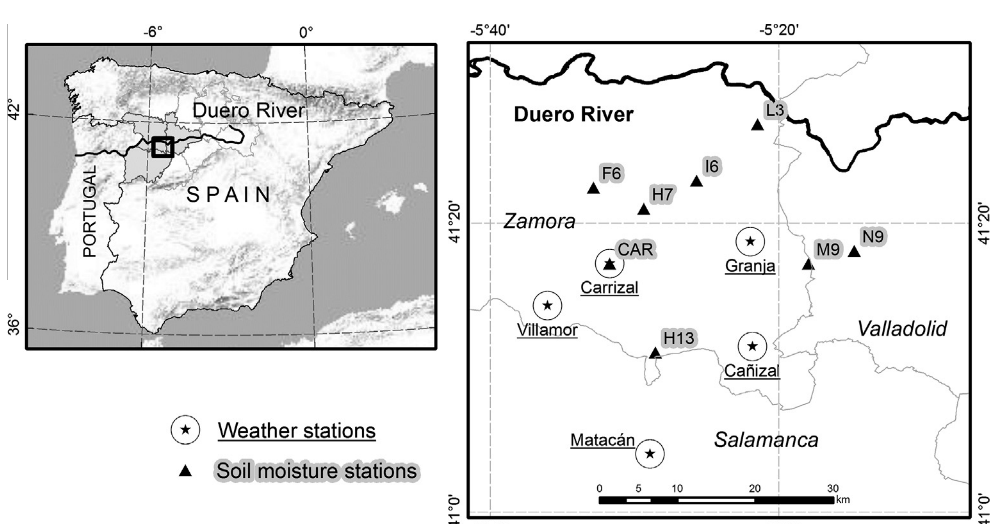

Fig. 1. Location of the REMEDHUS area (Spain) and the experiment layout.