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Appraisal of SMOS soil moisture at a catchment scale in a temperate maritime climate

Prashant K. Srivastava *, Dawei Han, Miguel A. Rico Ramirez, Tanvir Islam

Water and Environment Management Research Centre, Department of Civil Engineering, University of Bristol, Bristol BS8 1TR, United Kingdom

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SUMMARY

Soil moisture is one of the important variables in hydrological modelling, which is now possible to be measured with remote sensing. This study is an attempt to evaluate the Soil Moisture and Ocean Salinity (SMOS) satellite derived soil moisture for hydrological applications at a catchment scale. The Soil Moisture Deficit (SMD) derived from a Probability Distribution Model is used as a benchmark for all comparisons. Three approaches are used for the evaluation of SMOS soil moisture. The first approach is based on ROSETTA pedotransfer functions (PTFs), while second and the third are based on linear/non-linear and seasonal algorithms particularly for growing and non-growing seasons respectively. The field capacity and permanent wilting point estimated from the simulated Water Retention Curve (WRC) through ROSETTA are used for the transformation of SMOS data into SMD. The growing seasons used in this study belong to the months from March to November, while the non-growing seasons comprise of months from December to February. The highest performance is given by a combined growing and non-growing season algorithms with the Nash Sutcliffe Efficiencies (NSEs) of 0.75 and RMSE = 0.01 m^3/m^3 followed by the linear and non-linear algorithms (NSE = 0.40–0.42; RMSE = 0.02 m^3/m^3). The worst performance is revealed by the PTFs indicating that it should be used with caution for direct coarse scale SMOS applications (NSE = −24.98 to −40.23) and need more treatments regarding the spatial and depth wise mismatch. The overall analysis reveals that SMOS soil moisture is of reasonable quality in estimating Soil Moisture Deficit at a catchment level with a local adjustment algorithm combining growing and non-growing seasons.

1. Introduction

Land surface soil moisture is one of the important variables in hydrological processes, which influences the exchange of water and energy fluxes at the land surface/ atmosphere interface. The importance of estimating soil moisture is paramount for improving short- and medium-term meteorological modelling (Nandintsetseg and Shinoda, 2011), hydrological modelling (Milzow et al., 2011), the monitoring of plant growth (Deutsch et al., 2010), as well as contributing to the forecasting of hazardous events such as floods (Camici et al., 2011). The role of soil moisture in the top Earth's surface has been widely recognised as a key variable in numerous environmental studies including meteorology, hydrology, agriculture, and climate change (Jackson et al., 1995, 1999; Mladenova et al., 2011; Srivastava et al., 2013b). Therefore, it is very important to accurately monitor and estimate spatial and temporal variations of soil moisture.

Point based observations of soil moisture are currently limited to discrete measurements at particular locations, and such point-based measurements do not represent the spatial distribution exactly because soil moisture is highly variable both spatially and temporally (Engman, 1991; Wood et al., 1992; Fitzjohn et al., 1998; Wang and Qu, 2009) and are therefore inadequate for catchment level studies (Al-Shrafany et al., 2012, 2013). Numerous researchers have shown that near surface soil moisture content can be measured by optical and thermal infrared remote sensing, as well as passive and active microwave remote sensing techniques (Jackson, 1993; Owe et al., 2001; Scott and Bastiaanssen, 2003). With the advanced satellites like Soil Moisture Active and Passive (SMAP), Soil Moisture and Ocean Salinity (SMOS) and Advanced Microwave Scanning Radiometer – Earth Observing System (*AMSR*-E), it is expected that more accurate soil moisture measurements for hydrological modelling would be available. SMOS provides global measurements of Soil Moisture and Ocean Salinity, two key variables in the water cycle (Kerr et al., 2001; Silvestrin et al., 2001; Bindlish et al., 2011). SMOS was launched in November 2009 and carries a new instrument: an L-band radiometer named Microwave Imaging Radiometer with Aperture Synthesis (MIRAS). MIRAS is not the first L-band radiometer flown in space, but its a truly novel approach that sets it apart http://www.esa.int/SPECIALS/smos/.

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* Corresponding author. Tel.: +44 (0117) 331 5724 (O), mobile: +44 7401160526.
E-mail addresses: cepks@bristol.ac.uk, prashant.just@gmail.com (P.K. Srivastava).

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In hydrology, Soil Moisture Deficit (SMD) or depletion is a useful soil moisture indicator which represents the amount of water required to raise the soil–water content of the crop root zone to field capacity (Calder et al., 1983; Rushton et al., 2006). Researchers have found that the ratio between actual and potential evapotranspiration (PE) is closely related to SMD (Moran et al., 1994; Narasimhan and Srinivasan, 2005; Moore, 2007). It has been shown that the PDM model is very useful in estimating SMD from the meteorological data (Moore, 2007). The SMD estimated from the rainfall–runoff model can be converted into volumetric soil moisture content, if the field capacity (FC) and permanent wilting point (PWP) data are available for the soil under consideration. Rajkai et al. (2004) has reported that direct measurements of these variables is impractical for most applications especially for relatively large-scale problems. The ROSETTA model (a computer program based on pedotransfer functions) was developed by Schaap et al. (2001) to estimate the Water Retention Curve (WRC)of the soil. The term pedotransfer functions (PTFs) was first described as translating data that we have (e.g. soil survey data) into data that we need (e.g. soil hydraulic data) (Bouma, 1989). Estimates of the soil WRC using PTFs are useful in many studies, such as hydrological modelling and soil mapping (Børgesen and Schaap, 2005). Several researchers (Hall et al., 1977; Pachepsky et al., 2011; Rab et al., 2011; Gupta et al., 2012) reported that the Water Retention Curve is highly useful and efficient for estimating the FC and PWP of the soil. It has a potential to be used in a combination with satellite soil moisture data.

Some works are reported on SMOS soil moisture retrieval, downscaling, assimilation and its evaluation using point measured data (Kerr et al., 2001; Panciera et al., 2009, 2008; Pinori et al., 2008; Piles et al., 2011; Lacava et al., 2012; Srivastava et al., 2013a). However, no particular attention is given for its evaluation over a catchment scale particularly for hydrological applications, especially in a temperate maritime climate (Srivastava et al., 2012). In this work, an attempt has been made to evaluate the SMOS soil moisture product for hydrological applications at a catchment scale through three different approaches. All the three approaches are based on SMOS soil moisture content conversion to SMD. The first one is based on PTFs, while second and the third are based on linear/non-linear algorithms and season based algorithms (growing and non-growing) respectively. The outputs of the results are validated against the PDM Soil Moisture Deficit as a bench mark. This paper has the following structure. In Section 2, we detail the materials, method and algorithms used. Section 3 details the results and the performance of the approaches and discussion. Section 4 gives final remarks and conclusions of this work.

2. Materials and method

2.1. Study area and the datasets

The Brue catchment (135.5 Km^2) is chosen as the study area located in the south-west of England, 51.11°N and 2.47°W influenced primarily by the temperate maritime type of climate. The average altitude of this catchment is 105 m AMSL. The major land use is pasture land on clay soil with some patches of woodland in the higher eastern part of the catchment. It is a predominantly rural catchment of modest relief with spring-fed headwaters rising in the Mendip Hills and Salisbury Plain. The layout of the Brue catchment is shown in Fig. 1 along with the digital terrain model. The observed hourly rain gauge and river flow data for this study are obtained from the Environment Agency (UK) for the period February 2009 to January 2012. The data from the first 24 months (February 2009–January 2011) have been used for the calibration of the PDM and the remaining 12 months (February 2011–January 2012) are used for the validation purposes. The meteorological datasets are provided by the British Atmospheric Data Centre (BADC) that includes wind, net radiation, surface temperature and dew point. The soil texture data for the Brue catchment is obtained from the Soil Survey and Land Research Centre (SSLRC), UK and ISRIC-World Soil Information (Batjes, 2006). The SMOS data used in this study is procured for 1 year (February 2011–January 12) from the European Space Agency (ESA). The flowchart showing the methodology used in this study is represented by Fig. 2.

2.2. The SMOS products

The SMOS mission is a joint program of the European Space Agency (ESA), the National Centre for Space Studies, and the Industrial Technological Development Centre. The MIRAS instrument in the SMOS satellite acquires data of emitted microwave radiation at the frequency of 1.4 GHz (L-band). It is a dual polarized 2-D interferometer and is the first-ever, polar-orbiting, space-borne, 2-D interferometric radiometer designed to provide global information on surface soil moisture with an accuracy of 4% (Kerr et al., 2001). Level 2 products category is soil moisture or surface salinity swath-based maps which have been computed from Level 1c products. The conversion from Level 1c brightness temperatures to Level 2 maps includes a first step to mitigate the impact of Faraday rotation, Sun/Moon/galactic glint, atmospheric attenuation, etc., and it is done separately for Soil Moisture and Ocean Salinity. In this study the level 2 products (soil moisture swath based maps) are utilised for preparation of time series over the Brue catchment as other advance categories are still under development.

The SMOS soil moisture products are defined on the ISEA 4H9 grid i.e. Icosahedral Snyder Equal Area projection with aperture 4, resolution 9 and its shape of cells as hexagon (Pinori et al., 2008). The spatial resolution of the SMOS products is ~40 km with the soil moisture retrieval unit in m^3/m^3 (i.e. volumetric). The instrument provides records of brightness temperatures over incidence angles from 0° up to 55° across a 600 km swath (Pinori et al., 2008). Each point (or node) of this grid is known as a Discrete Global Grid (DGG) that has fixed coordinates and is assigned with an identificator the “DGG Id”. For the comparison between the catchment and SMOS soil moisture (SMOS SM), the SMOS pixel with its centroid over the catchment is extracted and considered for the subsequent analysis. The Beam 4.9 package with SMOS 2.1.3 plugin is used for the extraction. The ascending SMOS data products are chosen over the catchment in order to minimise the factors impacting soil moisture retrieval, such as vertical soil-vegetation temperature gradients.

It should be pointed out that there is a mismatch between the study catchment and SMOS pixels. Mismatch of catchment sizes and hydrological measurements is inevitable in practice. The commonly used rain gauge is the worst case example because hydrologists use a device about 20 cm in diameter to represent rainfall over a catchment of many square kilometres in size. The spatial mismatch between them is staggering, but this does not render the measurements from rain gauges invalid. Ideally, it would be great if SMOS pixels and the study catchment area of the same size. In practice, the mismatch is not a serious problem as long as SMOS derived SMD is able to provide useful soil moisture information for hydrological modelling.

2.3. Probability Distribution Model

There are many hydrological models available around the world and in this study, a typical model called Probability Distributed Model (PDM) is used. The PDM model is a fairly general conceptual