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How much water is used for irrigation? A new approach exploiting coarse resolution satellite soil moisture products

Luca Brocca[a,*], Angelica Tarpanelli[a], Paolo Filippucci[a], Wouter Dorigo[b], Felix Zaussinger[b], Alexander Gruber[b,c], Diego Fernández-Prieto[d]

[a] *Research Institute for Geo-Hydrological Protection, National Research Council, Perugia, Italy*
[b] *CLIMERS – Research Group Climate and Environmental Remote Sensing, Department of Geodesy and Geoinfomation, Vienna University of Technology, Vienna, Austria*
[c] *Department of Earth and Environmental Sciences, KU Leuven, Heverlee, Belgium*
[d] *European Space Agency, ESA-ESRIN, Frascati, Italy*

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ABSTRACT

Knowledge of irrigation is essential for ensuring food and water security, and to cope with the scarcity of water resources, which is expected to exacerbate under the pressure of climate change and population increase. Even though irrigation is likely the most important direct human intervention in the hydrological cycle, we have only partial knowledge on the areas of our planet in which irrigation takes place, and almost no information on the amount of water that is applied for irrigation.

In this study, we developed a new approach exploiting satellite soil moisture observations for quantifying the amount of water applied for irrigation. Through the inversion of the soil water balance equation, and by using satellite soil moisture products as input, the amount of water entering into the soil, and hence irrigation, is determined. Through synthetic experiments, we first assessed the impact of soil moisture measurement uncertainty and temporal resolution, also as a function of climate, on the accuracy of the method. Second, we applied the proposed approach to currently available coarse resolution satellite soil moisture products retrieved from the Soil Moisture Active and Passive mission (SMAP), the Soil Moisture and Ocean Salinity (SMOS) mission, the Advanced SCATterometer (ASCAT), and the Advanced Microwave Scanning Radiometer 2 (AMSR-2). Nine pilot sites in Europe, USA, Australia and Africa were used as case study to test the method in a real-world application.

The synthetic experiment showed that the method is able to quantify irrigation, with satisfactory performance from satellite data with retrieval errors lower than ~0.04 m^3/m^3 and revisit times shorter than 3 days. In the case studies based on real satellite data, qualitative assessments (due to missing in situ irrigation observations) showed that over regions in which satellite soil moisture products perform well, and which are characterized by prolonged periods without rainfall, the method shows good results in quantifying irrigation. However, at sites in which rainfall is sustained throughout the year, the proposed method fails in obtaining reliable performances. Similarly, low performances are obtained in areas where satellite products uncertainties are too large, or their spatial resolution is too coarse with respect to the size of the irrigated fields.

1. Introduction

It is estimated that over 70% of global freshwater is consumed by irrigation (FAO, 2006; Foley et al., 2011). Irrigated land comprises 1/5 of the world's cultivated area and supplies 2/5 of the world's food (Droogers et al., 2010). Climate change and population growth are expected to further increase the irrigation demand pushing more pressure on available freshwater for food production, and many areas which already experience water scarcity (Vörösmarty et al., 2000; Rockström et al., 2012; Kummu et al., 2016). Therefore, quantitative knowledge on resources used for irrigation is essential for stakeholders and companies involved in the management of agricultural services and food production that need accurate and timely information for ensuring food and water security (Deines et al., 2017). Additionally, information on irrigation is needed in many research applications e.g., for the assessment of the anthropogenic impact on the water and energy cycle (Bonfils and Lobell, 2007; Wada et al., 2014), to study the water budget closure in large scale hydrological and climate modelling (Döll and

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[*] Corresponding author at: Research Institute for Geo-Hydrological Protection, National Research Council, Via della Madonna Alta 126, 06128 Perugia, Italy.
E-mail address: luca.brocca@irpi.cnr.it (L. Brocca).

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Siebert, 2002), and for the evaluation of the impact of irrigation on precipitation and evapotranspiration dynamics (Alter et al., 2015).

Notwithstanding the important role of irrigation, its knowledge over large areas and over long periods is nearly absent. Most of the existing irrigation datasets are based on statistical surveys or simply identify areas equipped for irrigation (Salmon et al., 2015; Siebert et al., 2015), and usually are only valid for a specific year or a multi-year period). These datasets are potentially affected by large errors and subjective evaluations thus not being able to capture the spatial-temporal dynamic of irrigated areas (Deines et al., 2017). Alternatively, visible and optical remote sensing has been largely used for estimating irrigated areas (Ozdogan et al., 2010). Recent studies have shown the potential of remote sensing in mapping annual irrigation with high spatial resolution by using Moderate Resolution Imaging Spectroradiometer (MODIS) 250 (Ozdogan and Gutman, 2008; Pervez et al., 2014; Ambika et al., 2016; Teluguntla et al., 2017), Landsat 30 (Deines et al., 2017; Ozdogan et al., 2006; Pun et al., 2017), and geostationary (Romaguera et al., 2012) satellite imagery. Very recently, Sentinel-2 images, characterized by higher spatial resolution (10 m), have also been used for this purpose (Calera et al., 2017; Ferrant et al., 2017) and in the near future constellations of small satellites, e.g., cubesats, are expected to be very valuable for this purpose (McCabe et al., 2017).

While detecting irrigated areas has been widely investigated, the quantification of the water amount actually used for irrigation is much more problematic. Ground-based observations are essentially non-existent, except for very limited areas ($< 1–10\ \text{km}^2$) and/or time periods ($< 2–3$ years). Technical constraints, i.e., deployment of monitoring systems, and economic limitations, i.e., the cost of water and non-legal consumptions, impede an accurate determination of the actual water volume used for irrigation (see e.g., http://www.fao.org/nr/water/aquastat/irrigationmap/index40.stm), even on very local scales. Many existing studies focused on modelling irrigation water requirements but not on the actual water used for irrigation (Wada et al., 2014; Döll and Siebert, 2002). As most croplands are often over- or under-irrigated (Foley et al., 2011), the estimated irrigation water requirement is not necessarily equivalent to the actual irrigated water amount.

Also for the irrigation quantification, remote sensing can offer some solutions for monitoring the irrigation water use. Several studies exploited actual evapotranspiration (ET_a), estimates from remote sensing (e.g., MODIS and Landsat) and waterenergy balance modelling approaches to assess irrigation water amounts (Droogers et al., 2010; Romaguera et al., 2010; Wu et al., 2015; van Dijk et al., 2018). For instance, van Eekelen et al. (2015) employed the surface energy balance algorithm for land, SEBAL (Bastiaanssen et al., 1998) for mapping total ET_a that is split in ET_a induced by precipitation (for rainfed agro-ecosystems) and that by water withdrawals. The latter term is then used for indirectly estimating the water withdrawals for irrigation. The method was applied to the Incomati basin in Southern Africa obtaining annual values of irrigation withdrawals. The main problem of this study, as well as other similar ones, is the absence of in situ irrigation water observations, which makes it extremely difficult to evaluate the reliability and accuracy of the obtained estimates.

In addition to optical and thermal sensors, microwave sensors, which are able to provide estimates of soil moisture, can be used for detecting and quantifying irrigation due to the obvious increase in soil moisture after irrigation (Brocca et al., 2017; Jalilvand et al., under review; Kumar et al., 2015; Malbéteau et al., 2018; Singh et al., 2017; Zaussinger et al., 2018). The first study investigating this approach was carried out by Kumar et al. (2015) who used satellite soil moisture observations from ASCAT (Advanced SCATterometer), AMSR-E (Advanced Microwave Scanning Radiometer - Earth Observing System), SMOS (Soil Moisture and Ocean Salinity), ESA CCI SM (European Space Agency Climate Change Initiative Soil Moisture) and Windsat for the detection of irrigation over the Contiguous United States. By comparing modelled (by the Noah land surface model) and satellite soil moisture data, irrigated areas are inferred from (positive) biases between satellite and modelled data, as the latter does not include irrigation. The confounding effects of topography, vegetation, frozen soils and Radio Frequency Interference (RFI) prevented a clear identification of the irrigated areas even though some potential by using the ASCAT soil moisture product was observed over the plains of Nebraska. Qiu et al. (2016) evaluated soil moisture (from the ESA CCI SM product) and rainfall trend in China and found that satellite data can be used to detect irrigated areas as over those areas trends in satellite soil moisture and rainfall were significantly different. These differences were particularly significant over eastern China, where irrigation is quite extensive. Escorihuela and Quintana-Segui (2016) compared satellite soil moisture (from ASCAT, AMSR-E, SMOS and SMOScat – a MODIS-downscaled version of the official SMOS product) and modelled (by the SURFEX - Surface Externalisée - land surface model) data in the Northeast of the Iberian Peninsula. For the high resolution SMOScat product (1 km), a clear decrease in correlation between modelled and satellite data was observed at a small heavily irrigated region. Indeed, the land surface model does not take irrigation into account, and the low correlation was considered as an indication that SMOScat is able to detect the information of irrigation. Very recently, Lawston et al. (2017) used the new version of the Soil Moisture Active and Passive (SMAP) product at 9 km sampling for detecting the irrigation signal at three locations in the Western United States. As also shown in a modelling study by He et al. (2017), SMAP seems to be able to detect the irrigation signal, particularly in the Sacramento valley (California), while in the other two locations the results are less accurate.

In this study, we exploit satellite soil moisture information for quantifying the amount of water applied for irrigation. Specifically, we have developed an adapted version of the SM2RAIN algorithm (Brocca et al., 2014a) to estimate the total amount of water entering into the soil. Over irrigated areas, the SM2RAIN-derived water flux is composed of rainfall plus irrigation. Therefore, by removing the rainfall signal (e.g., obtained from rain gauge observations), we could be able to quantify irrigation. In two preliminary studies, Brocca et al. (2017) and Jalilvand et al. (under review) have demonstrated the feasibility of the proposed approach for two single locations in Nebraska and Iran (Urmia lake) and advocated the need to extend the analysis over multiple sites worldwide.

Two research questions are addressed here: 1) are we able to extract irrigation water information from coarse resolution satellite soil moisture observations? 2) which climatic and irrigation conditions are most favourable for estimating irrigation through coarse resolution satellite soil moisture observations?

Firstly, we perform a synthetic study with varying climatic, soil, and irrigation conditions in order to assess the potential of the proposed approach in a controlled environment. We also test different configurations for soil moisture observations with varying temporal resolution and uncertainty. Secondly, we apply the method at 9 pilot sites in Europe, USA, Australia and Africa by using all the current available coarse resolution satellite soil moisture products obtained by: 1) the SMAP mission; 2) the SMOS mission; 3) the ASCAT sensor on-board the Metop satellites; and 4) the Advanced Microwave Scanning Radiometer 2, AMSR2, sensor on-board the Global Change Observation Mission – Water, GCOM-W1.

The paper is organized as follows. The pilot sites and datasets are described in Sections 2 and 3. The adapted SM2RAIN method is described in Section 4 including details concerning the implementation of the synthetic and real-world experiments. Results are shown and discussed in Section 5. Finally, conclusions are drawn in Section 6.

2. Pilot sites

For the real-world analysis, we select 9 pilot sites located in the United States (US), Europe, Africa and Australia (see Fig. 1). The main driver for the selection of the sites is the presence of large scale irrigation over areas comparable to the spatial resolution of the used