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Research papers

Estimation of available water capacity components of two-layered soils using crop model inversion: Effect of crop type and water regime

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ABSTRACT

Characterization of the soil water reservoir is critical for understanding the interactions between crops and their environment and the impacts of land use and environmental changes on the hydrology of agricultural catchments especially in tropical context. Recent studies have shown that inversion of crop models is a powerful tool for retrieving information on root zone properties. Increasing availability of remotely sensed soil and vegetation observations makes it well suited for large scale applications. The potential of this methodology has however never been properly evaluated on extensive experimental datasets and previous studies suggested that the quality of estimation of soil hydraulic properties may vary depending on agro-environmental situations. The objective of this study was to evaluate this approach on an extensive field experiment. The dataset covered four crops (sunflower, sorghum, turmeric, maize) grown on different soils and several years in South India. The components of AWC (available water capacity) namely soil water content at field capacity and wilting point, and soil depth of two-layered soils were estimated by inversion of the crop model STICS with the GLUE (generalized likelihood uncertainty estimation) approach using observations of surface soil moisture (SSM; typically from 0 to 10 cm deep) and leaf area index (LAI), which are attainable from radar remote sensing in tropical regions with frequent cloudy conditions. The results showed that the quality of parameter estimation largely depends on the hydric regime and its interaction with crop type. A mean relative absolute error of 5% for field capacity of surface layer, 10% for field capacity of root zone, 15% for wilting point of surface layer and root zone, and 20% for soil depth can be obtained in favorable conditions. A few observations of SSM (during wet and dry soil moisture periods) and LAI (within water stress periods) were sufficient to significantly improve the estimation of AWC components. These results show the potential of crop model inversion for estimating the AWC components of two-layered soils and may guide the sampling of representative years and fields to use this technique for mapping soil properties that are relevant for distributed hydrological modelling.

1. Introduction

The capacity of the soil to store water available for plants, generally referred as available water capacity (AWC) is a key parameter for modelling the catchment-scale water balance. In particular, in tropical semi-arid contexts, where potential evapotranspiration equals or exceeds rainfall, recharge to groundwater is difficult to estimate from vadose-zone water balance (De Vries and Simmers, 2002) and it is particularly sensitive to the size of the soil water storage (Anuraga et al., 2006; Sreelash et al., 2013). Therefore, accurate estimates of AWC and its spatial variability at the catchment scale are needed to improve the sustainable management of groundwater resources. The increasing availability of high frequency and high resolution remote-sensing data now allows retrieving precise soil hydraulic properties maps of the top few centimeters of the soil (Montzka et al., 2011) but estimating

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AWC of the entire root zone at the catchment scale remains a challenge.

AWC depends on soil hydraulic properties (SHPs), soil depth and plant rooting characteristics. It may be defined from different points of view - pedologists, soil scientists, ecophysiologists - with different approaches and different levels of complexity, considering one or several layers corresponding to pedological horizons. A common definition of the AWC is the difference between the soil water content at field capacity and wilting point (Bruand et al., 2003). Those parameters can be determined in the field, which minimizes soil disturbance or in the laboratory which requires soil sampling and sample preparation that could distort the soil sample and increase the margins of errors. All methods are highly time-consuming and expensive (Steele-Dunne et al., 2010; Botula et al., 2012). Therefore, it is impractical to use them to obtain soil properties for catchments larger than a few hectares. For larger areas SHPs are generally estimated from soil characteristics that are easily available from soil maps (mainly textural properties) using pedotransfer functions (PTFs). However, PTFs are often site-specific and may lead to crude estimates of SHPs with large uncertainties when extrapolated over large areas (Vereecken et al., 1989, 1990; Wösten et al., 2001; Stumpp et al., 2009) or beyond the specific context (geomorphic regions or soil type) under which they are developed (McBratney et al., 2002). A more recent technique is Digital Soil Mapping (DSM) that couples field and laboratory observational methods with spatial and non-spatial soil inference systems (Lagacherie and McBratney, 2007). DSM makes an extensive use of technological and computational advances such as remote sensing and geostatistics for producing digital maps of soil types and soil properties (Lagacherie et al., 2008; Vaysse and Lagacherie, 2015). However, approaches based on DSM estimate basic soil properties such as soil texture, bulk density, and pH and still rely on PTFs to translate them into more functional properties (McBratney et al., 2003). They are thus also limited by the quality of the PTFs and their adequacy to the studied situation.

As AWC components are important parameters for hydrological models, model inversion is another alternative for retrieving them. The principle is to use *in situ* or remotely sensed observations corresponding to model outputs strongly linked with AWC components to estimate them using parameter estimation or data assimilation methods. Such approach has been carried out in several studies for estimating SHPs and soils depth using various types of models: hydrological models (Ritter et al., 2003; Ines and Mohanty, 2008; Charoenhirunyingyos et al., 2011), crop models (Guérif et al., 2006; Varella et al., 2010a,b; Sreelash et al., 2012), agro-hydrological models (Ferrant et al., 2016), Land Surface Models (Bandara et al., 2013, 2014, 2015) or SVAT (soil vegetation atmosphere transfer) models (Jhorar et al., 2002, 2004). Several studies have shown that SHPs of vertically homogeneous soils can be estimated through model inversion using surface soil moisture (see for example Montzka et al., 2011; Nagarajan et al., 2011). For multi-layered soils, profile soil moisture observations allow assessing SHPs (Ritter et al., 2003; Braga and Jones, 2004; Wohling and Vrugt, 2011; Li and Ren, 2011) but this requires large experimental settings which limits its spatial application. On the other hand, using only surface soil moisture measurements that can be spatially available from remote sensing, is not sufficient to provide unique and physically reasonable estimates of hydraulic properties for multi-layered soils through model inversion (Vereecken et al., 2008; Ines and Mohanty, 2008; Charoenhirunyingyos et al., 2011) because of the poor connection in the hydraulic processes between layers (Montzka et al., 2011), except in some particular situations (Shin et al., 2012; Bandara et al., 2013). Shin et al. (2012) also reported that the weakness of hydrological models in simulating plant root activities in the root zone results in relatively larger errors in the estimation of SHPs in crop land as compared to bare soil. As crop lands represent a large contribution to hydrologic processes within agricultural catchments, precise knowledge of AWC components is critical for managing water resources to maintain agricultural production. The known projections of climate change make this objective even more essential.

Recently, crop model inversion has been proposed by several authors to retrieve AWC components (Guérif et al., 2006; Varella et al., 2010a, 2010b; Sreelash et al., 2012). The main interest of using crop models for retrieving AWC components in crop lands is that they are more efficient than hydrological models, Land Surface Models or SVAT models in describing the specificity of crop behavior with regards to water processes (effect of crop type on rooting system characteristics and water needs, effect of crop management practices on the water balance). This is partly because they account AWC components impacts not only on the soil water balance, but also on the coupled carbon and nitrogen cycling (Ruget et al., 2002; Satti et al., 2004; Breda et al., 2006). The increasing availability of high frequency and high resolution vegetation and soil moisture data from remote sensing makes crop model inversion approach a potentially powerful tool for spatial applications, especially for parameterizing catchment-scale hydrological models.

However, accuracy of the parameter estimates strongly depends on environmental conditions such as climate and crop type (Varella et al., 2010b). Charoenhirunyingyos et al. (2011) and Sreelash et al. (2012) show that combining surface soil moisture and vegetation measurements in model inversion, by bringing information on both surface and root zone SHPs, improves substantially parameter estimation. However, these conclusions are based on synthetic experiments or very limited field datasets. In fact, few studies based on field data have been carried out to evaluate the potential of model inversion methods for estimating AWC components on multi-layered soils with observations potentially accessible from remote sensing and this problem is still considered as challenging (Mohanthy, 2013).

In this paper, we used an extensive field dataset from a tropical agricultural catchment in South India involving four types of crops across 3 years. The objectives are:

(i) to analyze the potential of model inversion methods for estimating AWC components (water content at field capacity and wilting point, soil depth) on two-layered soils with observations potentially accessible from remote sensing on a large set of field situations; and
(ii) to investigate the influence of the crop type and water regimes experienced by the crops on the accuracy of these estimations.

2. Materials and methods

2.1. Site information

The experimental catchment of Berambadi (84 km^2) is located in the Kabini river basin in South India (AMBHAS Site, www.ambhas.com, long term environmental observatory BVET http://bvet.obs-mip.fr; Braun et al., 2009; Ruiz et al., 2010; Violette et al., 2010). It is intensively used for agro-hydrological, remote sensing and hydrological investigations (Kumar et al., 2009). The land is used for agriculture and the crops are mostly rainfed or irrigated with groundwater. We used a total of 60 crop/soil/climate situations covering 4 crops across 3 years from May 2011 to Dec 2013 and 42 agricultural plots each approximately 1 ha in size, monitored for soil moisture and crop growth. Among them, 15