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Simulation of regional irrigation requirement with SWAT in different agro-climatic zones driven by observed climate and two reanalysis datasets

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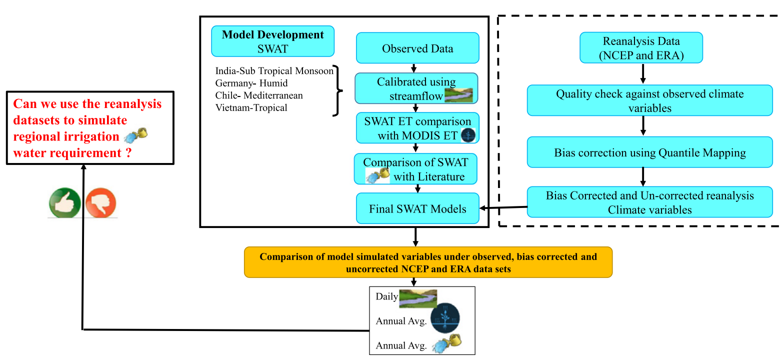
HIGHLIGHTS

- Application of SWAT in four different agro-climatic zones for simulating irrigation water demand was investigated
- MODIS generated ET was evaluated against the SWAT simulated ET
- Irrigation water requirement was evaluated under different scheduling scenarios
- Use of climate reanalysis data (NCEP and ERA-Interim) for agro-hydrological studies in data scarce catchments was evaluated

GRAPHICAL ABSTRACT



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ABSTRACT

Irrigation water is one of the most substantial water uses worldwide. Thus, global simulation studies about water availability and demand typically include irrigation. Nowadays, regional scale is of major interest for water resources management but irrigation lacks attention in many catchment modelling studies. This study evaluated the performance of the agro-hydrological model SWAT (Soil and Water Assessment Tool) for simulating streamflow, evapotranspiration and irrigation in four catchments of different agro-climatic zones at meso-scale (Baitarani/India: Subtropical monsoon; Ilmenau/Germany: Humid; Itata/Chile: Mediterranean; Thubon/Vietnam: Tropical). The models were calibrated well with Kling-Gupta Efficiency (KGE) varying from 0.74–0.89 and percentage bias (PBIAS) from 5.66–6.43%. The simulated irrigation is higher when irrigation is triggered by soil-water deficit compared to plant-water stress. The simulated irrigation scheduling scenarios showed that a significant amount of water can be saved by applying deficit irrigation (25–48%) with a small reduction in annual average crop yield (0–3.3%) in all climatic zones.
Many catchments with a high share of irrigated agriculture are located in developing countries with a low availability of input data. For that reason, the application of uncorrected and bias-corrected National Centers for Environmental Prediction (NCEP) and ERA-interim (ERA) reanalysis data was evaluated for all model scenarios. The simulated streamflow under bias-corrected climate variables is close to the observed streamflow with ERA performing better than NCEP. However, the deviation in simulated irrigation between observed and reanalysis climate varies from −25.5–45.3%, whereas the relative irrigation water savings by deficit irrigation could be shown by all climate input data. The overall variability in simulated irrigation requirement depends mainly on

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the climate input data. Studies about irrigation requirement in data scarce areas must address this in particular when using reanalysis data.

1. Introduction

The major proportion (about 70%) of the world's water resources is consumed by agriculture although the share of total water use varies drastically under different continents from around 10% in Europe to nearly 90% in South Asia (http://www.fao.org/nr/water/aquastat). However, fast population growth will increase the demand for food, resulting in increased future demand for agricultural irrigation. Rabie et al. (2013) postulated in a global study that 52 countries will face a water deficit crisis by 2025. Irrigated agriculture has expanded by 480% (47.3 to 276.3 Mha) since the last century. Nowadays, 18% of crop land is irrigated and the rest accounts for rainfed agriculture. The increase in irrigated agriculture is majorly concentrated to developing countries as they are more effected by population growth (Rockström and Falkenmark, 2000; Bruinsma, 2003; Siebert et al., 2005; Scanlon et al., 2007).

Water demand and water availability are two main parameters for effective water resources management and water scarcity is a main driver for water resources planning and optimization. In order to overcome the probable future water stress and to ensure food security, the irrigation water use efficiency must be optimized. Crop water requirement is the fundamental input for regional planning and policy making for irrigated agriculture (Santhi et al., 2005). Besides meteorological variables, crop water requirement also depends on soil physical properties and crop parameters like leaf area index, crop stage, rooting depth etc. (Doorenbos and Pruitt, 1977; Allen et al., 1998).

Hydrological models are tools that can simulate dynamic hydrological processes taking into consideration the spatio-temporal distribution of water in different compartments (Zuo et al., 2015). Irrigation requirement is mostly simulated at field scale for operational purpose to optimize the water use at farm scale by using one dimensional soil hydraulic models like SWAP (Soil-Water-Atmosphere-Plant System, van Dam et al., 1997; Droogers and Bastiaanssen, 2002; Singh et al., 2006; Ma et al., 2011) and Daisy (Abrahamsen and Hansen, 2000). However, there has been an increase in the number of studies on optimizing the resource allocation at aggregated scales like command area, catchment or watershed scale (Bastiaanssen et al., 2000). Early models for quantifying the irrigation water requirement at aggregated scale are CADSM (Command Area Decision Support Model, Walker et al., 1995) and EPIC (Erosion Productivity Impact Calculator, Williams et al., 1989; Meinardus et al., 1998). With the advanced application of remote sensing techniques, SEBAL (Surface Energy Balance Algorithm for Land, Bastiaanssen et al., 1998; Zwart and Bastiaanssen, 2007; Teixeira et al., 2009; Allen et al., 2011) was developed. Conceptual hydrological models allow the simulation of larger catchments including horizontal flows of water. Examples with application in irrigated catchments are SLURP (Semi-distributed, Land-Use-based, Runoff Processes, Barr et al., 1997; Kite, 1998; Kite and Droogers, 2000), SWAT (Soil and Water Assessment Tool, Arnold et al., 1998; Neitsch et al., 2011), WaSIM (Water flow and Balance Simulation Model, Niehoff et al., 2002; Schulla and Jasper, 2007) and WEAP (Water Evaluation and Planning System, Danner, 2006; Mehta et al., 2013; Esteve et al., 2015). Moreover, several studies have also been carried out by upscaling field scale models and by nesting the best components of different models (hydrology + plant growth; Ground water + plant growth). Jiang et al. (2015) used SWAP-EPIC for assessing the performance of irrigation and water productivity in the irrigated areas of middle Heihe River, China. Whereas, the irrigation performance was also estimated by using SEBAL and SWAP in Gediz Basin, western Turkey by Droogers and Bastiaanssen (2002).

Nowadays, the interpretation algorithms of satellite imagery from the terra moderate resolution imaging spectroradiometer (MODIS) have been approved (Mu et al., 2013) and used by many researchers in assessing the spatio-temporal hydrologic behavior of agricultural catchments (Stehr et al., 2009; Tang et al., 2009b; Zhang et al., 2009; Emam et al., 2017). Remote sensing can provide satisfactory estimates of irrigated areas and also crop water indicators by capturing the phenological development of crops through multi-temporal image classification (van Niel and McVicar, 2004; Thenkabail et al., 2009; Ozdogan et al., 2010; Pervez and Brown, 2010; Conrad et al., 2011; Romaguera et al., 2012; Peña-Arancibia et al., 2016; Zhang et al., 2018). Errors in the remotely sensed actual evapotranspiration (ET) are generally in the order of 10–20% in Australia (Glenn et al., 2011), whereas, the specific MODIS ET product was reported to have an error of 24.1% relative to the flux towers (Mu et al., 2013; Vervoort et al., 2014). In this paper, we always refer actual evapotranspiration as ET.

Reanalysis data from different spatial and temporal resolution [e.g., National Centers for Environmental Prediction (NCEP, Saha et al., 2010); ERA-interim, Dee et al., 2011; etc.] have been used in simulating the global as well as regional hydrological response of different agricultural catchments. Essou et al. (2016) compared different climate datasets to perform lumped hydrological modelling over 42 catchments in the United States and later on, evaluated the impacts of combining reanalysis and weather data to check the accuracy in discharge simulation over 460 Canadian watersheds (Essou et al., 2017). Wisser et al. (2008) used NECP data to simulate the global irrigation water demand and confirmed that the weather driven variability in global irrigation was $<10\%$ but it could be much higher at national scale ($\pm 70\%$). Since some reanalysis data provide time series of >30 years, therefore they have been increasingly used in studying climate trends (Poveda et al., 2006; Wang et al., 2006; Stammerjohn et al., 2008).

Amongst the hydrological models mentioned above, the application of SWAT has gained momentum during last 10–15 years for modelling agricultural catchments (van Griensven et al., 2012). Santhi et al. (2005) improved the capabilities of SWAT by introducing a canal irrigation component into the model for the effective regional planning of an irrigated agricultural catchment in Rio Grande, U.S. Xie and Cui (2011) developed SWAT for simulating paddy fields in the Zhanghe Irrigation District located in China. Dechmi et al. (2012) used SWAT to simulate the intensive agricultural irrigated catchment of the Del Reguero watershed in Spain. Panagopoulos et al. (2014) evaluated the economic effectiveness of different best management practices for reducing the irrigation water abstraction in Pinios, Greece. Maier and Dietrich (2016) compared different irrigation strategies, where different methods of auto-irrigation implemented into SWAT showed considerably different results for a humid catchment in Germany. Marek et al. (2016) investigated the simulation of the leaf area index (LAI) and ET in SWAT and found deficiencies, which may have an impact on the accuracy of simulated plant water uptake. Chen et al. (2018) proposed an improved auto-irrigation function for SWAT based on field studies in Texas (Chen et al., 2017). In addition to this, SWAT was used to find out the best management practices for irrigation considering crop water requirement, productivity, management strategies costs and crop market prices in Crete, Greece (Udias et al., 2018). The updated SWAT+ model will improve the control of auto-irrigation by decision tables (Arnold et al., 2018).