Agricultural Water Management 146 (2014) 324–334

Contents lists available at ScienceDirect

Agricultural Water Management

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

Uncertainty assessment of the agro-hydrological SWAP model application at field scale: A case study in a dry region

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ARTICLE INFO

Article history:
Received 30 November 2013
Accepted 7 September 2014

Keywords:
Soil water balance
Predictive uncertainty
Reliability
GLUE

ABSTRACT

Uncertainty analysis can provide useful insights into the sources and effects of uncertainty for decision makers to achieve the goals of reliability and sustainability in water management. This study presents parameters uncertainty of a physically based soil–water–atmosphere–plant (SWAP) model and its effect on model prediction within the generalized likelihood uncertainty estimation (GLUE) framework for two irrigated agricultural fields in a dry region of Iran. To simulate soil water dynamics of the two fields, the SWAP model is calibrated using soil moisture observation data. The results demonstrate that predictive uncertainty in soil moisture during the growing season in both fields is relatively small and a good model performance is achieved. Parameter uncertainty analysis of soil hydraulic parameters showed that in spite of similarity of soil texture in both the fields, the estimated parameters (i.e. posterior distribution) exhibit different behaviors. This was because of the dynamics of soil structure which varies considerably within cultivated fields during the growing season. Moreover, the simulated water balance fluxes (actual evapotranspiration and deep percolation) indicate that in irrigated agricultural fields in dry regions, the precision of actual evapotranspiration predicted by the SWAP model is high (i.e. a high degree of model reliability is achieved). However, deep percolation fluxes show higher variation (lower precision) and are more sensitive to soil hydraulic conductivity parameterization. Finally, this study reveals the importance of uncertainty analysis to estimate the degree of reliability associated with model predictions as an important first step for providing decision makers with realistic information about the models outputs.

1. Introduction

Agro-hydrological simulation models have been widely used for optimizing resources in agriculture for maximum crop growth and minimum environmental impact. In addition, these models describe the soil water fluxes, the soil vapor fluxes, and water and energy balances in the soil–crop–atmosphere system in detail (Van Dam, 2000). Numerous studies have applied agro-hydrological models to assess water balance or irrigation scheduling at field scale (e.g. Clemente et al., 1994; Droogers, 2000; Singh et al., 2006a,b). However, due to the inherent variability in natural processes and difficult or costly monitoring, the model input data and its internal parameters are rarely known with certainty (Wang et al., 2005). Thus, the parameters cannot be identified with ease. Assessment of parameter and predictive uncertainty of hydrologic models is essential for successful use of models in environmental management and a required assessment should be conducted before using its results in decision making processes (Ajami et al., 2008). Among agro-hydrological model applications, few studies have been conducted to investigate parameter uncertainty at field scale (e.g. Makowski et al., 2002; Lawless et al., 2008; He et al., 2009). The agro-hydrological SWAP (soil, water, atmosphere and plant) model based on the Richards' equation has been applied and tested under various conditions and has proven to produce reliable and accurate results (e.g. Droogers et al., 2000; Ahmad et al., 2002; Bonfante et al., 2010; Karimi et al., 2012). SWAP addresses the close interactions between soil water flow, surface water management, and vegetation development (Van Dam et al., 2008).

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http://dx.doi.org/10.1016/j.agwat.2014.09.008
0378-3774/

More recently, inverse approaches have been increasingly used to estimate (calibrate) model parameters. Estimation of the model parameters is subject to uncertainty, which leads to uncertainty in model predictions. In most applications, this uncertainty needs to be quantified to provide meaningful prediction of model results. In many applications, according to our best knowledge, none of the SWAP model parameter estimates were conducted through uncertainty assessment. Among such inverse approaches for SWAP calibration, PEST (Doherty, 1994) has been intensively used to identify parameters of the soil hydraulic functions (e.g. Jhorar et al., 2002; Singh et al., 2006b; Vazifedoust et al., 2008). However, most optimization algorithms have the disadvantage of being very sensitive to the starting value of the parameters, while also being prone to converge to local minima (Abbaspour et al., 2001) (see Pande (2013a,b) for more examples of different algorithms to aid global convergence). There are also robust optimization techniques that attempt to search for the whole parameter space to find a global minimum. For example, Ines and Droogers (2002) used GA to inversely estimate the soil hydraulic functions in the unsaturated zone for SWAP model application. Hupet et al. (2003) also linked several global search algorithms to SWAP for parameter optimization, such as the global multilevel coordinate search (GMCS) algorithm (Huyer and Neumaier, 1999) and its combination with the classical Nelder–Mead simplex (NMS) algorithm. Yet another major problem in inverse modeling is Equifinality of models (e.g. Abbaspour et al., 1997; Beven and Freer, 2001); the condition in which different parameter sets can lead to a similar model response due to poorly constrained inverse problem formulation (Arkesteijn and Pande, 2013). It has been accepted that the process of calibration cannot lead to a single 'optimal' parameter set but one has to find a probability distribution of parameters that represents the knowledge about parameter values. Hence, the parameters cannot be identified easily and different parameter sets may result in similar prediction which is known as the equifinality (Beven, 2001). On the other hand, well-constrained inverse problems identify model parameters better and yield robust simulations (Pande et al., 2009, 2012).

Yet, the vast majority of SWAP model calibrations are still conducted by optimization algorithms and deterministic perspectives (e.g. Droogers et al., 2008; Singh et al., 2010; Noory et al., 2011). Indeed, previous studies on SWAP model applications have largely ignored quantifying the parameter and predictive uncertainty when the model is calibrated based on soil moisture data, especially its effect on the simulation of water balance components. One method that provides a reasonable framework for assessing uncertainty and the issue of equifinality is the generalized likelihood uncertainty estimation (GLUE; Beven and Binley, 1992). It is an informal Bayesian method that uses prior information about parameter values and estimates uncertainty in model parameters. This method, based on Monte Carlo simulation, transforms the problem of searching an optimal parameter set into searching a set of parameter values that provide reliable simulations for a range of model inputs (Beven, 2006; Sreelash et al., 2012). In GLUE, parameter uncertainty accounts for all sources of uncertainty (i.e. input uncertainty, structural uncertainty, and parameter uncertainty) and the likelihood measure value that is associated with a parameter set implicitly reflects all these sources of error on model performance (Beven, 2001). GLUE has been widely used for assessing uncertainty in hydrological models (Li et al., 2010) and various other fields of modeling (e.g. Zheng and Keller, 2007; Juston et al., 2010). For instance, Zhang et al. (2006) compared GLUE with a non-linear least square optimization method and indicated that GLUE can produce a wider range of potential outputs that are more robust in model predictions of pesticide transport in soils at field scale. They also suggested that the prediction uncertainties are useful in evaluating risk in decision making. He et al. (2009) applied GLUE in estimating CERES-Maize model parameters for sweet corn production.

So far, little effort has been made to analyze the uncertainty of agro-hydrological models applied at field scale. Due to various boundary conditions, management practices and spatiotemporal variability in soil hydraulic properties, it is of great importance to investigate the uncertainty in model parameters that affect agro-hydrological model outputs. The aim of the present paper is to assess the parameter uncertainties and their effect on model prediction, within GLUE framework, for two irrigated agricultural fields (maize and wheat) in a dry region in Iran. This study also aims at investigating SWAP model Equifinality and parameter identifiability – refers to whether the single true value of a model's calibration parameters can theoretically be inferred (Lancaster, 2004) based on available data – of soil hydraulic parameters calibrated based on soil moisture measurements, and further assessing their effects on water balance fluxes prediction. The SWAP modeling results and uncertainty analysis from this study are believed to make useful contributions toward agricultural water management decision making processes.

2. Materials and methods

2.1. Site description and data set

The study area, Borkhar district, is located in central Iran, north of the historic city of Isfahan. Borkhar district is characterized as having a predominantly arid to semi-arid climate. Long term average annual rainfall is 164.7 mm, most of which falls in the winter months from December to April, therefore profitable crop production without reliable irrigation is impossible in the area.

Two farm fields were selected for this study: a fodder maize field and a wheat field. Field measurements were made at the fodder maize field during the summer season and at the wheat field during the winter season (Table 1) of the agricultural year 2004–2005 (Vazifedoust, 2007). The soil texture in both fields is relatively heavy (52% clay and 38% silt in the maize field and 46% clay and 36% silt in the wheat field) and the bulk densities of the topsoil layer (0–60 cm) are 1.4 ($g\,cm^{-3}$) and 1.6 ($g\,cm^{-3}$) for the maize and wheat fields, respectively. Access to water with good quality in this area provides suitable growing conditions for wheat and maize. Groundwater levels are deep (>100 m) with low salinity ($EC < 2\,dS\,m^{-1}$).

Daily meteorological data, including minimum and maximum temperature, relative humidity, vapor pressure, sunshine hours, wind speed and rainfall were obtained from a meteorological station in the vicinity of the site. During the growing season, the irrigation depths were constant and the two study fields received heavy traditional irrigation. The irrigation depth in the wheat field was 17 cm for each of the six events and was 16 cm in the maize field for each of the eight events throughout the period of crop growth. The data on crop characteristics including plant height, leaf area index (LAI) and rooting depth were also obtained from the emergence stage to the maturity stage during crop development at the two study fields. The crop characteristics data are described in terms of crop growth by the measured characteristics as a function of crop development stage. During the growth period, volumetric soil moisture content was measured at three soil depths (i.e. 0–15, 15–30 and 30–60 cm). The data were used in the model calibration stage.

2.2. The agro-hydrological SWAP model

The soil–water–atmosphere–plant (SWAP) is an integrated physically based simulation model for one-dimensional vertical