Journal of Hydrology 536 (2016) 192–207

Contents lists available at ScienceDirect

Journal of Hydrology

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

Multi-objective calibration of a hydrologic model using spatially distributed remotely sensed/in-situ soil moisture

Mohammad Adnan Rajib[a], Venkatesh Merwade[a,*], Zhiqiang Yu[b]

[a] Lyles School of Civil Engineering, Purdue University, USA
[b] Brandon Research Centre, Agriculture and Agri-Food Canada, Canada

ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form 13 February 2016
Accepted 17 February 2016
Available online 27 February 2016
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
AMSR-E
Calibration
Remote sensing
Soil moisture
SWAT
Uncertainty

SUMMARY

The objective of this study is to evaluate the relative potential of spatially distributed surface and root zone soil moisture estimates in calibration of Soil and Water Assessment Tool (SWAT) toward improving its hydrologic predictability with reduced equifinality. The Upper Wabash and Cedar Creek, two agriculture-dominated watersheds in Indiana, USA are considered as test beds to implement this multi-objective SWAT calibration. The proposed calibration approach is performed using remotely sensed Advanced Microwave Scanning Radiometer-Earth Observing System surface soil moisture (~1 cm top soil) estimates (NASA's Aqua daily level-3 gridded land surface product-version 2) in sub-basin/HRU level together with observed streamflow data at the watershed's outlet. Although application of remote sensing data in calibration improves surface soil moisture simulation, other hydrologic components such as streamflow, evapotranspiration (ET) and deeper layer moisture content in SWAT remain less affected. An extension of this approach to apply root zone soil moisture estimates from limited field sensor data showed considerable improvement in the simulation of root zone moisture content and streamflow with corresponding observed data. Difference in relative sensitivity of parameters and reduced extent of uncertainty are also evident from the proposed method, especially for parameters related to the subsurface hydrologic processes. Regardless, precise representation of vertical soil moisture stratification at different layers is difficult with current SWAT ET depletion mechanism. While the results from this study show that root zone soil moisture can play a major role in SWAT calibration, more studies including various soil moisture data products are necessary to validate the proposed approach.

1. Introduction

Parameter calibration is a necessary step in setting up a hydrologic model for any study. Regardless of the uncertainties in input weather data and imperfections in model physics, a calibrated model tends to provide an "acceptable" output. Simulation of surface and subsurface fluxes in a hydrologic model is strongly affected by the choice of objective variables in model calibration procedure and resultant parameter values adopted from therein (Abbaspour et al., 2007; Park et al., 2014). Similarly, several parameter combinations are possible during calibration, producing equally reasonable simulation results (equifinality; Beven, 1993). Therefore, parameters associated with subsurface fluxes get poorly optimized when models are typically calibrated against observed streamflow hydrograph (Immerzeel and Droogers, 2008; White and Chaubey, 2005).

Simultaneous use of multiple gauging stations in model calibration can help to reduce parameter uncertainty and improve streamflow simulations (e.g. Bekele and Nicklow, 2007; Chiang et al., 2014; Her and Chaubey, 2015; Zhang et al., 2008), but the outcomes are often region-specific (e.g. Gong et al., 2012) and are also affected by the spatial distribution of gauges included in the study (Migliaccio and Chaubey, 2007). Additionally, there is no literature which shows that use of multiple gauges can lead to better estimation of subsurface fluxes such as soil moisture and evapotranspiration (ET), including the reduction of uncertainty/equifinality of the associated parameters. Therefore, the traditional approach of model calibration using observed streamflow at one or more stations can still lead to a model where several components of the watershed's hydrologic system may remain virtually uncalibrated (Wanders et al., 2014). Considering these issues, good correspondence between observed and simulated streamflow is not sufficient to evaluate the simulation capability

* Corresponding author at: 550 Stadium Mall Dr., West Lafayette, IN 47907, USA. Tel.: +1 (765) 494 2176; fax: +1 (765) 494 0395.
E-mail address: vmerwade@purdue.edu (V. Merwade).

http://dx.doi.org/10.1016/j.jhydrol.2016.02.037
0022-1694/

of physically based hydrologic models (Demarty et al., 2005; Eckhardt, 2005; Gupta et al., 1998; Kuczera and Mroczkowski, 1998). Alternatively, the trade-off between model fits constrained by multiple hydrologic variables observed at different spatial scale of evolution might lead toward lower parameter uncertainty, improving model robustness and predictability and implicitly encountering possible deficiencies in model structure. The solution to this multi-objective calibration produces a parameter set that is optimal in a Pareto efficiency sense (Xie et al., 2012). Among different surface/subsurface components, soil moisture plays an important role in energy and water balance of hydrologic cycle (Brocca et al., 2012), and hence, ensuring accurate soil moisture accounting in a hydrologic model can lead to better simulation of hydrologic processes including ET, surface runoff generation, groundwater recharge, and streamflow. While obtaining in-situ monitoring data of soil water fluxes/state variables is a long-standing challenge, remotely sensed surface soil moisture estimates can be obtained at high temporal resolution for the entire globe (Wanders et al., 2014).

Most studies that use surface soil moisture estimates to improve model simulation involves assimilation of in-situ, synthetic or remotely sensed data (e.g. Alvarez-Garreton et al., 2015; Bolten et al., 2010; Brocca et al., 2010; Chen et al., 2011; Draper et al., 2011; Han et al., 2012a, 2012b; Houser et al., 1998; Lei et al., 2014; Pauwels et al., 2001, 2002; Reichle et al., 2002; Sawada et al., 2015; Scipal et al., 2008). Only few recent studies have applied remotely sensed surface soil moisture information in model calibration process (e.g. Kunnath-Poovakka et al., 2016; Milzow et al., 2011; Parajka et al., 2009; Sutanudjaja et al., 2014; Wanders et al., 2014). All these past studies conclude that using surface soil moisture, either in data assimilation or model calibration, improves model simulated surface soil moisture, without causing appreciable change in deeper layer (root zone) soil moisture and streamflow/surface runoff outputs. The limited success in modeling results from using remotely sensed soil moisture estimates is related to the shallow depth of assimilation/calibration which is in fact dependent on the sensing depth of the satellite product being used (1–5 cm top soil), and the model conceptualizations related to coupling of surface and root zone soil layers (e.g. Brocca et al., 2012; Chen et al., 2011; Han et al., 2012a).

Considering the role of root zone soil moisture in regulating subsurface hydrology, Parajka et al. (2006) and Silvestro et al. (2015) showed the use of an empirically derived root zone soil moisture index for calibrating a hydrologic model. Brocca et al. (2012) and Chen et al. (2011) recommended model calibration using both streamflow and root zone soil moisture prior to assimilating soil moisture data into the model, which can potentially improve the efficiency of data assimilation techniques. Despite the limitation of sensing depth from space-borne satellites and the scarcity of field based information, recent advancements in multi-model land surface data assimilation projects such as National Astronomy and Space Administration (NASA)'s North American Land Data Assimilation Systems (NLDAS; Xia et al., 2015a,b) and Soil Moisture Active Passive (SMAP; Entekhabi et al., 2014; Reichle et al., 2014) mission can lead to high resolution root zone soil moisture estimations. These estimates can ultimately be used to improve the representation of subsurface processes in hydrologic models through multi-objective calibration.

Given the potential availability of root zone soil moisture, the overall goal of this study is to evaluate the performance of the Soil and Water Assessment Tool (SWAT) while using both soil moisture information and streamflow for calibration. Specific objectives include: (i) use of remotely sensed sub-basin/HRU scale surface soil moisture estimates along with streamflow observations in a spatially distributed model calibration scheme; and (ii) use of root zone soil moisture and streamflow in similar spatially distributed approach. Accordingly, comparison of the outcomes from these two objectives are used to evaluate the relative influence of surface and root zone soil moisture estimates in improving SWAT's soil moisture accounting, streamflow simulation and parameter equifinality.

The Soil and Water Assessment Tool (SWAT) is selected for this study because it is a semi-distributed, continuous-time, process-based hydrology and water quality model (Neitsch et al., 2011) that is widely used globally to simulate hydrologic processes under different conditions and scales (Arnold et al., 2012; Gassman et al., 2007). Even with the recent remarkable advancements in developing new optimization algorithms and automatic tools specifically designed for SWAT, hydrologic calibrations of SWAT models can still be "conditional" (Abbaspour et al., 2015) and "sub-optimal" (Chen et al., 2011). Application of remote sensing data and/or associated data products, as shown in this study, is expected to overcome these limitations and provide more realistic hydrologic simulations.

2. Study area and data

The Upper Wabash and Cedar Creek watersheds in Indiana, USA (Fig. 1) are selected as the test beds for this study. Both watersheds are well suited for creating a SWAT model at two different scales; Upper Wabash (18,500 km^2) is suitable for the first objective because of its larger size to capture the variability in surface soil moisture from the coarse resolution satellite data, whereas field sensor-based profile/root zone soil moisture data are available for certain parts of Cedar Creek (700 km^2) to accomplish the second objective of this study. In order to evaluate the "relative" role of surface soil moisture, satellite data are also used for Cedar Creek watershed. Both watersheds have United States Geological Survey's (USGS) streamflow gauge station at the respective outlet as shown in Fig. 1. The landuse in both watersheds is mostly agricultural, although significant difference exists in the forest and developed portion. Table 1 presents a summary of their geospatial and hydro-climatic characteristics.

SWAT models for both watersheds are created in the ArcSWAT GIS interface by using the following data: (i) 30 m digital elevation model (DEM) from the USGS National Elevation Dataset (USGS-NED, 2013); (ii) 30 m land cover data for year 2006 from the National Land Cover Database (USGS-NLCD, 2013); and (iii) 1:250,000 scale State Soil Geographic Data (STATSGO) that is included within SWAT 2012 database. Total daily precipitation, average minimum and maximum daily temperature data covering the study period of 2004–2012 are obtained from the National Climatic Data Center for the stations that fall within or adjacent the watershed boundary. All other related climate variables, including solar radiation, wind speed and relative humidity, are obtained from the internal weather generator within ArcSWAT. Penman–Monteith equation is selected for computing potential evapotranspiration (PET).

For model evaluation, observed daily streamflow time series is obtained from respective USGS station located at each watershed's outlet (Fig. 1). Remotely sensed surface soil moisture data ($\sim$1 cm top soil) is extracted from the Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E). It is noteworthy that several algorithms have been so far applied to retrieve soil moisture information from AMSR–E, the most prominent of which have been developed by Jones et al. (2009), Koike et al. (2004), Njoku et al. (2003) and Owe et al. (2001). The data retrieved by the National Astronomy and Space Administration (NASA) following Njoku et al. (2003) (Aqua daily level-3 gridded land surface product-version 2 (AE_Land_3), Njoku, 2004) is used in this study. Metadata associated with this particular estimate, including data