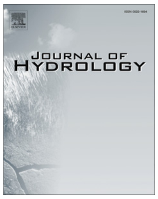
Journal of Hydrology 535 (2016) 637–651

Contents lists available at ScienceDirect

Journal of Hydrology

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



Misrepresentation and amendment of soil moisture in conceptual hydrological modelling

Lu Zhuo *, Dawei Han

WEMRC, Department of Civil Engineering, University of Bristol, Bristol, UK

ARTICLE INFO

Article history:
Received 26 October 2015
Received in revised form 14 February 2016
Accepted 17 February 2016
Available online 23 February 2016
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Renato Morbidelli, Associate Editor

Keywords:
Satellite soil moisture observations
Holding excess runoff
Soil moisture deficit (SMD)
Soil Moisture Deficit to Saturation (SMDS)
Xinanjiang (XAJ)
Soil Moisture and Ocean Salinity (SMOS)

SUMMARY

Although many conceptual models are very effective in simulating river runoff, their soil moisture schemes are generally not realistic in comparison with the reality (i.e., getting the right answers for the wrong reasons). This study reveals two significant misrepresentations in those models through a case study using the Xinanjiang model which is representative of many well-known conceptual hydrological models. The first is the setting of the upper limit of its soil moisture at the field capacity, due to the 'holding excess runoff' concept (i.e., runoff begins on repletion of its storage to the field capacity). The second is neglect of capillary rise of water movement. A new scheme is therefore proposed to overcome those two issues. The amended model is as effective as its original form in flow modelling, but represents more logically realistic soil water processes. The purpose of the study is to enable the hydrological model to get the right answers for the right reasons. Therefore, the new model structure has a better capability in potentially assimilating soil moisture observations to enhance its real-time flood forecasting accuracy. The new scheme is evaluated in the Pontiac catchment of the USA through a comparison with satellite observed soil moisture. The correlation between the XAJ and the observed soil moisture is enhanced significantly from 0.64 to 0.70. In addition, a new soil moisture term called SMDS (Soil Moisture Deficit to Saturation) is proposed to complement the conventional SMD (Soil Moisture Deficit).

1. Introduction

Overestimation and underestimation of flood peaks are common in hydrological modelling, especially in operational flood forecasting due to the errors in antecedent soil moisture estimation (Huza et al., 2014). This is usually caused by the accumulated errors in the model's soil moisture state variable which is difficult to rectify until the flood peaks are passed (by that time, it is too late for practical purposes). Therefore, it is important to assimilate the soil moisture observation data into an operational hydrological model to reduce error accumulation (Berthet et al., 2009; Brocca et al., 2012; Ottlé and Vidal-Madjar, 1994; Ridler et al., 2014; Wagner et al., 2007; Wanders et al., 2014).

Among all the operational hydrological model types, conceptual rainfall–runoff models have shown their superiority and popularity in real-time flood forecasting compared with other types of models used in an operational context (Christian, 1997; Perrin et al., 2001; Reed et al., 2004; Wood et al., 1997; Zhuo et al., 2014). This is because they are simple yet effective in modelling the most important features of the river flow (Kitanidis and Bras, 1980a,b; Zhao and Liu, 1995). However many conceptual models based on the variable soil water storage curve (to be explained later) have misrepresented soil moisture variable. This soil moisture misrepresentation can significantly reduce the model's capability in data assimilation during operational mode, because of its incompatibility with the observed soil moisture information. A number of attempts have been made by various studies to assimilate soil moisture observations in conceptual hydrological models. For example, Aubert et al. (2003) used a sequential assimilation procedure by introducing ground measured soil moisture data into a conceptual rainfall–runoff model and obtained improved flow prediction results; Brocca et al. (2010) revealed that adopting the Advanced SCATterometer (ASCAT) soil moisture index into a rainfall–runoff model could improve model's runoff prediction; contrarily Parajka et al. (2006) showed that assimilating the European remote sensing satellite (ERS) derived soil moisture data into a conceptual hydrological model would not improve the runoff model efficiency; Matgen et al. (2012) presented that coarse-resolution remotely sensed soil moisture data added little or no extra value for runoff prediction. It is clear the effect of soil moisture assimilation in flow modelling is mixed. Interestingly Matgen et al. (2012) raised an open research question in the study of

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* Corresponding author at: Water and Environmental Management Research Centre, University of Bristol, 93-95 Woodland Road, Bristol BS8 1US, UK.
E-mail address: lu.zhuo@bristol.ac.uk (L. Zhuo).

http://dx.doi.org/10.1016/j.jhydrol.2016.02.033
0022-1694/

whether the assimilation results could mainly be attributed to errors in the soil moisture estimates, or if it was mainly related to the hydrological model itself. Currently, no particular attention has been given to improve the soil moisture scheme in the conceptual hydrological models so that they can be more compatible with the observed soil moisture information. Therefore, an improved scheme is proposed in this study to rectify the weaknesses of the existing soil moisture accounting scheme in a widely used conceptual hydrological model called Xinanjiang (XAJ) (Zhao, 1980, 1992; Zhao and Liu, 1995) as a representative conceptual model. This is because there are many similar models to XAJ (such as PDM and HBV) so the result from XAJ would be of interest to a wide range of the hydrological modelling community. More detailed reasons for choosing XAJ as a representative model is presented later.

The new scheme includes two steps, which are discussed via a case study in the Pontiac catchment, through a comparative analysis with the observed soil moisture datasets. It is clear that field measurements do not easily suit operational conditions (Corradini, 2014) and soil moisture information derived from satellite earth observation data would significantly ease data acquisition (Aubert et al., 2003). There have been enormous investments by various organisations such as ESA (European Space Agency) and NASA (National Aeronautics and Space Administration), in a wide range of soil moisture observational programs (e.g., satellite missions such as ENVISAT (Environmental Satellite), SMOS (Soil Moisture and Ocean Salinity), and SMAP (Soil Moisture Active Passive). The availability of those modern satellite soil moisture data provides a great opportunity, but also poses a challenge to hydrological modellers on how to assimilate such information in hydrological models that have not been designed for them. Therefore in this study, an attempt has been made by correlating the modified XAJ soil moisture scheme through the comparison with the SMOS (Kerr et al., 2010) satellite retrieved soil moisture.

The novelty of this study is to improve the XAJ model's soil moisture accounting representation while keeping its high flow modelling accuracy. Maintaining flow modelling effectiveness is important because XAJ has been successfully and widely applied globally (see more detail in the model description section). It is expected that the amended scheme is more realistic in representing the soil moisture information, and hence improves the model's compatibility with the satellite soil moisture observations, as well as other soil moisture data types.

In this context, the overall methodology of this study is to first analyse the original concept and structure of the XAJ model, test the existing XAJ model over a selected catchment, and explore the issues in its current soil moisture scheme through a comparative analysis with the SMOS retrieved soil moisture. The XAJ model is then amended accordingly to overcome its soil moisture misrepresentations, and re-tested over the selected catchment to evaluate the modified model's flow performance, as well as its soil moisture representation (through the comparison with the SMOS retrieved soil moisture).

2. Data and methodology

2.1. Study area and datasets

The case study is carried out in the Vermilion River at the Pontiac catchment, mid-Illinois, in the United States (U.S.) (40.878°N, 88.636°W). The reason for choosing this catchment is because of its moderate vegetation coverage (the annual averaged Normalised Difference Vegetation Index retrieved from the MODIS (Moderate Resolution Imaging Spectroradiometer) satellite is around 0.4) which should give a better satellite soil moisture retrieval result than densely vegetated catchments (Al Bitar et al., 2012). Furthermore this medium-sized catchment (1500 km^2) has a similar spatial scale with the SMOS footprint, therefore there is no spatial mismatch between them. However if the satellite footprint is much smaller or larger than the catchment area, further studies are required such as using the spatial downscaling method. Pontiac is dominated mainly by hot summer continental climate (Peel et al., 2007), and is used primarily for agriculture purposes (Bartholomé and Belward, 2005; Hansen et al., 1998) with Mollisols soil type (Webb et al., 2000). The average annual rainfall depth is about 954 mm, and the average annual potential evapotranspiration demand is approximately 1670 mm. The layout of the Pontiac catchment is shown in Fig. 1 along with the location of its flow gauge, the National Aeronautics and Space Administration (NASA) Land Data Assimilation Systems 2 (NLDAS-2) grid points (a total of 20 0.125 × 0.125° NLDAS-2 grids with their central points shown in the figure) and river network.

The observed daily flow data is obtained from the U.S. Geological Survey for the period from January 2010 to December 2011. The data from the first two-thirds of the period (January 2010–April 2011) is used for the calibration of the XAJ model and the remaining one-third of the data (May 2011–December 2011) is employed for the validation purpose. The reason for using this two-year period of data is due to the limitation of the flow records in this catchment, and the selected period provides the most continuous flow dataset. The XAJ model's hydrological forcing (Peng et al., 2002) is provided by the NLDAS-2 (Mitchell et al., 2004). It includes precipitation (P) (Daly et al., 1994) and potential evapotranspiration (PET) at 0.125° spatial resolution and daily temporal resolution (converted from hourly resolution). Both PET and P datasets have been transformed into one catchment-scale dataset using the area-weighted average method to operate the lumped XAJ model. Readers are referred to Xia et al. (2012) for a full description of the NLDAS-2 data products. The SMOS level-3 soil moisture dataset (both ascending and descending orbits) used in this study is from the SMOS Barcelona Expert Centre (SMOS-BEC) (SMOS-BEC, 2014), covering the period between January 2010 and December 2011. The retrieved soil moisture dataset has been converted into a catchment-scale dataset by the same weighted average method.

2.2. SMOS soil moisture monitoring system

Compared with in-situ soil moisture measurement, satellite monitored soil moisture is more representative in a catchment-scale analysis, because of its large footprint (Fang and Lakshmi, 2014; Srivastava et al., 2013a, 2014). Among all the satellite soil moisture techniques (i.e., optical, thermal infrared and microwave bands), microwave bands (especially with longer wavelength such as L-band (21 cm)) show advantages in penetrating into deeper soil (∼5 cm) and have more capability in passing through cloud and some vegetation cover (Njoku and Kong, 1977). Therefore in this study, the microwave-banded SMOS (1.4 GHz, L-band) satellite is selected. The reason for choosing SMOS is not only because it is designed particularly for soil moisture monitoring, but also because it has a relatively long period of soil moisture data record since its launch in 2009 (Kerr et al., 2010). Furthermore, there have been a number of studies addressing the accuracy of the SMOS soil moisture in which the observations are able to provide useful information for catchment-scale research (Al Bitar et al., 2012; Djamai et al., 2015; Louvet et al., 2015; Srivastava et al., 2013a). The SMOS retrieved soil moisture observation has a spatial resolution of 35–50 km (Kerr et al., 2010, 2001) with its unit in m^3/m^3. SMOS has a global coverage at the equator crossing times of 6 am at the local solar time (LST) (ascending) and 6 pm (LST, descending) (Kerr et al., 2012). Readers are referred to Kerr et al.