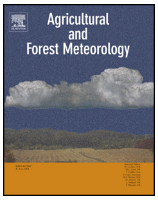
Agricultural and Forest Meteorology 217 (2016) 74–88

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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



Calibration of a distributed hydrology and land surface model using energy flux measurements

Morten A.D. Larsen[a,*], Jens C. Refsgaard[b], Karsten H. Jensen[c], Michael B. Butts[d], Simon Stisen[b], Mikkel Mollerup[e]

[a] Technical University of Denmark, Department of Management Engineering, Frederiksborgvej 399, 4000 Roskilde, Denmark
[b] Geological Survey of Denmark and Greenland, Øster Voldgade 10, 1350 Copenhagen, Denmark
[c] University of Copenhagen, Department of Geosciences and Natural Resource Management, Øster Voldgade 10, 1350 Copenhagen, Denmark
[d] DHI, Agern Alle 5, DK 2970 Hørsholm, Denmark
[e] The Danish Road Directorate, Guldalderen 12, 2640 Hedehusene, Denmark

ARTICLE INFO

Article history:
Received 21 May 2015
Received in revised form
12 November 2015
Accepted 18 November 2015
Available online 6 December 2015

Keywords:
Hydrology/land surface modelling
Calibration
Water and energy fluxes
Evapotranspiration
Energy closure imbalance

ABSTRACT

In this study we develop and test a calibration approach on a spatially distributed groundwater–surface water catchment model (MIKE SHE) coupled to a land surface model component with particular focus on the water and energy fluxes. The model is calibrated against time series of eddy flux measurements from three sites of different land surface type (agriculture, forest and meadow) and river discharge data from the 2500 km^2 Skjern River catchment in Denmark. The approach includes initial calibrations of three one-dimensional models representing the three land surface types using the flux measurements for calibration. This step provides initial values for the subsequent modelling and calibration at catchment scale. To test the validity of the approach, two additional catchment scale distributed simulations were performed with no calibration and only calibration of the one-dimensional models, respectively. In addition, a subsequent validation period was simulated. A mean energy closure imbalance of 20% was seen for the three sites. For the distributed simulations, the energy imbalance was accounted for by two energy balance closure hypotheses ascribing the error to either energy fluxes or net radiation. In general, the distributed calibration approach improved model results substantially compared to using default values (no calibration) or calibration of the one-dimensional models only. For the distributed model simulations, the assumption regarding the energy balance closure had a substantial impact on the parameter sensitivities and on the simulated discharge and energy balance. During calibration, the simulation with corrected energy fluxes showed better performance on discharge than the simulation with corrected net radiation whereas the reverse was true for the validation period. Regarding energy fluxes, the simulation with corrected net radiation was superior in both the calibration and validation period.

1. Introduction

Water and energy fluxes between land surface and atmosphere are important components of atmospheric and hydrological processes. These fluxes can be quantified by the use of land surface models (LSM) or soil–vegetation–atmosphere-transfer models (SVAT). The calculation of e.g. evapotranspiration in SVATs and LSMs is based on solving the energy and radiation equations often on a sub-daily basis and they therefore differ from the less physically stringent schemes often used in many traditional hydrological models which are based on potential evapotranspiration. LSMs, originating from atmospheric sciences, include spatially distributed, often large scale descriptions of land surface processes. Examples include the Noah model (Rosero et al., 2010) and the CLM model (Lawrence et al., 2011). LSMs are typically coupled with or forced by atmospheric models and have recently been included in fully coupled climate-hydrology models (Maxwell et al., 2011; Shrestha et al., 2014). SVATs, originating from soil and hydrological sciences, are one-dimensional descriptions typically used for small-scale descriptions linked with soil water flow models (Mauser and Schädlich, 1998; Ridler et al., 2012). When included in spatially distributed hydrological models they possess the potential for providing improved evapotranspiration descriptions and enable hydrological catchment models to better utilise remote sensing data to force and constrain hydrological models (Stisen et al., 2011a). SVATs have also recently been included in fully

---

[*] Corresponding author.
E-mail address: madla@dtu.dk (M.A.D. Larsen).

http://dx.doi.org/10.1016/j.agrformet.2015.11.012

coupled climate-hydrology models (Butts et al., 2014; Larsen et al., 2014). LSMs and SVATs linked to spatially distributed hydrological models are basically similar, and hence we shall in the following refer to both of them as SVAT models.

Assessment of parameter values is critical for the use of SVAT models and an essential challenge is related the vast number of parameters often seen in this type of models. Franks et al. (1997, 1999), Beven and Franks (1999) and Gupta et al. (1999) all highlight the high uncertainty in the predictive capabilities of multi-parameter SVATs due to equifinality. Yet; Franks et al. (1997, 1999) still show good results in terms of reproducing point site flux measurements from the FIFE area in Kansas, USA, and in the Amazon area in Brazil. The added value of a multi-criteria approach as opposed to a single criterion method is confirmed by Gupta et al. (1999) and Demarty et al. (2004). Pollacco et al. (2013) apply an objective function weighting algorithm based on the uncertainties related to remote sensing based surface soil moisture and evapotranspiration calibration variables. Currently no explicit guidelines have been developed on calibrating complex and distributed SVAT and hydrology models.

Parameter estimation for hydrological models is traditionally performed by use of calibration where parameter values are modified to obtain best possible fit between model simulations and observed target data. While calibration was previously often performed manually by a trial-and-error approach, parameter optimisation by inverse modelling is now the method of choice (Gupta et al., 1998; Madsen, 2003; Moore and Doherty, 2005). An example is the study by Sun et al. (2013) where inverse calibration based on Monte Carlo–Bayesian techniques was used for calibrating a model both against energy fluxes at point scale and runoff at catchment scale (4.9 km^2). In Ingwersen et al. (2011) inverse calibration was used to simulate the water and energy budget for a winter wheat stand at plot scale. Similarly Ridler et al. (2012) utilized inverse techniques for calibrating the combined MIKE SHE/SWET model to simulate energy fluxes at point scale in Mali.

A particular problem related to calibration of SVAT models is that observations of water and energy fluxes are usually not available from operational monitoring networks but only from a few research stations and often for short periods (Wilson et al., 2002; Franssen et al., 2010; Leuning et al., 2012). In addition, energy flux data are known to often have problems with energy balance closure which severely hampers parameter optimisation by inverse modelling, as a SVAT model per definition assumes a closed energy balance (Twine et al., 2000; Choi et al., 2009) and a failure to meet this demand can result in significant biases in long term climate model simulations (Grimmond et al., 2010). Also, the lack of measured energy balance closure will yield an erroneous parameterization when the fluxes are used for the calibration of a hydrological model. Therefore certain assumptions need to be made to account for the lack of closure. To accommodate this, Beven (2006) suggested creating artificial hypotheses to provide closure.

Catchment water balances are linked to energy balances, because the latent energy/evapotranspiration appears as a key element in both balances. The observed catchment runoff and the catchment water balance assessed by hydrological models hence include important information also on the energy balance. On a catchment scale (603 km^2) Barr et al. (2012) used distributed flux tower measurements of evapotranspiration against measured precipitation and discharge for a residual analysis on water balance closure concluding a 15% lack of energy flux closure compared to the measured net energy. For catchment scale (205 km^2) model calibration, Li et al. (2011) used the CLM4 model, modified to include a runoff scheme, to evaluate both runoff and energy fluxes. Similarly, operating on a regional to continental scale Maurer et al. (2002) simulated energy flux components while the model was manually calibrated only against runoff.

The objectives of the present study is to develop and test a methodology for calibrating and assessing parameters of a SVAT model linked to a spatially distributed hydrological model by using observations of both energy fluxes and catchment runoff. A comprehensive literature study was carried out to obtain feasible initial values and range of variation for parameters for the considered land surface types. The impact of energy imbalance is of particular emphasis and we analyse to which extent inclusion of discharge observations in the calibration process will improve the model performance and robustness.

2. Methodology

2.1. Study area and data

The Skjern catchment (2500 km^2) is located in the western part of the Jutland peninsula, Fig. 1. The catchment is dominated by sandy soils generated by glacial outwash plains from the last glacial period Weichsel and intersected by older till deposits from the previous glacial period Saalian (Greve et al., 2007). The topography reaches 130 m above sea level in the eastern part of the catchment and the Skjern River flows into Ringkøbing fjord at sea level to the west. The yearly average precipitation for the catchment is 940 mm for the period 2000–2009 based on direct measurements. When corrected for undercatch using standard monthly correction factors (Allerup et al., 1998) the average precipitation amounts to 1130 mm. In the same period the mean annual temperature is 9.3 °C and the mean monthly temperatures range between 2.1 and 17.3 °C. Inside the catchment flux towers are placed at the three predominant surface types; agriculture (61%), meadow/grass (24%) and forest (13%), Fig. 1. At all sites measurements of short-, long-wave and net radiation components; latent (LE), sensible (H) and soil heat fluxes (G); soil water content; precipitation; air temperature; wind speed; and water table levels have been carried out since late 2008. Measurements of radiation and energy fluxes are based on standard methods. Radiation components are measured using a NR01 Hukseflux radiometer (www.hukseflux.com), LI-COR eddy covariance equipment is used for measuring LE fluxes, Gill sonic anemometers for measuring H fluxes, and Hukseflux plates for measuring G fluxes.

The energy flux data used in the study have undergone quality control as part of the processing (Ringgaard, 2012) (Step 1.3, Fig. 2). Inaccurate observations caused by e.g. low turbulence conditions were replaced by data representing similar conditions. Replacement of data was thus for periods with low energy fluxes and therefore this source of uncertainty is expected to be of minor significance. Individual data points clearly outside the expected range at the time of day and season were considered as outliers and removed (equal to 0.2% on average between LE, H and the three stations weighted relative the areal share). For two periods July 21-August 16 and August 24–October 28, 2009, no flux measurements were available from the agricultural site and data were replaced from the forest site. As these periods are mostly placed in the spin-up period (see below) the calibration results are not expected to be significantly affected.

2.2. Modelling system and setup

This study uses the spatially distributed MIKE SHE hydrological modelling system capable of including all key hydrological processes such as ET, channel flow, overland flow, unsaturated flow, saturated flow as well as irrigation and drainage (Graham and Butts, 2005). The land surface model SWET component (Overgaard, 2005) is used in the analysis. SWET is based on the Shuttleworth–Wallace model (Shuttleworth and Wallace, 1985). It considers vegetation