Environmental Modelling & Software 94 (2017) 140–156

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

Bridging rigorous assessment of water availability from field to catchment scale with a parsimonious agro-hydrological model

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ARTICLE INFO

Article history:
Received 30 March 2016
Received in revised form
23 September 2016
Accepted 17 February 2017

Keywords:
AquaCrop-Hydro
Crop water productivity
Semi-distributed model
Conceptual model
Upscaling

ABSTRACT

While simple crop and hydrological models are limited with respect to the number and accuracy of the processes they incorporate, complex models have high demand for data. Due to the limitations of both categories of models, there is a need for new agro-hydrological models that simulate both crop productivity and water availability in agricultural catchments, with low data and calibration requirements. This study aimed at developing a widely applicable parsimonious agro-hydrological model, AquaCrop-Hydro, which couples the AquaCrop crop water productivity model with a conceptual hydrological model. AquaCrop-Hydro, simulating crop productivity, the daily soil water balance and discharge at the catchment outlet, performed well for an agricultural catchment in Belgium. The model can be used to investigate the effect of agricultural management and environmental changes from field to catchment scale in support of sustainable water management in agricultural areas.

1. Introduction

Crop simulation models integrate various processes in the soil-crop-atmosphere continuum that determine crop growth and production. Hence, they are useful tools to investigate management strategies to optimize crop productivity and resource use efficiency. Such investigations usually focus on one individual field because of the point-based nature of crop models. However, optimization of the use of resources, particularly water, is not a local issue. A management strategy that optimizes crop water productivity in one farmer's field, may only be successful if it does not negatively affect neighbouring farmers. On an even larger scale, agricultural water management affects a whole catchment where different stakeholders, including households, industry and ecosystems, with different goals are making use of the available water resources (Bergez et al., 2012). It is clear that management strategies that are optimized for crop water productivity by a crop model, may fail to result in sustainable water use because catchment processes are disregarded.

Hydrological models, by contrast, simulate hydrological processes in a catchment and simulate crop transpiration as a part of the catchment soil water balance. However, as these models primarily focus on the simulation of hydrological processes, they rarely consider crop growth and management practices affecting crop transpiration and production explicitly. The hydrological models that do include physically based equations to estimate crop transpiration, such as the (semi)-distributed SWAT (Arnold et al., 1998; Douglas-Mankin et al., 2010), MIKE SHE (Refsgaard and Storm, 1995) and APEX (Gassman et al., 2010) models, show relatively high computational complexity. Moreover, they require a vast amount of data and elaborate calibration, or make use of parameters that are difficult to measure in the field. Despite the trend to apply remote sensing data as input or calibration data for agro-hydrological models (Boegh et al., 2004; Moulin et al., 1998), data availability remains a widespread issue (Grayson et al., 2002). Consequently, the application of such data-demanding models renders time- and resource-consuming, or even unfeasible in data-scarce regions.

These limitations of existing crop and hydrological models urge for another approach. A coupling between both types of models, combining their advantages and functionality, can be a solution to obtain agro-hydrological models that (i) simulate crop production and water productivity at field scale, as well as upscale their effects on hydrological processes and water availability at catchment scale, (ii) consider the effect of management and environmental changes on crop transpiration, crop (water) productivity and catchment

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http://dx.doi.org/10.1016/j.envsoft.2017.02.014
1364-8152/

hydrological processes, (iii) are parsimonious, i.e. require a feasible amount of easily obtainable input data and parameters to be calibrated, without compromising much the accuracy of the model results, and (iv) are widely applicable to various agricultural catchments with different environmental and agronomic conditions.

Previous attempts have been made to couple crop and hydrological models to capitalize the strengths of both and enable accurate investigation of agricultural management and environmental changes within a catchment. The WOFOST crop model (Boogaard et al., 2014) has been coupled to MetaSWAP (van Walsum and Supit, 2012) and to the distributed WEP-L model (Jia, 2011) for climate change impact assessment. Also, the DAISY crop model (Abrahamsen and Hansen, 2000) has been combined with MIKE SHE for investigation of nitrogen fluxes in agricultural catchments (Styczen and Storm, 1993; Thorsen et al., 2001). DSSAT crop models (Jones et al., 2003) have been linked to hydrological models to optimize irrigation management and drainage design (McNider et al., 2014; Singh and Helmers, 2008). Also extensive modeling systems, which integrate all aspects, dimensions, scales and actors involved in agricultural management, link crop and hydrological models (Jakeman and Letcher, 2003; Letcher et al., 2006).

However, most of these model combinations fail to fit all four above mentioned criteria. Being based on the distributed physically based model MIKE SHE, high data requirements remain an issue for the DAISY-MIKE SHE model (Boegh et al., 2004; Thorsen et al., 2001). The same is true for agro-hydrological models based on the data-demanding DSSAT crop models (Jones et al., 2003) and the fully integrative modelling systems (Jakeman and Letcher, 2003). Moreover, when developed for a specific application, the existing model combinations are only applicable for a certain region or crop (McNider et al., 2014). Also, problems to accurately represent spatial heterogeneity within the catchment due to the fixed model structure or grid size of the sub-models should be mentioned (Bithell and Brasington, 2009; Thorsen et al., 2001).

Therefore, the aim of this study was to develop a parsimonious, physically sound and widely applicable agro-hydrological model, AquaCrop-Hydro, to simulate crop productivity and water availability in agricultural catchments without vast data requirements for model input and calibration. The new model was developed by extending the AquaCrop crop water productivity model (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009; Vanuytrecht et al., 2014a) with a lumped conceptual hydrological model to simulate catchment hydrology. The performance of AquaCrop-Hydro to simulate crop production as well as discharge at the catchment outlet was evaluated for an agricultural catchment in Belgium.

2. Methodology

2.1. The AquaCrop-Hydro model

Fig. 1 depicts the AquaCrop-Hydro model flowchart. AquaCrop-Hydro is the combination of a crop model operating at field scale and a hydrological model working at catchment scale. The two models are integrated through an off-line, one-directional link, in which the crop model output is used as input for the hydrological model component. Model simulations are conducted on a daily time step.

AquaCrop-Hydro applies a semi-distributed approach, as it requires the catchment area to be divided into homogenous land units (LUs) with similar land use, soil and agro-climatological characteristics. A model user can describe an LU as small as an individual field if detailed field observations are available, but it can be larger when its characteristics originate from basic information from literature, maps, agricultural statistics or farmer knowledge. For each LU, crop production and the soil water balance are simulated using AquaCrop (FAO, 2015), a parsimonious process-based crop water productivity model. Next, the soil water balance at catchment scale is derived from simulated soil water balance components of all individual LUs. Subsequently, river discharge at the catchment outlet is simulated by means of a lumped conceptual hydrological model, derived from a top-down model structure identification protocol (VHM approach) by Willems (2014). The total flow volume at the catchment outlet is considered a good indication of catchment water availability. The different simulation steps are further elaborated in the following paragraphs.

2.1.1. AquaCrop simulation of soil water balance and crop production at field scale

AquaCrop simulates daily crop canopy cover development, transpiration, dry aboveground biomass production, yield and the soil water balance, based on user-specified inputs of weather, crop characteristics, soil and groundwater properties as well as management practices of the cultivated field (Fig. 1). While the field scale soil water balance is calculated for each day of the simulation period, crop development and production simulations are confined to the crop growing period. A simulation period can span several years and included several crop growing or fallow periods. These growing- and off-season periods are linked as specified by the user in an AquaCrop project file.

Since AquaCrop is a water-driven model, crop biomass and yield production are simulated proportional to the amount of water transpired by the crop. Transpiration, in its turn, depends on the simulated crop canopy cover and weather conditions. The simulated amount of crop yield per unit evapotranspiration is defined as the crop water productivity. During this simulation procedure the model accounts for the effect of water stress, air temperature, atmospheric CO_2 concentration, and soil salinity on root zone expansion, canopy development and crop production (Raes et al., 2009; Vanuytrecht et al., 2011). Also management practices such as crop choice (Van Gaelen et al., 2013; Vanuytrecht et al., 2016), sowing dates (Abrha et al., 2012; Mhizha et al., 2014; Tsegay et al., 2015), soil fertility management (Shrestha et al., 2013; Van Gaelen et al., 2015), weed management (Van Gaelen et al., 2016), field surface management including mulches and water harvesting (Biazin and Stroosnijder, 2012; Bird et al., 2016), as well as irrigation management (Garcia-Vila et al., 2009; Geerts et al., 2010) are considered by the AquaCrop simulation procedure.

Crop growth and production are adjusted to water stress on the basis of the simulated soil water content in the root zone. Therefore, AquaCrop calculates the daily soil water balance considering incoming (rainfall, irrigation, capillary rise) and outgoing (surface runoff, deep percolation, evaporation, crop transpiration) water fluxes. While rainfall and irrigation are user-specified inputs, other components of the soil water balance are simulated on the basis of the simulated crop development as well as input of climate and soil characteristics (total available water (TAW) and saturated hydraulic conductivity) for up to 5 soil horizons.

Transpiration (Tr, Eq. (1)) and evaporation (E, Eq. (2)) are simulated as separate components of the soil water balance. However, both are proportional to the evaporative power of the atmosphere (reference evapotranspiration ET_0) and simulated crop canopy cover via the crop transpiration (Kc_{Tr}) and evaporation (Ke) coefficients respectively (Eqs. (1) and (2)). In addition, transpiration and evaporation are adjusted to the soil water content and corresponding water stress (expressed with soil water stress (Ks) or evaporation reduction (Kr) coefficient). Transpiration, for example, will decrease if the water content falls below a crop-specific