Bulgarian Journal of Agricultural Science, 24 (No 3) 2018, 380–390
Agricultural Academy

COUPLING HYDROLOGICAL AND CROP MODELS FOR IMPROVED AGRICULTURAL WATER MANAGEMENT – A REVIEW

EDWIN K. KANDA[1*]; TAFADZWANASHE MABHAUDHI[2]; AIDAN SENZANJE[1]
[1]*University of KwaZulu-Natal, School of Engineering, P. Bag X01, Scottsville, 3209, South Africa*
[2]*University of KwaZulu-Natal, School of Agricultural, Earth and Environmental Sciences, P. Bag X01, Scottsville, 3209, Pietermaritzburg, South Africa*

Abstract

Kanda, E.K., T. Mabhaudhi and A. Senzanje, 2018. Coupling hydrological and crop models for improved agricultural water management – A review. *Bulg. J. Agric. Sci.*, 24 (3): 380–390

Understanding the relationships among plant, soil, and water is important in agricultural water management practices. Simulation of the soil water balance is central to improving crop water productivity. Individual crop or hydrological models have shortcomings due to the simplification of the surface or subsurface processes. Coupling of crop and hydrological models helps in understanding the complex processes involved in crop production. This review highlights the application of coupled crop and hydrological models in simulation of crop response to water availability. The hydrological models considered are CHAIN-2D, HYDRUS-1D, HYDRUS 2D/3D, and MODFLOW. The crop growth models considered are the water-driven model (AquaCrop), solar-radiation driven model (EPIC), and the carbon-driven models (WOFOST and DSSAT). HYDRUS-2D is the successor to CHAIN-2D. MODFLOW is a popular model especially in simulating groundwater flow while HYDRUS is satisfactory in the simulation of water dynamics in the vadose zone. From the review, it can be deduced that HYDRUS-1D has been coupled with all the crop models considered except DSSAT. EPIC – CHAIN-2D and MODFLOW-DSSAT were the other applications. Further research needs to consider linking 2D soil water models with any of the crop growth models for a better representation of the soil water dynamics and therefore accurate simulation of the soil water balance.

Key words: crop growth; irrigation management; soil water dynamics; soil water model

Introduction

The demand for the limited freshwater resources is on the increase due to population growth which has elevated the domestic and agricultural water use, urbanization and industrialization. Irrigation is important in ensuring expanded crop production in marginal (arid and semi-arid) areas. Because of climate change, traditionally arable lands are susceptible to droughts which cause a reduction in yields or even crop failure and therefore, irrigation is necessary to stabilize yields. The understanding of the interactions among the plant, soil and water is important in making decisions regarding agricultural water management.

Yield and biomass production are complex processes which rely significantly on the interaction between the soil and crop and are influenced by human activities (Vereecken et al., 2016). The improvement of crop water productivity requires reduction in non-beneficial components such as runoff, soil evaporation and percolation. Therefore, the focus is the surface and subsurface interaction and more specifically the soil water balance. Irrigation scheduling requires the analysis of the soil water balance to ensure that appropriate amount of water is applied to the crop. Simulation of the soil water balance needs the accurate representation of the infiltration process, runoff, drainage, root water uptake and evapotranspiration (Ritchie, 1998). Soil water balance

*Corresponding author: kandaedwin@gmail.com

models utilize either simple bucket approach where the only input data required include rainfall/irrigation, evapotranspiration and soil properties or those which describe soil water dynamics in a complex and rigorous way including the interactions of the various components of the system (Zhang et al., 2002). In crop models, the soil water balance serves to estimate the soil water content (driver for nutrient mineralization) and the water stress indices which drives the functioning of the plant (Brisson et al., 2006)

Most hydrological models that are used in agriculture focus primarily on the soil physical processes and simplify the process of transpiration, root water uptake and crop growth while crop models, on the other hand, include detailed carbon assimilation and crop development processes but are inadequate in describing the root zone processes (Vereecken et al., 2016).

Complex crop and hydrological models require detailed or many input parameters which may not be available or are expensive to acquire. They also have complicated procedures which require the users to have sufficient knowledge and skills in modelling. On the other hand, simple and user-friendly models have limitations due to simplification of processes. Therefore, no single model can simulate satisfactorily all the outputs required for decision making in agricultural water management. Hence, it is important to integrate two or more models in such a way as to maximize and minimize on their individual strengths and weaknesses respectively.

The main reason for coupling crop and hydrological models is to help in the understanding of the complex processes which cannot be represented by a single model due to their spatial and temporal dynamics. Most crop models are point scale models and therefore do not consider spatial heterogeneity. Being point-scale models, simulation of water distribution in one dimensional (vertical) as it is done by most models do not represent the actual field scenario which comprises heterogeneous soils and slopes among other aspects. Further, for the simulation of crop response to various water regimes on a regional or catchment scale to be achieved, crop models need to be coupled with distributed hydrological models. Simple models consider only some processes of the hydrological cycle and thus simplify others depending on the intended purpose of the model. Thus, two or more simple models are linked to provide a relatively accurate representation of the processes considered in the system than when individual models are used.

There are several crop growth and hydrological models available in the literature. It is therefore difficult to exhaustively review all the models. The crop and hydrological models considered are those which have been linked together in the available literature. Further, this review focuses on a few hydrological models which have been used to simulate subsurface flow processes. The crop models considered represent each of the radiation-driven, carbon-driven and water-driven approaches. The articles reviewed were sourced from Google Scholar with the key phrases such as "crop model", "hydrological model", "soil water model", "hydrological and crop models coupling" and "crop models/hydrological models linking/combination". It is hoped that this review would help in understanding the opportunities available in coupling crop and hydrological models to better represent the complex processes in the cropping system and subsequently facilitate decision making regarding water management practices in the agricultural sector.

The rest of this review paper covers the brief description of the hydrological and crop models, coupling mechanism, applications of the linked models in evaluating a variety of farm management practices like irrigation, uncertainty analysis in coupled models and finally, conclusions and future research.

Brief Description of the Models

Hydrological models

There are several criteria for classifying hydrological models. Jajarmizadeh et al. (2012), described the basis for hydrological categorization as; (1) simulation approach where models can be said to be physically-based, conceptual, empirical and stochastic, (2) spatial representation (lumped or distributed), (3) temporal representation e.g. steady-state models; and (4) the method of solving the equations governing the processes to be modelled e.g. analytical, numerical or hybrid models.

Classification by Devi et al. (2015) placed hydrological models into three categories namely; physically based (mechanistic), conceptual and empirical. Mechanistic models are white box models. They are complex models which require numerous input data. The soil water movement is solved by numerical techniques. In conceptual models, the processes are represented by interconnected reservoirs. The processes are represented by semi-empirical equations. These types of models require large amount of data for calibration. Empirical models are derived from observed or measured data. Regression and Artificial Neural Networks fall under empirical models.

Finally, for hydrological models in the subsurface zone, Ranatunga et al. (2008), categorized soil water models as either simple or complex model based on the representation of the soil profile and how the water dynamics is solved. Simple models use a fixed number of soil layers and solve the water movement using the tipping bucket approach. Complex models, on the other hand, use a continuous soil profile and the water movement is represented by solving the equations based on Darcy's law and the Richards' equation. The water movement in complex models can be in one or two dimensional.

Most hydrological models use numerical methods such as finite element and finite difference due to the non-linearity of the equations governing the soil water flow.

HYDRUS – 1D and 2D/3D models

HYDRUS model simulates the water movement and solute transport in a variably saturated porous media in one dimensional (HYDRUS-1D) and two/three dimensional (HYDRUS – 2D/3D) while taking into account the root water uptake (Šimůnek et al., 2005; Šimůnek et al., 2006). HYDRUS -1D can simulate in vertical, horizontal and inclined directions while HYDRUS – 2D/3D simulates in 2D vertical or horizontal planes, in axis-symmetrical 3D domains, or in fully 3D domains. The model has been used in the simulation of processes such as precipitation, irrigation, crop water uptake, capillary rise and deep percolation (Šimunek et al., 2012). The applications of HYDRUS-1D and 2D/3D were recently reviewed by Šimůnek et al. (2016) which included agricultural practices such as drip irrigation, furrow irrigation, groundwater recharge, salinization and transport of solutes among others.

The 1D and 2D forms of Richard's Equation is given by Equation 1 and 2 respectively (Šimůnek et al., 2005; Šimůnek et al., 2006).

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] - S \qquad [1]$$

where θ = volumetric water content [L^3L^{-3}], h = soil water pressure head [L]; K = unsaturated hydraulic conductivity [LT^{-1}]; S = general sink/source term [$L^3L^{-3}T^{-1}$] which accounts for uptake of water by the roots; t = time [T]; z = vertical space coordinate [L].

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] - S \qquad [2]$$

where, θ, K, h, and t are as described in Equation 1 while x, is the horizontal space coordinate [L].

The model uses the Galerkin finite-element method to solve the two equations presented above.

CHAIN_2D

CHAIN – 2D is a numerical model used to simulate the movement of water and solutes in two-dimensional (Šimůnek et al., 1994). It is the predecessor to HYDRUS – 2D. Like HYDRUS model, CHAIN – 2D uses Galerkin finite-element method to solve the equation governing the water flow. The model has been applied to simulate the effect of crop rooting pattern on water uptake and nitrate leaching (Benjamin et al., 1996), comparison of nutrient leaching under sprinkler, furrow and drip irrigation (Wang et al., 1997) and nitrate leaching to tile drains in flood-irrigated field (Mohanty et al., 1998). It has also been used to simulate leaching of tracer chemicals such as bromide and atrazine in corn fields under furrow and sprinkler irrigation systems (Butters et al., 2000). From the studies above, it is evident that CHAIN-2D found favour in the simulation of solute transport. There are no applications past the year 2000 possibly due to the development of HYDRUS-2D.

MODFLOW

MODFLOW is a three-dimensional numerical model that simulates ground-water flow through a porous media by solving Equation 3 using a finite-difference method (Harbaugh et al., 2000).

$$S_s\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial z}\right] + \frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial z}\right] + \frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right] + W \qquad [3]$$

where K_{xx}, K_{yy}, and K_{zz} = hydraulic conductivity along the x, y, and z coordinate axes, (LT^{-1}); h = the potentiometric head (L); W = volumetric flux per unit volume representing sources and/or sinks of water, (T^{-1}); S_S = specific storage of the porous material (L^{-1}); and t = time (T)

The model was initially developed as a groundwater model but it has been modified and expanded to improve its capabilities to simulate groundwater-surface water interactions, solute transport, vadose zone flow and optimization of groundwater management decisions (Barlow and Harbaugh, 2006). The model has been used widely including among others the design of drainage systems (Mirlas, 2009), analysing the contribution of artificial recharge in irrigated fields (Mirlas et al., 2015) and simulating the interaction between rivers and groundwater (Brunner et al., 2010). Although it has been used widely, the evapotranspiration-recharge package (water budget approach) makes MODFLOW underestimate the influence of vadose zone flow on groundwater (Twarakavi et al., 2008).

Crop models

There are several classification criteria for crop models. Motha (2011) generalized crop models into empirical and mechanistic. Empirical models are equations (mostly regression) representing crop response to water and field management factors such as fertilizer application. Mechanistic models, on the other hand, incorporate the physiological processes of crops as they interact with environmental factors.

Based on the crop growth engines, crop models can be classified as carbon-driven, solar radiation-driven and water-driven models (Todorovic et al., 2009). The three approaches are illustrated in Figure 1 (Stuckens, 2010).

Carbon-driven models as those that base crop growth on the assimilation of carbon during the photosynthesis process. In this modelling approach, the growth processes and phenology development are controlled by temperature, radiation, and carbon dioxide concentration (Todorovic et al., 2009). Examples of carbon-driven models include the crop models belonging to Wageningen group such as World Food Studies (WOFOST) among others and Crop Growth (CROPGRO) model which is incorporated in the Decision Support System for Agrotechnology Transfer (DSSAT). This category of models have a hierarchical structure in which the model is organized into levels where the higher-level responses is an aggregate combination of lower-level processes and thus, the model structure could be said to be dynamic, hierarchical, state-variable based, explanatory and deterministic (Bouman et al., 1996). Due to their hierarchical nature, carbon-driven models have a very sophisticated structure and therefore require detailed and substantially large input parameters for proper calibration which thus limits their use in the simulation of crop growth processes (Todorovic et al., 2009).

In Radiation – driven models, biomass is proportional to the Radiation Use Efficiency (RUE) which is a term representing the interception of direct solar radiation by the crop (Todorovic et al., 2009). Examples include Crop Environment Resource Synthesis (CERES), Erosion Productivity Impact Calculator (EPIC), Simulator Multidisciplinary for Crop Standard (STICS), and Agricultural Production Systems simulator (APSIM). Unlike the carbon-driven models, radiation-driven models avoid the sub-divisions into hierarchical levels and the explanation of lower hierarchical processes which thus, results in less complex structure (Todorovic et al., 2009). However, radiation-driven models have disadvantages in that there are inconsistencies and variations in approximations of RUE in intra-crop and inter-crop species and crop groups, an unpredictable relationship of RUE between localities and seasons and unreliability in normalization of RUE for climatic conditions (Steduto and Albrizio, 2005). The demerits hamper the sturdiness and predictive ability of radiation-driven models (Albrizio and Steduto, 2005).

In water-driven models, biomass is directly proportional to the rate at which the crop transpires the water through the conservative water productivity (WP) parameter (Todorovic et al., 2009). Examples of models in this category include CropSyst (Cropping System simulation) and AquaCrop model. CropSyst uses both water-driven and radiation-driven modelling approaches (Stöckle et al., 2003). However, according to Bauböck (2014), in CropSyst, the biomass – transpiration relationship becomes unstable under low vapour pressure deficit and as a result, the radiation-driven modelling approach is the main growth engine. Therefore, AquaCrop is the only water driven model currently available in the literature. The advantage of water-driven models over the radiation-driven models is that they allow for the normalization of WP parameter to account for climatic conditions and thus, the model becomes robust with higher extrapolative capability on condition that the normalization is done through the reference evapotranspiration rate instead

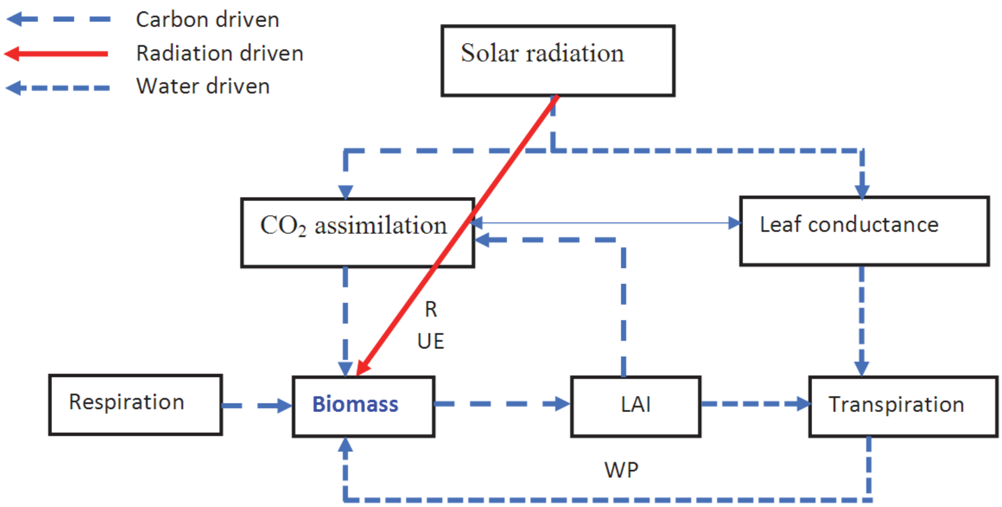

Fig. 1. Simulation of biomass production in crop models

of vapour pressure deficit which is mostly used in radiation-driven models (Steduto and Albrizio, 2005). The conservative nature of WP parameter allows water-driven models to be extrapolated for different locations and also future climate when the CO_2 concentration is expected to increase (Steduto et al., 2007).

AquaCrop Model

AquaCrop was developed by the Food and Agricultural Organization (FAO), as a water driven model, to address the complexity problems associated with the previous models and therefore present user-friendly model which require fewer input data and at the same time the model is robust, simple and accurate enough as it gives emphasis to the important physiological processes and agronomic practices in crop production (Steduto et al., 2009). It is aimed at the relevant users such as agricultural officers, water resource and irrigation officers, agricultural economists and other policy experts who require simple and reliable models for decision making (Hsiao et al., 2009). AquaCrop simulates the potential yields of major crops such as forage, vegetable, grain, fruit, oil, root and tubers with respect to varying water regimes which can be from rainfall and irrigation (Steduto et al., 2009).

In AquaCrop, canopy development is described as canopy cover (CC) instead of the leaf area index (LAI) like other crop models and therefore the model is simple and takes into account the variation in plant density and incomplete CC in water stress conditions (Evett and Tolk, 2009). Other notable features include the partitioning of the evapotranspiration (ET) into crop transpiration (Tr) and soil evaporation (E), developing a simpler model for canopy growth and senescence, treating the final yield (Y) as a product of final biomass (B) and harvest index (HI), and, dividing the effects of water stress into canopy growth, canopy senescence, Tr, and HI (Steduto et al., 2009). AquaCrop uses empirical soil drainage ability function in calculating the soil water movement (Ahuja et al., 2014) which is a modified tipping bucket approach.

AquaCrop has been applied in simulating crop response to water stress of various crops such as Teff, barely, cotton, maize, canola, tomatoes, potatoes among others (Farahani et al., 2009; Heng et al., 2009; Araya et al., 2010a; Araya et al., 2010b; Zeleke et al., 2011; Tsegay et al., 2012; Katerji et al., 2013; Montoya et al., 2016). In these studies, the model was found to be satisfactory in simulating the yields and biomass in optimal water conditions but tend to be unsatisfactory especially in severe water stress conditions.

The model has also been applied in irrigation management strategies aimed at improving the water productivity and water use efficiency of crops. These include deficit irrigation (Shrestha et al., 2013; Linker et al., 2016) and field management practices such as weed control, soil fertility and mulching (Tsegay et al., 2012; Van Gaelen et al., 2014; Van Gaelen et al., 2015; Van Gaelen et al., 2016). Although the model is good in simulating crop growth, especially, in optimal water conditions, Al-kaisy et al. (2011) in a comparative study between AquaCrop and HYDRUS-1D found that AquaCrop was ineffective in simulating the soil water dynamics especially at lower depths (more than 10 cm).

WOFOST Model

WOFOST model was developed by the Centre for World Food Studies in Wageningen in the Netherlands, as a tool for simulating crop response to a variety of climatic and soil conditions (Diepen et al., 1989). The model is complex and requires many input parameters which limit their wider applicability especially in data-scarce conditions (Diepen et al., 1989; Todorovic et al., 2009).

WOFOST simulates crop growth and yields based on three approaches (i) optimal water and fertility conditions, (ii) optimal fertility but limited water conditions, and (iii) limited fertility conditions (Diepen et al., 1989).

The model was applied in the prediction of wheat yields at a national level for twelve countries in Europe with satisfactory results (Supit, 1997). In comparing a group of models including STICS and CropSyt Rötter et al. (2012), found that WOFOST slightly over-estimated the grain yield of spring barley in central and northern Europe but it estimated relatively well the crop phenology.

The soil water balance in WOFOST uses the tipping bucket approach with three sections namely the variable rooting depth, rooting depth up to the water table and water table to a depth of 10 m (van Ittersum et al., 2003). Eitzinger et al. (2004) found that WOFOST overestimated the soil water content of winter wheat and barley and this was attributed to the fact that the model assumes homogeneous soil layer and therefore the multiple layer approach which accounts for soil heterogeneity and sophisticated methods for root water uptake needed to be considered.

EPIC Model

EPIC is a radiation-driven model developed to simulate crop growth and other processes involved in the plant environment such as drainage, irrigation, fertilizers, soil erosion, tillage, among others (Williams, 1990). EPIC model with its sub-routines such as weather, crop-growth, management, soil, economic, among others can be used in comparing several management strategies at field scale or larger scale (Rinaldi, 2001). The model uses the tipping bucket approach in the simulation of soil water balance (Connolly, 1998).

Kiniry et al. (1995), developed the model parameters for crops and forages such as barley, wheat, canola and wheatgrass grown in Canada and USA. Bryant et al. (1992) used satisfactorily EPIC model to simulate the effect of water stress on yields of maize. Cabelguenne et al. (1999) found that EPIc either over-estimated or under-estimated yields of maize, sorghum, soybean, sunflower and wheat, especially during severe water stress conditions. Similarly, Steduto et al. (1995) found EPIC to overestimate yield and dry matter during water stress conditions. However, under optimal rain-fed conditions, the EPIC model simulated satisfactorily the yield and water content of wheat, maize and alfalfa in China plains (Wang and Li, 2010).

DSSAT Cropping Model

The DSSAT is an integrated computer software suite with independent models for simulating crop and soil systems, where some are radiation driven and others are carbon-driven (Jones et al., 1998). The independent programs in DSSAT enable the simulation of cropping practices for both short and long periods of time and thus, enables the assessment and prediction of the uncertainties associated with crop and farm management practices (Jones et al., 2003). DSSAT underwent some revisions predominantly in the consolidation of its cropping model, largely inspired by the modular structure of APSIM model, which led to the revision of the CROPGRO model (Jones et al., 2001) and the introduction of modular DSSAT Cropping System Model (DSSAT-CSM) (Jones et al., 2003). The soil water balance in DSSAT is based on the tipping bucket approach.

Hydrological – Crop Model Linking Mechanism

The integration of hydrological and crop models requires the precise simulation of soil water movement. Therefore, the point of linkage of the two models would be the soil water module or subroutine. Models can be linked or coupled in three main ways; 1) light coupling, 2) external linking using a central coupler, and 3) full coupling (Vereecken et al., 2016).

In light coupling, the two independent models are linked in such a way that the output of the first model is the input of the other one and that the coupling strategy uses the existing modelling concepts without developing new ones (Barthel, 2006). The advantage of this coupling method is that the models are executed independently and only require the same input/output format for the shared data (Vereecken et al., 2016). This coupling approach is sometimes referred to as loose coupling. Antle et al. (2001), described loose coupling as a construction of a modelling system where the state variables in one model are used to drive the other model and therefore the executions are done sequentially. The disadvantage of this coupling method is the linking of sub-routines rather than their integration and therefore does not capture the interactions and feedbacks which exist in the real-world (Rotmans and van Asselt, 2001).

The second approach is where the independent models are connected via a central coupler and therefore the two models must include a software where it allows communication with the central coupler and hence, it necessitates slight changes in the codes of the two models (Vereecken et al., 2016). Antle et al. (2001), referred to this type as close coupling where the models share some common sub-processes in the system and thus, the temporal and spatial representation of the model may be dictated by the individual models.

In full coupling, the processes in the two models and the boundary conditions are solved simultaneously (Furman, 2008). Antle et al. (2001), refers to this coupling as integration where the model would have a single set of drivers and variables for all the processes in the system and therefore, the coupled model operates in temporal and spatial scale independent of constraints imposed by the individual models.

Coupled Model Applications

In a study by Mckinnie (2003), HYDRUS-2D and DSSAT were used to simulate water flow and nutrient leaching in potato farms. HYDRUS -2D was used to simulate nitrate-nitrogen transport in the soil. The soil water balance module in DSSAT was unchanged but changes were introduced in the crop growth module to reduce the volume of soil water available to plants. From this study, it was apparent that DSSAT did not sufficiently simulate the soil water dynamics and nutrient transport. HYDRUS-2D simulated satisfactorily the nitrate transport and thus combining it with DSSAT made sense. Although this study was not entirely on model coupling, it provided a basis that DSSAT was not accurate in simulating water and nitrate dynamics and thus necessitating a combination of soil water models coupled with growth models for the better representation of cropping systems.

In a study to demonstrate the potential benefit of combining crop growth model and hydrological model, Li et al. (2012), coupled WOFOST and HYDRUS – 1D for modelling irrigated maize production. Soil water balance, soil water content and the groundwater depth was computed by HYDRUS while carbon assimilation and allocation to the crop parts was computed by WOFOST. The crop height, rooting depth and LAI computed by WOFOST was then used as inputs in HYDRUS in the subsequent step. The results of the coupled model were in good agreement with the observed data under water-stress conditions. Also, the coupled model performed better than stand-alone WOFOST model due to the contribution of HYDRUS in simulating soil moisture and root water uptake more precisely. Following the same approach, Zhou et al. (2012) coupled WOFOST and HYDRUS – 1D to optimize on irrigation and simulation of wheat production under variable moisture conditions. The study found that an irrigation strategy guided by root water uptake could save 27% of the water. The study also determined the suitable groundwater depth for wheat growth at 1.5 m.

To enable estimation of irrigated maize yields on a regional scale, Li et al. (2014), assimilated remote-sensed data (LAI) into WOFOST- HYDRUS – 1D coupled model using the ensemble Kalman filter. The coupling mechanism for WOFOST and HYDRUS – 1D followed the approach adopted by Li et al. (2012) where crop parameters and soil parameters were derived by WOFOST and HYDRUS – 1D respectively. The study found that assimilation of remote sensed data into the coupled model enabled relatively good regional estimation of maize yields.

To minimize depletion of groundwater sources for irrigation and optimize crop production, Hu et al. (2010), combined the use of MOFLOW, Soil Water Assessment Tool (SWAT), and DSSAT for wheat and maize. DSSAT water balance equation was used to compute areal recharge while SWAT calculated the recharge from the mountainous region. Both types of recharges were input into MODFLOW as flux/head boundary conditions. The results showed that 39% water saving could be achieved when 40% of groundwater equilibrium condition is applied to the crops throughout the season and at reproductive stages.

In another study, Akhtar et al. (2013), combined HYDRUS – 1D and AquaCrop in the optimization of irrigation schedules for cotton. Due to the deficiency of AquaCrop in simulating capillary rise, HYDRUS – 1D was used to simulate the capillary rise. AquaCrop was then used to develop optimum irrigation schedules considering the contribution by groundwater in the form of capillary rise. The study found that due to the shallow groundwater conditions, the contribution of capillary rise is paramount in the determination of optimum irrigation schedules.

Furthermore, Peña-Haro et al. (2012), coupled WOFOST, MODFLOW and HYDRUS – 1D. The models were coupled in two ways; through input/output approach where the output from one model forms the input of the other model, and through the wrapping of the model codes to allow linkages. WOFOST was used to compute LAI and rooting depth which formed the input in HYDRUS – 1D. HYDRUS computed ET which was then fed back to WOFOST and recharge from the vadose zone which formed the input to MODFLOW. MODLOW computed the pressure heads due to groundwater which formed lower boundary condition in HYDRUS – 1D. The integrated model was tested in a hypothetical maize field. This study showed the importance of integrating interdependent processes such as crop growth and soil water conditions. LAI depends on the available moisture in the soil which in turn is influenced by the level of groundwater.

A study by Wang et al. (2015), demonstrated the application of a coupled EPIC and HYDRUS – 1D model to assess the effects of irrigation management on the growth of wheat. The coupling of the models was done by coding the subroutines using FORTRAN 90 for Windows system. Soil water flow and solute (soil nitrate) transport were simulated through the HYDRUS's Richards's equation and convention-dispersion equation respectively. EPIC output in terms of LAI and root depth was used as input in HYDRUS – 1D to simulate the soil water content. Biomass and grain yield from EPIC helped in the computation of water use efficiency. The coupled model was used to determine the irrigation depths for years corresponding to 75%, 50% and 25% rainfall occurrence. Hao et al. (2015) also coupled EPIC and HYDRUS – 1D to simulate the influence of shallow groundwater conditions and salinization on irrigated crop yields on a regional scale. The study found that high soil salinity and water logging affected crop yields in some of the areas. These two studies demonstrate the ability of coupled crop growth model (EPIC) and HYDRUS – 1D to simulate soil water dynamics and solute transport and the respective crop response.

Finally, Wang et al. (2014), coupled EPIC and CHAIN – 2D models for the simulation of the growth of melons in response to furrow irrigation management practices. The coupling of the two models was done using FORTRAN 90 for Windows system. The coupled model was used to compute the soil water content, LAI, yield and water use of the crop. The simulated values from the coupled model were in good agreement with the observed data. The basis for coupling in this study was the precise simulation of the root water uptake.

From the above studies, HYDRUS – 1D is a popular model for simulating the soil water dynamics. The model has been coupled with all the three types of crop-growth models i.e. water driven (AquaCrop), carbon-driven (WOFOST) and radiation-driven (EPIC). The popularity of HYDRUS – 1D stems from its ability to satisfactorily simulate soil water distribution and salt dynamics which is relevant in crop production. Loose or tight modelling is the favoured coupling approach. Full coupling does not gain sufficient applicability due to the need for wide changes in the codes for the models to be configured which might result in a complex model.

Most crop models are based on field scale where the soil water component is simulated in 1D. Flow in the unsaturated zone is modelled by solving the 1D, 2D or 3D forms of the Richards' Equation. The soil water distribution and solute transport under irrigation methods such as surface or subsurface drip irrigation is a 2D or 3D problem. Kandelous and Šimůnek (2010) found that HYDRUS – 2D is a useful tool for simulating soil water dynamics under subsurface drip irrigation and that in cases where the wetting patterns of the emitters overlap, HYDRUS – 2D/3D is required for a fully 3D simulation. It is our opinion that HYDRUS – 2D/3D coupled with the appropriate crop model can yield satisfactory results where the soil water dynamics and nutrient transport in the soil are accurately simulated in 2D.

Models that use Richard's Equation perform satisfactorily in simulating soil water dynamics than those which rely on simple bucket or cascade approach. Gandolfi et al. (2006) compared one-dimensional models that use the two approaches and found that the models that use Richard's Equation satisfactorily captured the soil water distribution better while the conceptual models using cascade approach performed poorly especially in heavy soils.

A comparison of WOFOST and AquaCrop by Todorovic et al. (2009) for simulating the response of sunflower to water availability found that the two models performed reasonably well but WOFOST was better under water-stressed conditions. However, considering simplicity and lower parameter requirements in AquaCrop, this limitation outweighs the benefits in cases of data scarce environments. According to Motha (2011), the main focus of AquaCrop is crop response to water availability. AquaCrop is, thus, the appropriate model in areas where water scarcity is a problem.

It can be inferred, therefore, that coupling AquaCrop with a suitable soil water dynamic model may be a realistic way of simulating crop response to water availability and at the same time achieving a balance between model simplicity and accuracy.

Uncertainties in Model Coupling

Understanding the uncertainties in crop and hydrological models is necessary so that adequate measures are put in place to minimize the modelling errors or provide probabilities on the model output for decision making. According to Liu and Gupta (2007), the sources of uncertainty in modelling are the model structure, parameters, and data. Data used as inputs or initial conditions to the model can have measurement errors due to the nature of the instrument used or representative error arising from spatial or temporal incompatibility. Uncertainty also arises due to errors in the estimation of parameters used in the model. Wagener et al. (2001), suggested that parameter uncertainty could be minimized by reducing the model complexity and increasing the information available for determination of model parameters through the use of more output variables. Wagener and Gupta (2005) associated model structure uncertainty with the simplifications of the real-world processes.

The errors in the individual models described above are propagated to the coupled model thus compounding the level of uncertainty. The nature of the coupling can also induce another uncertainty in the coupled model. Coupling models, according to Antle et al. (2001), leads to additional conceptualization and computational problems which elevates the uncertainty levels.

The steps for uncertainty analysis in models as discussed by Monod et al. (2006) are (1) determination of probability distribution functions of the input factors (2) generation of input factor values by using methods such as Monte Carlo sampling (3) computation of the model outputs for each scenario considered and (4) analysis of the model output distributions.

Uncertainty analysis is followed by sensitivity analysis to determine the parameters which have a greater influence on the model outputs. The sensitivity analysis for coupled WOFOST and HYDRUS-1D models by Li et al. (2012) indicated that the yield of maize was majorly influenced by the parameters related to crop physiology like green area and environmental factors such as sowing date computed by the crop model, and soil hydraulic parameters and groundwater conditions computed by the hydrological model.

Conclusions and Future Research

Linking of crop models with hydrological models is necessary to accurately represent the processes in the plant-soil systems. Soil water balance is important in agricultural water management since it influences practices such as irrigation scheduling. The flow of water in the root zone can be simulated more precisely using dynamic models using Richard's Equation than the simple bucket models. HYDRUS-ID is a popular model for simulating one-dimensional water dynamics in a porous media. The model has been loosely coupled with AquaCrop, EPIC and WOFOST for improved simulation of crop response to water availability. This review has demonstrated that coupling hydrological models with appropriate crop models can help in the optimization of irrigation management practices. Soil water movement under irrigation is a two-dimensional problem which requires the use of two-dimensional models. Therefore, future studies need to consider coupling two-dimensional soil water flow model with a crop growth model.

References

Ahuja, L., L. Ma, R.J. Lascano, S. Saseendran, Q. Fang, D.C. Nielsen, E. Wang and P.D. Colaizzi, 2014. Syntheses of the current model applications for managing water and needs for experimental data and model improvements to enhance these applications. In: L.R. Ahuja et al. (eds), Practical Applications of Agricultural System Models to Optimize the Use of Limited Water, *American Society of Agronomy,* Wisconsin, USA, pp. 399-438.

Akhtar, F., B. Tischbein and U.K. Awan, 2013. Optimizing deficit irrigation scheduling under shallow groundwater conditions in lower reaches of Amu Darya River Basin. *Water Resources Management*, **27** (8): 3165-3178.

Al-kaisy, E.M., E.A. Alani and M.M. Abid, 2011. Using AquaCrop model for supplementary and rain fed irrigation in North Iraq. In: 21st International Congress on Irrigation and Drainage, Tehran, Iran, pp. 229-241.

Albrizio, R. and P. Steduto, 2005. Resource Use Efficiency of field-grown sunflower, sorghum, wheat and chickpea: I. Radiation Use Efficiency. *Agricultural and Forest Meteorology*, **130** (3): 254-268.

Antle, J.M., S.M. Capalbo, E.T. Elliott, H.W. Hunt, S. Mooney and K.H. Paustian, 2001. Research needs for understanding and predicting the behavior of managed ecosystems: lessons from the study of agroecosystems. *Ecosystems*, **4** (8): 723-735.

Araya, A., S. Habtu, K.M. Hadgu, A. Kebede and T. Dejene, 2010a. Test of AquaCrop model in simulating biomass and yield of water deficient and irrigated barley (*Hordeum vulgare*). *Agricultural Water Management*, **97** (11): 1838-1846.

Araya, A., S. Keesstra and L. Stroosnijder, 2010b. Simulating yield response to water of Teff (Eragrostis tef) with FAO's AquaCrop model. *Field Crops Research*, **116** (1): 196-204.

Barlow P.M. and A.W. Harbaugh, 2006. USGS directions in MODFLOW development. *Groundwater*, **44** (6): 771-774.

Barthel, R., 2006. Common problematic aspects of coupling hydrological models with groundwater flow models on the river catchment scale. *Advances in Geosciences*, **9**: 63-71.

Bauböck, R., 2014. Simulating the yields of bioenergy and food crops with the crop modeling software BioSTAR: the carbon-based growth engine and the BioSTAR ET0 method. *Environmental Sciences Europe*, **26** (1): 1-9.

Benjamin, J., L. Ahuja and R. Allmaras, 1996. Modelling corn rooting patterns and their effects on water uptake and nitrate leaching. *Plant and Soil*, **179** (2): 223-232.

Bouman, B., H. Van Keulen, H. Van Laar and R. Rabbinge, 1996. The 'School of de Wit'crop growth simulation models: a pedigree and historical overview. *Agricultural Systems*, **52** (2): 171-198.

Brisson, N., J. Wery and K. Boote, 2006. Fundamental concepts of crop models illustrated by a comparative approach. In: D. Wallach, et al. (eds), Working with Dynamic Crop Models, *Elsevier B.V*, Amsterdam, pp. 257-279.

Brunner, P., C.T. Simmons, P.G. Cook and R. Therrien, 2010. Modeling surface water-groundwater interaction with MODFLOW: some considerations. *Groundwater*, **48** (2): 174-180.

Bryant, K., V. Benson, J. Kiniry, J. Williams and R. Lacewell, 1992. Simulating corn yield response to irrigation timings: Validation of the EPIC model. *Journal of Production Agriculture*, **5** (2): 237-242.

Butters, G., J. Benjamin, L. Ahuja and H. Ruan, 2000. Bromide and Atrazine leaching in furrow and sprinkler irrigated corn. *Soil Sci. Soc. Am. J*, **64**: 1723-1732.

Cabelguenne, M., P. Debaeke and A. Bouniols, 1999. EPICphase, a version of the EPIC model simulating the effects of water and nitrogen stress on biomass and yield, taking account of developmental stages: validation on maize, sunflower, sorghum, soybean and winter wheat. *Agricultural Systems*, **60** (3): 175-196.

Connolly, R., 1998. Modelling effects of soil structure on the water balance of soil–crop systems: a review. *Soil and Tillage Research*, **48** (1): 1-19.

Devi, G.K., B. Ganasri and G. Dwarakish, 2015. A review on hydrological models. *Aquatic Procedia*, **4**: 1001-1007.

Diepen, C.v., J. Wolf, H.v. Keulen and C. Rappoldt, 1989. WOFOST: a simulation model of crop production. *Soil Use and Management*, **5** (1): 16-24.

Eitzinger, J., M. Trnka, J. Hösch, Z. Žalud and M. Dubrovský, 2004. Comparison of CERES, WOFOST and SWAP models in simulating soil water content during growing season under different soil conditions. *Ecological Modelling*, **171** (3): 223-246.

Evett, S.R. and J.A. Tolk, 2009. Introduction: can water use efficiency be modeled well enough to impact crop management? *Agronomy Journal*, **101** (3): 423-425.

Farahani, H.J., G. Izzi and T.Y. Oweis, 2009. Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton. *Agronomy Journal*, **101** (3): 469-476.

Furman, A., 2008. Modeling coupled surface–subsurface flow processes: a review. *Vadose Zone Journal*, **7** (2): 741-756.

Gandolfi, C., A. Facchi and D. Maggi, 2006. Comparison of 1D models of water flow in unsaturated soils. *Environmental Modelling & Software*, **21** (12): 1759-1764.

Hao, Y., X. Xu, D. Ren, Q. Huang and G. Huang, 2015. Distributed modeling of soil water-salt dynamics and crop yields based on HYDRUS-EPIC model in Hetao Irrigation District. *Transactions of the Chinese Society of Agricultural Engineering*, **31** (11): 110-116.

Harbaugh, A.W., E.R. Banta, M.C. Hill and M.G. McDonald, 2000. MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model-User Guide to Modularization Concepts and the Ground-Water Flow Process, *U.S. Geological Survey*, Virginia, USA.

Heng, L.K., T. Hsiao, S. Evett, T. Howell and P. Steduto, 2009. Validating the FAO AquaCrop model for irrigated and water deficient field maize. *Agronomy Journal*, **101** (3): 488-498.

Hsiao, T.C., L. Heng, P. Steduto, B. Rojas-Lara, D. Raes and E. Fereres, 2009. AquaCrop—the FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. *Agronomy Journal*, **101** (3): 448-459.

Hu, Y., J.P. Moiwo, Y. Yang, S. Han and Y. Yang, 2010. Agricultural water-saving and sustainable groundwater management in Shijiazhuang Irrigation District, North China Plain. *Journal of Hydrology*, **393** (3): 219-232.

Jajarmizadeh, M., S. Harun and M. Salarpour, 2012. A review on theoretical consideration and types of models in hydrology.

Journal of Environmental Science and Technology, **5** (5): 249-261.

Jones, J., B. Keating and C. Porter, 2001. Approaches to modular model development. *Agricultural Systems*, **70** (2): 421-443.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L. Hunt, P.W. Wilkens, U. Singh, A. J. Gijsman and J.T. Ritchie, 2003. The DSSAT cropping system model. *European Journal of Agronomy*, **18** (3): 235-265.

Jones, J., G. Tsuji, G. Hoogenboom, L. Hunt, P. Thornton, P. Wilkens, D. Imamura, W. Bowen and U. Singh, 1998. Decision support system for agrotechnology transfer: DSSAT v3. In: G.Y. Tsuji, et al. (eds) Understanding Options for Agricultural Production, *Springer*, Netherlands, pp. 157-177.

Kandelous, M.M. and J. Šimůnek, 2010. Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D. *Agricultural Water Management*, **97** (7): 1070-1076.

Katerji, N., P. Campi and M. Mastrorilli, 2013. Productivity, evapotranspiration, and water use efficiency of corn and tomato crops simulated by AquaCrop under contrasting water stress conditions in the Mediterranean region. *Agricultural Water Management*, **130**: 14-26.

Kiniry, J.R., J.R. Williams, D. Major, R. Izaurralde, P.W. Gassman, M. Morrison, R. Bergentine and R. Zentner, 1995. EPIC model parameters for cereal, oilseed, and forage crops in the northern Great Plains region. *Canadian Journal of Plant Science*, **75** (3): 679-688.

Li, Y., W. Kinzelbach, J. Zhou, G. Cheng and X. Li, 2012. Modelling irrigated maize with a combination of coupled-model simulation and uncertainty analysis, in the northwest of China. *Hydrology and Earth System Sciences*, **16**: 1465-1480.

Li, Y., Q. Zhou, J. Zhou, G. Zhang, C. Chen and J. Wang, 2014. Assimilating remote sensing information into a coupled hydrology-crop growth model to estimate regional maize yield in arid regions. *Ecological Modelling*, **291**: 15-27.

Linker, R., I. Ioslovich, G. Sylaios, F. Plauborg and A. Battilani, 2016. Optimal model-based deficit irrigation scheduling using AquaCrop: A simulation study with cotton, potato and tomato. *Agricultural Water Management*, **163**: 236-243.

Liu, Y. and H.V. Gupta, 2007. Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework. *Water Resources Research*, **43** (7).

Mckinnie, F.W., 2003. Monitoring and modeling water and nitrogen transport in the vadose zone of a vegetable farm in the Suwannee River Basin. Masters Thesis, *University of Florida*, Florida, USA.

Mirlas, V., 2009. Applying MODFLOW model for drainage problem solution: A case study from Jahir irrigated fields, Israel. *Journal of Irrigation and Drainage Engineering*, **135** (3): 269-278.

Mirlas, V., V. Antonenko, V. Kulagin and E. Kuldeeva, 2015. Assessing artificial groundwater recharge on irrigated land using the MODFLOW model. *Earth Science Research*, **4** (2): 16.

Mohanty, B., R. Bowman, J. Hendrickx, J. Simunek and M.v. Genuchten, 1998. Preferential transport of nitrate to a tile drain in an intermittent-flood-irrigated field: Model development and experimental evaluation. *Water Resources Research*, **34** (5): 1061-1076.

Monod, H., C. Naud and D. Makowski, 2006. Uncertainty and sensitivity analysis for crop models. In: D. Wallach, et al. (eds) Working with Dynamic Crop Models: Evaluation, Analysis, Parameterization, and Applications, *Elsevier B.V*, Amsterdam pp. 55-100.

Montoya, F., D. Camargo, J.F. Ortega, J.I. Córcoles and A. Domínguez, 2016. Evaluation of Aquacrop model for a potato crop under differentirrigation conditions. *Agricultural Water Management*, **164**: 267-280.

Motha, R.P., 2011. Use of crop models for drought analysis. In: M.V.K. Sivakumar et al. (eds), Expert Group Meeting on Agricultural Drought Indices, *World Meteorological Organization*, Murcia, Spain, pp. 138-148.

Peña-Haro, S., J. Zhou, G. Zhang, C. Chen, F. Stauffer and W. Kinzelbach, 2012. A multi-approach framework to couple independent models for simulating the interaction between crop growth and unsaturated-saturated flow processes. In: R. Seppelt et al. (eds), 6th International Congress on Environmental Modelling and Software, Leipzig, Germany, pp. 1224-1231

Ranatunga, K., E.R. Nation and D.G. Barratt, 2008. Review of soil water models and their applications in Australia. *Environmental Modelling & Software*, **23** (9): 1182-1206.

Rinaldi, M., 2001. Application of EPIC model for irrigation scheduling of sunflower in Southern Italy. *Agricultural Water Management*, **49** (3): 185-196.

Ritchie, J., 1998. Soil water balance and plant water stress. In: G.Y. Tsuji et al. (eds), Understanding options for agricultural production, *Kluwer Academic Publishers*, pp. 41-54.

Rotmans, J. and M.B. van Asselt, 2001. Uncertainty management in integrated assessment modeling: towards a pluralistic approach. *Environmental Monitoring and Assessment*, **69** (2): 101-130.

Rötter, R.P., T. Palosuo, K.C. Kersebaum, C. Angulo, M. Bindi, F. Ewert, R. Ferrise, P. Hlavinka, M. Moriondo and C. Nendel, 2012. Simulation of spring barley yield in different climatic zones of Northern and Central Europe: a comparison of nine crop models. *Field Crops Research*, **133**: 23-36.

Shrestha, N., D. Raes and S.K. Sah, 2013. Strategies to improve cereal production in the Terai region (Nepal) during dry season: simulations with aquacrop. *Procedia Environmental Sciences*, **19**: 767-775.

Šimůnek**, J., M.T. Van Genuchten and M. Sejna,** 1994. The CHAIN_2D Code for Simulating Two-dimensional Movement of Water, Heat, and Mutiple Solutes in Variably-Saturated Porous Media, Version 1.1, Report 136, US Salinity Laboratory, USDA, ARS, Riverside, California, Šimůnek J., M.T. Van Genuchten and M. Sejna, 2005. The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media, Version 3, *University of California Riverside*, Riverside, California, USA.

Šimůnek**, J., M.T.v. Genuchten and M. Šejna,** 2006. The HYDRUS Software Package for Simulating Two- and Three Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media. *PC Progress*, Prague, Czech Republic.

Šimunek**, J., M.T. Van Genuchten and M. Šejna,** 2012. HYDRUS: Model use, calibration and validation. *Transactions of the ASABE*, **55** (4): 1263-1274.

Šimůnek**, J., M.T. van Genuchten and M. Šejna,** 2016. Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone Journal*, **15** (7).

Steduto, P. and R. Albrizio, 2005. Resource use efficiency of field-grown sunflower, sorghum, wheat and chickpea: II. Water use efficiency and comparison with radiation use efficiency. *Agricultural and Forest Meteorology*, **130** (3): 269-281.

Steduto, P., T C. Hsiao and E. Fereres, 2007. On the conservative behavior of biomass water productivity. *Irrigation Science*, **25** (3): 189-207.

Steduto P., T.C. Hsiao, D. Raes and E. Fereres, 2009. AquaCrop-The FAO Crop Model to Simulate Yield Response to Water: I. Concepts and Underlying Principles. *Agronomy Journal*, **101** (3): 426-437.

Steduto, P., V. Pocuca, A. Caliandro and P. Debaeke, 1995. An evaluation of the crop-growth simulation submodel of epic for wheat grown in a Mediterranean climate with variable soil-water regimes. *European Journal of Agronomy*, **4** (3): 335-345.

Stöckle C. O., M. Donatelli and R. Nelson, 2003. CropSyst, a cropping systems simulation model. *European Journal of Agronomy*, **18** (3): 289-307.

Stuckens, J., 2010. Monitoring and modelling of a citrus plant production system via integration of in-situ and hyperspectral remote sensing data. Doctoral dissertation, K.U Leuven, Leuven, Belgium.

Supit, I., 1997. Predicting national wheat yields using a crop simulation and trend models. *Agricultural and Forest Meteorology*, **88** (1-4): 199-214.

Todorovic, M., R. Albrizio, L. Zivotic, M.-T. A. Saab, C. Stöckle and P. Steduto, 2009. Assessment of AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. *Agronomy Journal*, **101** (3): 509-521.

Tsegay, A., D. Raes, S. Geerts, E. Vanuytrecht, B. Abraha, J. Deckers, H. Bauer and K. Gebrehiwot, 2012. Unravelling crop water productivity of Tef (Eragrostis Tef (zucc.) trotter) through AquaCrop in northern Ethiopia. *Experimental Agriculture*, **48** (02): 222-237.

Twarakavi, N.K.C., J. Šimůnek and S. Seo, 2008. Evaluating interactions between groundwater and vadose zone using the HYDRUS-based flow package for MODFLOW. *Vadose Zone Journal*, **7** (2): 757-768.

Van Gaelen, H., N. Delbecque, B. Abrha, A. Tsegay and D. Raes, 2016. Simulation of crop production in weed-infested fields for data-scarce regions. *The Journal of Agricultural Science*, **154** (6): 1026-1039.

Van Gaelen, H., D. Raes and J. Diels, 2014. A model based approach towards environment-specific field management strategies for upgrading crop water productivity. *Communications in Agricultural and Applied Biological Sciences*, **79** (1): 15-20.

Van Gaelen, H., A. Tsegay, N. Delbecque, N. Shrestha, M. Garcia, H. Fajardo, R. Miranda, E. Vanuytrecht, B. Abrha and J. Diels, 2015. A semi-quantitative approach for modelling crop response to soil fertility: evaluation of the AquaCrop procedure. *The Journal of Agricultural Science*, **153** (07): 1218-1233.

van Ittersum, M.K., P.A. Leffelaar, H. Van Keulen, M.J. Kropff, L. Bastiaans and J. Goudriaan, 2003. On approaches and applications of the Wageningen crop models. *European Journal of Agronomy*, **18** (3): 201-234.

Vereecken, H., A. Schnepf, J. Hopmans, M. Javaux, D. Or, T. Roose, J. Vanderborght, M. Young, W. Amelung and M. Aitkenhead, 2016. Modeling soil processes: Review, key challenges, and new perspectives. *Vadose Zone Journal*, **15** (5).

Wagener, T. and H.V. Gupta, 2005. Model identification for hydrological forecasting under uncertainty. *Stochastic Environmental Research and Risk Assessment*, **19** (6): 378-387.

Wagener, T., D.P. Boyle, M.J. Lees, H.S. Wheater, H.V. Gupta and S. Sorooshian, 2001. A framework for development and application of hydrological models. *Hydrology and Earth System Sciences Discussions*, **5** (1): 13-26.

Wang, D., S.R. Yates, J. Simunek and M.T. v. Genuchten, 1997. Solute transport in simulated conductivity fields under different irrigations. *Journal of Irrigation and Drainage Engineering*, **123** (5): 336-343.

Wang, J., G. Huang, H. Zhan, B.P. Mohanty, J. Zheng, Q. Huang and X. Xu, 2014. Evaluation of soil water dynamics and crop yield under furrow irrigation with a two-dimensional flow and crop growth coupled model. *Agricultural Water Management*, **141**: 10-22.

Wang, X., G. Huang, J. Yang, Q. Huang, H. Liu and L. Yu, 2015. An assessment of irrigation practices: Sprinkler irrigation of winter wheat in the North China Plain. *Agricultural Water Management*, **159**: 197-208.

Wang, X.C. and J. Li, 2010. Evaluation of crop yield and soil water estimates using the EPIC model for the Loess Plateau of China. *Mathematical and Computer Modelling*, **51** (11): 1390-1397.

Williams, J.R., 1990. The erosion-productivity impact calculator (EPIC) model: a case history. *Philosophical Transactions: Biological Sciences*: 421-428.

Zeleke, K.T., D. Luckett and R. Cowley, 2011. Calibration and testing of the FAO AquaCrop model for canola. *Agronomy Journal*, **103** (6): 1610-1618.

Zhang, L., G.R. Walker and W.R. Dawes, 2002. Water balance modelling: concepts and applications. In: T.R. McVicar et al. (eds), Regional Water and Soil Assessment for Managing Sustainable Agriculture in China and Australia, *Australian Centre for International Agricultural Research*, Canberra, pp. 31-47.

Zhou, J., G. Cheng, X. Li, B. X. Hu and G. Wang, 2012. Numerical modeling of wheat irrigation using coupled HYDRUS and WOFOST models. *Soil Science Society of America Journal*, **76** (2): 648-662.

Received November, 8, 2017; accepted for printing April, 30, 2018