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Sensitivity of drainage to rainfall, vegetation and soil characteristics

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ABSTRACT

Rainfall, vegetation characteristics and soil hydraulic properties influence deep drainage patterns in agricultural landscapes, but more information is required on the variability of their interactions with site conditions. Therefore, the objective of the study was to investigate the impact of the interactions of soil permeability, vegetation rooting depth and growth duration on drainage in 3 sites in northern New South Wales, Australia. Local sensitivity analysis was used on drainage estimated by two biophysical models—WaterMod 3, with a crop growth module, and HYDRUS-1D without a crop growth module. The effect of saturated hydraulic conductivity (K_s), growth duration (GD), rooting depth (RD), annual rainfall, and their interactions on deep drainage was evaluated at 3 sites. Simulations were conducted using 30 years of randomly selected climate data from 115 years historical data. Rainfall variability was similar in all 3 sites, so annual rainfall was the dominant factor dictating drainage in all 30 rainfall-years whereas GD was more important than RD after accounting for rainfall and drainage was least sensitive to K_s. The minor impact of RD was ascribed to the soil water content being at the lower extraction limit of crops due to potential evaporation being greater than rainfall in almost all months of the rainfall-year. The importance of GD varied between rainfall-years and sites, and was generally higher at high annual rainfall. We conclude that the level of precision at which model inputs are defined would vary with annual rainfall level. Therefore, GD could be defined on a rough scale in low rainfall zones, whereas more precise definitions are necessary at high rainfall. This would depend on classification of rainfall zones based on reliable rainfall data.

1. Introduction

Reliable estimation of drainage of soil water below the rooting zone (deep drainage) is required for dry land salinity risk assessment, improved irrigation management, and monitoring the fate of agrochemicals in ecosystems. Field methods of assessing deep drainage (drainage, hereafter) using soil flux meters, lysimeters or soil tracers are costly, laborious, and sometimes unreliable, especially in low rainfall areas (Bond, 1998; Walker et al., 2002). Moreover, the benefit of these point measurements is limited because they do not incorporate the spatial and temporal variations of drainage (Tseng and Jury, 1993). Consequently, alternative procedures that combine simulation modelling with appropriate soil and climate datasets have become popular methods of estimating drainage because of their low cost/benefit ratios and their flexibility (possibility of rapidly assessing a variety of potential scenarios). This facilitates the prediction of long-term drainage patterns from short term trials using historical climate data. Also, important factors influencing drainage patterns (e.g. rainfall distribution, soil hydraulic properties) could be identified, thereby promoting the transfer of results from one area to another with minimum requirement for additional data (Walker et al., 2002).

In spite of the advantages, model outputs often have many uncertainties that emanate from input inaccuracies associated with the inherent variability of environmental factors (e.g. soil and climate), measurement errors, and approximations using pedotransfer functions. Likewise, model structural defects due to inaccurate simplifying assumptions and computational error also increase uncertainties in model predictions (Zhang et al., 2002). The problem is exacerbated by the fact that drainage is often a very small and highly variable component of soil water balance. Its magnitude is similar to or less than the errors in measurements of seasonal rainfall and evapotranspiration. Furthermore, drainage is influenced by many factors, including the amount and distribution of rainfall, soil characteristics (Asseng et al., 2001), and farming system as well as cropping sequence (Keating et al., 2002). Generally, high levels of drainage can be expected in high rainfall areas dominated by soils with low water holding capacity (WHC) (Asseng et al., 2001), and mainly having annual cropping systems with shallow rooting vegetation (Keating et al., 2002). By contrast, minimum drainage occurs in low rainfall regions dominated by soils of high WHC (e.g. clay), and perennial systems having deep rooting vegetation (e.g. lucerne) or mixed and/or opportunity cropping systems. Although the effect of these factors is generally known, the impact

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of their interactions is still not well understood. This is because of the general scarcity of information between these interactions as function of drainage flux (Walker et al., 2002). The importance of input parameters in soil water balance models are often ranked by sensitivity analysis (SA), but developing credible models based on the limited information usually available is still difficult. All these factors present major challenges for extrapolating drainage estimates from the farm to system level.

Sensitivity analysis is the systematic evaluation of the impact of variations in input parameters on model outputs (Lane and Ferreira, 1980; Saltelli, 2000). Thus, it quantifies and ranks the level of dependence of model output on particular inputs. The factor that causes the greatest variance would need to be evaluated with greater precision, whereas approximations or estimations would suffice for less important factors. Hence SA ensures that resources are judiciously allocated during sampling and data collection for model parameterization. This will enhance confidence in model predictions at different scales, and improve understanding of drainage processes.

Models of different levels of complexity have been used to extrapolate drainage results over temporal and spatial scales, encompassing a range of soil types and climatic zones. They range from complex models such as APSIM (McCown et al., 1996; Keating et al., 2003), which requires greater input data, to simple one-dimensional ones with much smaller input requirements, example WaterMod 3 (Johnson, 2002) and HYDRUS-1D (Simunek et al., 2005). Despite this, HYDRUS-1D has been widely used in water balance modelling, recharge estimation, and nitrate and pesticide leaching in soils (Sarmah et al., 2005, 2006). Similarly, the capacitance module used for describing infiltration in WaterMod 3 constitutes the hydrological component of widely used pasture models, example the sustainable grazing systems (SGS) pasture model in Australia (Johnson et al., 2003).

Therefore, the objective of this study was primarily to investigate the effects of rainfall, soil permeability (K_s), vegetation rooting depth (RD) and growth duration (GD) factors and their interactions on drainage estimated by two one-dimensional water balance models—WaterMod 3 and HYDRUS-1D. Secondly, to examine how the relationships between the factors and drainage change in varying environmental conditions at 3 sites in northern New South Wales (NSW). Also, to ascertain if the relationships change with the model used in the prediction of drainage.

2. Materials and methods

2.1. Models

Detailed descriptions of the models used in this study have been given elsewhere—WaterMod 3 (Johnson, 2002; Johnson et al., 2003), and HYDRUS-1D (Simunek et al., 2005). The former operates on a daily time-step while the one for HYDRUS-1D is user-defined. In this study the daily time-step is also used in the HYDRUS-1D simulations. Although both models can describe soil water movement and redistribution by solving Richard's equation (1938), there is an option to use a simpler capacitance approach in WaterMod 3. Unlike Richard's equation, the capacitance model can be used to estimate soil parameters directly without using the water retention curve, which makes it 5–10 times faster (Johnson, 2002).

2.1.1. Modelling soil water movement

The capacitance approach in WaterMod 3 was used for describing water movement down the soil profile (Johnson et al., 2003). The soil hydraulic characteristics (SHC) therein were determined for four soil layers (surface, A, B1 and B2) in each of the 3 study sites. Drainage is considered as the residual water remaining unaccounted for in the soil water balance for the B2 soil layer. In HYDRUS-1D, movement of soil water is described by solving Richard's equation (1938) for saturated–unsaturated conditions. In this case, SHC were obtained from the soil water retention curve, $\theta(h)$, described by van Genuchten (1980). This is combined with pore-size distribution model of Mualem (1976) to describe the unsaturated hydraulic conductivity function $K(h)$ (Table 1).

2.2. Modelling soil water loss to the atmosphere

Transpiration in WaterMod 3 is calculated in terms of potential evapotranspiration (PET) obtained from climate data, ground cover, and root distribution in the soil layers as well as soil water distribution (Table 1). PET in the climate data is estimated from class A

Table 1

Infiltration and water loss modules in WaterMod 3 and HYDRUS-1D.

WaterMod 3	HYDRUS-1D
Modelling soil water infiltration	
Capacitance model: $q = K_s\left(\frac{\theta-\theta_{dp}}{\theta_s-\theta_{dp}}\right)^{\sigma}, \quad \theta \geq \theta_{dp}$	Richard's equation (1938): $\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x} + \cos\alpha\right)\right] - S$ van Genuchten equation (1980): $\theta(h) = \theta_r + \frac{\theta_s-\theta_r}{[1+\lvert\alpha h\rvert^n]^m}, \quad h < 0, \quad \theta(h) = \theta_s, \quad h \geq 0$ Unsaturated hydraulic conductivity (Mualem, 1976): $K(h) = K_s S_e^l [1-(1-S_e^{1/m})^n]^2; \quad m = 1-1/n, \quad n > 1$ $S_e = \frac{\theta-\theta_r}{\theta_s-\vartheta_r}$
Soil water loss to the atmosphere	
Transpiration demand = crop ground cover × potential transpiration rate.	No crop growth module.
Ground cover: $f_{crop} = 1 - \exp(-kW), \quad k = \frac{\ln(10)}{W_{90}}$	Water uptake/volume/time (Feddes et al., 1978): $S(h) = \alpha(h)S_p$
Crop transpiration/soil layer = GLF × f_{root} × transpiration demand	Actual water uptake distribution: $S(h) = \alpha(h)b(x)T_p$
	Actual transpiration: $T_a = T_p \int_{L_R} \alpha(h,x)b(x)\,dx$
Root distribution	
Fraction of roots in soil layer: $f_{root} = f_0 \exp\left(\frac{-\xi z}{z_d}\right), \quad \xi = \frac{\ln(2)}{z_h}$	Rooting depth: $L_R = L_m f_r(t)$ $f_r(t) = \frac{L_0}{L_0+(L_m-L_0)e^{-rt}}$

q = flux of water; K_s = saturated hydraulic conductivity (m/day); θ = soil water content (m^3/m^3); θ_{dp} = drainage point (field capacity) (m^3/m^3); θ_s = saturation point (m^3/m^3); σ is a constant controlling the rate of decline of water available for infiltration; h = pressure head (m); t = time (day); x = spatial coordinate (m); S = sink term (m^3/m^3 day); α = angle between flow direction and vertical axis; K = unsaturated hydraulic conductivity (m/day); θ_r = residual water content (m^3/m^3); l is a pore-connectivity parameter; S_e = effective water content (m^3/m^3); α, n and m are empirical fitting parameters; f_{crop} = fraction of ground covered by crop; W = crop dry weight (kg/m^2); W_{90} = dry weight for 90% light interception. GLF is the growth limiting factor, f_{root} = fraction of roots in the soil layer; z_d = depth of the root profile (m); z = depth in the soil profile; f_0 is the value of f_{root} at z = 0 and z_h is the root depth at which f_{root} has declined to 50% of its surface value. $S(h)$ = water uptake rate; $\alpha(h)$ = root water uptake stress response function; S_p = potential water uptake rate (day)$^{-1}$; $b(x)$ = normalized water uptake distribution (m^{-1}); T_p = potential transpiration rate (m/day); T_a = actual transpiration (m/day); L_R = rooting depth (m); L_m = maximum rooting depth (m); $f_r(t)$ = root growth coefficient; L_0 = initial rooting depth (m); r = growth rate (day)$^{-1}$.