Reflections on modelling near-surface soil water conditions to inform management opportunities

Verburg K[1], Zeleke KT[2], Rich SM[3], Broster JC[2], Chen C[3], Luo T[3], Huth NI[4], Holzworth DP[4], McBeath TM[5], Eberbach PL[2], Swan TD[1], Holding J[6], Condon G[7], Condon K[7]

[1] CSIRO Agriculture and Food, GPO Box 1700, Canberra ACT 2601. kirsten.verburg@csiro.au
[2] Gulbali Institute for Agriculture Water Environment, Charles Sturt University, Boorooma Street, Wagga Wagga, NSW 2678
[3] CSIRO Agriculture and Food, PMB5, Wembley WA 6913
[4] CSIRO Agriculture and Food, 203 Tor Street, Toowoomba QLD 4350
[5] CSIRO Agriculture and Food, Waite Campus, Locked Bag 2, Glen Osmond, SA 5064
[6] Farmlink Research Ltd, P.O. Box 521, Temora NSW 2666
[7] Grassroots Agronomy, PO Box 73, Junee NSW 2663

Abstract

Near-surface soil environmental conditions affect seed germination and fertiliser availability. Understanding the soil water dynamics is hence critical for predicting the success of innovations intended to improve crop establishment and early vigour. Modelling is a useful tool to gain this understanding. However, despite many decades of soil water monitoring and modelling, there is surprisingly little model verification of the near-surface dynamics. Here we reflect on our experiences with modelling the near-surface soil water conditions across several projects focussed on stubble management, deep sowing and deep fertiliser application.

Keywords

Seed germination, crop establishment, deep sowing, deep fertiliser placement

Introduction

Early sowing to improve crop water use efficiency and dry sowing to accommodate larger programs, along with changes in autumn rainfall patterns, have prompted Australian grain industries to consider a range of innovations intended to improve crop establishment and early vigour (Rich et al. 2022; Roper et al. 2022; Stummer et al. 2023). The ability to predict near-surface soil environmental conditions (i.e., soil water and temperature to ~ 25 cm depth) in the period leading up to sowing and early in the crop growing season is critical to the development and evaluation of many of these strategies. For example, deep sowing or deep fertiliser application rely on the subsurface soil to be wetter than the surface soil, so it is important to assess how often this occurs. Residue management aims to create differences in evaporative demand, potentially changing both soil water and temperature dynamics in the near-surface soil, but how much difference can it make? To extrapolate field experimentation with modelling analyses, the modelling capability needs to be verified first. The aim of this paper is to share lessons from model testing of APSIM 'Next Generation' (Holzworth et al. 2018) using soil water data from small plot and field experiments to inform future measurement and modelling efforts.

Methods

APSIM model

We used APSIM 'Next Generation' (Holzworth et al. 2018) testing both the SoilWat (Probert et al. 1998) and SWIM3 (Huth et al. 2013) water balance models. Simulations were parameterised using either soils from the APSoil database (Dalgliesh et al. 2006) or site-specific soil characterisations.

SoilWat is a 'tipping bucket' model that draws on parameterisation of volumetric water contents at the soil lower limit of water extraction (*LL*), the drained upper limit (*DUL*) and the maximum soil saturation (*SAT*). Between *DUL* and *SAT,* a layer-specific fraction ($swcon_i$) of the present water drains to the next layer every day. Any water exceeding SAT (originating either from infiltration or from the layer above) will drain immediately to the next layer, unless the amount exceeds the saturated conductivity *Ksat* (if provided). Between *LL* and *DUL*, dynamics in soil water is governed by soil water extraction by crops (or weeds), evaporation (from the surface layer) and redistribution of water within the soil profile (*unsat_flow*). The latter is in theory driven by gradients in soil water potential. However, the equations in SoilWat use the gradient in soil water content (gradient_sw) along with two diffusivity parameters that apply across the profile (*diffuse_const* and *diffuse_slope*; Verburg, 1996):

$$unsat\_flow = \text{diffusivity} * \text{gradient\_sw}$$

where

$$\text{gradient\_sw} = ((\text{sw}_i - \text{sw}_{i+1}) / (\text{dlayer}_i + \text{dlayer}_{i+1})/2),$$
$$\text{diffusivity} = \textit{diffuse\_const} \times \exp\{\textit{diffuse\_slope} \times (\text{theta}_i + \text{theta}_{i+1})/2\},$$
$$\text{theta} = \text{sw} - \textit{LL},$$

and sw = volumetric soil water content, dlayer = layer thickness, theta = soil water content exceeding LL, and the subscripts i and i+1 refer to the layers between which the unsaturated flow is calculated. Default suggested values for *diffuse_const* and *diffuse_slope* are linked to soil texture: 40 and 16 for clay, 88 and 35 for loam and 250 and 22 for sand (Dalgliesh et al. 2016; Cichota et al. 2021). SoilWat models first stage evaporation as being driven by atmospheric demand (up to a cumulative amount *U*) and second stage evaporation as time dependent (*cona* × √(time)) but limited by available soil water in the first layer.

SWIM is a physically-based model that solves a set of equations whereby the gradients in soil water potential are the driving force for water movement up or down the soil profile, the hydraulic conductivity (a function of soil water content) adjusts the rate of movement (lower at lower water contents), all the while keeping track of the changes in soil water content to ensure mass balance (Verburg et al. 1996). While the original model drew on user-entry of parameters describing the soil water retention (relationship between soil water content and the soil water potential) and the hydraulic conductivity function (relationship between hydraulic conductivity and soil water content), Huth et al. (2013) introduced a version (SWIM3) whereby these parameters are automatically estimated based on the soil's values of *SAT*, *DUL* and *LL*, as well as a user-supplied *Ksat*. As conductivity often drops rapidly away from saturation, a second point defines the conductivity at the *DUL*. Default values set this *DUL* to be at a water potential of -10 kPa and a rate of 0.1 mm/day (applicable to the whole profile).

Summer fallow management experiments

Soil water was monitored continuously at depths varying between 6 cm and 26 cm in 12 site-years of summer fallow experiments comparing stripper and draper header front stubbles at 8 sites in southern NSW. The experiments were undertaken in farmer fields and measurements were made using soil water potential (Chameleon) or time domain reflectometry (TDR) sensors. The site-year experiments were characterised by above average rainfall and stubble loads. Additional small plot stubble load experiments were undertaken at the Wagga Wagga site with one experiment including a 'weedy' treatment.

Bare soil experiments

Soil water was monitored continuously at 5, 10, 15, 20, 30 and 50 cm depths in small bare plots along with site specific rainfall over a period of 20-22 months on light and heavy soils at three sites in SA and WA.

Sensibility testing

Hypothetical evaporation experiments were simulated using the soil profiles of Hochman et al. (2016).

Results and discussion

Experimental findings and challenges

Many site-year experimental data sets, comparing soil water under stripper and draper stubbles, displayed considerable variation between replicate measurements due to inherent spatial variability of the systems, e.g., in residue cover and in soil properties, including that of the depth of texture change. The variability meant it was difficult to obtain statistically significant treatment differences. However, this also indicates that variability is part of the system and that only larger treatment differences may be detectable and relevant. Under the experimental conditions experienced (relatively wet and high stubble loads) the effects of stubble configuration differences on soil water under stripper vs. draper stubbles were generally too small at the measurement depths of 6-26 cm.

Despite the experiments aiming for weed-free conditions, soil water extraction by temporary weeds that still emerged often had a large effect on the soil water dynamics and tended to override stubble effects. In a few of the site-years of the stubble experiments, it was observed that draper stubbles experienced higher weed pressures than stripper stubbles. This aspect is part of the system, and the generality of that observation needs to be tested further. A similar system aspect is that of stripper stubbles not breaking down at the same rate as draper stubbles due to less contact with the soil surface, even after sowing of the next crop (stubbles bent flat instead of broken up). Again, this is currently based on anecdotal evidence as the number of replicate measurements of stubble amounts was not sufficient to overcome variability in this difficult measurement.

The relative effects of fallow stubble cover and configuration versus summer weeds align with those of earlier work studying and explaining these effects in the context of plant available water for the subsequent crop (e.g., Verburg et al. 2012; Hunt et al. 2013, Zeleke 2017). However, in the context of near-surface soil water conditions for e.g. seed germination, the relative effects of weeds and stubble will be timing dependent. Weeds tended to briefly get away and dominate soil water dynamics during January and February but be better controlled during March and April. Stubble configuration/load effects during the latter period depend on timing of rainfall, duration of dry spells and the evaporative demand which declines during those months. Final conclusions about benefits of stripper vs draper stubbles require further experimental observations for drier fallow conditions (especially during March and April) and lower stubble loads.

The design of the experiments also needs to consider whether the treatments are intended to test the effect of a particular management practice (completely weed free) or are to reflect their implementation under practical grower practice (weeds controlled at earliest opportunity). In view of the observed variability in fallow systems, careful selection and management of measurement locations is critical to ensure these are representative and that other factors of influence are all equal (e.g., stubble load, weeds), particularly if the aim is to identify specific treatment effects (e.g., stubble configuration). Where treatments are to represent practical farmer implementation, and hence incorporate multiple factors, the number of replicates may need to be increased to untangle any specific treatment differences. In addition, photographic evidence or measurement of weeds and stubble cover near the measurement probes is key to interpretation of results, as is an understanding of soil properties with depth (e.g., to avoid a texture change at the measurement depth).

Model verification findings and challenges

A known limitation of the SoilWat model was the minimum depth of its first layer – typically 10-15 cm to not limit the evaporation calculation which can only draw on water stored in the first layer. The model is hence not suited for studies into seed germination differences at depths within the top 10 cm. The SoilWat model was able to reflect the contrasting patterns in soil water conditions averaged across the 0-10 cm layer compared with those at deeper depths (e.g. 10-20 or 20-30 cm depth) provided the choices for the diffusivity parameters were tested against the site data. However, having only three texture-based default diffusivity parameter sets proved limiting. In addition, the simulation of hypothetical evaporation experiments demonstrated that the use of the default loam diffusivity values in loam soils with large differences between *DUL* and *LL* created unrealistic evaporation and soil water dynamics. This was caused by too much upwards flow and the surface soil not drying out. Such behaviour was already known for texture contrast (i.e., duplex) soils where it is recommended to use the diffusivity values of the subsoil. More nuanced guidance for parameterisation would be warranted, although this is only critical for simulation scenarios where the results would be sensitive to evaporation affected near-surface soil water conditions.

Testing of SoilWat and SWIM3 was complicated by the effects on soil water dynamics of undocumented weeds. Their presence could often be established by studying the daily changes in soil water content or potential, noting unusually large changes and relatively sudden changes, especially those altering multi-day trends or occurring to depth (where available). Good weed control or at least management documentation and photographic evidence (at sensor site level) is key to detailed model verification.

The SWIM3 model in most cases correctly reflected the extent of soil drying at the measurement depths during late summer/early autumn when weeds were effectively controlled, evaporative demand was lower and rainfall events occurred more frequently. Wetting up of the soil in response to rainfall was also simulated well. There remain uncertainties over the model’s ability to simulate soil drying during high evaporative demand conditions experienced in December to February (due to experimental data often being affected by weed soil water extraction) and during prolonged drying (limited data suggests the model was unable to capture the observed continued drying). The latter may indicate that the predicted hydraulic conductivity function results in too low conductivities at low water contents. A closer look at how the model predicts the water retention and hydraulic conductivity functions would hence be warranted. A sensitivity analysis of the various parameters of influence may provide insights into ways of optimising hydraulic conductivity in dry soil without affecting the dynamics on the wet end.

Availability of soil water measurements at multiple depths strengthens the model verification considerably, as this helps narrow down whether ‘missing water’ is further down in the profile (having transited through the layer of interest), has not reached it yet (stored in layer above) or was indeed lost at a higher rate. The sphere of influence of measurements needs to be considered when comparing observations and model predictions, like those of SWIM3, obtained using thin layers. This is especially critical near the surface where the gradients in soil water can be very steep. It is also critical that the sphere of influence does not reach beyond the soil surface. To date this has prevented measurements within the top 5 cm of soil that would be critical to verify SWIM3's prediction of steep soil water gradients across this depth. We also noted considerable temperature sensitivity of some of the soil water sensors. While most noticeable in diurnal dynamics of near-surface measurements, the measurement deviations induced by seasonal temperature trends are more at risk of masking the true soil water dynamics and are more easily overlooked.

In conclusion, improving and confirming model verification requires detailed attention to both experimental aspects (experimental design, measurements, conditions) and model technical aspects (understanding the model algorithms and parameterisation).

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