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MULTI-LAYER SOIL HYDROLOGY MODELLING IN OVERSEER®

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Abstract

Overseer is a decision support tool used widely by councils and farmers to manage nitrogen leaching, among other environmental impacts of farming. In the current Overseer model, soil water is simulated using a single 'layer' to represent all the soil water within the 0–600 mm depth range. This leads to some limitations in Overseer's ability to simulate situations such as changing soil properties with depth, or to simulate soil moisture and drainage at other depths.

In this project we modified the soil hydrology model so that the soil is represented as a sequence of 100 mm layers, with water flowing from layer to layer. Most of the water transport equations remained largely unchanged. However, the evapotranspiration equation needed to be modified to account for the change in root density with depth in the soil.

The performance of the multi- and single-layer Overseer versions was compared over a range of soil types and rainfall conditions. The multi-layered Overseer model on average simulated less evapotranspiration than the single-layer version, resulting in the annual drainage being higher in the multi-layer model. Comparisons of the two models with measured drainage indicated that both models had similar precision, but the multi-layer model had a positive bias. Subsequent refinement of the evapotranspiration parameters reduced this bias.

With these changes, the multi-layer soil hydrology model could easily be extended down to 1,000 mm using S-map data, and potentially deeper with some assumptions, to represent deep-rooted forage crops such as lucerne. However, it should be noted that the nutrient distribution model still uses a single layer, and that the empirical relationship between drainage and nitrate leaching has only been established at 600 mm depth.

While the introduction of a multi-layer soil profile is a conceptual improvement, the Overseer model still has limitations in its ability to simulate the saturated conditions that occur in poorly drained soils, and further improvements in the soil hydrology model would be needed to address this.

Background

Soil water models range in complexity from simple water budget models to physically based models that use numerical methods to solve the highly non-linear Richard's equation (e.g. Vogeler & Cichota 2018; Pollacco, Fernández-Gálvez, Ackereet, al. 2022; Pollacco, Fernández-Gálvez, Channa, et al. 2022). The choice of method will depend on the purpose of the model (i.e. the question it is trying to answer) and the availability of suitable input data and computing resources.

Overseer currently models soil water in pasture by treating the top 600 mm as a single layer (Wheeler 2021) based on the water balance model of Porteous et al. (1994). Soil water contents at saturation, field capacity, and wilting point for the layer are calculated using soil data from 0 to 300 and 300 to 600 mm layers, which are then aggregated. Separate empirical models are used to calculate the soil moisture in the 0–100 mm layer for the purposes of calculating an evaporation modifier and the soil moisture and drainage to 300 mm for the DCD[1] sub-model. While Overseer reports annual outputs, the hydrology sub-model operates on a daily time-step.

Shepherd (2019) compared the soil hydrology model in Overseer with another single-layer soil hydrology model (Woodward et al. 2001) and with measured drainage data from 33 sites. There was a good correlation between the measured annual drainage and the Overseer estimates, although the agreement was worse for the high drainage sites. Unfortunately, Overseer was run using either monthly or annual rainfall data and an estimated daily rainfall pattern rather than actual daily rainfall data. This makes it difficult to ascertain the degree to which any lack of fit is due to differences between the assumed and actual rainfall patterns or some other shortcoming in the model.

In this project we looked at implementing a multi-layer tipping-bucket model as an initial step to improve the accuracy of the single-bucket hydrology model. In a tipping-bucket model, the soil is divided into a number of horizontal layers, and water from one layer drains into the next lower layer as the soil layer exceeds field capacity. This allows both the simulation of different degrees of soil saturation down the profile and for changes in the soil properties with depth (where data are available). Note that this is a simplification of the physical process, as water still drains when soil moisture is below field capacity and can move upwards by capillary motion.

The modified model was then tested by comparing it with the single-layer model and measured data. However, as drainage measurements tend to focus on well-drained soils, we conducted 'sensibility' tests to examine the model behaviour over a wider range of soil types.

It should be noted that the movement of nitrogen and other nutrients was not considered as part of this project. Neither was the interaction of the soil hydrology model with other components of Overseer. These aspects would need to be investigated before implementing any changes to the Overseer soil hydrology model. The model modifications and testing are discussed in further detail in Giltrap et al. 2022.

Multi-layer model description

The single-layer soil hydrology model in Overseer is based on a daily water balance using a single homogeneous layer to represent the soil from 0 to 600 mm (Wheeler 2021). Each day, water inputs from irrigation and rainfall are added to the soil moisture, while losses from

[1] DCD = dicyandiamide, a nitrification inhibitor

evapotranspiration, runoff, and drainage are subtracted. Single values for the field capacity, wilting point, and saturated conductivity (k_{sat}) are used. Overseer uses separate empirical calculations to calculate the soil moisture content over 0–100-mm and 0–300-mm depths, which are used in the evaporation and DCD drainage calculations, respectively.

A simple multi-layer model was implemented by modifying the soil hydrology model to represent the soil water in the top 600 mm as a series of connected layers of 100 mm thickness, with layer-specific data used for field capacity and wilting point (where available).

The calculations of water inputs and outputs largely used the same methods as Wheeler (2021), with the following differences.

- Rainfall and irrigation inputs were added to the top layer.
- Surface runoff was subtracted from the incoming water.
- For layers beneath the surface, the water input was equal to the drainage from the layer above.
- Drainage for each layer was calculated after the incoming water had been added.
- Evapotranspiration was modified using the method of Brown et al. (2009) to account for the depth distribution of transpiration losses.
- The soil moisture for 0–600-mm depth was calculated by summing the soil moisture of the individual layers.
- The drainage loss at 600 mm is equal to the drainage from the bottom layer.

The soil moisture for the layered model was calculated as:

$$SM_{L,t} = SM_{L,t-1} + DailyInput_{L,t} + DailyIrrigation_{L,t} - AET_{L,t} - ROSurface_{L,t} - ROdrain_{L,t} \quad (1)$$

where:

SM_{Lt} is the soil moisture in layer L at time t (mm)
$DailyInput_{L,t}$ is the daily input from rainfall and snowmelt for L = 1, or from drainage from higher soil layers for L > 1
$DailyIrrigation_{L,t}$ is daily irrigation ($mm \cdot d^{-1}$) for L = 1, or 0 for L > 1
$AET_{L,t}$ is the actual evapotranspiration from layer L ($mm \cdot d^{-1}$)
$ROsurface_{L,t}$ is the runoff from the surface for L = 1, 0 otherwise ($mm \cdot d^{-1}$)
$ROdrain_{L,t}$ is drainage from layer L ($mm \cdot d^{-1}$).

The soil layers are defined for all soils as: 1 = 0–100 mm, 2 = 100–200 mm, 3 = 200–300 mm, 4 = 300–400 mm, 5 = 400–500 mm, 6 = 500–600 mm.

Modification of evapotranspiration calculation

Most of the terms in Equation (1) were calculated using the same methods as the single-layer model (Wheeler 2021). However, the transpiration process needed to be updated to reflect the fact that transpiration losses will tend to be higher in the upper soil, where root densities are higher compared to the deeper soil levels. This affects the $AET_{L,t}$ term, as the actual evapotranspiration from each layer is the sum of the actual evaporation and transpiration.

Evaporation is calculated using the same method as Wheeler (2021). However, it is assumed that all evaporation losses are removed from layer 1.

$$Evaporation_L = \begin{cases} Max\left(\left(Min\left(PET \times (1 - cover), SM_L - SM_{L.wp}\right)\right), 0.1 \times PET \times (1 - cover), L = 1\right) \\ 0,\ L > 1 \end{cases} \quad (2)$$

where:

cover is a term representing the monthly crop cover

$SM_{L,wp}$ is the soil moisture for layer L at the wilting point.

Transpiration is modified using the method of Brown et al. (2009), where transpiration demand is met starting at the top layer and working downwards according to the available water and plant root density in each layer.

The total transpiration demand is given by:

$$TotTranspDemand = PET - \sum Evaporation_L \quad (3)$$

where:

PET is the potential evapotranspiration

$Evaporation_L$ is the actual evaporation from layer L.

The transpiration demand from any given layer is the total transpiration demand minus the sum of the actual transpiration from higher levels.

$$TranspDemand_L = \begin{cases} TotTranspDemand,\ L = 1 \\ TotTranspDemand - \sum_{l=1}^{L-1} Transp_l, L > 1 \end{cases} \quad (4)$$

where:

$Transp_l$ is the actual transpiration from layer *l* (mm).

The actual transpiration from each layer is calculated by:

$$Transp_L = \begin{cases} 0,\ SM_L \leq SM_{L,wp} \\ Min\left(kl_L\left(SM_L - SM_{L,wp}\right), TranspDemand_L\right), SM_L > SM_{L,wp} \end{cases} \quad (5)$$

where:

kl_L is the water extraction coefficient representing the proportion of the available water that can be extracted each day.

We used the model of Teixeira et al. (2018), modified to include the effect of root depth (H. Brown, pers. comm.) to calculate the value of kl_L with depth.

$$kl_z = \begin{cases} kl_0,\ z \leq z_0 \\ kl_0 exp\left(-\lambda_{kl}\frac{z - z_0}{RootDepth - z_0}\right),\ z_0 < z < RootDepth \\ 0,\ z \geq RootDepth \end{cases} \quad (6)$$

where:

kl_z is the value of *kl* (dimensionless) at depth z (mm)

kl_0 is the value of *kl* at the soil surface

λ_{kl} is the decay constant for *kl* with depth

RootDepth is the root depth (in mm)

z_0 is the depth to which *kl* is constant (assumes $z_0 < RootDepth$).

Equation (6) gives the value of *kl* at a point depth in the soil. This was modified to give the average value of *kl* over a soil layer of any thickness. For a soil layer ranging from depth z_1 to z_2 ($z_1 < z_2$):

$$kl_{layer} = \begin{cases} kl_0,\ z_1, z_2 \le z_0 \\ \frac{kl_0}{z_2 - z_1}\left(z_0 - z_1 + \frac{RootDepth - z_0}{\lambda_{kl}}\left(1 - exp\left(-\lambda_{kl}\frac{z_2 - z_0}{RootDepth - z_0}\right)\right)\right),\ z_1 \le z_0 \le z_2 \le RootDepth \\ \frac{kl_0}{z_2 - z_1}\frac{RootDepth - z_0}{\lambda_{kl}}\left(exp\left(-\lambda_{kl}\frac{z_1 - z_0}{RootDepth - z_0}\right) - exp\left(-\lambda_{kl}\frac{z_2 - z_0}{RootDepth - z_0}\right)\right),\ z_0 \le z_1 < z_2 \le RootDepth \\ \frac{kl_0}{z_2 - z_1}\frac{RootDepth - z_0}{\lambda_{kl}}\left(exp\left(-\lambda_{kl}\frac{z_1 - z_0}{RootDepth - z_0}\right) - exp(-\lambda_{kl})\right), z_0 \le z_1 \le RootDepth \le z_2 \\ \frac{kl_0}{z_2 - z_1}\left(z_0 - z_1 + \frac{RootDepth - z_0}{\lambda_{kl}}(1 - exp(-\lambda_{kl}))\right), z_1 \le z_0 \le RootDepth \le z_2 \\ 0,\ z_1, z_2 \ge RootDepth \end{cases} \quad (7)$$

Model validation

Lysimeter data

The performance of the single-layer and multi-layer Overseer models was tested using the experimental drainage data set used by Shepherd (2019). These data consisted of 33 measurements from 19 lysimeter/small plot experiments and included both irrigated and non-irrigated systems. Figure 1 shows the distribution of the model errors (defined as $\frac{Drainage_{model} - Drainage_{observed}}{Drainage_{observed}} \times 100\%$). Both models had similar precision (standard deviation of the errors), but the initial parameterisation of the multi-layer model (Fig. 1b) had a bias of 18%, indicating a tendency to overestimate drainage, while the single-layer model (Fig. 1a) had a bias of only 2%. The initial set of transpiration parameters used in the multi-layer model were based on Texeira et al. (2018) and tended to underestimate transpiration losses relative to the single-layer model. This then led to an overestimation of drainage. These parameters were subsequently improved (R. Cichota, pers. comm.), resulting in a bias of 4% (Fig. 1c). Both sets of transpiration parameters are given in Table 1.

Table 1. Parameters for the transpiration model for ryegrass.

Parameter	Original	Revised
Maximum root depth (mm)	600	1,500
kl_0	0.11	0.1
z_0 (mm)	150	150
λ_{kl}	4.5	4.5

Note: Original parameters derived from Texeira et al. (2018); revised parameters from R. Cichota (pers. comm.)

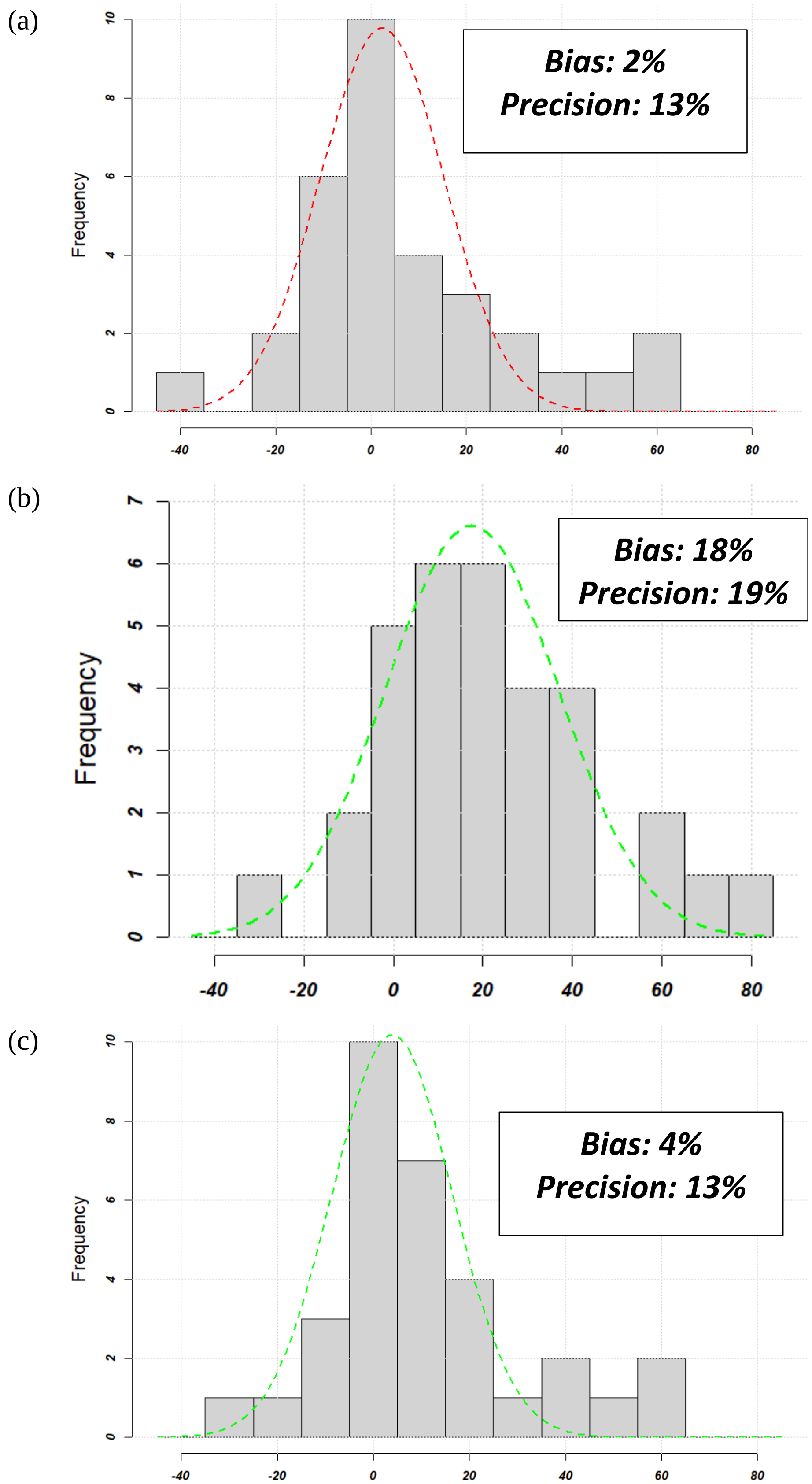
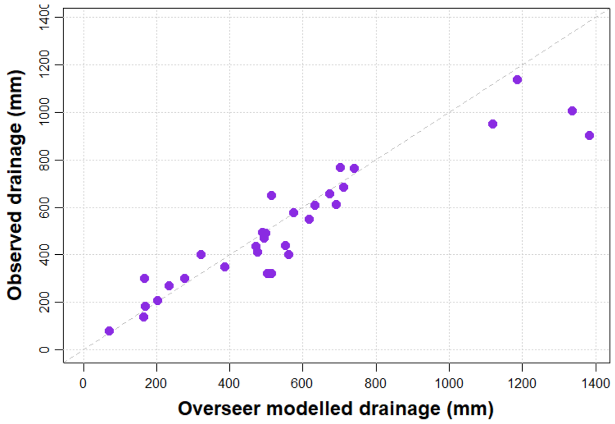
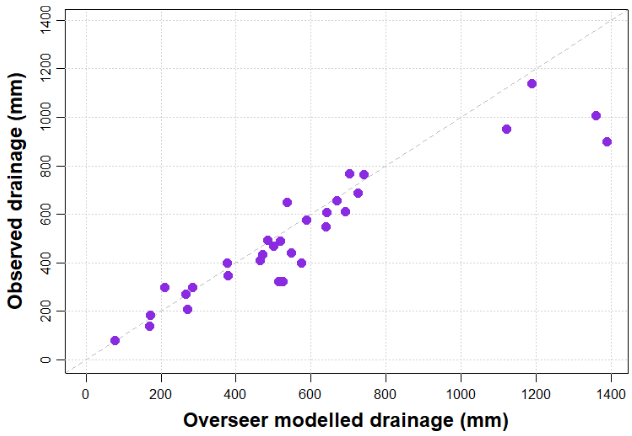


Figure 1. Distribution of model errors for annual drainage using observations from the lysimeter/small plot experiments. (a) single-layer Overseer (current version), (b) multi-layer model (with original parameterisation), (c) multi-layer Overseer (revised parameterisation).



(a)



(b)

Figure 2. Observed vs modelled annual drainage using (a) single-layer Overseer (current version) and (b) multi-layer Overseer (revised parameterisation).

Figure 2 shows the observed drainage plotted against the modelled drainage for both the current single-layer and (revised) multi-layer Overseer simulations. There is good agreement between the observations and both models, except for the observations where the drainage observed was >800 mm, where Overseer over-predicted the drainage.

Sensibility testing

Both the single-layer and multi-layer versions of Overseer compared well to the experimental drainage observations. However, the experimental data don't cover the full range of soil types used in New Zealand pastures. For the sensibility testing we defined six qualitative behaviour classes that cover the range of drainage behaviours and examined the model simulations to see if they showed the expected qualitative behaviour.

Figure 3 shows the soil moisture from 0 to 600 mm for soils from each of the behaviour classes simulated using the multi-layer soil hydrology model under three different rainfall scenarios: dry = 429 $mm \cdot y^{-1}$, medium = 954 $mm \cdot y^{-1}$, and wet = 1,643 $mm \cdot y^{-1}$.

In all cases the soil moisture remained below field capacity for the whole year. While this behaviour may occur in well-drained soils, for poorly drained soils one would expect to see periods where the soil was above field capacity, particularly in high-rainfall years.

One possible explanation for this is that the saturated conductivity (k_{sat}) values used in Overseer are too high for poorly drained soils. Overseer currently sets k_{sat} based on the soil drainage class. Several reports (e.g. Horne 2014; Pollacco et al. 2014) have suggested using lower k_{sat} values, particularly for poorly drained soils. Our sensibility tests support this.

Another potential issue is the treatment of impermeable layers. At the moment Overseer treats water that reaches an impermeable layer as immediately drained. In reality it may drain very slowly and therefore remain in the soil profile for a longer time. While this might not affect the annual drainage, it could have impacts on monthly drainage and on other processes such as runoff, transpiration, and denitrification.

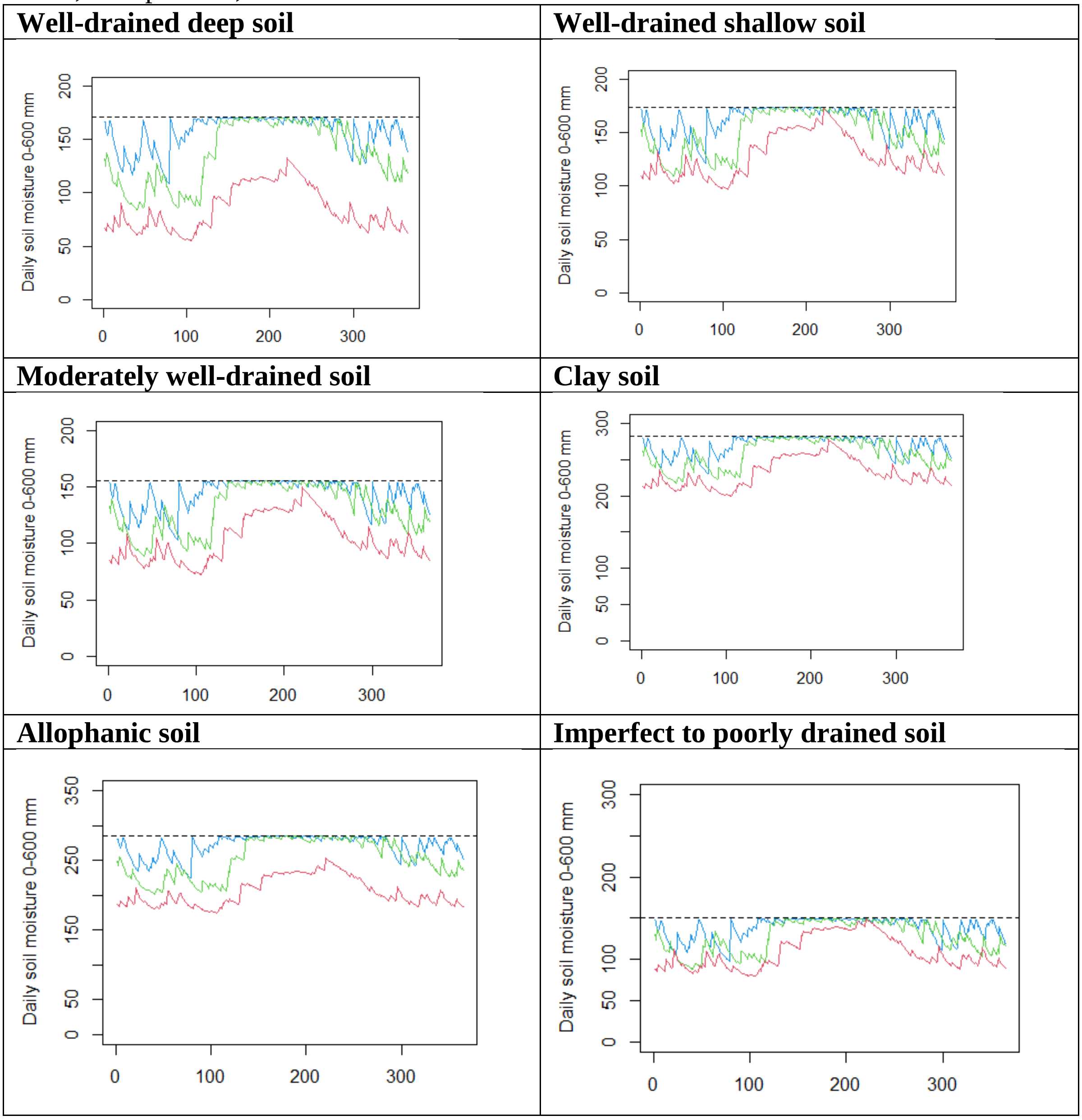


Figure 3. Simulated soil moisture from 0 to 600 mm for soils from each of the behaviour classes, simulated using the multi-layer soil hydrology with three climate scenarios: red = dry (429 mm·y^{-1}), green = medium (954 mm·y^{-1}), and blue = wet (1,643 mm·y^{-1}) rainfall). Dashed line indicates field capacity.

Extending the soil hydrology model below 600 mm

The multi-layer soil hydrology model can easily be extended to depths below 600 mm simply by increasing the number of layers simulated. However, at this stage the nutrient transport model is limited to 600 mm. S-map data are available down to 1,000 mm (Lilburne et al. 2012), but data for lower depths are rare. However, S-map data could be extended down to 1,500 mm by extending the properties of the lowest functional horizon down to this depth. This method assumes the soil depth is at least 1,500 mm and would not account for the presence of an impermeable layer or an increase in the proportion of gravels at depth. This might not be an unreasonable assumption for soils used to grow deep-rooting plants.

Summary and future directions

The Overseer soil hydrology model was adapted from a single 0–600 mm layer model to a multi-layer model. This required changing the transpiration model to account for the decrease in transpiration with depth in soil. The multi-layer soil model had a similar performance to the current single-layer Overseer model when tested using experimental drainage from the farmlet data set. However, the multi-layer model performance was sensitive to the transpiration parameters used. The advantage of the multi-layer soil model is that it enables greater flexibility to simulate drainage and soil moisture at different depths, and means that the soil properties can vary with depth (where data are available). It also makes it easier to extend the model below 600 mm to simulate deep-rooting plants.

The nutrient transport model still uses a single 0–600 mm layer. The current nitrogen-leaching simulation uses an empirical model that is specific to leaching at 600 mm (Wheeler 2018a, b). Converting this to a multi-layer model would require additional work to develop a model that could be applied at different depth ranges.

The sensibility testing showed that the Overseer model (both single- and multi-layer versions) had some limitations in simulating soil moisture on non-well-drained soils. It has been suggested that the default values for k_{sat} for poorly drained soils are too high, and this is an area where further model improvements could be made.

While both the single- and multi-layer versions of Overseer produced similar results for drainage at 600 mm, there are likely to be difference in the simulated soil moistures, as the multi-layer model allows the soil moisture to vary with depth while the single-layer model assumes uniform soil moisture. This could affect other processes that rely on soil moisture (e.g. denitrification), so further testing is required to understand the full implications of switching Overseer to a multi-layer soil hydrology model.

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