Simulation of Perched Watertables in a Duplex Soil

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Abstract Duplex soils cover about 60% of the agriculture region of Western Australia. They commonly are sands overlaying slow draining clayey subsoils. Winter rainfall often causes a perched watertable to develop on the clayey subsoil, affecting drainage, runoff, soil aeration, soil nitrogen and hence crop growth. A multi-layer cascading type soil water module was modified to simulate the dynamics of a perched watertable in a duplex soil. A wheat crop module was extended to account for growth effects by aeration deficit. These modules, together with soil nitrogen and residue modules were linked within APSIM (Agricultural Production Systems Simulator) model to simulate wheat growth, yield, soil water and soil N. A macroflow conductivity parameter was introduced to the soil water module, to control the flow of water through macropores. The reduction of macroflow conductivity at the clayey subsoil leads to a backup of water at the sand - clay interface, causing occurrence of a perched watertable. Subsequent drainage of water from the profile depends on macroflow and the general soil water conductivity. If a perched watertable enters into the rooting zone, root growth is reduced. After a period of time, leaf growth and rooting depth will be reduced and only a few centimetres of roots survive under aeration deficit. The simulated consequences of perched watertable on drainage, runoff, denitrification, root depth and grain yield are discussed.

1. INTRODUCTION

Waterlogging is common in many agricultural regions worldwide (Kozlowski, 1984) with substantial adverse effects on crop growth (eg., Belford *et al.*, 1985; Meyer and Barrs, 1988). In Western Australia, about 60% of the crop production occurs on yellow or yellow-grey duplex soils (Turner, 1992), comprising the Dy series of Northcote *et al.* (1975). The soils are characterised by a shallow sandy or loamy A horizons, which overlie yellowish clayey subsoils. The clay subsoil is often compacted and poorly drained. The concentration of rainfall in the winter period on these duplex soils results in a frequent perching of a watertable above the clay subsoil which causes major limitations to crop production (eg. Turner, 1992; Belford *et al.*, 1991). Field studies have been conducted to improve wheat production in this environment, but results were always season and site specific (eg. Belford *et al.*, 1991; Gregory *et al.*, 1992). As crop models have been used to optimise management practices under variable environments (Van Keulen and Seligman, 1987; Stapper and Harris, 1989; Keating *et al.*, 1991), the application of a simulation model may be useful in extrapolating results from these experiments.

The APSIM wheat model consists of crop growth, soil water, nitrogen and residue modules linked within the Agriculture Production Systems SIMulator APSIM (McCown *et al.*, 1996) and enables interactions between growth, soil water, N and plant residues to be simulated. To date, little effort has been given to accounting for perched watertables and the effects of aeration deficits on crop growth within the APSIM modules

The objective of this research was to modify the APSIM water balance and wheat modules to simulate the time course of a perched watertable on a duplex soil and to take into account aeration deficit on crop growth.

2. METHODS

2.1 Model

APSIM is a software tool that enables sub-models (or modules) to be linked to simulate agricultural systems (McCown *et al.*, 1996). Four modules, eg. wheat crop (NWHEAT), soil water (SOILWAT), soil N (SOILN) and residue (RESIDUE) are most relevant to the simulation of wheat-based cropping systems. NWHEAT, SOILWAT and SOILN have evolved from experience in Australia with the CERES crop and soil models (Ritchie *et al.*, 1985 and Jones and Kiniry, 1986), and the PERFECT model (Littleboy *et al.*, 1992), as modified by Probert *et al.* (1995; 1997) and Keating *et al.* (1997). Probert *et al.* (1995) have developed the new residue module RESIDUE.

2.2 Soil water module

The soil water module SOILWAT simulates the vertical water movement in a layered soil system using a multi-layer cascading approach. It is based on the water balance model by Ritchie *et al.* (1985) and Littleboy *et al.* (1992) and has been described in detail by Probert *et al.* (1995, 1997).

2.3 Perched watertable

To simulate a perched watertable above a poor draining soil layer a new parameter $mwcon_i$ was introduced, describing the macroflow conductivity separately for each layer, *i*. This conductivity controls the flow rate through macropores, which is not controlled by the soil water conductivity $swcon_i$ (Probert et al., 1997) in a multi-layer cascading approach. Previously, all the vertical water flow, which was not controlled by $swcon_i$ on a daily time step passed to the next deeper layer without any time delay (eg. Ritchie et al., 1985; Probert et al., 1997). This assumed that any amount of rainfall can flow through the macropores in less than a day. With the parameter $mwcon_i$ the water flow through macropores can be restricted to a slower rate or even stopped, as in the modified CERES model for groundwater simulations (Pfeil *et al.* 1992a). In cases when $mwcon_i$ is less than 1, only a proportion of this water flows to the next layer and the remaining water fills the current soil layer eventually up to saturation. If water is left in that layer in excess of saturation, that exceeding water is distributed to the next layer above. This is repeated until all layers above the slowly draining layer are filled up to saturation. In cases when water backs up to the surface, it is added to runoff.

NO_3 and urea move according to their concentration with the flow of water (Probert *et al.* 1997). Under backing up conditions, only the net downwards flow of water moves NO_3 and urea.
The perched watertable in the profile is calculated as the proportion of the water content between drained upper limit (DUL) and saturation (SAT) in a layer, when the next layer below is saturated (Pfeil *et al.* 1992a). Perched watertables drain from the profile according to the parameters $swcon_i$ and $mwcon_i$. With this simple empirical approach the appearance and dynamics of perched watertables can be simulated in cascading "bucket" water balance models.

2.4 Wheat crop module

The wheat crop module NWHEAT describes the development and growth, water uptake, N uptake, crop N dynamics, different stress factors and stress responses of a wheat crop (Keating *et al.*, 1997). It was influenced strongly by the CERES models (Ritchie *et al.*, 1985 and Jones and Kiniry, 1986), but with substantial modifications by Keating *et al.* (1997). The modification of the active (in terms of uptake) rooting front rates included a separate control of root depth elongation and root proliferation within each soil layer. The potential root elongation rate per day (0.22 cm per °Cd) is reduced by the minimum of either a crop water deficit factor, a soil layer water content factor or a layer specific root hospitality factor. The root hospitality factors are input parameters and represent root elongation constrains due to, eg. soil diseases, soil insects, soil acidification or soil compaction. The crop module NWHEAT is describe in more detail by Keating *et al.* (1997).

Aeration deficit effects are modelled with a number of simplified assumptions based on a range of experiments on aeration deficit effects on crop growth (Cannel *et al.*, 1980; Belford, 1981; Cannel *et al.*, 1984; Belford *et al.*, 1985; Meyer and Barrs, 1988; Belford *et al.*, 1991; Thomson *et al.*, 1992; Musgrave, 1994) and other crop models simulating aeration deficit effects on root and crop growth (Lizaso, 1993; Pfeil *et al.*, 1992a).

In a first step, a soil layer aeration deficit factor AF_i with the range of (0., 1.) for each rooted soil layer *i* is calculated:

$$AF_i = \frac{SAT_i - SW_i}{SAT_i - DUL_i} \tag{1}$$

with SAT_i as the saturated soil water content, SW_i as the soil water content and DUL_i as the drained upper limit in a soil layer *i*.

If a rooted soil layer *i* is filled with water below an effective threshold ($P2_{AF}$, 0.6) for a minimum time ($P4_{AF}$, 3 days) the root system will be effected. The root depth (R_{depth}) will be reduced so that a root depth of $P3_{AF}$ (5 cm) can survive in a saturated soil layer which is next to a non-saturated layer above:

$$\text{if } AF_i < P2_{AF} \text{ for more than } P4_{AF} \text{ then}$$
$$R_{depth} = Dlayer_i - thick_i + P3_{AF} \tag{2}$$

with $Dlayer_i$ as the bottom depth of the layer *i* in the profile and $thick_i$ as the layer thickness. The root length density will then be set to zero in the saturated layers:

$$\text{if } AF_i < P2_{AF} \text{ for more than } P4_{AF} \text{ then} \quad RLD_i \text{ to } RLD_m = 0.0 \tag{3}$$

with m as the soil layer with the deepest roots.

To calculate aeration deficit on crop growth, first an aeration deficit factor $AF1$ with the range of (0., 1.) is calculated as:

$$AF1 = \left[\frac{\left(\sum_{i=1}^{m} AF_i \right)}{m} \right]^{P5_{AF}} \tag{4}$$

The parameter $P5_{AF}$ is currently set at 3.0. A crop aeration deficit factor $AF2$ is then calculated as the maximum of $AF1$ and the crop sensitivity to aeration deficit AFS with the range of (0., 1.):

$$AF2 = \max(AF1, AFS) \tag{5}$$

taking into account a reduced sensitivity of crop growth to aeration deficit from maximum sensitivity at emergence to no sensitivity during grainfilling (Figure 1).

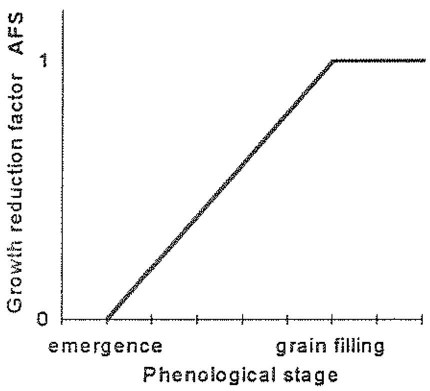

Figure 1: Crop sensitivity (AFS) to aeration deficit.

According to a different sensitivity of growth processes to aeration deficit, two aeration deficit factors are calculated, which effect after a time period of ($P6_{AF}$, 3 days) leaf area growth ($AF2_{LAI}$) and tillering ($AF2_{tiller}$):

$$\text{if } AF1 > P6_{AF} \text{ then equation 6, 7}$$
$$\text{if } AF2 < P7_{LAI} \text{ then} \quad AF2_{LAI} = AF2 \tag{6}$$

$$\text{if } AF2 < P7_{tiller} \text{ then} \quad AF2_{tiller} = AF2 \tag{7}$$

with $P7_{LAI}$ as a threshold for aeration deficit affecting LAI (1.) and $P7_{tiller}$ as a threshold for aeration deficit affecting tillering (1.).

$AF2_{LAI}$ and $AF2_{tiller}$ are components of each of the equation controlling the processes LAI and tillering respectively (Keating *et al.* 1997), in a way that the aeration deficit factor becomes only effective when it has the most growth limiting impact on the process. Note, that the current set of time requirements for root and crop growth effects ($P4_{AF}$ and $P6_{AF}$) are both at 3 days. With reducing the root depth after 3 days according to an aeration deficit only a small proportion (depends on the absolute rooting depth) of the root system remains effected by aeration deficit. Hence, if $P4_{AF} = P6_{AF}$, the largest effects on crop growth are assumed to be through the reduced root system, as less water and nutrients will be available for uptake.

3. RESULTS

The simulated perched watertable and crop growth was compared with different wheat crops grown at different sowing dates in four seasons on a duplex soil at Beverley, Western Australia (Gregory and Eastham, 1996; Gregory and Eastham, unpublished). Rainfall distribution, observed and simulated perched watertable (depth from soil surface) for the 1992 season are show in Figure 2.

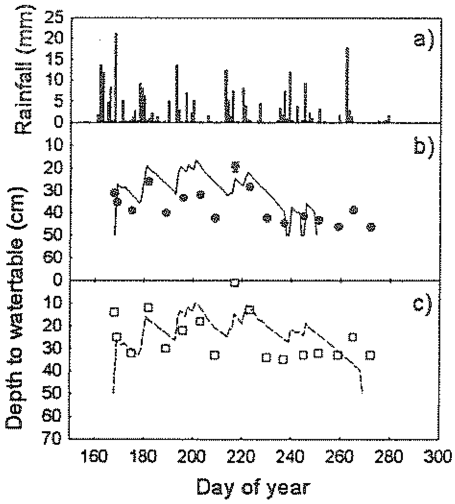

Figure 2: a) Rainfall distribution for Beverley in 1992. b) Observed average (●) and simulated (——) ($swcon_i$ = 0.14) perched watertable. c) Observed maximum (□) and simulated (– – –) ($swcon_i$ = 0.11) perched watertable.

For these simulations, $mwcon_5$ (40-50 cm) was set to zero, resulting in water flowing through this layer only according $swcon_5$. The soil water conductivity was set to 0.14 for the simulation in Figure 2b and to 0.11 for the simulation of the slower draining profile in Figure 2c, to reproduce the observed average (average of 50 replicates) and the observed maximum (highest or closest to soil surface observed watertable, due to low soil water conductivity) depth of a perched watertable, respectively. Whereas the first appearance of the perched watertable was simulated well, difficulties occurred with simulating the actually depth of the watertable to the surface and the drop out of the watertable later in the season. For the following simulations the parameter $swcon_5 = 0.11$ was used.

Figure 3 shows the annual rainfall and simulated perched soil watertable depth above 30 cm (cumulative daily soil excess water above 30 cm below soil surface - SEW_{30}, after Belford *et al.* 1990) for the period April to October between 1911 and 1990 at Beverley. The average April to October rainfall is 352 mm, varying between 151 and 565 mm. This variation in rainfall caused simulated perched watertables being between 0 and 2893 SEW_{30}.

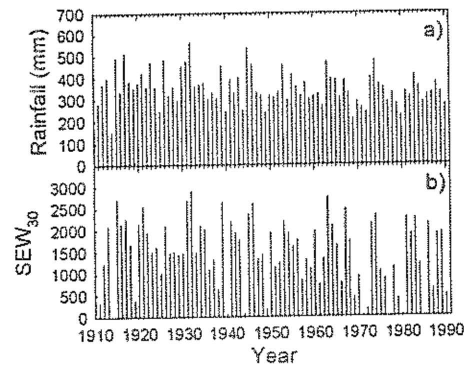

Figure 3: a) Cumulative yearly rainfall for Beverley from 1911 to 1990. b) Cumulative depth of perched watertables above 30 cm soil depth (SEW_{30}, Belford *et al.* (1991)).

Frequently perched watertables in a duplex soil have a large impact on the soil water balance and some soil nitrogen processes (Table 1). The simulations without and with a perched watertable have shown, that drainage (below 70 cm) was reduced by a perched watertable, but surface runoff increased substantially and denitrification increased from an average of 1 kg N/ha to 6 kg N/ha (for the 0 to 130 cm soil profile).

When the perched watertable reaches into the advancing root system of a crop, root depth growth stops or the root system will even be reduced. Root depth increase with and without a simulated aeration deficit affecting root growth is shown for Beverley in 1992 in Figure 4. Note the restriction on root depth between DOY 180 and 260 associated with a simulated watertable between 10 and 30 cm from the surface.

Table 1: Simulation results without a watertable (A) and with a watertable (B). Drainage below 70 cm, denitrification for a 0-130 cm soil profile. Duplex soil, Beverley, 0.8% organic C in 0-10, wheat after lupins, no N fertiliser application.

	Drainage (mm)	Runoff (mm)	Denitrification (kg N/ha)
A			
Range	0-316	0-35	0-1
Mean	123	5	1
B			
Range	0-114	0-245	0-12
Mean	78	48	6

A reduced root system can have profound effects in years with terminal drought, when a reduced rooting depth means less water uptake from the deeper soil profile. The cumulative probability distribution for grain yields i) without a perched watertable, ii) with a perched watertable but without aeration deficits and iii) with a perched watertable plus aeration deficit effects on crop growth are shown in Figure 5.

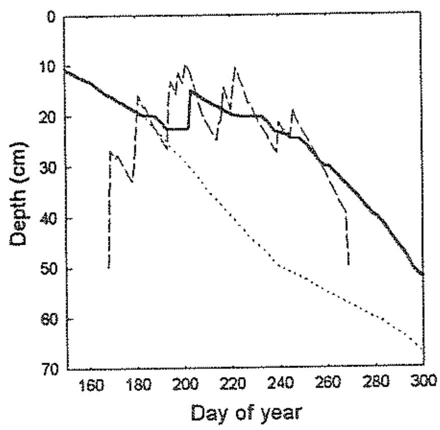

Figure 4: Simulated perched watertable (— — —) for a duplex soil at Beverley, 1992, with (———) and without (··········) aeration deficit responds.

The simulations with a perched watertable but without aeration deficit effects on root growth resulted in a slightly larger grain yield than the simulations without a perched watertable. Simulating a perched watertable and its effects on root and crop growth caused an average yield reduction of 0.45 t/ha.

4. DISCUSSION AND CONCLUSIONS

Some simple modifications to soil and crop modules in APSIM have enabled watertables and their major effects on the crops and soil system to be simulated.

The first appearance and subsequent presence of the perched watertable was simulated reasonably on the Beverley data sets. Simulated depth to the top of the watertable was generally within 10-15 cm of that observed in piesometers.

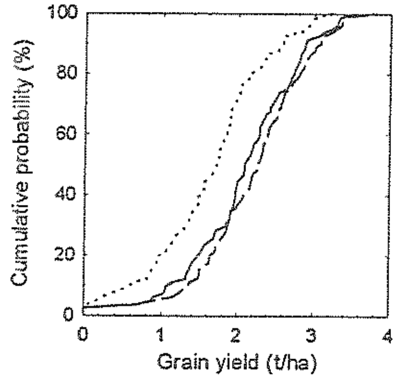

Figure 5: Simulated cumulative probability distribution for grain yields on a duplex soil at Beverley, without a perched watertable ($mwcon_5$ = 1.0; $swcon_5$ = 0.11) (——), with a perched watertable ($mwcon_5$ = 0.0; $swcon_5$ = 0.11) but without aeration deficit effects on root and crop growth (— — —) and with a perched watertable ($mwcon_5$ = 0.0; $swcon_5$ = 0.11) plus aeration deficit effecting root and crop growth (··········).

A simular result was observed by Pfeil *et al.* (1992b) with a similar approach. Regardless of these small differences in predicted and observed watertable height it was possible to accurately simulate the effects of the perched watertables on crop growth (Asseng *et al.* 1997).

The sensitivity of crop growth to rooting depths has already been highlighted for Western Australian wheat growing environments (Asseng *et al.* 1995). These results again stress the importance of more accurate simulations of root systems in depth and time for crop and grain yield predictions.

Consequently, the modified APSIM model is now much better suited to the analysis of wheat production systems in situations that exhibit waterlogging phenomena. Both, management issues, like sowing date, rate and timing of fertiliser application, choice of genotypes as well as breeding issues, like selecting for different sensitivities to aeration deficit of genotypes (Thomson *et al.*, 1992) can be now investigated by the model for wheat farming on waterlogging soils. However, further testing will be needed for the description of waterlogging effects on root growth, biomass production and grain yield, especially with data from other sites. Additionally, the effect of a perched watertable on denitrification will require more testing with measured field data.

The rather extensive number of introduced parameters allows currently various sensitivity analysis. However, some of them will be taken out or hard wired in a later stage of development to further simplify the model.

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