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Modelling of Water and Solutes in Permanent Raised Beds

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Abstract:

Permanent raised beds (PRB) are an agricultural cultural method that can improve crop productivity and health of soils. Australian Centre for International Agricultural Research (ACIAR) has funded a number of projects in developing countries but was concerned that the short-term benefits may be at the cost of long-term losses due to solute pollution of groundwater or salinisation of the beds. A modelling study was undertaken to consider the water and solute flow in raised beds in relation to the soil physical properties to improve understanding of the PRB system. HYDRUS(1D, 2D/3D) was used as the modelling platform. The domain used for the simulations is shown in figure 1. The results show that a simple model for infiltration into the raised beds is useful for estimating the width of the raised bed for most soils especially if the sorptivity was measured on a trial bed. Compaction of the furrow between the beds commonly occurs due to vehicle traffic. Compaction under the furrow was simulated and this showed that water penetration horizontally was slowed as cumulative infiltration with time was reduced. However, for the same amount of cumulative infiltration the penetration horizontally was greater than when no compaction occurred. Drainage of the beds when an impermeable layer occurs in the soil shows that a simple inversion of the moisture characteristic relationship could be used to estimate the water potential profile in the bed. This also shows that for clay soils the beds must be excessively high for them to drain effectively through seepage to the furrow. The leaching of fertilizers by furrow irrigation was investigated to determine at what distance from the furrow fertilisers should be placed to reduce leaching during irrigation. This distance was shown to be soil dependent. Salinisation due to evaporation from a shallow water table is likely to occur if a saline watertable occurs at < 0.5 m in sand and < 1.5 m in loam and clay soils unless properly managed.

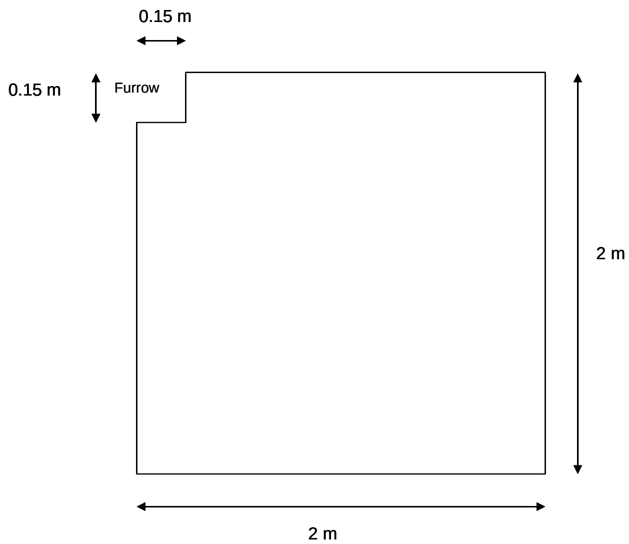

Figure 1. The domain used in the generic modelling simulations. No flow boundary conditions occur on the right hand vertical boundary and on the left hand vertical boundary below the depth of the furrow.

Keywords: *Permanent raised beds, solute transport, moisture content, infiltration, irrigation*

1. INTRODUCTION

Permanent raised beds (PRB) provide a means of increasing the crop productivity, profitability and sustainability of irrigated and rainfed cropping systems (Hobbs et al. 2008; Connor et al. 2001). Principally these improvements occur due to improved soil structure and drainage and the use of direct-drilling of crops in the beds. PRB for irrigated cropping as an element of conservation agriculture, have been utilised in Mexico, Western Asia, Southern Asia, Australia, Eastern China, parts of Africa and the Sub-continent, to improve irrigation water productivity, increase yields, reduce mechanical inputs and labour, increase fertiliser efficiency, and combat salinity and rising water tables (Peries et al. 2003; Friedrich, 2003; Hamilton et al., 2003). In rice-wheat systems of South Asia, irrigation water savings of 20-30% and significant yield increases were often reported (Ram et al. 2005; Hussein et al. 2003) and are attributed to factors such as shorter irrigation time, improved light interception and reduced water logging. Substantial yield gains and water savings have been gained from PRB in other regions such as Mexico (Sayre et al. 2005). An evaluation of PRB systems in Asia and Australia was reviewed by Roth et al. (2005).

The Australian Centre for International Agricultural Research (ACIAR) has been funding a number of PRB projects in developing nations around the world but is concerned about issues not covered by short-term studies. Several of the issues with PRB include a) are there any long-term environmental implications from the introduction of this technology, b) could the PRB be better designed, c) where should fertiliser be placed, and d) what are the interactions of PRB with climate and irrigation? Modelling of water and solute transport in PRB was seen as a way to investigate some of these issues.

The two-dimensional modelling program HYDRUS2D (Simunek, 1999) was used to simulate water and solute transport a) initially for a generic PRB to investigate the interaction of the properties of the beds with height, spacing, fertilizer placement etc, and then b) four case studies from ACIAR projects in India, Pakistan, Indonesia and China were simulated. A quasi-analytical solution for infiltration into PRB is compared with the numerical simulations from HYDRUS2D, to determine if this could provide a simple guide to estimating bed width. In this paper we concentrate on the understanding gained from the generic modelling and only consider results from each of the particular projects when this adds to the insights gained. Here we will present a synthesis of the findings of this modelling (for more details see Cook et al., 2007).

2. METHODS

Both the HYDRUS1D (Simunek et al., 1998) and HYDRUS2D/3D (Simunek, 1999) programs were used in the simulations. These solve the Richards equation for flow of water in soil:

$$\partial\theta / \partial t = -\nabla\left(k(h).\nabla h\right) - U \qquad (1)$$

where θ is the volumetric water content [L^3 L^{-3}], *k* is the hydraulic conductivity which is a function of ψ [L] the matric potential, *h* is the hydraulic head [L], *U* is a sink term [L^3 L^{-3} T^{-1}] and ∇ is the vector differential operator. The transport of solutes is convective diffusion equation which for a non-reactive and absorbed solute is:

$$\partial\theta c / \partial t = \nabla\left(\theta D \nabla c\right) + \nabla qc - Uc \qquad (2)$$

where D is the dispersion coefficient [L^2 T^{-1}], *c* is the solute concentration [M L^{-3}] and *q* is the volumetric flux density [L T^{-1}]. The domain that was used in the simulations uses the concept of symmetry of flow about the centre of the bed so that only half the bed has to be simulated (Figure 1).

2.1. Infiltration

Infiltration into the bed was simulated using HYDRUS2D for three different soil types *viz* clay, loam and sand from the data base associated with HYDRUS2D. This range of soil properties was chosen to provide the likely range of soil properties that will occur. Some field soils may still occur outside of the range of these properties. These simulations are taken as being the ‘true’ values when compared with the quasi-analytical solutions approach outlined below. The soil physical properties for these soils based on the soil moisture retention model of van Genuchten (1980) are presented in Table 1.

For the generic irrigation modelling we considered water flow to occur by furrow irrigation from a furrow at the left hand boundary of the domain. Infiltration was simulated with a constant head condition on the surface of the furrow with the head varying with the depth in the furrow (i.e. the head at the base was 0.15 m), and with the uppermost part of the furrow 0 m. The bottom boundary condition was assumed to be either free drainage, or no-flow which bound the range of possibilities. The effect of compaction in the furrow was also simulated by reducing the hydraulic conductivity of the soil under the furrow to a depth of approximately 0.1 m.

Table 1. Soil physical properties and van Genuchten (1980) parameters for soils chosen from the HYDRUS2D database. See section 3.3 for definition of α and *n*.

Soil	θ_r (m^3 m^{-3})	θ_s (m^3 m^{-3})	α (m^{-1})	*n*	K$_s$ (m s^{-1})	S (m s$^{-1/2}$)
Sand	0.045	0.43	14.5	2.68	8.35x10^{-5}	1.55x10^{-3}
Loam	0.078	0.43	3.6	1.56	2.89x10^{-5}	3.40x10^{-3}
Clay	0.068	0.38	0.8	1.09	8.35x10^{-5}	1.55x10^{-3}

These infiltration simulations were compared with a simplified model of infiltration into the furrow using the 2-parameter infiltration equations of Philip (1957). Details on the derivation of these are in Cook et al. (2007). These simple infiltration equations predict the position of the wetting front in both the vertical and horizontal plane from the furrow. They are:

$$\begin{aligned} z(t) &= \left(S\sqrt{t} + At\right)/\Delta\theta_s,\; t \le t^* = \left(S/(K_s - A)\right)^2 \\ &= \left(I^* + K_s t\right)/\Delta\theta_s,\; t > t^*, I^* = S\sqrt{t^*} + At^* \end{aligned} \tag{3}$$

where $z(t)$ is the penetration depth for a piston wetting front [L], *S* is the sorptivity (Philip, 1957) [L T$^{-1/2}$], *A* is a parameter related to saturated hydraulic conductivity (K_s [L T^{-1}]) and a good estimate is $A = 0.36K_s$, t^* is the joining time (Philip, 1987) and $\Delta\theta_s = \theta_s - \theta_n$ is the water content difference between the initial value θ_n and the saturated value θ_s. If the penetration depth required is some value *Z* related to the rooting depth of the crop, then the time for the penetration depth to reach this depth (τ [T]) is:

$$\begin{aligned} \tau &= \left[\sqrt{S^2 + 4AZ\Delta\theta_s} - S\right]^2 / 4A^2,\; \tau \le t^* \\ &= \left(Z\Delta\theta_s - I^*\right)/K_s,\; \tau > t^* \end{aligned} \tag{4}$$

The width that the wetting front will have penetrated into the bed during this time (*W*) is:

$$W = \sqrt{2\tau\lambda_c K_s / \Delta\theta_s} \tag{5}$$

where λ_c is the macroscopic capillary length scale and can be estimated from *S* K_s and $\Delta\theta$ (White and Sully, 1987).

2.2. Solutes

To determine how the placement of fertilizer would affect the loss of solutes from the beds during irrigation a layer of non-adsorbed solute was placed on the bed surface and the distance horizontally from the furrow edge to where the solute front occurs was determined. The value of *D* is taken as 0.5 m based on the domain size (Simunek et al. 1999). The simulations to consider fertilizer placement were run until drainage occurred at 2 m. This is possibly more water than should sensibly be applied in a single irrigation but since leaching of salt from the soil is also required (Cook et al., 2006) simulated irrigation is not far from the requirements and as the washout distance (X_c) is time dependent results are also applicable for less irrigation. X_c was calculated as the horizontal distance to where the concentration of solute was 99% of the initial concentration of 1mmol m^{-3}.

We also simulated evaporation from the soil surface with a saline water table at a constant depth. Three depths *viz* 0.5, 1.0 and 1.5 m were chosen for the watertable depth. From these simulations we determined the time it would take for the solutes to reach the soil surface (T1) and for the concentration at the surface to increase by 100 times that at the water table (T2). Simulations were carried out with initial concentrations of 1 mmol m^{-3} for fertilizer washout and salinisation simulations. For the salinisation simulations a constant potential evaporation rate of 5 mm day^{-1} was assumed.

2.3. Drainage

Drainage from the beds is possible through seepage from the sides of the beds as well as through the bottom of the beds. To investigate this we chose the two extreme simulations where drainage only occurred through seepage faces on the sides of the bed and where both seepage face and free drainage from the bottom of the domain occurred. The initial soil condition was saturation throughout the domain. Simulations were run for 10 days and no flow at the soil surface was assumed, so only drainage and not drying by evaporation was considered, so that only the effect of internal soil drainage could be considered.

3. RESULTS AND DISCUSSION

3.1. Infiltration

The penetration of the wetting front into the beds using the simple model gave reasonable results for the horizontal penetration (W) except for the clay soil (Fig.2c). S was initially calculated from the horizontal infiltration rate into a soil column with a head of zero at the intake surface using HYDRUS1D. The head during the HYDRUS2D simulations varied from 0.15 m to zero, so S was calculated again using an the intake head value of 0.15 m. When this latter value of S (head = 0.15 m) is used the prediction of W for the clay soil when compared to the HYDRUS2D simulations improves markedly. For the loam and sand soils the improvement was not so dramatic when S was calculated with a head of 0.15 m. The vertical penetration ($z(t)$) was calculated with the simple model compared well with the HYDRUS2D simulations with some underestimation at early times and some overestimation at long times (Fig 2def). This indicates that the simple infiltration model could be useful for design of bed width if S was measured for that soil with the intake surface head that will be applied during infiltration. After 1 day of infiltration W is greatest for the clay due to much larger value of S for this soil.

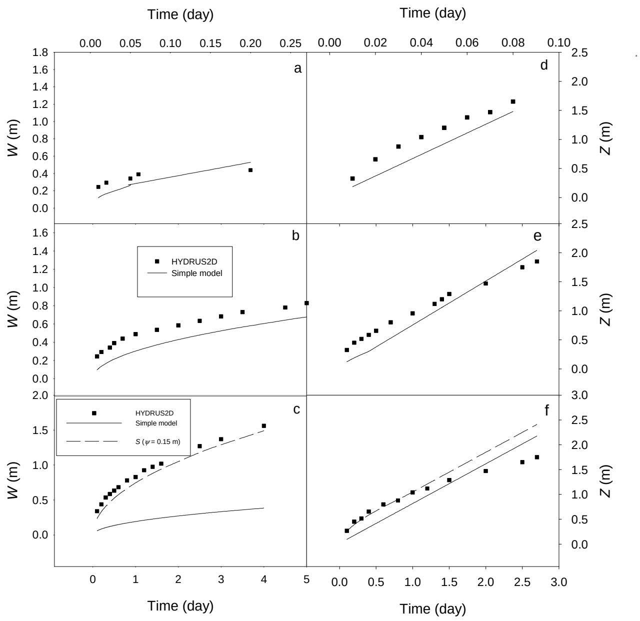

Figure 2. Penetration of wetting front horizontally into the bed from the edge of the furrow (W); a) sand, b) loam (lower time scale used), and c) clay, and the vertical penetration below the furrow (Z); d) sand, e) loam and f) clay. The second line for the clay is where a different value of S was used (see text). Note different time and length scales are used.

The effect of a compaction zone under the furrow was simulated and this showed that the penetration horizontally was slower as infiltration overall was reduced. However, for the same amount of infiltration, penetration horizontally was greater (Cook et al., 2007). This means it will take longer for the water to reach the centre of the beds when compaction of the furrow occurs, but less water will be required.

3.2. Solutes

The results showed that X_c with time were similar for the sand and loam soils (Fig 3a) but that when X_c is plotted versus cumulative infiltration (I) the clay and loam soils are similar (Fig 3b). This suggests that washout is reduced for a 100 mm irrigation event when fertilizer is placed on the surface at distances of 0.25, 0.4 and 0.45 m from the edge of the furrow, for sand, loam and clay respectively, then washout could be reduced. Thus placement of soluble agrochemicals away from the furrow edge would reduce leaching losses and possible efficacy. However, simulations for each of the application case studies showed that rainfall carried the fertilizer down the soil profile and into the flow path of the irrigation water, resulting in limited reduction in leaching from placement of the fertilizer (Cook et al., 2007). These results, however, are only for highly soluble and non-adsorbed fertilizers. There will still be an advantage in placing fertilizers, and other agrochemicals away from the furrow edge and in the plant row, particularly if dry conditions are likely after application.

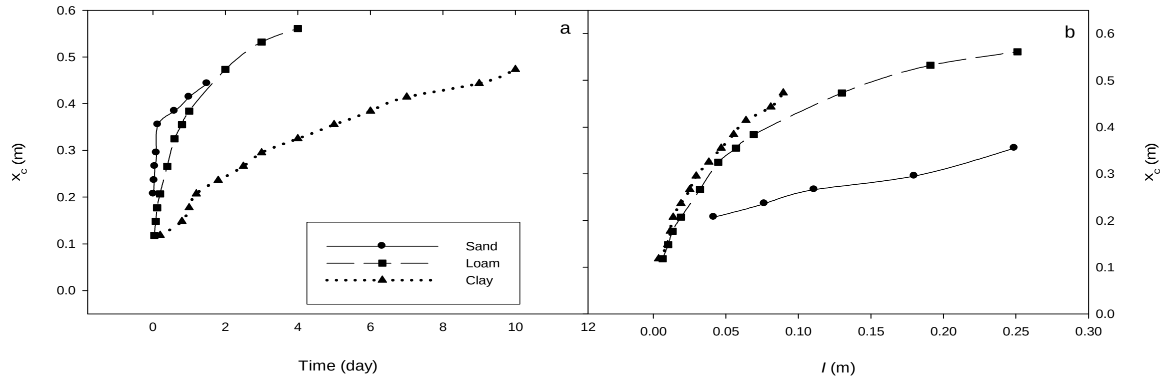

Figure 3. Washout distance (X_c) with a) time and b) cumulative infiltration (I) for sand, loam and clay soils.

The other solute simulations considered the rise of salt in the beds when a saline watertable exists. The simulations show what is now ‘conventional wisdom’ with regard to capillary rise from saline watertables (Fig 4). The results are, the water table must be close to the surface < 0.5 m for sand soils to cause salinisation, for the clay and loam soils the time for the solute to reach the surface of the bed is similar but when the watertable depth (Z_w) is < 1.5 m the time required to reach 100 mmol m^{-3} is less for the loam soil due to its greater hydraulic conductivity, and loam and clay soils require flushing events to reduce salt at least once per year when the Z_w < 1.5m.

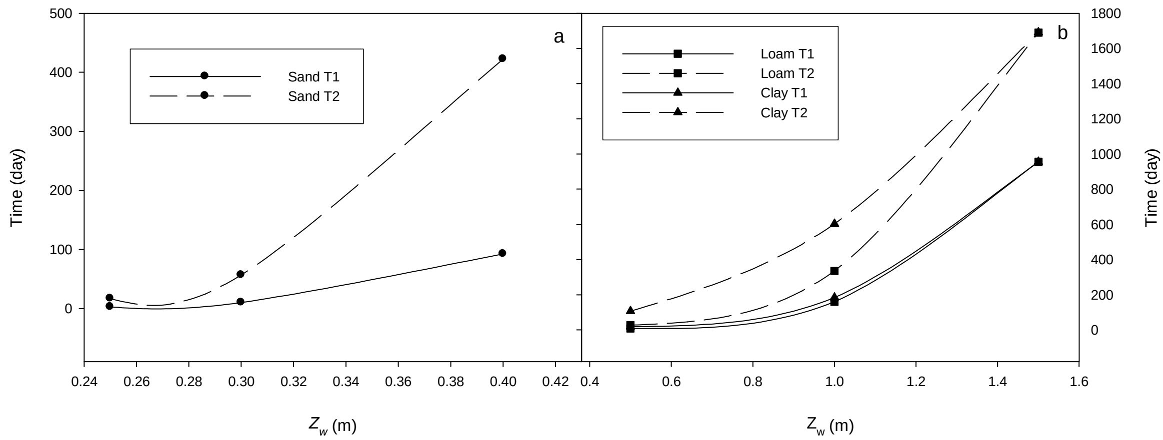

Figure 4. Depth of the watertable (Z_w) with time for solutes to reach the soil surface (T1) and increase to 100 mmol m^{-3} (T2); a) sand soil and b) loam and clay soil. Note different scales on both axis in each panel.

Initial simulations for the Indonesian and China PRB case studies indicated that solutes would accumulate up in the middle of the bed. This possible build up of salt was tested in greater detail for the China case study and found to be occurring. Irrigation management is being adjusted to prevent this becoming a long term issue. The Pakistan case study where rainfall was greater than, in particular, that in China, salts did not accumulated in the bed.

3.3. Drainage

Drainage of the beds was simulate with the domain initially saturated, and free drainage at 2 m. Results show that after 10 days approximately 70, 20 and < 2mm had drained from the sand loam and clay soils respectively (Fig 5). Even though the clay soil has the lowest matric potential through out the profile the air-filled porosity was the lowest and poor aeration problems is likely (Cook et al., 2007). This indicates that the beds are unlikely to assist with drainage of clay soils and that evaporation will be the main driver of lowering the water content in these soil types (Cook and Rassam, 2002). This is an extreme case and beds are likely to have a better structure and less likely to become anaerobic.

When the bottom boundary condition on the domain is changed to a no-flow condition the drainage of the beds can only occur by seepage through side of the bed. This leads to a situation where the watertable fixes the matric potential at zero at the base of the bed. It can be shown (Cook et al. 2007) that the water content profile in the bed can be described by:

$$Z_b = \left[p / \left(p - \Delta\theta \right)^{1/m} - 1 \right]^{1/n} / \alpha \qquad (6)$$

where α is a parameter related to the air-entry potential, n is a parameter related to the rate of change of water content with matric potential, z is the height of above the bottom of the bed and $m = n - 1/n$, $\Delta\theta = \theta_s - \theta$ and $p = \theta_s - \theta_r$, θ_r is the residual water content,. This equation is derived from the van Genuchten (1980) equation. Equation (6) was able to fit the simulated results for drainage from the beds very well (Figure 6). For $\Delta\theta$ = 0.1 the values of Z_b calculated for the three soils are 0.06, 0.37 and 91 m for sand, loam and clay soils respectively. What this shows is that beds are unlikely to be useful in providing extra drainage of the soil for clays with no structure. However, the beds are known to improve drainage on such soils possibly through the removal of surface water and the evaporative drying due to the extra surface area (Cook et al., 2007). This could allow earlier planting to occur in some climates. Thus narrow beds where the increased surface area is greater would be more useful in drying out of clay soils than wide beds.

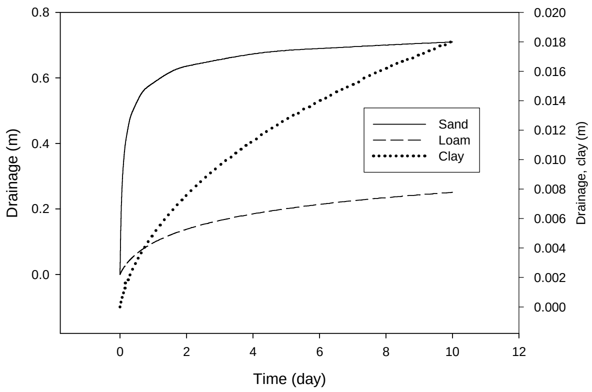

Figure 5. Cumulative drainage with time for sand, loam and clay form an initially saturated domain with free drainage on the bottom boundary.

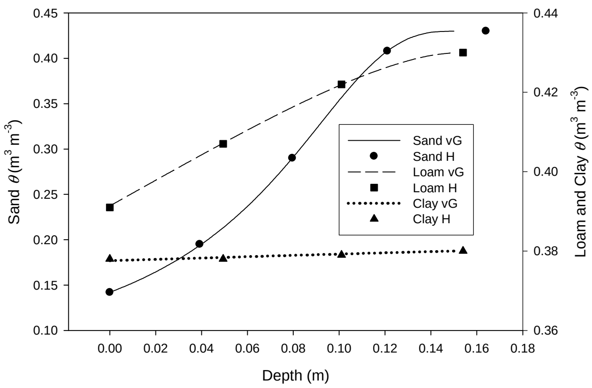

Figure 6. Comparison of water content profiles in the centre of the bed form simulation (H) with estimates using equation (5) (vG).

4. CONCLUSIONS

Our simulations give insight into the behaviour of PRB during some irrigation, solute transport and drainage scenarios. These will assist in improving the design of future more specific PRB simulations. Insights obtained include:

- An approximate infiltration equation is useful in the design of bed width, but only when the sorptivity is directly measured,
- Agro-chemicals placed on the soil surface and away from the furrow edge leach less when furrow irrigation occurs than if place up to the furrow edge, but rainfall reduces the potential effect of this placement,
- Salinisation of the soil is likely with a steady-state saline watertable at < 0.5 m in sand and < 1.5 m in loam and clay soils unless actively managed,
- PRB are unlikely to assist with drainage of unstructured clay soils but are a useful way to increase drainage in wet climates for loam and sand soils.

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