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Final report

Small research and development activity

SRA	**Modelling water and solute processes and scenarios for optimisation of permanent raised bed systems in China, India, Pakistan and Indonesia**
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1 Acknowledgments

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2 Executive summary

This report presents the results of simulations of water and solute transport in permanent raised beds (PRBs) for four case studies related to projects already funded by ACIAR, complemented by generic modelling of water and solute transport in PRBs. The work not only constitutes the simulations but also includes considerable efforts in: assimilation of data, estimation of soil properties, collation of climate data, estimation of crop rooting patterns, simulation of water and solute transport and post-processing of the simulation data. Simple models for estimating optimal bed width for wetting by furrow irrigation and drainage of beds when low permeability soils occur at the base of the beds are presented.

2.1 Generic modelling

The bed width estimation model does not work well for sands and clays but is improved if accurate sorptivity data is used in the calculations. The drainage model is shown to work well and can be used to estimate the bed height to obtain adequate aeration in the beds if seepage through the bed face is the main drainage process.

The main advantages of PRBs found in this work are;

1. good utilisation of water and fertilizers are possible if bed configuration is correct
2. beds can provide much better aeration for all soils following irrigation and especially clay soils.

The main disadvantages of PRBs that will need further investigation or ongoing scrutiny are;

3. bed width in relation to wetting of the bed
4. salt build up in the centre of beds
5. leaching of salts and agro-chemicals to the groundwater.

The numerical modelling of infiltration suggests that compaction below the furrow does not greatly increase lateral penetration of water into beds, but a no flow bottom boundary condition at the base of the modelling domain greatly enhance lateral wetting. This suggests that low permeablility layers within the soil below the bed depth could enhance lateral wetting of the beds.

Studies of solute washout from the beds suggest that for soluble agro-chemicals placement away from the furrow should occur if irrigation is not going to leach these from the beds. These simulations are only for uniform soils with irrigation from the furrow. Rainfall and layering within real soils will alter this result and this was shown in the simulations for the specific project case studies.

Salinisation is simulated to occur when the water table is within 0.5 m for sands and 1.5 m for loams and clays of the soil surface (or bottom of root zone). These results maybe useful in already salinised sands where permanent beds may offer a means to recover productive use of these soils, so long as the sand leached from them to the furrows can be managed.

2.2 India case study

In developing the input for these simulations some useful soil property estimates for the soil properties at the two sites were generated. These data were based on a combination of experimental data and estimation using pedotransfer functions.

The simulations suggest that the present width of the beds, of 0.575 m at the base, could be increased for both soils and still allow thorough wetting of the beds. Experiments in the field would be required to confirm this.

The simulations indicate excessive infiltration and drainage for the rice crops on both soils using the present flooding regime. This is particularly so for the sandy loam soil where over 10 ML/ha are estimated to infiltrate during the rice growing season.

The solute simulations show that placement of fertilizer is unlikely to make much difference with regard to fertilizer losses. This is due to rainfall transporting the solute down and into the zone where the irrigation water can 'capture' it and transported it to depth. Fertilizer losses to the groundwater during the rice cropping season could be excessive due to excessive drainage.

The simulations suggest that salt is likely to accumulate during the wheat cropping season but then be flushed out during the rice growing season.

2.3 Indonesia case study

The soil properties of these simulations were only derived from particle size distributions using pedotransfer functions. Given the sparse soil property data, this case study yielded the least reliable of any of the case study simulations.

Simulations of drainage of the beds by seepage through the bed faces indicated that in order for the air-filled porosity of the soil at the surface of the bed to be 8% the bed height would need to be ≈ 2 m. This is not a practical possibility but it indicates that aeration will be a problem in the wet season at this site unless the soil properties can be changed.

Simulations showed that furrow irrigation of the PRB bed configuration would take > 2 days for wetting to the centre of the 1.2 m wide beds, while beds half the width would wet in less that 1 day. These results indicate that furrow irrigation would not be a viable option for these soils under the given bed configuration.

Simulations showed that in order to wet the raised bed from the surface in the dry season at least three strips, one 0.2 m in width down the middle of the bed and two 0.1 m wide at the mid-point between the middle and edge of the bed, would be required on PRB configurations, but one strip 0.4 m wide down the middle of the bed would be sufficient for wavy beds. Calculations also showed that an irrigation of 18 mm would be required and for the 1.2 m wide beds this represents a volume of water of 21.6 L per one meter length of bed.

Simulations suggest for the two years used in the simulations that rice yields would be unaffected by drainage via deep drainage or seepage from all sites and bed configurations but vegetable crops would have yields reduced due to aeration problems.

The simulations suggest that insufficient water could be harvested from the beds during the wet season to meet the full irrigation of crops in the dry season. This suggests that either only limited irrigated dry season crops could be grown or other sources of water will be required.

Simulations suggest that fertilizer uptake in the wet season is best at Wakan site. Salt accumulation is possible from irrigation at the centre of beds especially for the wavy configuration during the dry season, but is likely to be flushed out in the wet season.

2.4 China case study

The soil properties data for this case study are the best of any of the projects with only the hydraulic conductivity data having to be estimated using pedotransfer functions. This means that these simulations should be the most reliable.

Simulations of the PRB project in the Hexi Corridor (Gansu Province) suggest that management of solutes, both fertilizer and salt will be critical to the success of this project. In particular salt may accumulate under the middle of the bed. An occasional 'over-topping' irrigation to displace this salt from the beds to depth may be required. Monitoring of the solute concentrations within the soil will be required and strategies need to be devised if this project is to be a long term success.

The salt that will be displaced to deep drainage in this project may also constitute a longer term problem with regard to pollution of the groundwater. Monitoring of bores should be considered as a precautionary approach.

Crop yields should be close to optimum using the present irrigation practices, assuming otherwise optimum nutrient supply and pest and disease management conditions.

2.5 Pakistan case study

Good measurements of some soil properties existed for this case study. This meant that the properties that had to be estimated with pedotransfer functions were well bounded and the soil properties presented should be sound. The hydraulic conductivity values should be close to the field values as they are based on measured infiltration or values estimated from sorptivity.

The simulations for the case study at Mardan, like the case study in China suggest that management of solutes, both fertilizer and salt will be critical to the success of this project. There is the potential for salt accumulation under the centre of the wide beds (1.3 m spacing). Simulations suggest that irrigation to displace salt to depth may be required on wide beds. The simulations for the narrow beds (1/2 width of wide beds) suggest that salt management will be easier with narrow beds as the displacement is more one-dimensional. However, longer term simulations are required to fully explore strategies. Given that the water table is relatively shallow (≈3 m below the surface) careful monitoring of both water table height and quality are required at this site. Displacement of soluble agro-chemicals to below the root zone are possible in the monsoonal maize cropping season.

Crop yields should be close to optimum if optimal irrigation practices are used on PRBs. However, even with optimal irrigation practices basin irrigation may cause a yield decline due to poor aeration post-irrigation. This shows that PRBs have an advantage for crop yield at this site.

3 Introduction

In March 2005, ACIAR sponsored an international workshop held in Griffith, NSW, to evaluate the performance of permanent raised bed (PRB) systems, making it possible for the first time to systematically assess the current situation with respect to developing PRB systems suited to a wide variety of climatic, crop, soil and socio-economic conditions. From the information assembled in the workshop proceedings (see Roth et al., 2005), a number of critical research gaps that required continued investment were identified. One of the recommended research gaps to be addressed was further work to optimise bed configuration, as this is often driven by machinery specifications rather than clearly defined optimum crop spacings and bed: furrow geometry as a function of soil hydraulic properties. As a result, design criteria for permanent beds in terms of the infiltration and drainage and a structured framework for analysis of the experimental result are not well developed. The second significant gap related to improving nutrient and solute management to optimise fertiliser placement and to minimise the risk of salt build-up. The workshop concluded that the long-term environmental consequences of these beds with respect to enhanced solute transport are not well known.

The above issues have also been identified within four ongoing ACIAR projects introducing permanent raised beds. In the course of these projects, a number of cross-cutting issues have emerged that need to be addressed to ensure permanent raised bed systems are not potentially generating a new set of environmental problems in the future, such as salt accumulation in bed centres; increased NO_3 and pesticide contamination of ground water (GW) under permanent raised bed systems as macropores get established and bypass flow can take place; insufficient leaching fractions and salt build-up in soil profiles in the arid climates (China, NW Indo-Gangetic Plain) as a result of overall reduction in irrigation applications under permanent raised bed systems. Addressing these issues is experimentally too demanding and at the same it lends itself easily to a modelling exercise.

Accordingly, the aim of this small research activity (SRA) is to underpin the sustainable development of permanent raised bed systems in Asia and Australia through collaboration with researchers leading ACIAR funded permanent raised bed system projects. This will be achieved through the following specific objectives:

- to develop design criteria for optimising bed design from analytical and numerical modelling of water and solute transport in permanent raised beds
- to design fertilizer placement strategies that maximise fertilizer usage and minimise leaching to groundwater based on modelling
- to determine whether salinisation of the beds is likely with time in some soil/bed configuration/climate/water quality scenarios.

The general approach was to utilise data collected in four ongoing ACIAR PRB projects and where the project leaders (PL) of those projects had identified a number of modelling scenarios for which they needed more in-depth modelling. These projects were:

- in India: LWR/2000/089 – Permanent beds for irrigated rice-wheat and alternative cropping systems in north-west India and south-east Australia (PL Dr Liz Humphreys)
- in Indonesia: SMCN/1999/005 – Improved soil management on rainfed vertisols in Nusa Tenggara (PL Dr Judy Tisdall)
- in China: LWR/2002/094 – Promotion of conservation agriculture using permanent raised beds in irrigated cropping in the Hexi Corridor, Gansu, China (PL Dr Jack McHugh)

- in Pakistan: LWR/2002/034 – Refinement and adoption of permanent raised bed technology for the irrigated maize-wheat cropping system in Pakistan (PL Greg Hamilton)

To achieve the above objectives, this SRA carried out case studies for each of the above projects using 2D solute and water transport modelling to evaluate the above issues using HYDRUS2D (Simunek et al., 1999). The analysis was carried out by Drs Freeman Cook and John Knight (post-retirement fellow) of CSIRO Land and Water and, who are two of Australia's leading scientists in 2D water and solute modelling. Modelling scenarios and reality checking was carried out interactively with the project leaders of the four ACIAR PRB projects, facilitated through two workshops, one at the inception of this SRA, and one towards its completion. In addition analytical modelling was carried out to develop simplified methods for calculating the width of the bed so that wetting of the whole bed will occur. Analysis of the HYDRUS 2D data along with solute transport based on the use of stream tubes was considered likely to yield some useful dimensionless variables for bed design.

This report documents the analysis framework, the modelling output and recommendations on; optimised bed geometries under different climatic and soil conditions, fertilisation regimes and placement, irrigation and bed geometries to avoid salinisation of the bed systems.

4 Simple infiltration model

A simple model for predicting the advance of a wetting front into a raised bed is developed below. This will be compared with more exact solutions of the infiltration and numerical results.

For a raised bed of rectangular section with half bed width *W* [L], initial water content θ_i and satiated water content θ_s [L^3 L^{-3}], the storage capacity (I_c [L]) to fill in a horizontal plane is:

$$I_c = W(\theta_s - \theta_i) \tag{4.1}$$

The cumulative horizontal infiltration (I_h [L]) into the bed from a free water surface on the face can be approximated by (Philip, 1957);

$$I_h = St^{1/2} \tag{4.2}$$

Where *S* is sorptivity [L T$^{-1/2}$], and *t* is time [T]. Now from this we can approximate the time to fill the bed (τ) as the time it takes for I_h to equal I_c and hence is given by:

$$\tau = [W(\theta_s - \theta_i)/S]^2 \tag{4.3}$$

The sorptivity is related to the capillary length scale (λ_c) by (White and Sully, 1987):

$$\begin{aligned} \lambda_c &= S^2/(2\Delta\theta_s \Delta K_s) \\ \Delta\theta_s &= \theta_s - \theta_i \\ \Delta K_s &= K_s - K(\theta_i) \approx K_s \end{aligned} \tag{4.4}$$

Where K_s is the saturated hydraulic conductivity [L T^{-1}] and $K(\theta_i)$ is the hydraulic conductivity at θ_i and K_s >> $K(\theta_i)$. Now substitution of eqn (4.4) in eqn (4.3) and rearranging gives:

$$W = \left(\frac{2\tau\lambda_c K_s}{\Delta\theta_s}\right)^{1/2} \tag{4.5}$$

Equation (4.5) contains two unknowns of the system τ and *W*. This could be solved by plotting a graph of τ and *W*, but there may be a better way. We assume that vertical infiltration can be estimated with (Philip, 1957):

$$I_v = St^{1/2} + At \tag{4.6}$$

We want the vertical infiltration to only penetrate to some depth, *Z*, and the penetration depth of a piston front can be estimated as:

$$z(t) = I_v/(\theta_s - \theta_i) = (St^{1/2} + At)/\Delta\theta_s \tag{4.7}$$

where *A* = 0.36 K_s is the value for a Burgers soil and is considered to be a good estimate of *A* (Philip, 1987). Then substituting *Z* for *z*(*t*) and rearranging (4.7) gives an estimate of τ:

$$\hat{\tau} = \left[\sqrt{S^2 + 4AZ\Delta\theta_s} - S\right]^2 / 4A^2 \qquad (4.8)$$

This will at least give a first order estimate of *W*.

5 Generic modelling

To investigate the general effects of the soils' properties on flow of water and solutes, simulations were carried out using three soil types *viz* sand, silt and clay chosen from the HYDRUS2D database (Schaap et al., 1998; Schaap and Leij, 1998). The soil physical properties are shown in table 5.1.

Table 5.1. Soil physical properties and van Genuchten (1980) parameters for soils chosen from the HYDRUS2D database.

Soil	θ_r (m3 m-3)	θ_s (m3 m-3)	α (m-1)	n	K_s (m s-1)	S (m s-1/2)*	D_s (m s-1/2)
Sand	0.045	0.43	14.5	2.68	8.35x10-5	1.55x10-3	5.38x10-5
Loam	0.078	0.43	3.6	1.56	2.89x10-6	3.40x10-4	1.05x10-5
Clay	0.068	0.38	0.8	1.09	5.56x10-7	3.93x10-5	5.51x10-6

*Derived for an initial matric potential of -10 m.
†Derived for an initial matric potential of -0.01 m.

The sorptivity (*S*) values in table 1 were derived by simulating water flow into a horizontal soil column. The initial matric potential was chosen as -10 m. The resulting infiltration data was regressed against $t^{1/2}$ (r^2 = 1 for all soils) and the slope is then *S* (eqn (4.1)). Similarly the desorptivity (D_s) was derived from simulation of a horizontal column of soil with an initial matric potential of -0.01m and a dry front applied at one end. The desorptivity is then derived from flux when this scales with $t^{1/2}$.

For both the simple model and the generic numerical simulations a simplified flow domain was chosen and is shown in figure 5.1. This domain and these soils will be used to investigate infiltration, drainage, placement of fertilizer and salinisation from a groundwater table.

5.1 Numerical modelling

To investigate the effects of infiltration processes into soil from the furrow both analytical (section 4) and numerical models (below) were developed. These models were used to investigate certain processes related to the infiltration of water into the soil.

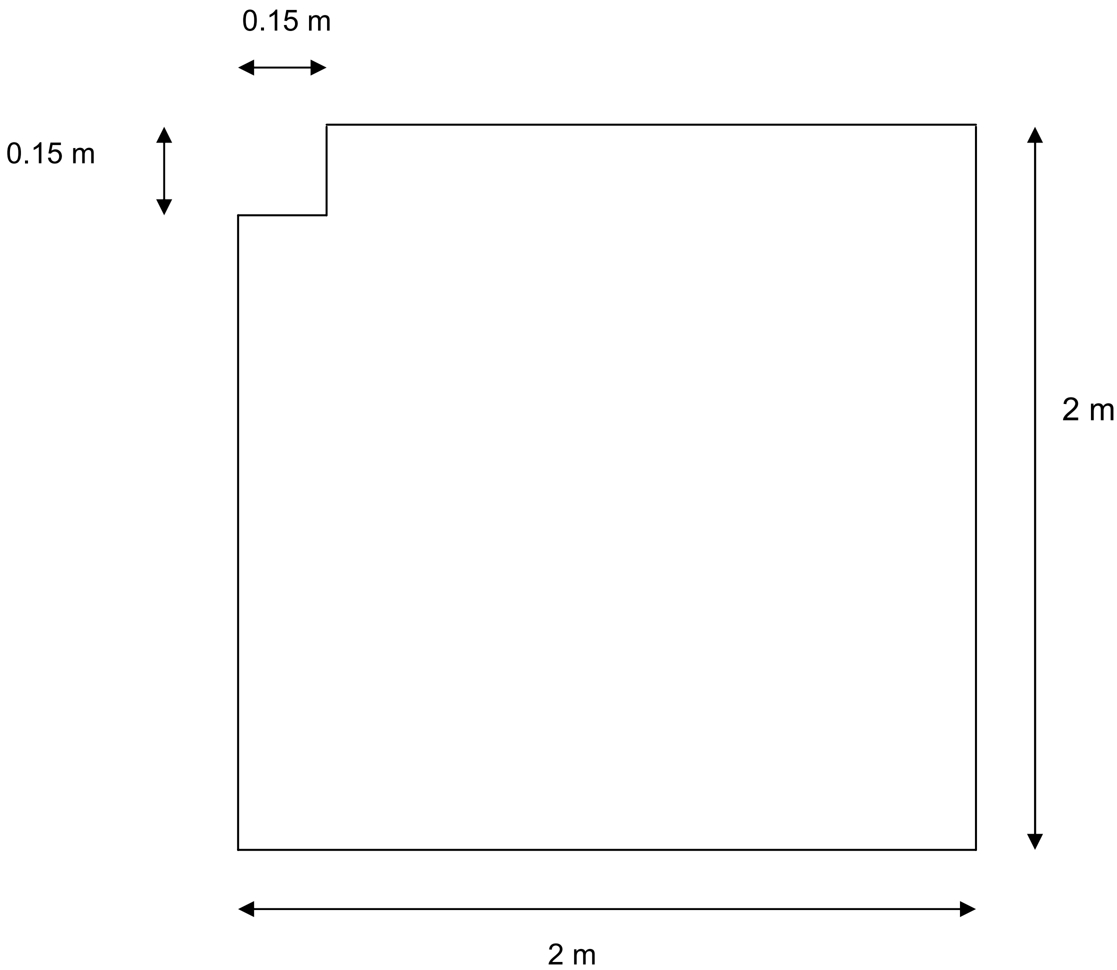

Figure 5.1. Flow domain for the generic investigations of soil effects on water and solute movement. The notch at the side is a stylised furrow.

5.1.1 Infiltration

The flow domain used in these investigations is shown in figure 5.1. The boundary conditions for the infiltration simulations were a constant pressure boundary condition on the soil in the furrow, with a head varying from 0.15 m at the bottom of the furrow and 0 at the top. The upper boundary was a no-flow boundary and the bottom boundary was either free drainage or no-flow. The latter bottom boundary condition can be considered similar to a constant watertable at depth or an impermeable layer. The initial condition was chosen as a uniform matric potential of -10 m. This was considered a reasonable value for initiation of irrigation of the beds.

The domain was chosen to be 2 m wide to allow simulations of possible bed widths to be investigated and compared and contrasted with the simple model above. The simple model does not take into account the effect of pressure on the boundary, which would be expected to result in the wetting front advance deviating from $t^{1/2}$ behaviour. The penetration depths (*W* and *Z*) were obtained from the simulations and are compared to those calculated with the simple model (figs 5.2 and 5.3). These simulations had a bottom boundary condition of free drainage.

Apart from for the sand *W* was underestimated by eqns (4.1) and (4.2). One reason for this may be that S was calculated from infiltration with the intake boundary at a potential of zero. *S* was calculated for the clay soil with the intake boundary potential increased to 0.15 m and *S* increased to 1.52×10^{-4} m s^{-1}. This had the effect of improving the simple models prediction of *W* in the clay soil. Recalculating *S* in this way would be likely to improve the comparison for the loam soil but would exacerbate the overestimation for the sand.

The simple model (figure 5.3) underestimates *Z* for all soils when the values of *S* in table 5.1 are used. When *S* for the clay was increased as described above the comparison between the simple model and the simulations was good for the clay. Recalculating *S* in this way would be likely to improve the comparison for the loam and sand soil but would exacerbate the overestimation of *W* for the sand. It would appear that the simple model is highly sensitive to the sorptivity value and as such may have limited utility.

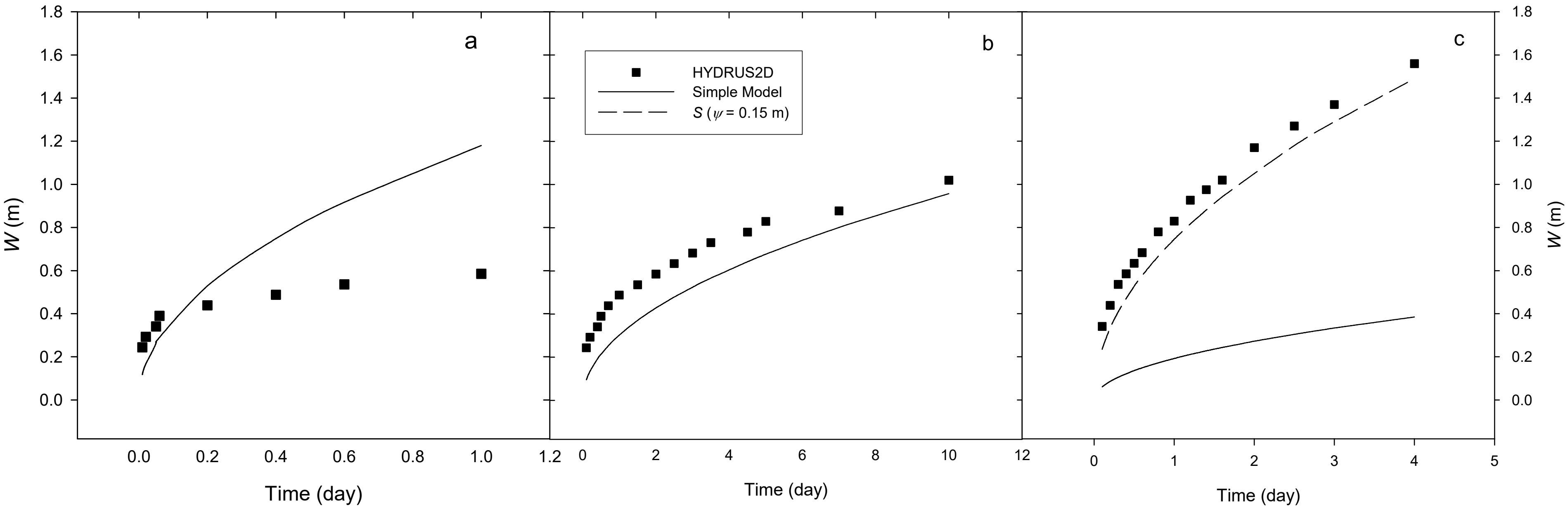

Figure 5.2. W (the horizontal penetration of water into the bed) with time for a) sand, b) silt and c) clay soil. The data points are derived from numerical simulation and the lines are calculated with eqns (4.1) and (4.2). The dashed line was calculated with S calculated for simulated infiltration into a horizontal clay column with a potential on the intake boundary of 0.15 m.

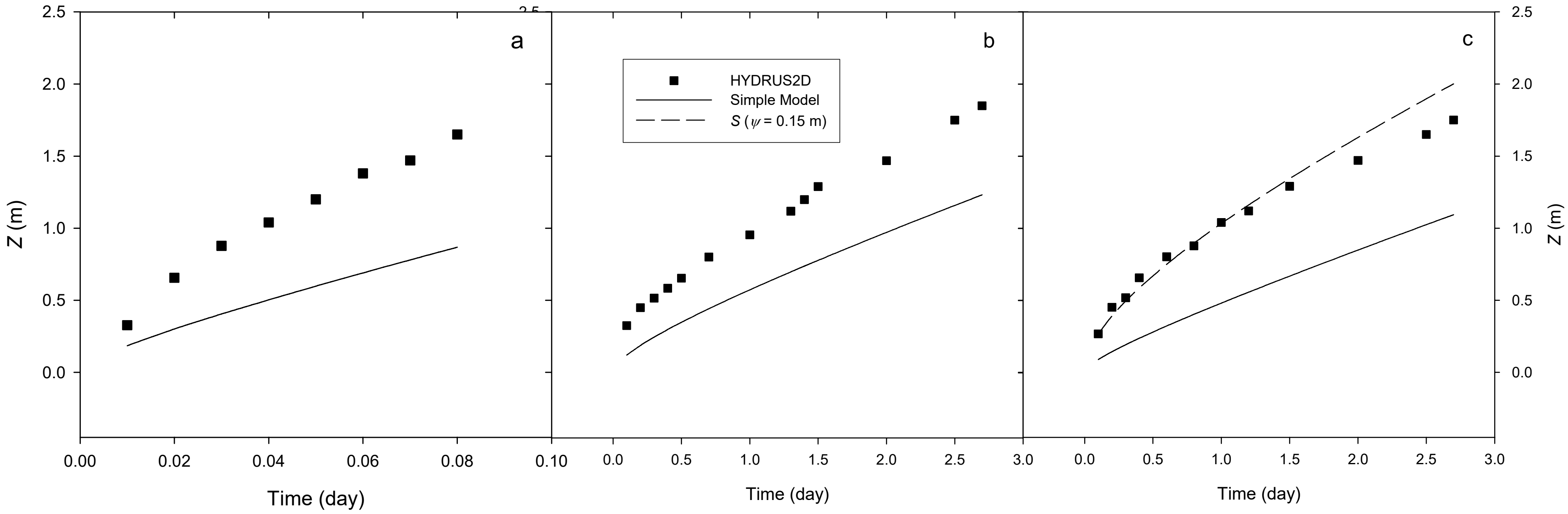

Figure 5.3. Z (the vertical penetration of water into the bed) with time for a) sand, b) silt and c) clay soil. The data points are derived from numerical simulation and the lines are calculated with eqns (4.1) and (4.2). The dashed line was calculated with S calculated for simulated infiltration into a horizontal clay column with a potential on the intake boundary of 0.15 m.

The effect of the bottom boundary condition being changed to a no-flow boundary condition resulted in saturated conditions building up in the soil and the horizontal penetration of wetting increasing (fig. 5.4). Obviously bringing the no-flow condition closer to the bottom of the bed will speed up the rate of horizontal penetration of the wetting front. Preventing flow to depth however will result in water-logging conditions and salinisation of the bed as an salts added in the irrigation water will accumulate in the soil.

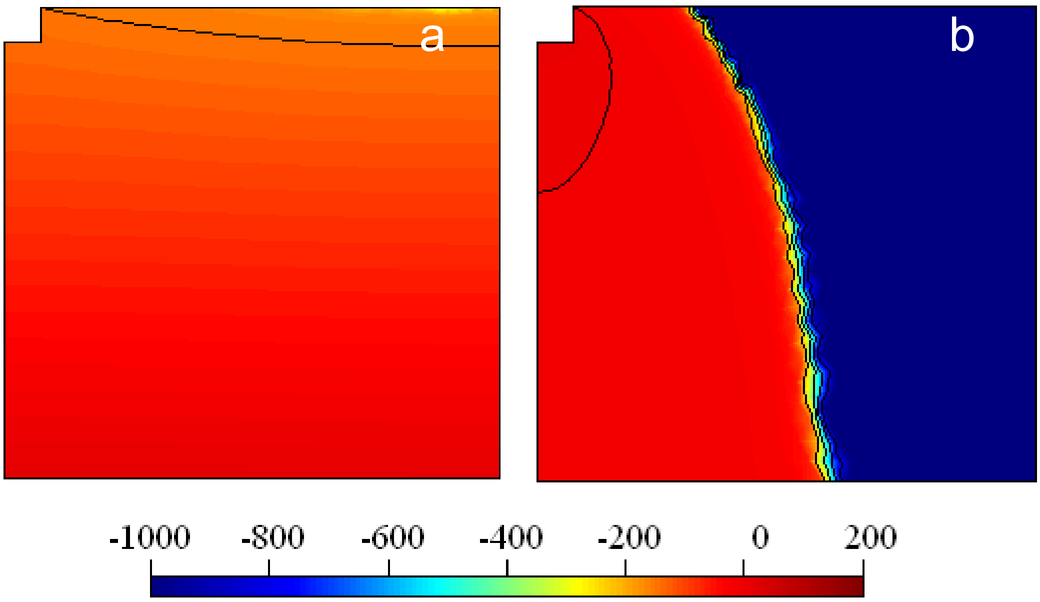

Figure 5.4. Matric potential profiles from simulations of infiltration into beds with a) no-flow and b) free drainage as the bottom boundary conditions. The scale of matric potential is in units of cm. The soil is sand and the time is after 0.6 days of infiltration.

To see if compaction of the soil in the furrow may also increase the horizontal penetration a zone of soil, approximately 0.1 m thick, under the furrow with K_s reduced by 100 fold was introduced. This had little effect on the horizontal penetration (fig. 5.5) and has possibly reduced the horizontal spreading. The reason is that the amount of infiltration is restricted by this layer, so that less water has infiltrated into the soil at the same time. To make a valid comparison we need to compare the wetting patterns after the same amount of infiltration has occurred. When compare in this way we can see that the restricted layer has helped to increase the horizontal penetration (fig. 5.6). Compaction of the base of the furrow may be a way to increase lateral spread but it will come at increasing the time to infiltrate the same volume of water. It is likely to be useful where K_s of the soil is high.

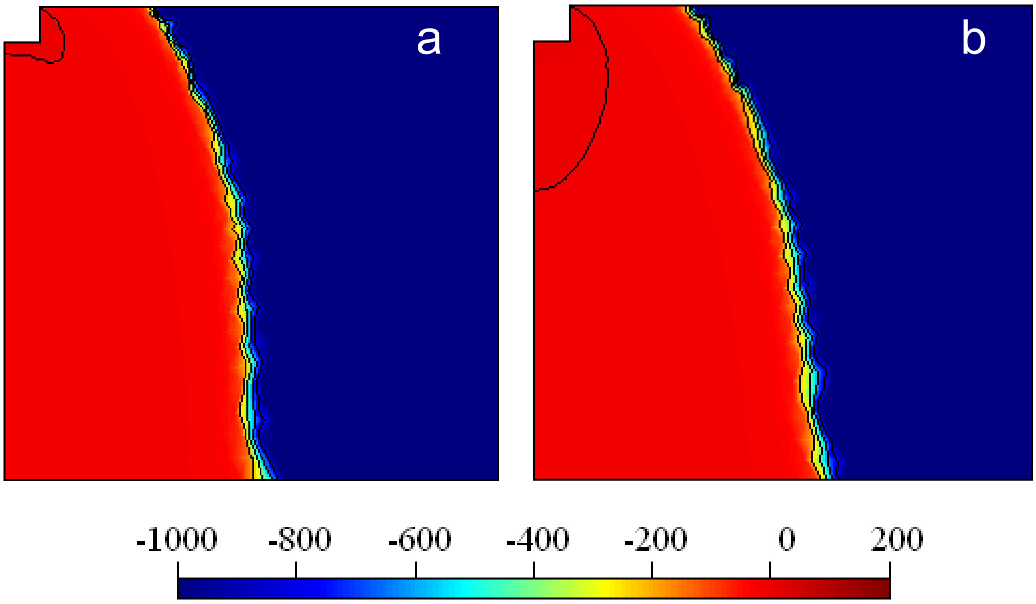

Figure 5.5. Matric potential profiles from simulations of infiltration into beds with a) restricted layer under the furrow and b) same soil properties throughout the domain. The scale of matric potential is in units of cm. The soil is sand and the time is after 0.6 days of infiltration.

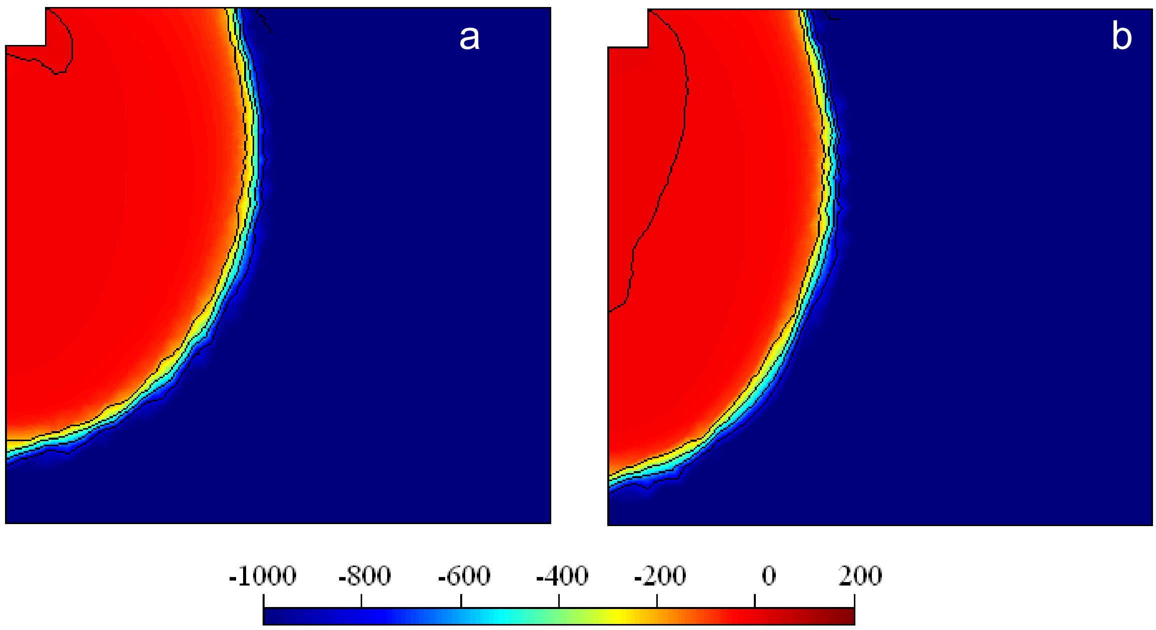

Figure 5.6. Matric potential profiles from simulations of infiltration into beds with a) restricted layer under the furrow and b) same soil properties throughout the domain. The scale of matric potential is in units of cm. The soil is loam and the time is 5.1 day for a) and 2.5 day for b). The reduction in K_s in the restricted zone is 100 fold.

5.1.2 Drainage

The simple drainage of the beds is straightforward. If the bottom boundary condition is a free drainage condition then the bed will drain with the rate of drainage decreasing with time (fig. 5.7). The amount drained is substantially different for each soil with as little as 2 mm of drainage in the clay and as much as 70 mm for sand during 10 days. The potential gradient at the end of 10 days is not very different for all soils (fig. 5.8a)

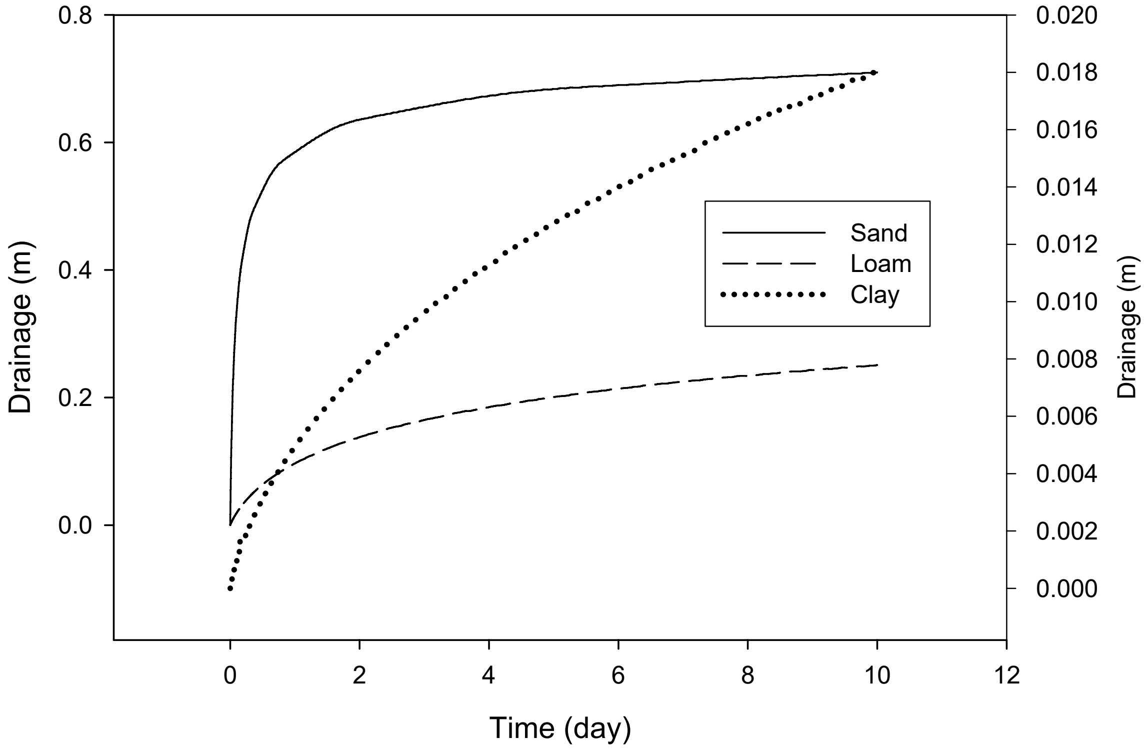

Figure 5.7. Cumulative drainage from a saturated soil domain with a free drainage bottom boundary at 2 m for sand, loam and clay soils. The right-hand y-axis is associated with the clay soil.

The potential profiles indicate that even though little water has drained from the clay soil, this drainage has resulted in this soil having the highest potential at the surface of the bed (fig. 5.8a). The water content profile is still highest for the clay and after 2 days and < 4% of the pore space has been drained (fig. 5.8b). This is likely to result in an aeration problem for this soil. However, no evaporation is included in this simulation and as Cook and Rassam (2002) showed this is an important process in the drainage/drying out of slowly permeable soils.

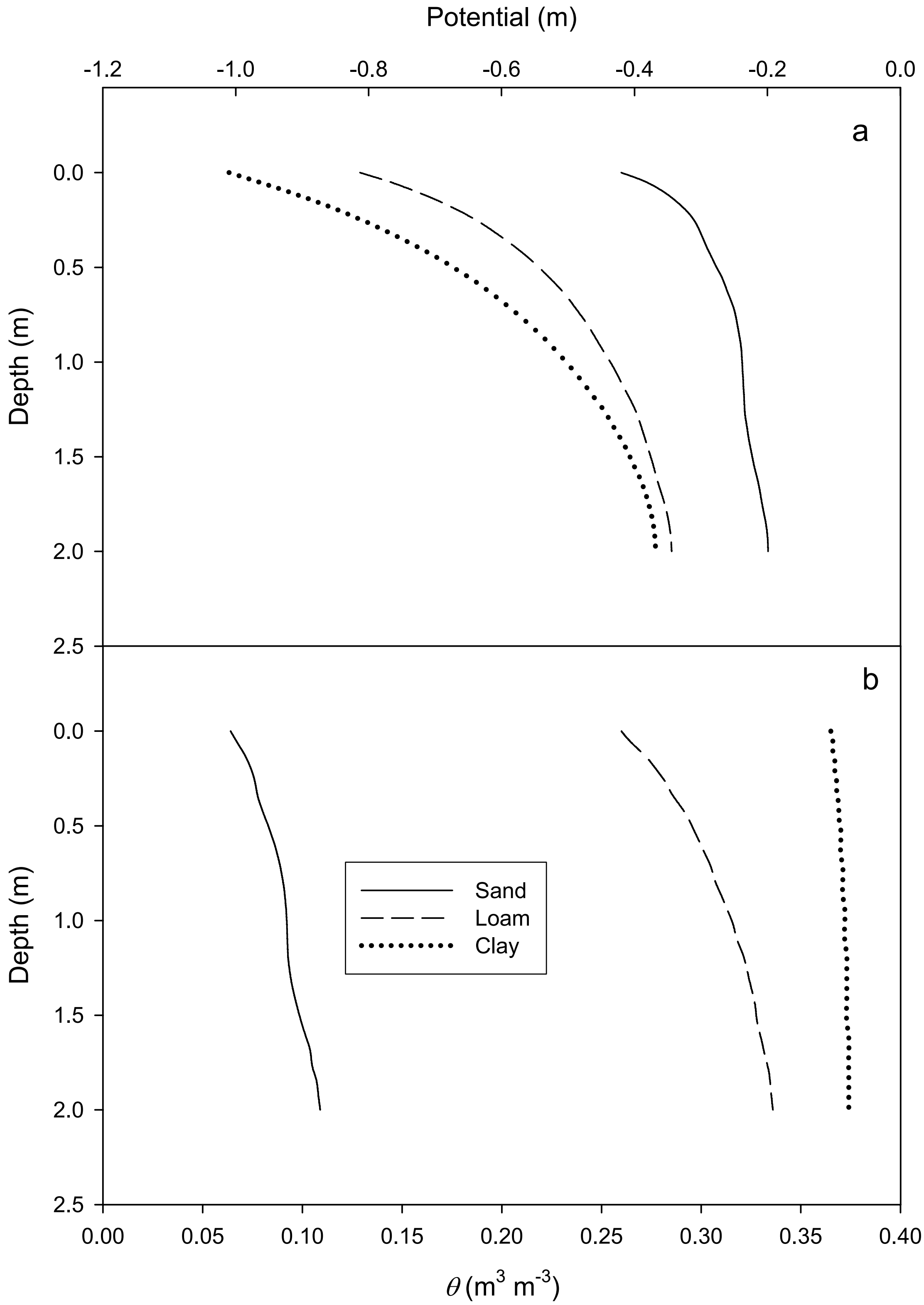

Figure 5.8. Profiles of a) potential and b) water content (θ) for sand, loam and clay soils after 10 days drainage. The wrinkles in the sand profile are a numerical artifice.

The other extreme in the drainage regime would be to have a no-flow bottom boundary condition and a seepage face on the side and bottom of the furrow. This was also simulated and seepage loss was small especially for the clay soil (not shown). The potential profiles (not shown) in all the soils is the same at the end of 10 days of drainage but water content profiles are quite different (fig. 5.9b). The proportion of pore space drained is negligible in the clay soil and much more substantial in the sand (fig. 5.9a).

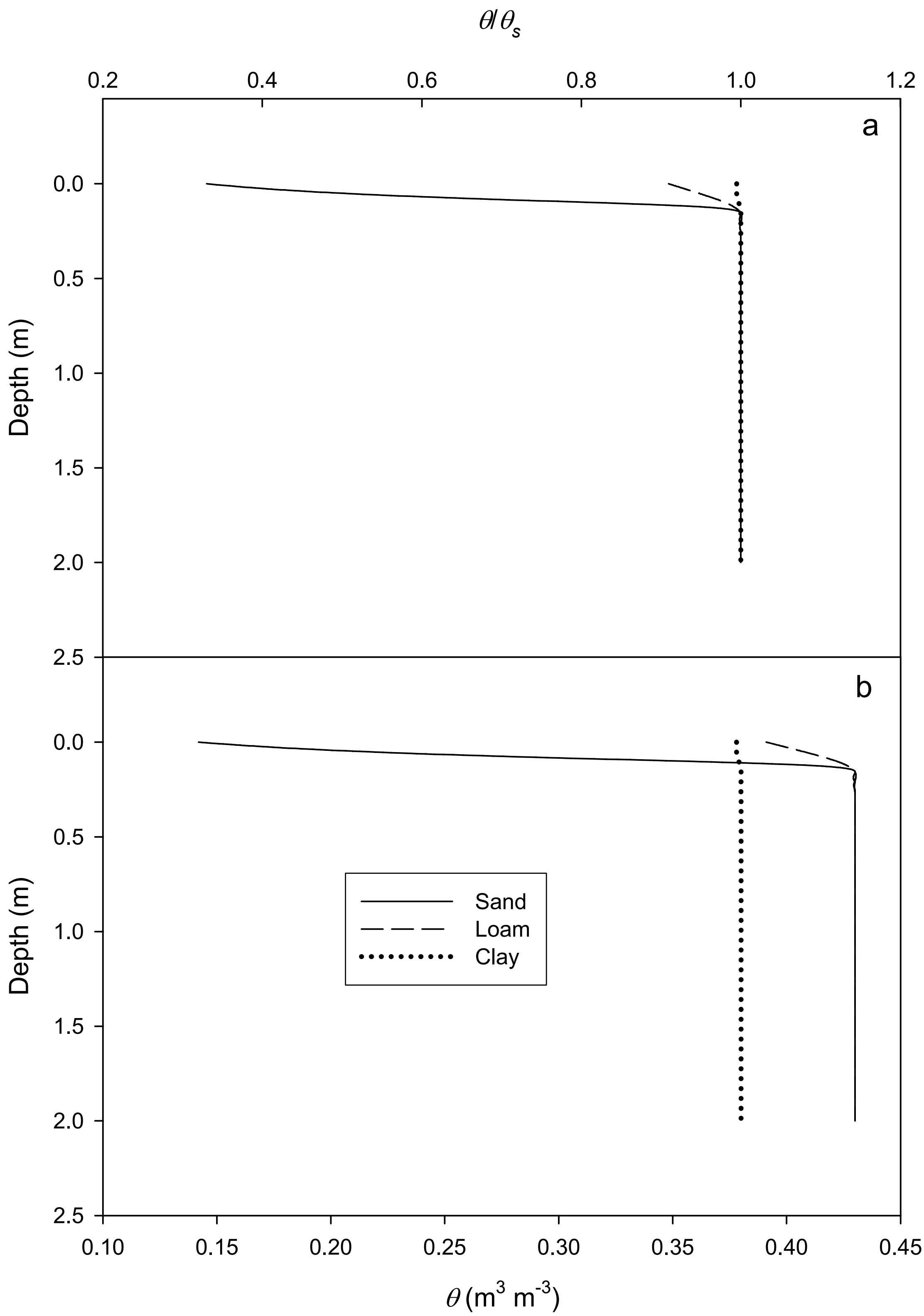

Figure 5.9. a) Proportion of pore space water filled (θ/θs) and b) water content with depth for sand, loam and clay soils after 10 days of drainage. Drainage only occurred through a seepage face on side and bottom of the furrow and the profile was initially saturated.

What these simulations also indicated was that raising the height of the bed would only be effective in increasing aeration in sandy soils where it is unlikely to be required. The problem is related to the α parameter in Table 5.1. This determines the point where the shoulder occurs in the moisture characteristic. Above this shoulder the water content changes only slowly with decreasing potential and below this more rapidly. The characteristic length scale that will relate to the height of the bed would be $1/\alpha$. For the soils here this give values of $1/\alpha$ of sand 0.07 m, loam 0.28 m and clay 1.25 m.

The moisture characteristic curve can be used as a design tool for the height of the beds as in a situation where the drainage only occurs by seepage at the base of the bed the potential at this depth is zero and will increase approximately linearly with height above this depth. Thus we can rewrite the van Genuchten (1980) equation as:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + |\alpha z|^n\right]^m} \qquad (5.1)$$

Where z is the height above the bottom of the bed and m = 1 -1/n. Equation (5.1) was used to generate water content profiles for the three soils and compared with the points obtained from the HYDRUS2D simulations (fig.5.10). This shows that where drainage is restricted at some shallow depth eqn (5.1) can be used to predict the water content profile.

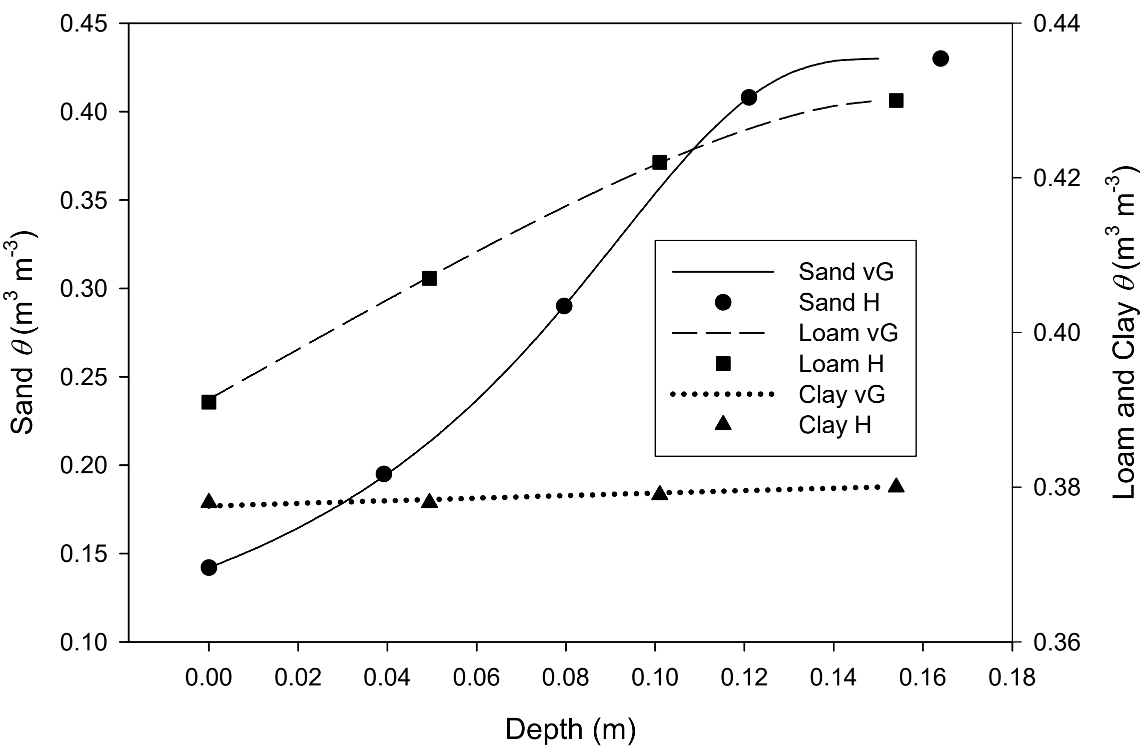

Figure 5.10. Comparison of water content profiles within the bed obtained from HYDRUS2D simulations (H) and eqn (5.1). The simulations were for no flow conditions at the bottom boundary and seepage on the furrow faces.

Equation (5.1) can be rearranged to provide an estimate of the bed height related to the amount of drained porosity:

$$z_b = \frac{1}{\alpha}\left\{\left[\frac{p}{p-(\theta_s-\theta)}\right]^{1/m} - 1\right\}^{1/n} \qquad (5.2)$$

Where $p = \theta_s - \theta_r$. Equation (5.2) was used to predict the bed height for the three soils for $(\theta_s - \theta)$ = 0.1 and resulted in values of z_b of 0.06, 0.37 and 91 m for sand, loam and clay soils respectively. This shows that for soils with properties in the range of sand loam it is possible to use raised beds to assist drainage and equation (5.2) would help in designing the height of beds. However, for soils with properties similar to clay raised beds will be unlikely to assist in drainage of these, unless they are well aggregated. In well aggregated clay soils the large inter-aggregate pores will drain when they are formed into beds. Equation (5.2) will be valid but the parameters required will be those derived for the larger-pore section of the dual-porosity moisture characteristic curve.

5.1.3 Fertilizer placement and solute leaching

The placement of fertilizer to reduce leaching losses to groundwater can be deduced from the velocity vectors during the infiltration process. To also get an idea of the depth of penetration we have simulated solute transport by placing a layer of solute on the upper surface of the domain and looking at where the solute moves to during irrigation from the furrow. Rainfall will also result in transport of solutes to depth but this is not something that can be controlled by bed design. The effect of rainfall will be covered under the simulations for each individual project.

The simulations were only run until drainage of water occurred. The amount of water applied was in excess of what would be a sensible irrigation volume as the aim is to leach water beyond 2 m during the irrigation. The initial condition for the solute concentration was a concentration of 1 mmol m^{-3} throughout the bed. The solute was assumed to be sodium chloride with no adsorption. Thus these simulations are a worst case situation as some adsorption is likely for fertilizers but may be representative of nitrate.

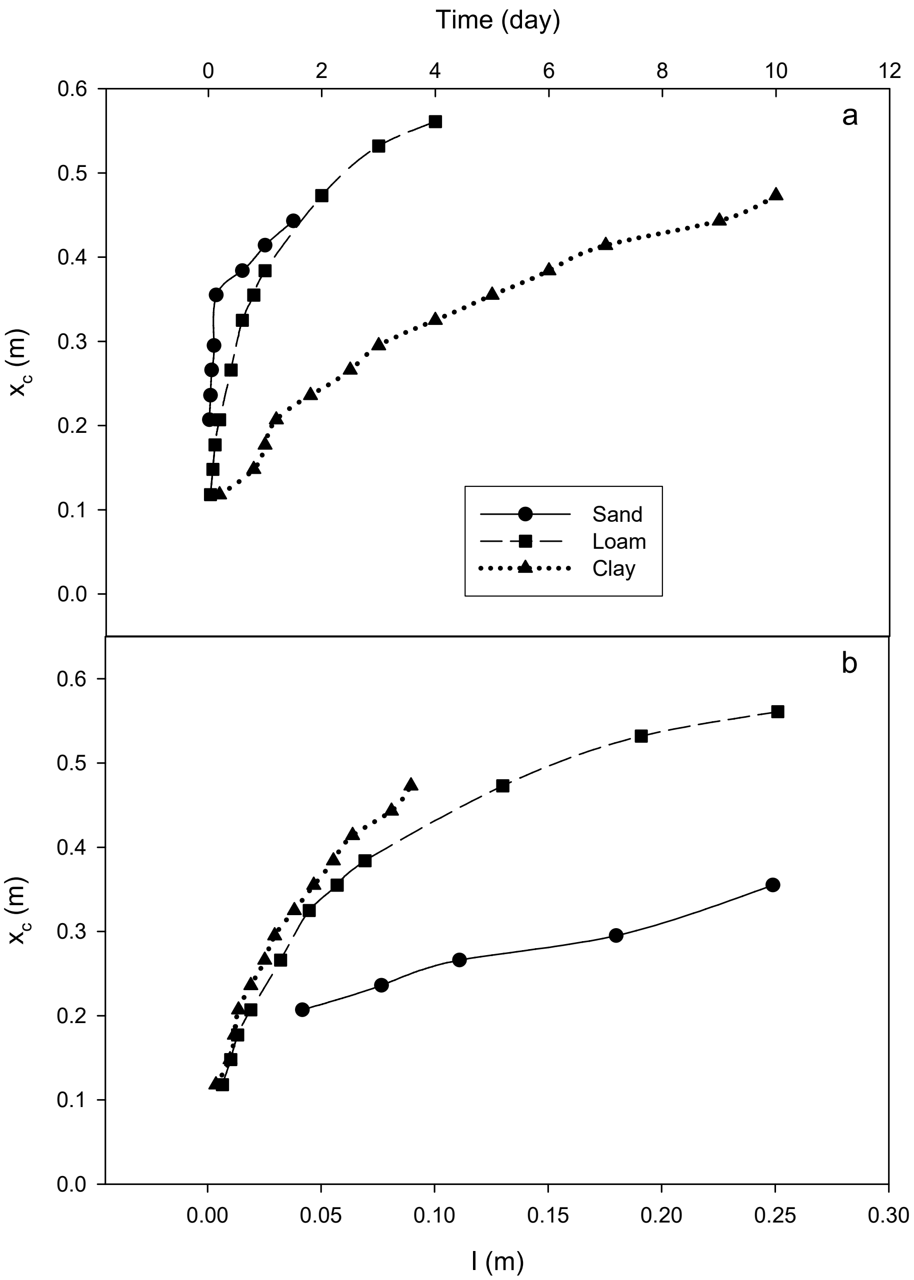

Figure 5.11. The washout distance (Xc) with a) time and b) cumulative infiltration derived from simulations for three soil types.

Infiltration washes the solute the solutes out of the bed. The distance from the furrow to the solute horizontal distance washout front (X_c) is an indication of where solute is likely to be leached from during furrow irrigation. The time course of this washout front is provides an indication of where to place fertilizers to minimise leaching (fig. 5.11a). For example if an irrigation was of 1 days then solutes placed approximately 0.4, 0.35 and 0.2 m from the furrow would not have been washed out for sand, loam and clay soils respectively. The increase in X_c with time is similar for the sand and the loam. For the clay soil X_c increases more slowly with time.

A better way of presenting this information is to plot the washout front versus the cumulative infiltration (fig. 5.11b). Now it is the loam and clay that are similar in their rate of increase in X_c with infiltration (*I*) and sand that increases more slowly with *I*. The results indicate that in all soils that by irrigation of about 0.1 m of water the rate of increase in X_c has markedly decreased. The distance of X_c for the three soils is approximately 0.25, 0.4 and 0.45 m for sand, loam and clay respectively. To minimise leaching fertilizers should be place approximately 0.4 m from the edge of the beds in loams to clays and can be placed approximately 0.3 m from the edge of the beds for sandy soils.

5.1.4 Salinisation from a shallow water table

If a shallow water table occurs at depth due to over irrigation or other reasons than due to evaporation salts can accumulated in the bed and result in detrimental conditions for plant establishment and growth. Here we will investigate the process of salt accumulation in the bed in relation to the depth of the water table. For this process the simulation parameters we will consider as representing the process of salinisation are, the time for the solute to reach the top of the bed and the time for this concentration to reach 100 times that in the water table.

The simulations were run with the initial potential condition of the soil being in equilibrium with the water table. The initial solute concentration was 1 mmol m^{-3} in the soil (water) at and below the water table. The bottom boundary condition was at a constant pressure to maintain the water table and the incoming water had a concentration 1 mmol. The upper boundary condition was atmospheric with a potential evaporation rate of 0.05 m day^{-1} (5 mm day^{-1}).

Simulations were run for different depths in the range where solutes accumulated at the soil surface. Where the watertable was deeper than the range presented, solutes did not accumulate at the surface within 1000 days. A typical profile for one of these simulations at 1000 days is shown in figure 5.12, and shows that the solutes have only risen about 0.3 m above the water table in a loam soil when the water table was at a depth of 2.0 m and the evaporation rate at the soil surface was 0.05 m day^{-1}. When the depth of the water table is changed the rise will be different as the upward potential gradient is larger nearer to the water table.

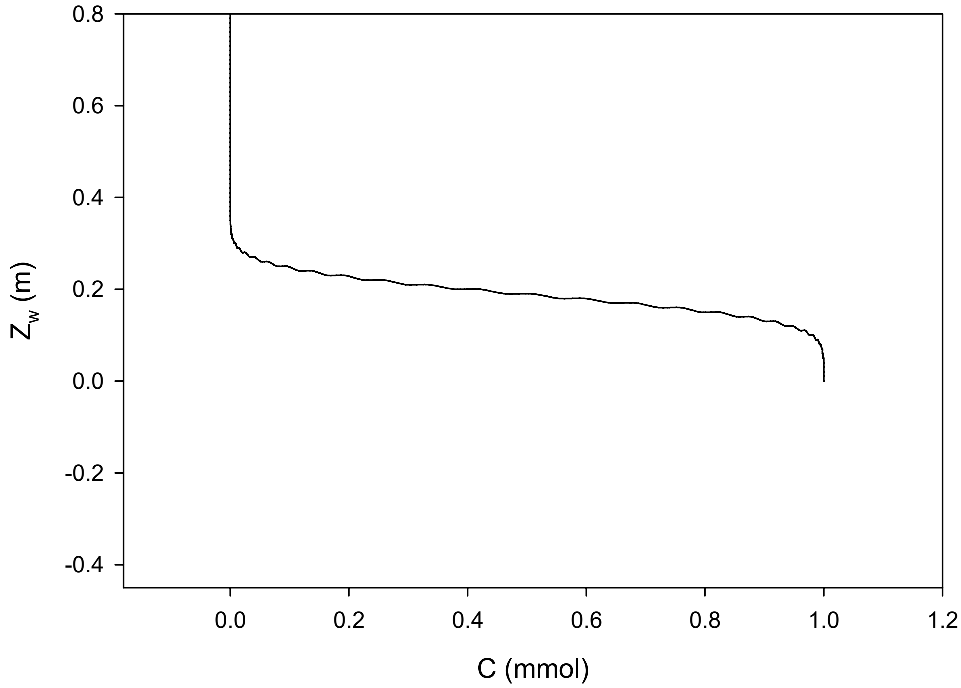

Figure 5.12. Concentration of solute (*C*) with height above the water table (Z_w) for loam soil after 1000 days of simulated evaporation from the soil surface. The concentration of water at the water table is 1 mmol m^{-3} and the watertable is maintained at a depth of 2 m.

The effect of changing the depth of the water table was simulated by determining the time for the solutes to reach the soil surface (T1) and the time for the solute concentration at the soil surface to reach 100 mmol m^{-3} (T2) (fig. 5.13). The loam and clay soils had similar behaviour but the sand was very different. For the sand a water table as shallow as 0.5 m below the bed is unlikely to cause salinisation of the bed. For the loam and clay soils a water table this close to the surface would cause salinisation of the bed in less than 110 days. The water table would need to be greater than 1.5 m depth to not have the possibility of salinising the beds in loam and clay soils. When there is sufficient downward flux of water and the water table is not rising, a water table depth of even 1 m may be possible in loam or clay soils. These results suggest, at least for sands that permanent raised beds may offer a possibility to recover productive use of salinised soils if the beds are raised to a adequate height. There will still be a requirement to manage the salt that would leach from such beds.

The whole of the question of salinity and irrigation has recently been reviewed in depth by Cook et al. (2007). They suggest that in any irrigation scheme planning for drainage and salt disposals is required prior to commencement of irrigation otherwise salinisation is likely some time in the future.

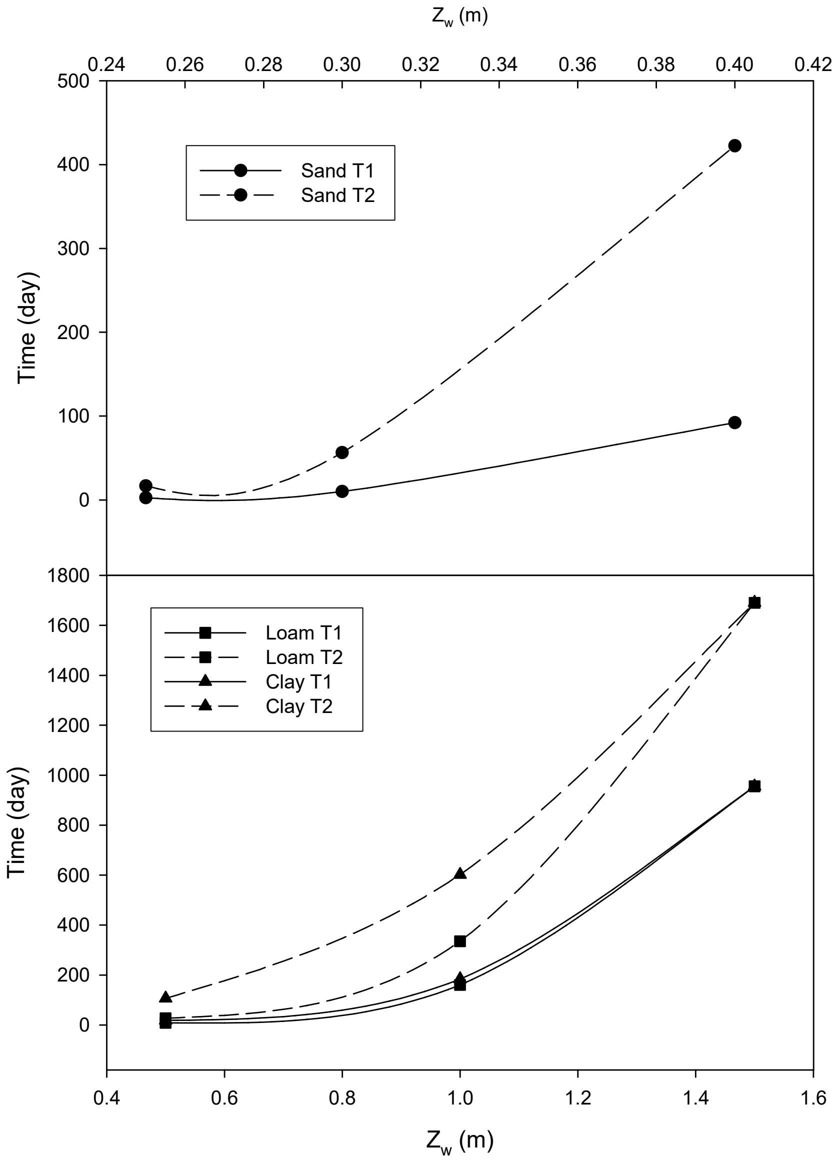

Figure 5.13. Time for solutes to reach the surface (T1) and reach 100 mmol m-3 at the surface (T2) when a water table with a solute concentration is at depth Zw below the soil surface.

6 Project case studies

A range of simulations determined by input from the project leaders of the four projects listed in Section 3 were performed for sites located in four different countries. This means that the simulations have covered a wide range of possible soil and water management regimes and complement the generic simulations with more specificity. The four locations are: Ludhiana (Punjab, India); Lombok (West Nusa Tengara, Indonesia); Zhangye in the Hexi Corridor (Gansu Province, China) and Mardan (North West Frontier Province, Pakistan).

6.1 India case study

This raised beds project is situated in the Punjab province of India and is located on two different sites near Ludhiana. At both of these sites the cropping regime is one of irrigated wheat and rice. More details on the project can be found in Kukal et al. (2005) and a series of papers contained in Humphreys and Roth (2008). The project's two trial sites are sited on two soil types and the physical properties of these soils were derived from measurements and estimates derived from these measurements. They were then used along with the simulations to estimate the likely environmental implications from this project and if the bed design could be improved. Specifically, issues that the modelling was to address were evaluations of two-dimensional infiltration in relation to bed geometry, the potential for PRB to reduce irrigation water use, and the fate of solutes under wheat and rice grown on PRB.

The watertable is deep at both sites (>50 m) and drainage as such will not be simulated as a separate section but will be part of the simulations on the wheat and rice crops. Simulations will also be carried out for a flat soil condition and for rice where this soil is puddled to reduce the infiltration rate.

Fertilizer leaching and salinisation will also be part of the simulations for wheat and rice. Two fertilizer placements will be considered one where the fertilizer is placed on the furrow side of the plant and the other where it is placed beside the centre of the bed. The fertilizer will be assumed to be in a band 0.1 m wide and incorporated to a depth of 0.1 m.

HYDRUS2D does not allow dynamic changing of the boundary conditions, so the simulations had to be run in sequence, with the boundary condition in the furrow changing from a constant pressure condition during irrigation and an atmospheric boundary condition at all other times. This required many simulation runs.

6.1.1 Soil properties

The two trials sites of the project were established on a sandy loam soil and a loam soil, respectively. These soils are described in depth in the project reports (Humphreys et al., 2007) but here we will concentrate on the soil physical properties. The measured values are listed below in table 6.1.1.

Table 6.1.1. Soil physical properties for loam and sandy loam soils for various depths. The water content (θ) is shown measured at two different potentials (ψ). The particle size data are presented with the Australia and silt (0.002 – 0.02 mm) and American silt (0.002 – 0.02). This results in different values for the proportion of sand and silt with the American values shown in brackets.

Depth (m)	Bulk Density (Mg m^{-3})	θ (ψ = -154 m) (m^3 m^{-3})	θ (ψ = -1 m) (m^3 m^{-3})	Sand	Silt	Clay
Loam soil						
0 - 0.15	1.55	0.09	0.34	0.40 (0.387)	0.41 (0.423)	0.19
0.15 - 0.3	1.79	0.09	0.34	0.33 (0.354)	0.45 (0.426)	0.22
0.3 - 0.6	1.70	0.1	0.35	0.30 (0.361)	0.41 (0.409)	0.23
0.6 - 2.0	1.68	0.12	0.35	0.30 (0.338)	0.44 (0.412)	0.25
Sandy loam soil						
0 - 0.15	1.61	0.07	0.26	0.62 (0.459)	0.19 (0.351)	0.19
0.15 - 0.3	1.78	0.07	0.27	0.63 (0.397)	0.19 (0.423)	0.18
0.3 - 0.6	1.61	0.05	0.21	0.66 (0.472)	0.15 (0.338)	0.19
0.6 - 2.0	1.53	0.05	0.2	0.67 (0.478)	0.15 (0.342)	0.18

From the particle size and bulk densities the van Genuchten parameters for moisture characteristic function were calculated using procedures described by Schaap et al., 1998, Schaap and Leij, 1998a; Schaap et al., 2001 and are shown in table 2. The saturated hydraulic conductivity was estimated from the measured values of unsaturated hydraulic conductivity at -0.01 and -0.07 m potential by using the following equation based on Mualem (1976):

$$Ks = \frac{k(\psi)}{Se^{0.5}\left[1-\left(1-Se^{1/m}\right)^{m}\right]^{2}}$$

$$Se = \frac{\theta(\psi)-\theta_r}{\theta_s-\theta_r} \qquad (6.1)$$

$$\theta(\psi) = \theta_r + \frac{\theta_s-\theta_r}{\left[1+|\alpha\psi|^{n}\right]^{m}}$$

$$m = 1-1/n$$

where ψ is the potential at which the measurement was made with a disc permeameter (White and Perreau, 1989; Cook and Broeren, 1994). The resulting mean values of Ks are shown in table 6.1.2.

Table 6.1.2. Soil hydraulic properties for loam and sandy loam soils in Punjab, India.

Depth (m)	θ_r (m^3 m^-3)	θ_s (m^3 m^{-3})	α (m^{-1})	*n*	K_s ($m\ s^{-1}$)
Loam soil					
0-0.15	0.056	0.366	1.07	1.477	1.43 x10^{-06}
0.15-0.3	0.050	0.317	1.69	1.291	7.12 x10^{-07}
0.3-0.6	0.056	0.341	1.40	1.351	1.70 x10^{-06}
0.6-2.0	0.060	0.350	1.28	1.366	2.62 x10^{-06}
Sandy loam soil					
0-0.15	0.053	0.357	1.62	1.386	3.86x10^{-06}
0.15-0.3	0.044	0.312	1.94	1.293	7.67x10^{-06}
0.3-0.6	0.052	0.359	1.71	1.379	5.37x10^{-05}
0.6-2.0	0.054	0.374	1.51	1.433	6.17x10^{-05}

6.1.2 Cropping regime

Cropping regime in Punjab is to grow wheat during winter/spring and rice summer/autumn. Wheat is usually sown the first week in November and harvested early April. The irrigation regime is to irrigate with approximately 100 mm prior to sowing and then with 70 mm about 21 days after sowing (DAS) and whenever the potential deficit is 80 mm. This usually results in about three irrigations besides the pre-sowing and 21 DAS. The roots grow to about 1.8 m and a radial spread of about 0.2 m.

For rice this is transplanted in mid June and harvested in early October. The irrigation regime will be the same as used on the flat soil of continuous ponding for the first 15 days and then to irrigate again 2 days after ponding has ceased.

6.1.3 Simulation of infiltration

The bed configuration as studied by the PRB project in India is shown in figure 6.1.1.

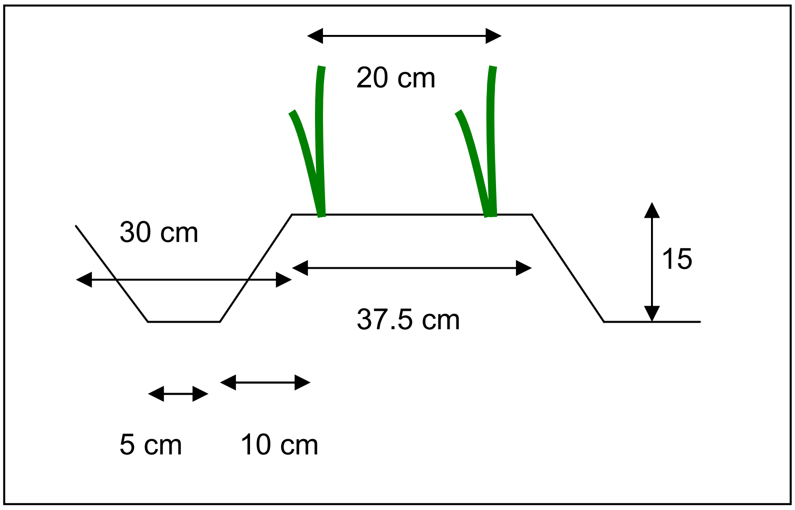

Figure 6.1.1. Bed configuration in Punjab, India.

This is taken as the base configuration for the modelling with modelling of the half-space due to symmetry (fig. 6.1.2). The first simulations were infiltration of water from the furrow into the beds, as this was needed to determine approximately how long to irrigate for (apply a constant boundary pressure boundary condition in the furrow). The extent of wetting was determined by monitoring the potential at the monitoring points shown in figure 6.1.2.

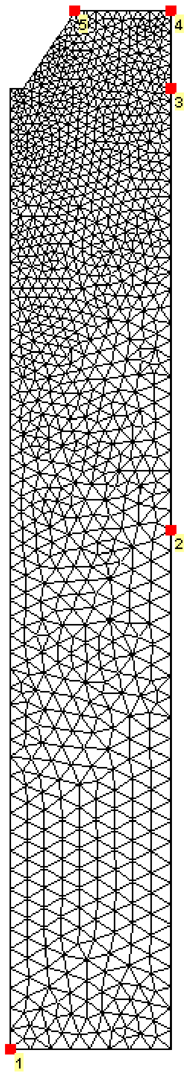

Figure 6.1.2. The spatial domain used for the simulations showing the finite element mesh and the observation points that were monitored. The observation points are labelled 1 to 5.

The infiltration from raised beds was simulated using HYDRUS2D. The initial condition was assumed to be that the soil was at a uniform potential of -10 m. Infiltration from the furrow occurred with a depth of water of in the furrow of 0.1 m. The infiltration rate with time for the base configurations of both soils shows that the water infiltrates into the sandy loam soil much faster than the loam soil (fig. 6.1.3). It takes approximately 1.5 days for 100 mm of water to infiltrate into the loam soil while this depth will infiltrate in less than 0.5 day for the sandy loam soil. In both cases the infiltration into a flat soil is much faster as the intake surface area is the same as the soil surface area, whereas for the PRB's this ratio is 0.405.

The different rate of infiltration for these two soils means that the same irrigation management with regard to furrow lengths and contact times should not be used for both soils. It should be noted that these simulations are performed with the mean values for the soil physical properties and the actual results will vary with each field.

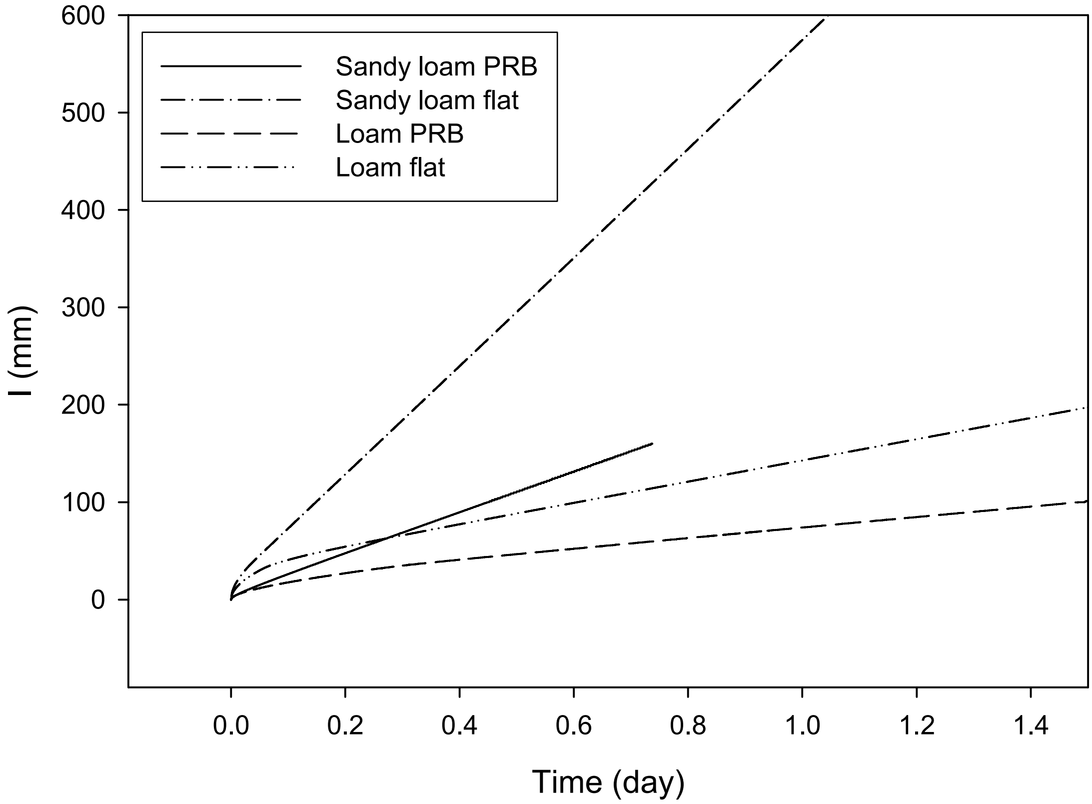

Figure 6.1.3. Infiltration (I) with time for sandy loam and loam soils from the furrow into permanently raised beds (PRB) and one dimensional infiltration (flat). Infiltration rate for the PRB was calculated as the volume/horizontal surface area. The water depth in the furrow and one the surface of the flat soil was 0.1 m.

Further simulations with different beds widths suggested that for the sandy loam soil the present configuration (fig. 6.1.4a) or beds which are wider by 0.2 m (fig. 6.1.4b) or 0.4 m (fig. 6.1.4c) would be possible. A bed with width 0.775 m is about the limit if the bed is to wet to the centre (points 3 and 4) with irrigations of 70 or 100 mm. For beds wider than the 0.775 m the wetting front reaches the centre of the bed only after irrigation for a longer time (fig. 6.1.4d). The depth of penetration of the wetting front is also less that 1 m (point 2) when the bed is 0.975 m wide which may restrict the rooting depth of the crop. Even if larger irrigations than 100 mm where used the generic modelling above suggests that the lateral penetration into the beds would not increase greatly.

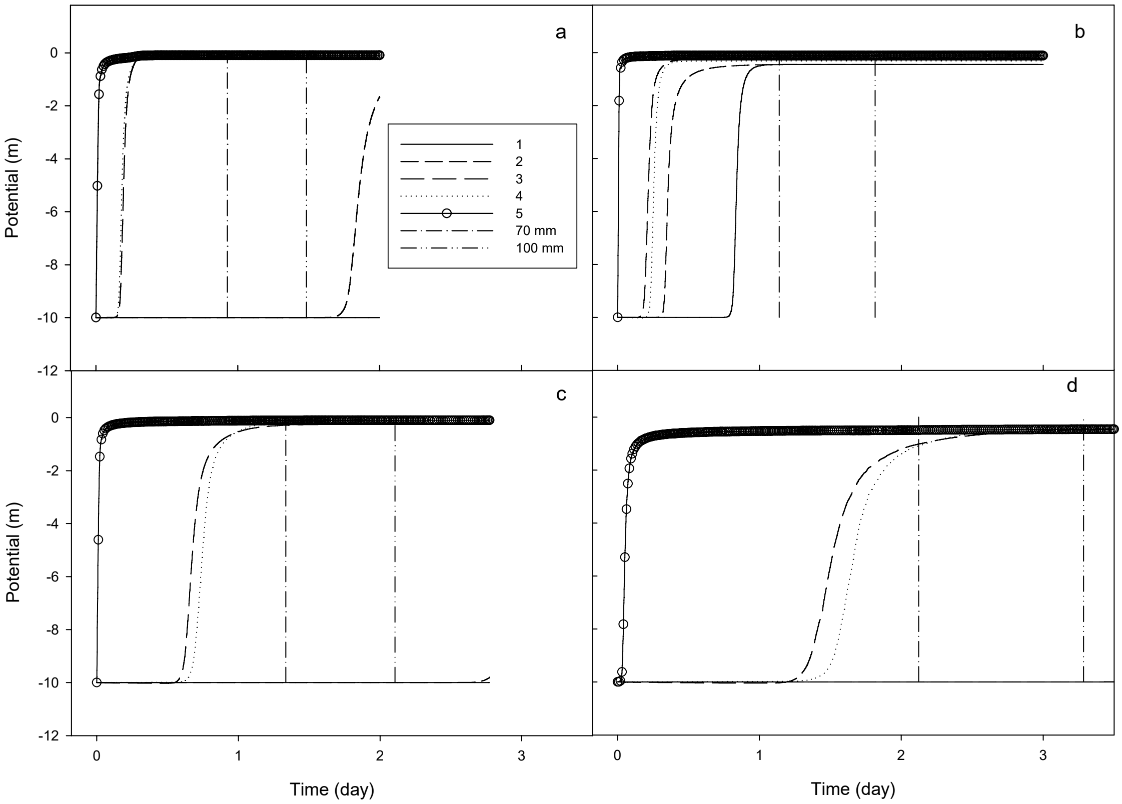

Figure 6.1.4. Infiltration into the loam soil with bed widths of a) 0.375, b) 0.575, c) 0.775 and d) 0.975 m. The numbers 1 to 5 refer to the observation points in fig. 6.1.2. The lines show the time course of the potential measured at each of these. Two other lines show the time that irrigation amounts of 70 and 100 mm would take to infiltrate.

For the loam soil the simulations suggested that the beds could be wider than the present configuration with the wetting front reaching the centre of the bed for all four of the configurations simulated (fig. 6.1.5a,b,c) with irrigations of 70 and 100 mm. For the configuration with a bed width of 0.975 m, the wetting front did reach the centre but the depth of wetting would not have reached 1 m (point 2) with such irrigations. For these wider beds it would be possible to have larger less frequent irrigations and this may result in an overall water saving as the rainfall could be better exploited. Such exploration both with simulation and experimentally should be considered in the future.

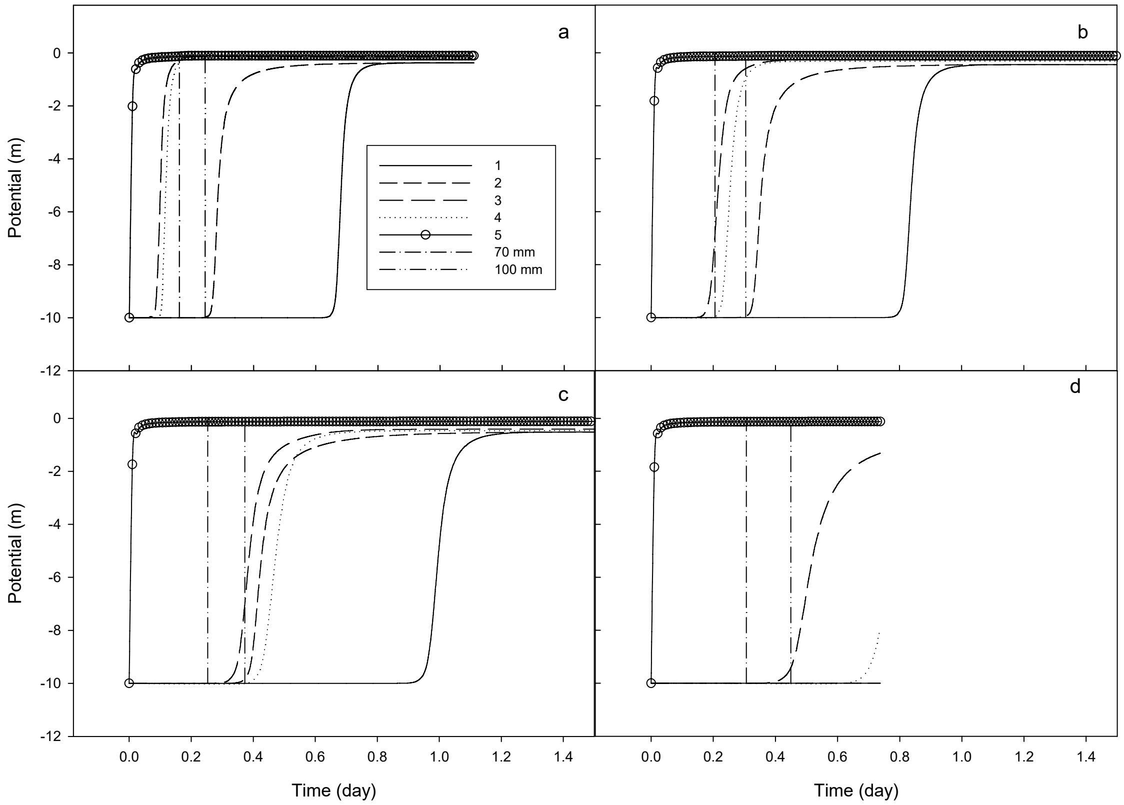

Figure 6.1.5. Infiltration into the sandy loam soil with bed widths of a) 0.375, b) 0.575, c) 0.775 and d) 0.975 m. The numbers 1 to 5 refer to the observation points in fig. 6.1.2. The lines show the time course of the potential measured at each of these. Two other lines show the time that irrigation amounts of 70 and 100 mm would take to infiltrate.

As mentioned above with irrigations of 70 and 100 mm the depth of wetting would be reduced for the wider beds. The penetration of the wetting front for the 0.975 m wide bed would have only been 0.425 m in the centre of the bed for an irrigation of 70 mm (fig. 6.1.6).

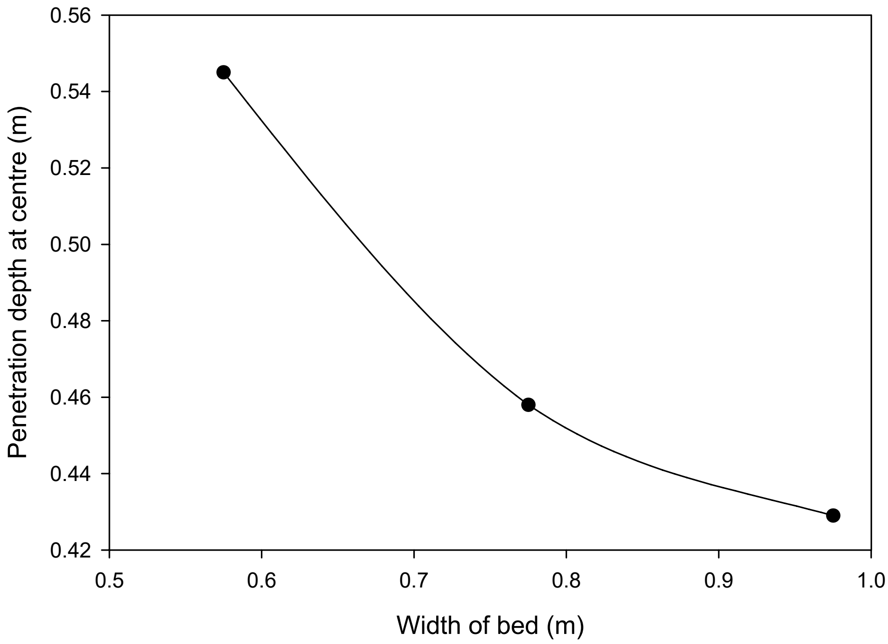

Figure 6.1.6. The depth of wetting front penetration below the bed surface for 70 mm of irrigation with width of the bed.

6.1.4 Water balance and solute transport under wheat

The climate data used in this simulation is for the year of 1980 which was chosen randomly from the data set available from 1971 to 1997. This year has a higher pan evaporation of 1838 mm compared with an average for this period of 1675 mm and also more rainfall with 1038 mm compared to the average of 797 mm. The initial condition was assumed to be that the soil was at a uniform potential of -10 m. Infiltration from the furrow occurred with a depth of water of in the furrow of 0.1 m. This required splitting the simulations into parts and then ‘stitching’ together the output files afterwards.

Irrigation was scheduled as discussed above. This resulted in an initial irrigation of 100 mm and three subsequent irrigations of 70 mm. The cumulative irrigation, rainfall, and potential evapotranspiration (PET) are the same for both sandy loam and loam soils (fig. 6.1.7). The actual evapotranspiration and drainage are shown for the loam and sandy loam soils in figure 6.1.7. There is little difference between the actual evapotranspiration from the soils but there is significantly more drainage to depth for the sandy loam soil compared with the loam. This is due to the higher hydraulic conductivity of the sandy loam soil. This results in more drainage of a salt like solute from the sandy loam soil compared to the loam soil (figs 6.1.8, 6.1.9).

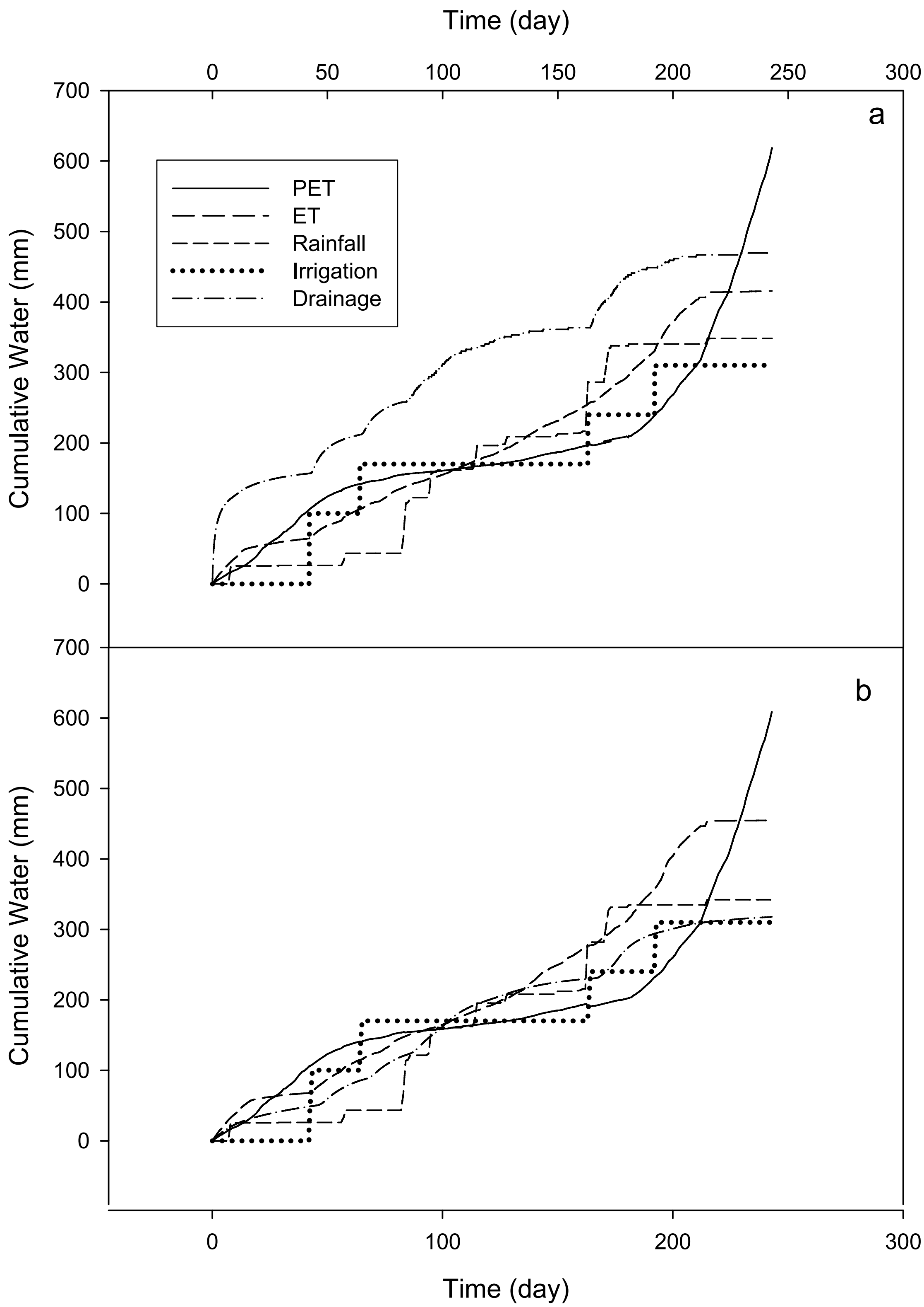

Figure 6.1.7. The cumulative water inputs and outputs for a) sandy loam and b) loam soils planted to wheat with climate data from 1980.

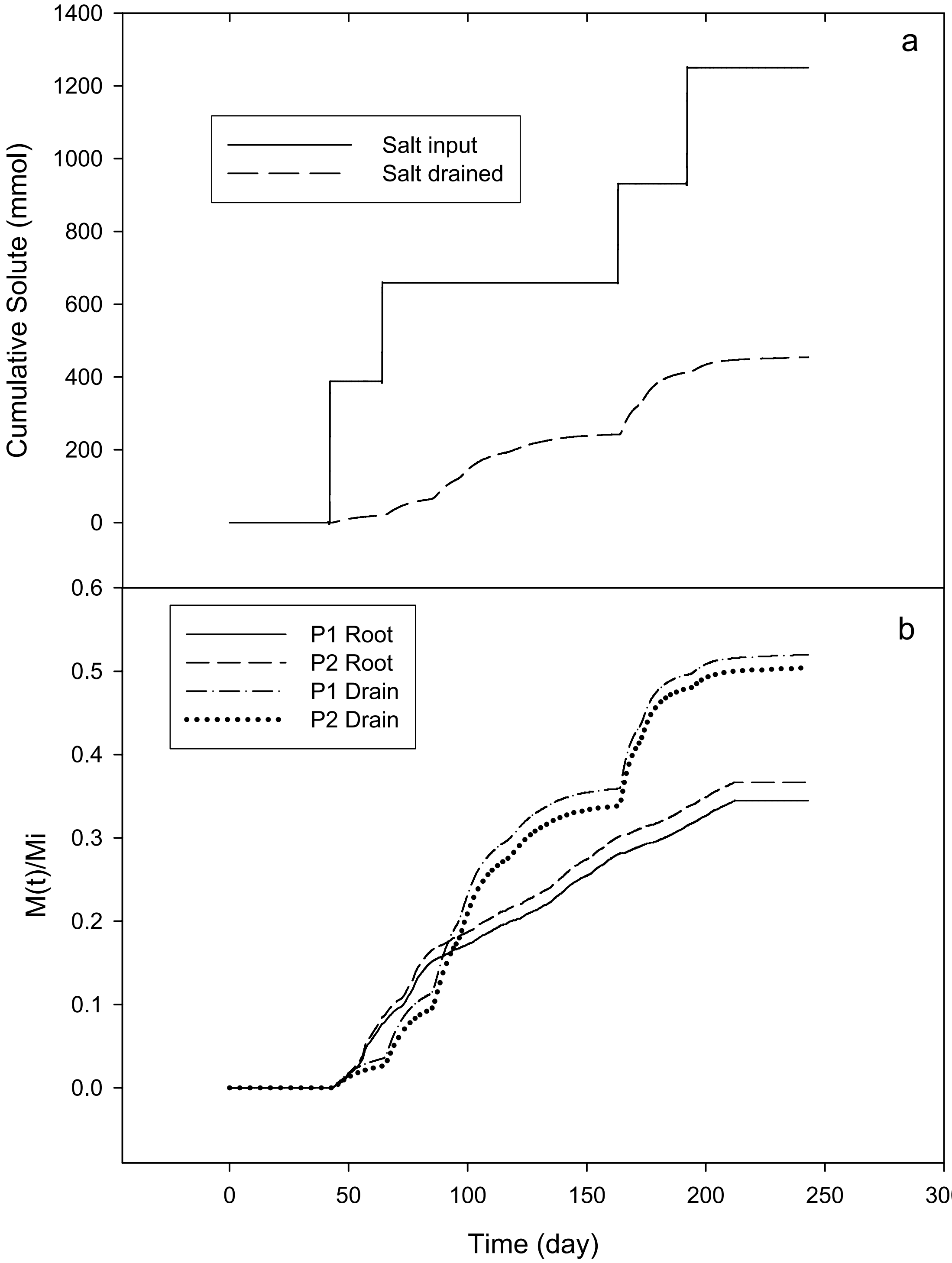

Figure 6.1.8. The simulated solute fluxes for the sandy loam soil during the growing of wheat a) input and drainage of salt with the irrigation water b) drainage and plant uptake of a solute with placement P1 between the plant and furrow edge and P2 between the plant and centre of the bed. Mi is the total solute input during the simulation and M(t) is the amount of solute either drained or taken up by roots at time (t).

Simulation sets were run with the fertilizer solute placed in a 0.1 m wide by 0.1 m deep band starting either on the edge of the bed nearest the furrow or adjacent to the centre of the bed. This solute had an initial concentration of 1 mmol m^{-3} and was a non reactive solute (not absorbed by the soil). This represents the worst case scenario for loss of the solute. Root uptake of the solute occurred as a passive process along with the uptake of water. These solute properties are representative of a solute like nitrate.

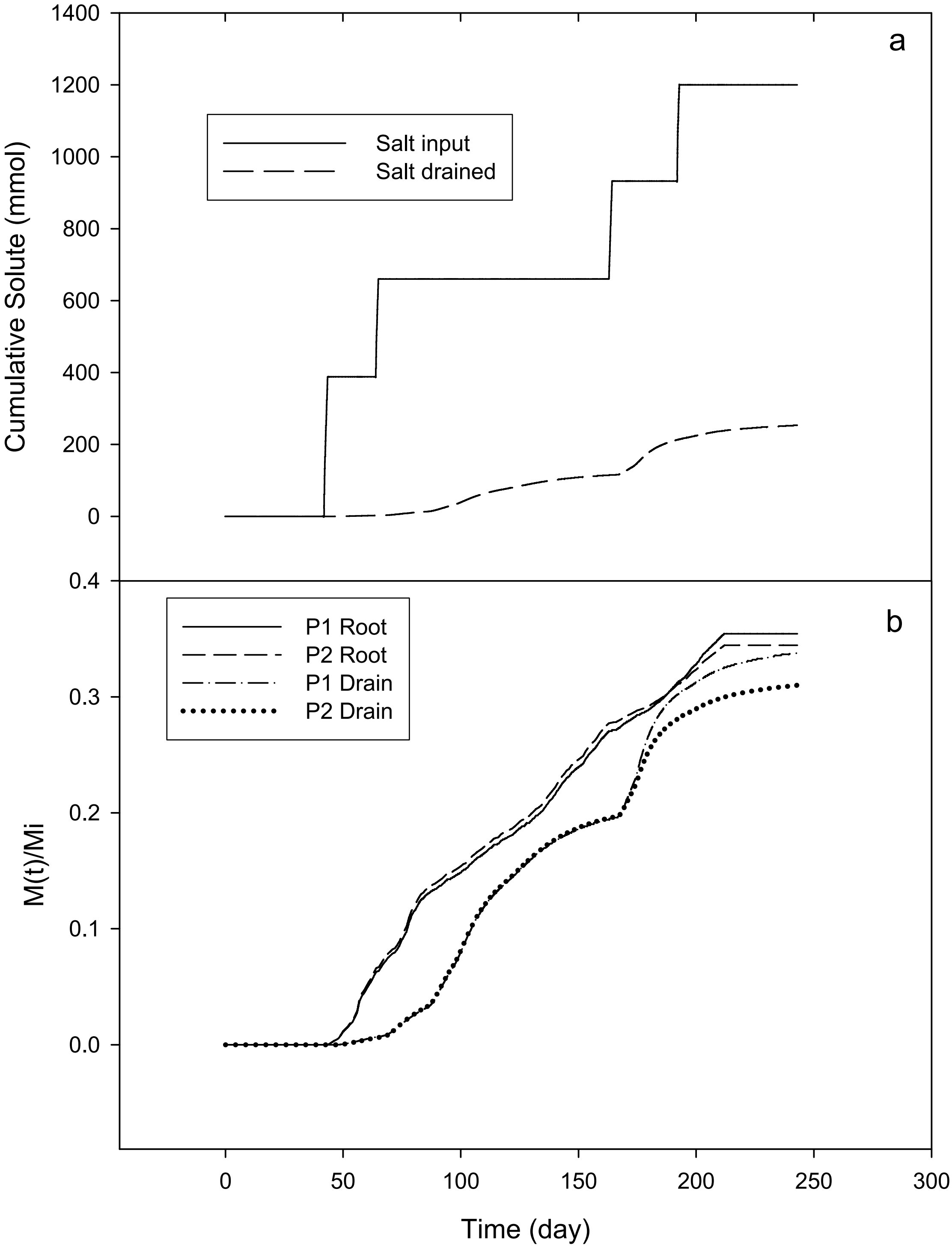

Figure 6.1.9. The simulated solute fluxes for the loam soil during the growing of wheat a) input and drainage of salt with the irrigation water b) drainage and plant uptake of a solute with placement P1 between the plant and furrow edge and P2 between the plant and centre of the bed. Mi is the total solute input during the simulation and M(t) is the amount of solute either drained or taken up by roots at time (t).

The placement of the 'fertilizer' did not greatly affect the proportion drained or taken up by the plant (fig. 6.1.9). There is also no difference between the amount of plant uptake between the 2 soils but there is a difference in the amount drained with less lost to drainage in the loam soil. This is possibly due to rainfall which leaches the fertilizer down the soil profile to where the irrigations can transport it further down the soil profile away from uptake by the plant roots. This is in contrast to the generic simulations where without rain the placement of fertilizer was considered important.

6.1.5 Water balance and solute transport under rice

The rice regime that was simulated consisted of 15 days of simulation without a crop following the harvesting of wheat. The initial conditions were obtained from the final simulation run of the wheat crop. This was followed by rice being transplanted, fertilized and followed by 15 days of irrigation. The placement of fertilizer was only simulated for the interrow placement following the above results for wheat. Subsequent irrigations followed for 1 day after two days following cessation of ponding. The irrigation events are clearly discernable in irrigation plot in figure 6.1.10. This may have resulted in excessive irrigation for the sandy loam soil but it was considered that a consistent irrigation pattern would offer more insight into the behaviour at these sites. The hydraulic conductivities used in the simulation of the sandy loam were based on data provided. Subsequently further information was provided after the simulations had been completed (Humphreys et al., 2008) which suggested that the infiltration rate under ponded conditions would be 1/30 of the saturated hydraulic conductivity used in the simulations and when the soil was puddled the infiltration rate was further reduced to 1/90 of the value used in the simulations for the sandy loam soil. Thus the simulations presented here represent a worst case scenario of what might occur if compaction of the furrows and/or puddling was not used on the sandy loam soil.

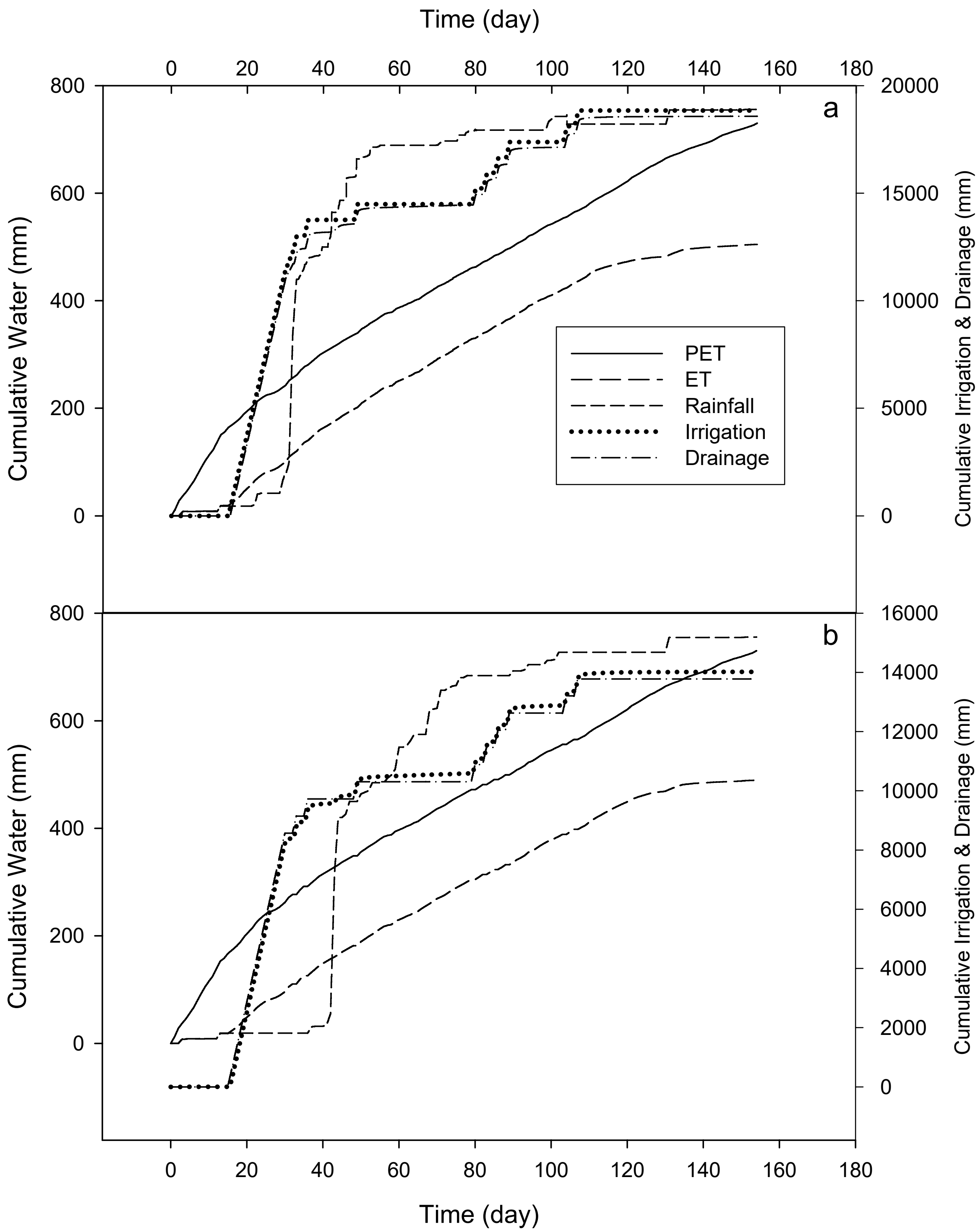

Figure 6.1.10. Simulation of the cumulative water used in growing rice for the sandy loam soil for a) beds and b) a flat paddy.

Simulations of a flat paddy situation for both soils was included as a contrast with the raised beds. These proved to be difficult to simulate and took considerable execution time (5 days for one part of the simulation). The flat section of the graphs for evapotranspiration ET in the paddy and raised beds in the period prior to the initially flooding of the soil surface is due to lower soil evaporation. During ponding ET proceeds at the PET and in the drying off period prior to harvest the ET again drops below PET due to both lower soil evaporation and lower transpiration..

The simulated water use on beds and flat paddies is excessive with estimates of 188 and 140 ML ha^{-1} for the beds and flat paddies respectively. This results in excessive drainage with volumes of 186 and 138 ML ha^{-1} for the beds and flat paddies respectively. This simulation is a worst case scenario as the infiltration data of Humphreys et al. (2008) suggest that the infiltration will be at least 1/30 of these values. This would give irrigation and drainage volumes of 6.3 and 6.2 ML respectively for the beds, and 4.7 and 4.6 respectively for the flat paddies. The lower values for the flat paddies are due to the lower hydraulic conductivity of the topsoil (table 6.12).

From the excessive irrigation and drainage the solute transport to the water table would also be expected to be excessive. This is clearly seen to be true in figure 6.1.11a,c where the salt input for irrigation and salt drained are similar in magnitude. Given that comments above about the infiltration rate being much less than the values used in the simulation much lower values of salt leaching and root water uptake are likely.

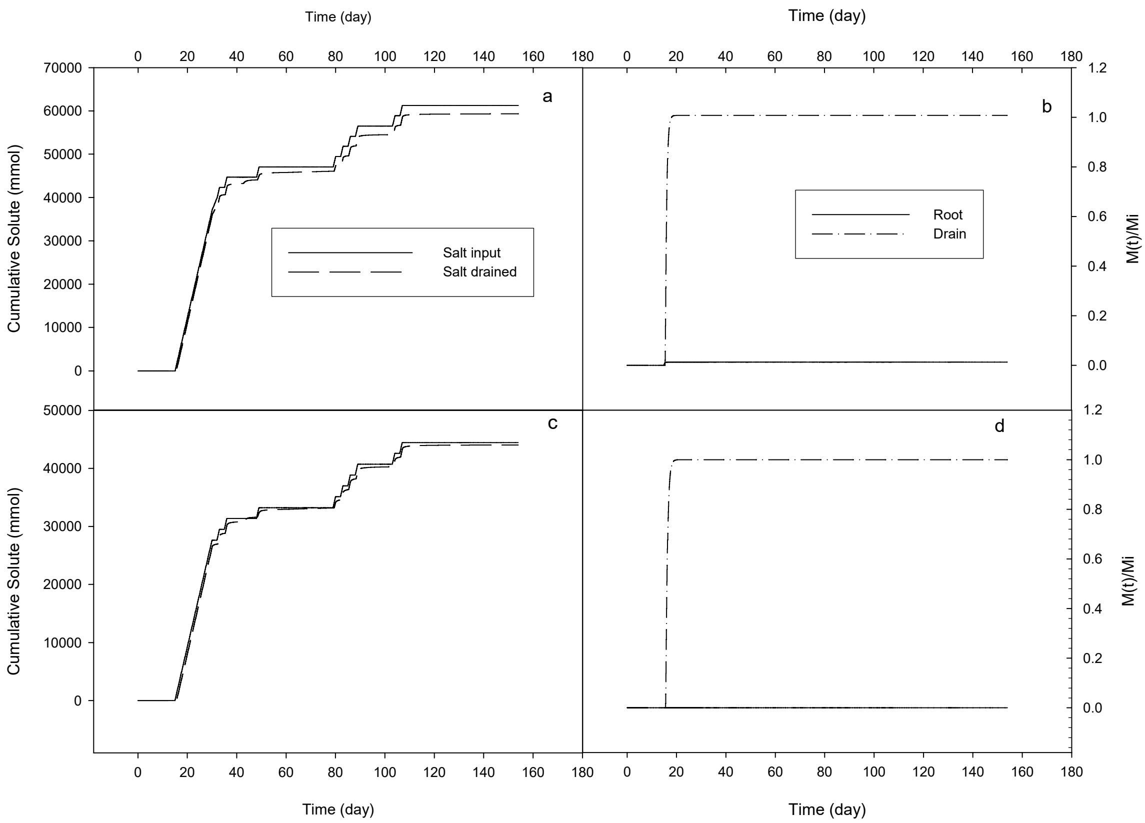

Figure 6.1.11. Salt input from irrigation water and drainage beyond 2 m depth for sandy loam soil with a) beds and c) flat paddies. Proportion of fertilizer mass of applied taken up by roots and drained for b) beds and d) flat paddies.

These results highlight the problem of simulation of water and solute transport when the data inputs into the model do not reflect the real field situation.

The results for irrigation on the loam soil result in much less infiltration and drainage due to the lower hydraulic conductivity of this soil. The infiltration results for the loam flat paddy will be similar for the puddle flat paddies of the sandy loam soil. The infiltration is simulated to be 16.6 ML ha^{-1} for the beds and 26.3 ML ha^{-1} which is a saving in water of 10 ML ha^{-1} (fig. 6.1.12). The drainage in both beds and flat paddies is still substantial at 14 ML ha^{-1} for the beds and 27 ML ha^{-1} for the flat paddies The irrigation volumes calculated here are very similar to those found by Humphreys et al. (2008) for this soil. This suggests that these simulations are likely to be much closer to the real field situation than those for the sandy loam.

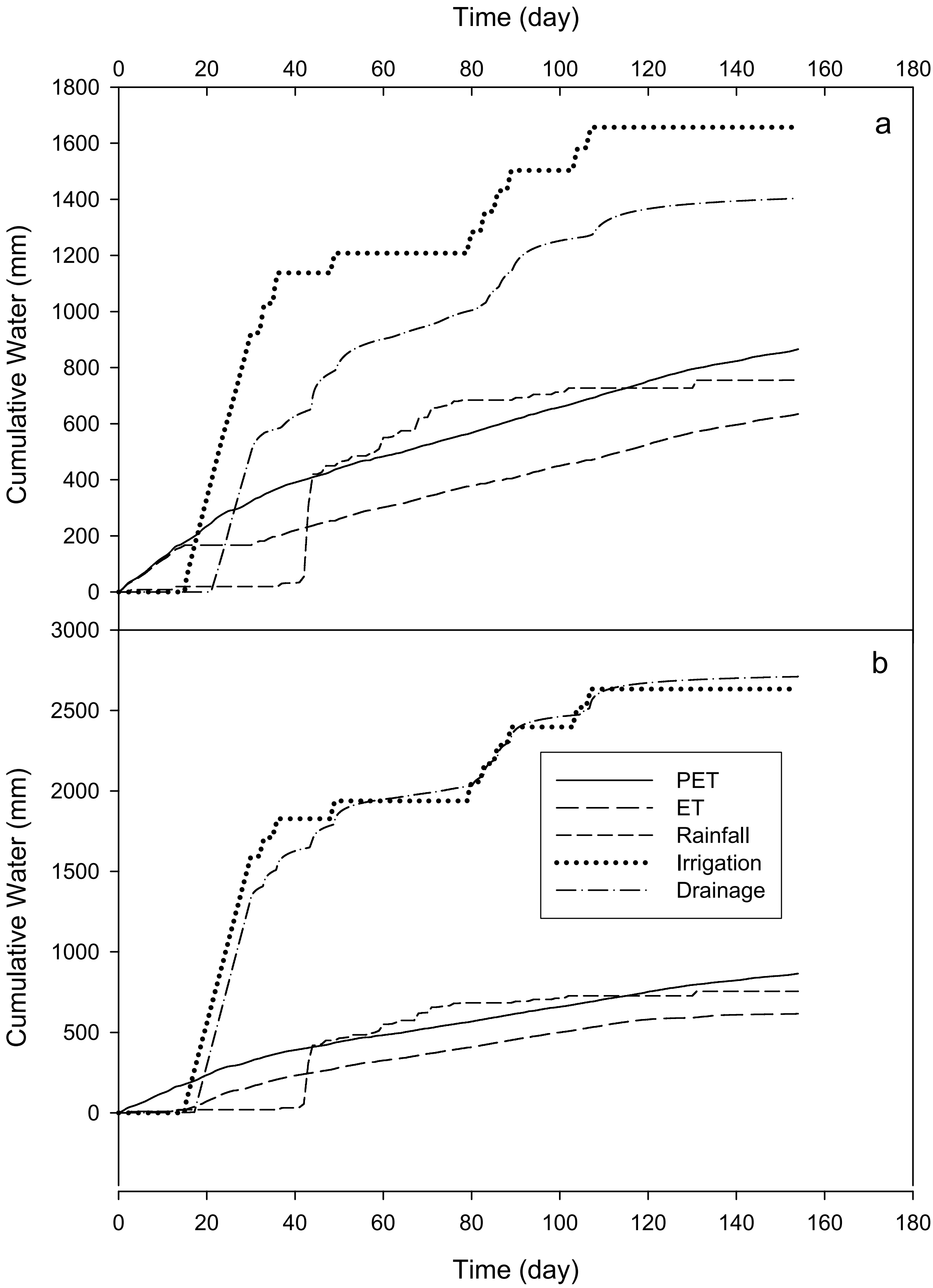

Figure 6.1.12. Simulation of the cumulative water used in growing rice for the loam soil for a) beds and b) a flat paddy.

Even for the loam soil the substantial drainage still results in considerable solute transport to the water table (fig. 6.1.13). This will result in any salt and agrochemicals being transported to the groundwater. The beds due to the lower infiltration will reduce this amount compared to the flat paddy situation.

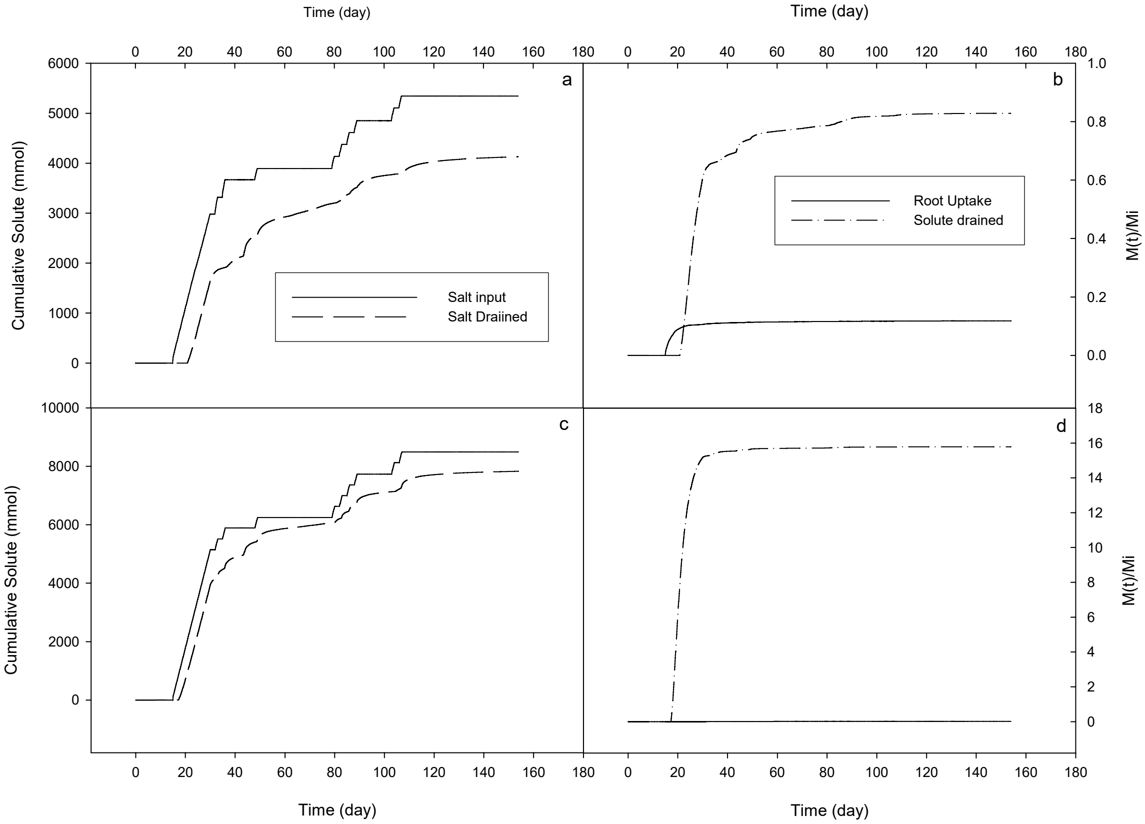

Figure 6.1.13. Salt input from irrigation water and drainage beyond 2 m depth for loam soil with a) beds and c) flat paddies. Proportion of fertilizer mass of applied taken up by roots and drained for b) beds and d) flat paddies.

The amount of fertilizer solute that is taken up by the roots is more that 10% for the bed situation but simulated as zero for the flat paddies. This latter value is incorrect due to the problem created by the upper boundary condition. It is likely to be less that the bed value but greater than zero. Most of this fertilizer is still predicted to end up in the groundwater. This suggests that highly soluble fertilizers are undesirable during rice growing and slow-release fertilizers may be preferable.

Further checking of the simulations is possible as the simulation suggest that considerable drying to depth will occur after the last rice irrigation and prior to planting of wheat (fig. 6.1.14). This is mainly due to evaporative drying of the soil profile and compares well with the measured data using neutron probes (fig. 6.1.15). The other point to note is that both simulations and measured water content profiles show considerable change I water content at a depth of 1.6 m. This supports the suggestion of excessive drainage shown by the simulations.

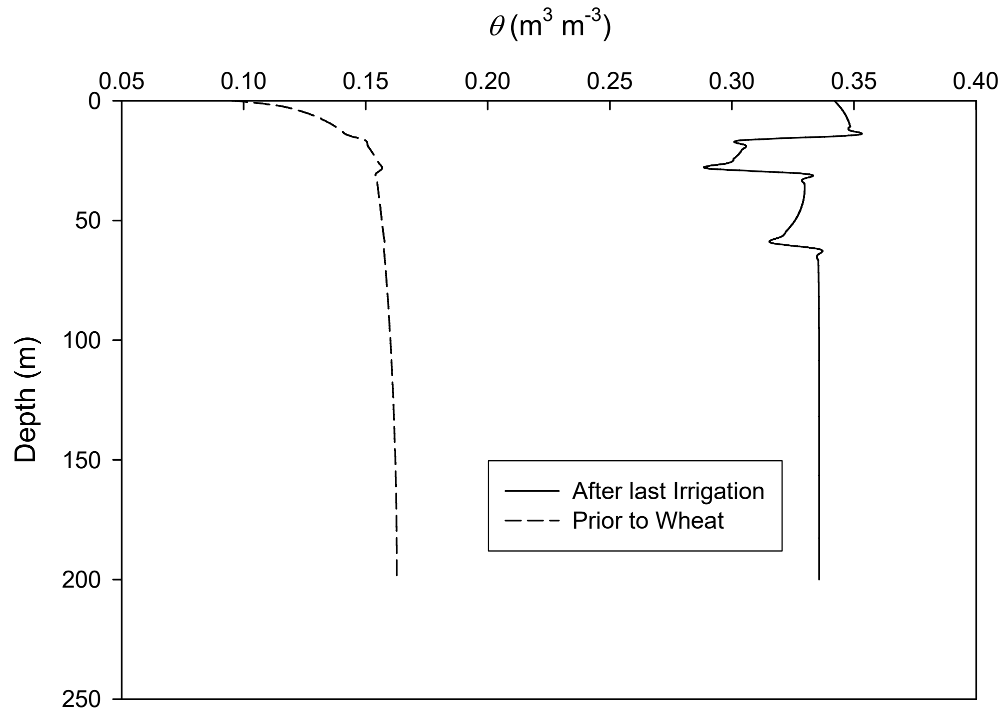

Figure 6.1.14. Water content profiles in the sandy loam soil following the last irrigation and prior to planting of wheat.

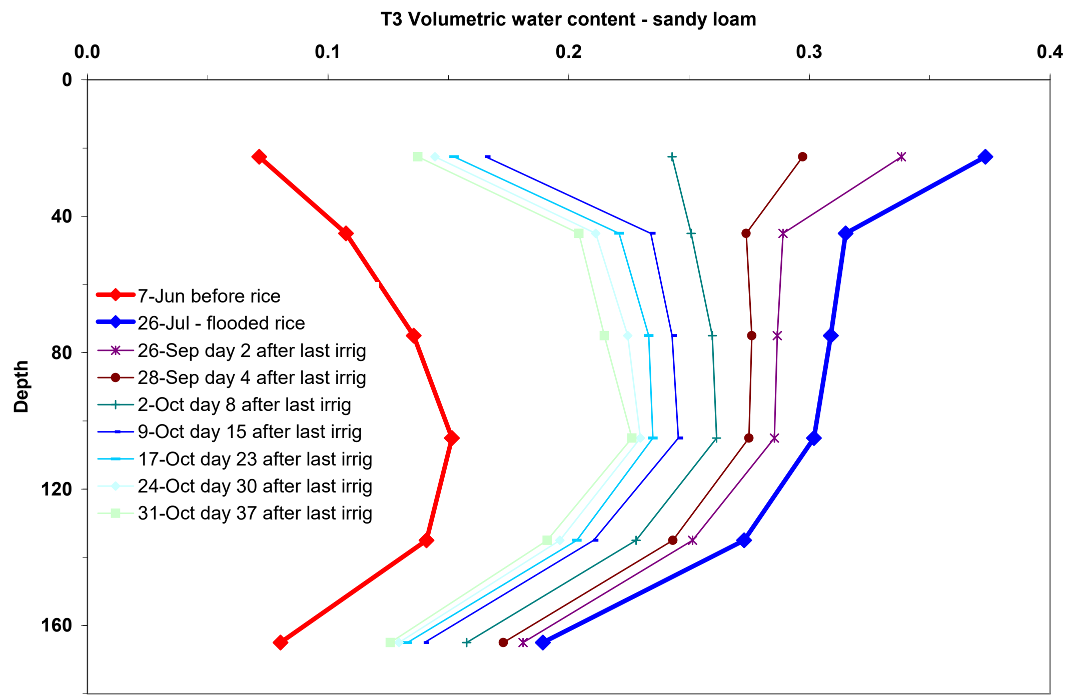

Figure 6.1.15. Measured water content profiles for rice at the end of the crop. (E. Humphreys pers. comm.).

6.2 Indonesia case study

This raised beds project is situated on the island of Lombok, in the West Nusa Tenggara province of Indonesia. Site locations on Lombok are shown in fig. 6.2.1.; site 1 will be herein called Wakan and site 2 herein called Kawo. At both of these sites the cropping regime is one of monsoonal rice as the main crop and soybeans or other vegetable crops as a second or third crop, depending on the total rainfall in a given monsoon season. Hence, in some of the project's experimental treatments two vegetable crops were tried. More details on the project can be found in Ma'shum et al. (2005). The project's experiments are sited on Vertisols with high clay contents. The only physical properties were the particle size distributions and these were for the top 0.3 m of soil. The physical properties of the soils were estimated from these data below.

The wet season provides surplus rain but also water-logs the soil. One of the aims in the simulations for this project is to look at the design of beds in relation to drainage. Water harvesting of excess water via seepage into the furrows occurs during the wet season and provides an opportunity to harvest and store water for supplementary irrigation in the dry season. Therefore, this case study will also examine the bed design with respect to the amount of water harvested. Supplementary irrigation supplied during the dry season is mainly used to grow the vegetable crops. At present this is applied by hand. We will estimate the volume of water that could be applied at each watering, the frequency of irrigation required to maximise the crop yield and the placement of this irrigation for best wetting of the bed.

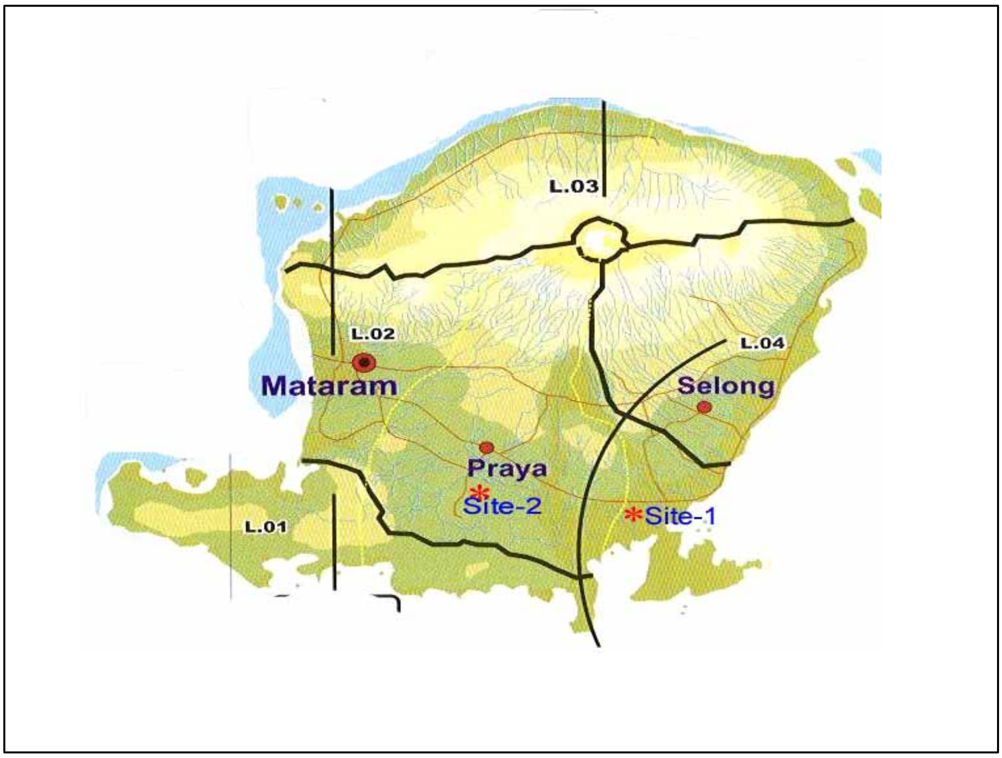

Figure 6.2.1. Map of Lombok showing location of the two experimental sites used by the Indonesian PRB project in West Nusa Tenggara (provided by J. Tsidall).

Fertilizer placement to assess leaching will not be part of the simulations here as this was shown in the Indian case study simulations to not be of importance in the leaching of solutes when rainfall can push the solutes down into the irrigation stream. Salinisation during the dry season will be simulated. Salinisation is unlikely to be a long-term problem in this project as, leaching to depth or by seepage to the furrows of any salt accumulated in the dry season, will occur in the wet season.

6.2.1 Soil properties

Both the Kawo and Wakan sites are characterised by Vertisols (black, grey or brown cracking clays). The only physical properties available for these soils are particle size distribution (table 6.2.1). The swell-shrink properties of Vertisols make their soil hydraulic behaviour variable, something that is problematic to model even when good soil hydraulic property data is available. It presents an even greater challenge to interpreting modelling outputs when texture is the only data available. Hence, the results presented for this case study need to be interpreted with caution, as the modelling only partially captures the effects of swell-shrink on water dynamics, and in this case is also based on a relatively low level of data input. The fact that most of the simulations are for the soil in the moist to wet range means that some of the difficulties with this shrink-swell behaviour are avoided.

Table 6.2.1. Soil textural properties for Wakan and Kawo soils at three depths. The particle size data are presented with the Australia and silt (0.002 – 0.02 mm) and American silt (0.002 – 0.02) in brackets. This results in different values for the proportion of sand and silt with the American values shown in brackets.

Depth (m)	Sand	Silt	Clay
Wakan soil			
0 - 0.10	0.264 (0.225)	0.176 (0.215)	0.560
0.10 - 0.20	0.235 (0.200)	0.173 (0.208)	0.592
0.20 - 0.30	0.163 (0.130)	0.135 (0.148)	0.722
Kawo soil			
0 - 0.10	0.178 (0.189)	0.226 (0.218)	0.596
0.10 - 0.20	0.140 (0.154)	0.201 (0.187)	0.659
0.20 - 0.30	0.125 (0.097)	0.148 (0.176)	0.727

From the particle size the van Genuchten parameters for moisture characteristic function and saturated hydraulic conductivity were calculated using (Schaap et al., 1998, Schaap and Leij, 1998; Schaap et al., 2001) and are shown in table 6.2.2.

Table 6.2.2. Soil hydraulic properties for Vertisols on Lombok.

Depth (m)	θ_r (m3 m-3)	θ_s (m3 m-3)	α (m-1)	n	K_s (m s-1)
Wakan soil					
0 - 0.10	0.098	0.488	2.03	1.213	2.19 x10-06
0.10 - 0.20	0.099	0.496	2.08	1.192	2.01 x10-06
0.20 - 0.30	0.102	0.508	2.03	1.180	2.03 x10-06
Kawo soil					
0 - 0.10	0.0956	0.478	2.07	1.221	2.07x10-06
0.10 - 0.20	0.0970	0.485	2.08	1.210	2.10x10-06
0.20 - 0.30	0.102	0.501	2.10	1.173	1.92x10-06

The estimated van Genuchten parameters are similar for all three depths at each site and are also similar for each site. Without further measurements it is not possible to know if this is correct. Given these results it would seem judicious for some soil physical measurements to be made at each site. The results also mean that the generic simulations for drainage and irrigation give very similar results. Hence only the results for the Wakan soil will be presented unless the results differ significantly.

From the estimated moisture characteristics estimates of the amount of water required for each irrigation can be determined by:

$$\Delta\theta_I = (\theta_s - \theta_r)\left[\left(1+|\alpha\psi_f|^n\right)^m - \left(1+|\alpha\psi_e|^n\right)^m\right] \qquad [6.2]$$

where $\Delta\theta_I$ is the required change in water content, ψ_f and ψ_e are the potentials at the fill (after irrigation) and empty (prior to irrigation) points . The values for both soils with ψ_f = -0.1 m and, ψ_e = -10 or -154 m, show that, although the available water storage (ψ_f = -0.1 m and ψ_e = -154 m) is substantial (≈ 260 mm per m of soil) the amount of readily available water (ψ_f = -0.1 m and ψ_e = -10 m) is not large (≈ 60 mm per m of soil) (table 6.2.3). The available water capacity is high but consistent with other data on vertisol (Foley and Harris, 2007; Ordonez Fernadanez et al., 2007) and the readily available water is similar to the values in Tisdal (2005)

Table 6.2.3. Water storage properties for Wakan and Kawo soil derived using eqn (4.2.1).

Soil	Depth (m)	$\Delta\theta_I$ (ψ_e = -10 m)	$\Delta\theta_I$ (ψ_e = -154 m)
Wakan	0-0.1	0.066	0.266
	0.1-02	0.059	0.253
	0.2-03	0.062	0.257
Kawo	0-0.1	0.067	0.266
	0.1-02	0.065	0.263
	0.2-03	0.057	0.244

The total volume required for each irrigation can be determined from the volume of soil to be irrigated and the values in Table 6.2.3.

6.2.2 Drainage

Drainage of the beds in the wet season is important with regard to growing of vegetable crops. The extreme case will occur when drainage of the beds is only by seepage to the furrows. Simulation of drainage from initially saturated beds with drainage only by seepage through the sloping bed furrow face and rounded wavy bed face to a height above the furrow of 0.15 m was performed using the mesh grids and spatial domains shown in fig. 6.2.2. Drainage via the seepage faces will cease when there is no longer a positive water potential to push water across the seepage face. Simulation results show that for the wavy beds where the midpoint of the beds is 0.4 m above the furrow height, the drained porosity at the middle and top of the bed is greater than the drained porosity for the same point in the permanent raised beds (PRB). This is in part due to midpoint height for the PRB being 0.2 m above the furrow height, while for the wavy beds the mid-piont is 0.4 m above the furrow height (fig. 6.2.2). Results show that at the top and centre of the beds only 5 and 3 % of the porosity will be drained for wavy and PRB beds respectively (fig. 6.2.3b, d). This may result in aeration problems for the vegetable crops but will be a good result for rice where anaerobic conditions are desired.

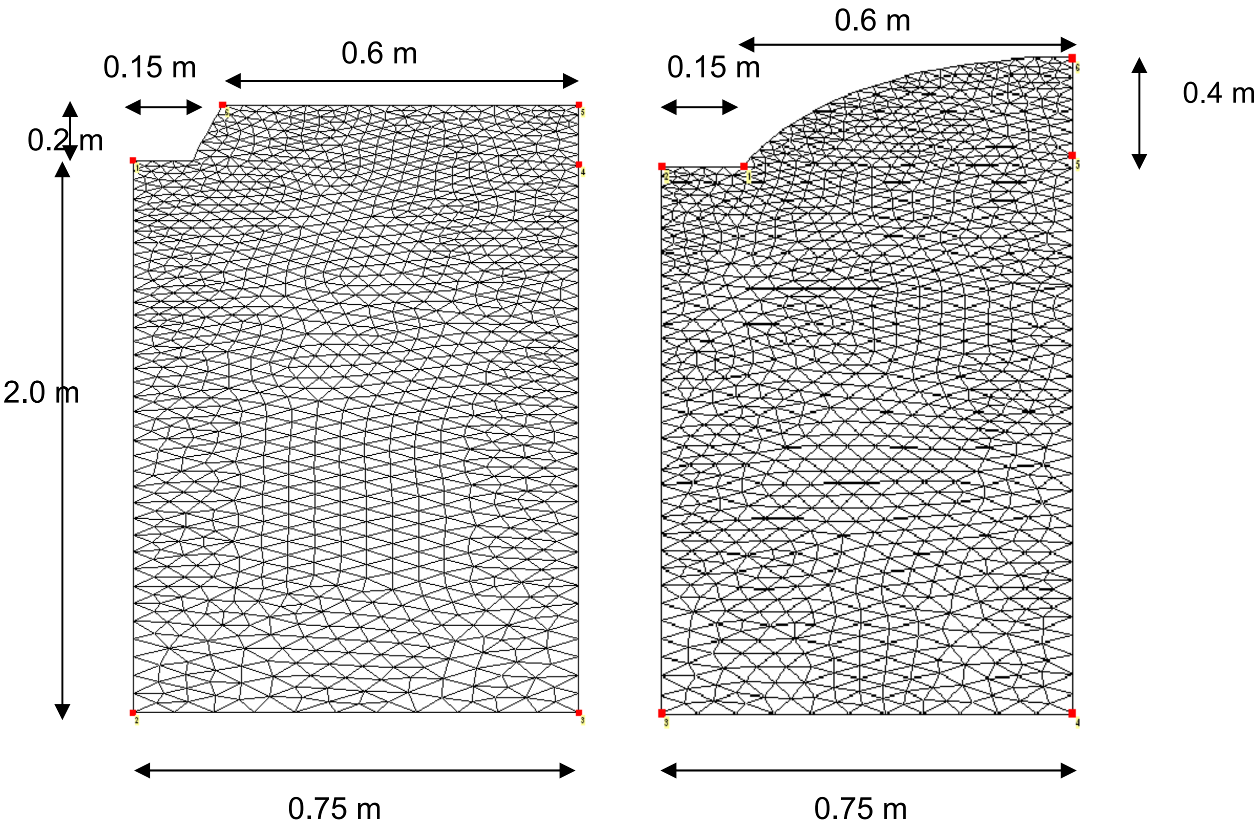

Figure 6.2.2. Domains for the simulation with PRB (left) and wavy bed. The red squares and numbers indicate the observation points that are monitored during the simulation.

An estimate of the bed equilibrium potential and water content profiles can be obtained with equation (5.2) developed earlier. Using eqn (5.2) the estimated bed height to give a drained porosity of 0.1 m^3 m^{-3} was found to be > 1.6 m (table 6.2.3). Given the present bed heights of 0.4 (wavy) and 0.2 m (trapezoidal) these results would suggest that increasing the bed height would be an option, particularly for vegetables in the wet season, but an increase to 2 m is likely to be impractical.

Table 6.2.4. Values of the bed height related to the amount of drained porosity (Z_b) predicted by eqn (5.2) for the Wakan and Kawo soils using the data in table 6.2.2.

Soil	Layer (m)	z_b (m)
Wakan	0 - 0.1	1.67
	0.1 - 0.2	2.05
	0.2 - 0.3	1.87
Kawo	0 - 0.1	1.61
	0.1 - 0.2	1.69
	0.2 - 0.3	2.22

Simulations of drainage from saturation where the bottom boundary condition is assumed to be free drainage (the potential gradient is assumed to be = -1) gives results where the middle, top of the beds reach air-filled porosities of about 8% after 6 days (fig. 6.2.3a,c). This is quite low but as Cook and Rassam (2002) showed evaporation is an important soil draining process in tropical climates and may increase the air-filled porosity.

Note that in figure 6.2.3 there are some oscillations in the results at the start of the simulation for the 2 m depth node. This occurs due to the large gradient across the boundary but smoothes out relatively quickly. The mid point in the wavy beds is 0.2 m higher above the furrow than the mid point for the PRB, which results in a lower water content for the wavy beds than the PRB at the mid point when seepage is the only drainage mechanism (fig. 6.2.3b,d).

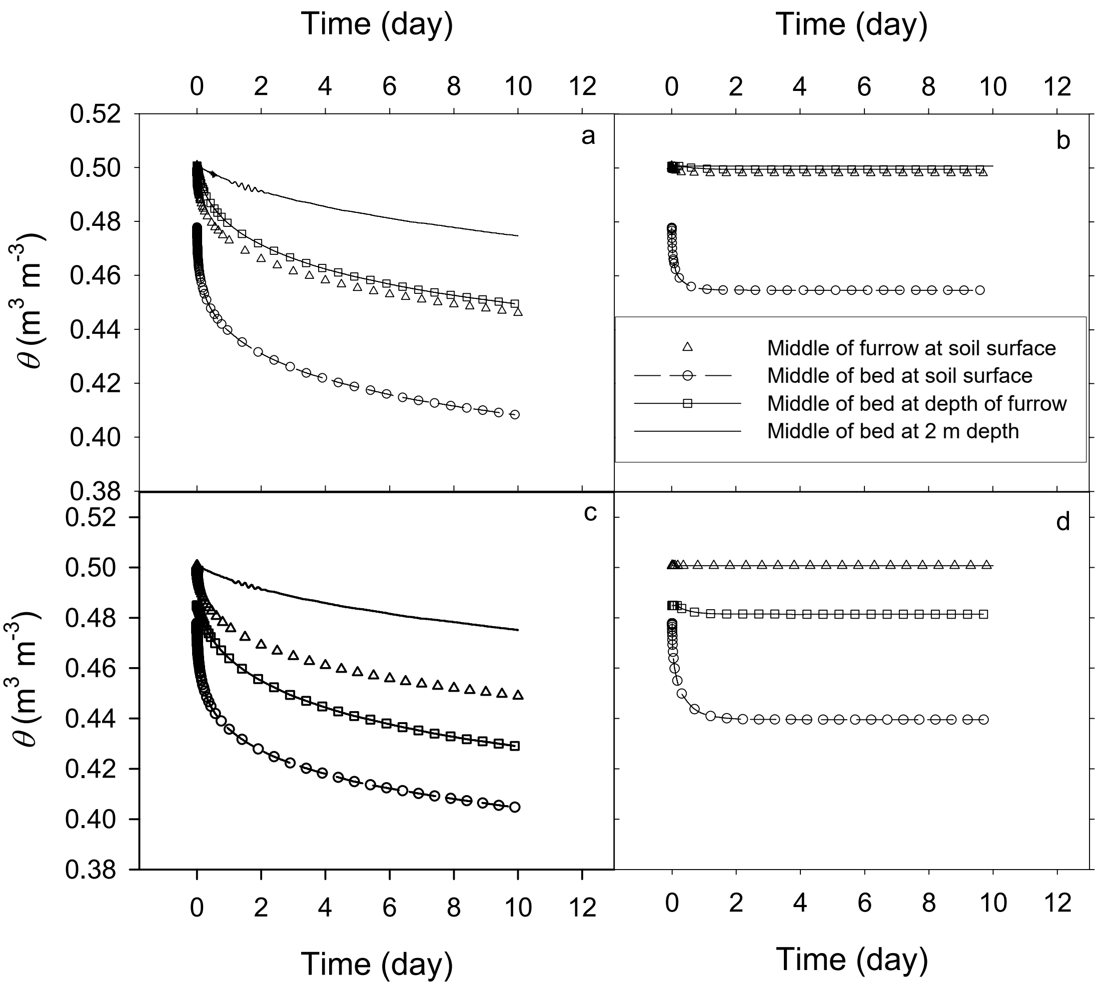

Figure 6.2.3. Water content (θ) versus time for node points shown in fig. 6.2.2 above for a) PRB with free drainage, b) PRB with only seepage drainage to the furrow, c) wavy beds with free drainage and d) wavy beds with drainage only by seepage to the furrow.

The bed height for the PRB was raised to 2 m and the simulations repeated. It was difficult to start with a head of 2 m at the top of the above the furrow, so the head had to be adjusted until a stable result was obtained. The results of the simulations show that at the top of the bed the time course for the water content is the same for free drainage or seepage to the furrow (fig. 6.2.4). This suggests that raising the height of the bed would be effective in increasing the air-filled porosity.

However, beds of 2 m in height are impractical but eqn (5.2) can be used to determine an estimate of bed height versus drained porosity. For example a bed height of 0.6 m is predicted to result in 5% air-filled porosity at the top of the bed. Equation (5.2) will overestimate the air-filled porosity, as the due to the low hydraulic conductivity equilibrium has not been reached even after 10 days in the simulations.

Since it is height above the furrow that will be important for drainage of the beds the wavy beds result in less volume of soil at the maximum height than the PRB and so are not a useful shape. The fact that the wavy beds are 0.2 m higher in the middle than the PRB means that analysis of the effect of the beds on crop yield will be complicated. Raising the PRB to 0.4 m would have offered a better comparison in the experimental work.

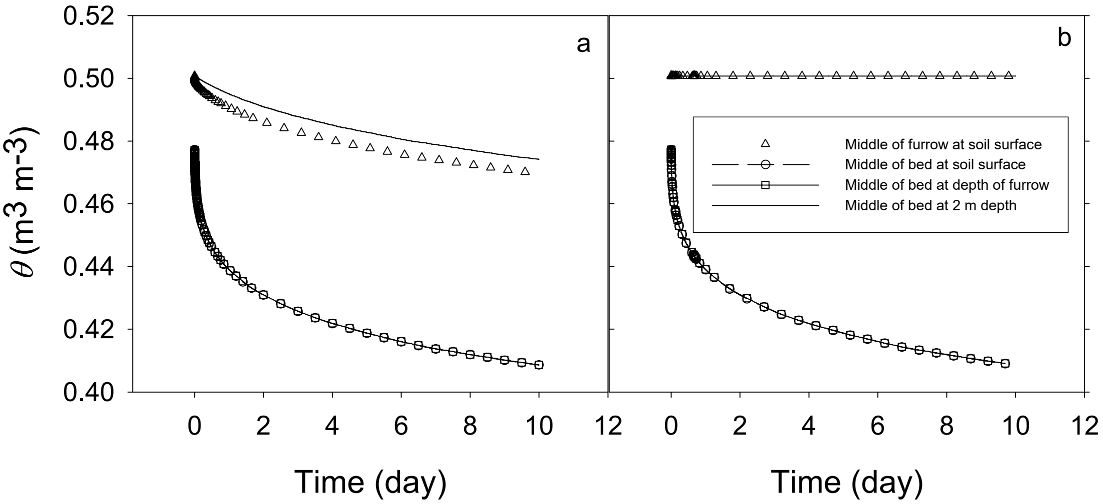

Figure 6.2.4. Water content (θ) versus time for node points (legend) for a) PRB with bed height 2 m and free drainage and b) PRB with bed height 2 m and drainage to furrow by seepage.

6.2.3 Wet season water balance, harvestable water and solute transport

Rice and vegetables are grown in the wet season. Simulations were preformed with these two crops and two different boundary conditions for PRB and wavy beds at both sites. Although the soil properties were the same at both sites the climate was different which meant that simulations at both sites were required. Climate data supplied was monthly totals of rainfall and pan evaporation from November 2001 to October 2004 inclusive. During this period the wettest and driest wet seasons were chosen. The wet season is from November through to April inclusive. For both these crops the parameters of interest are; the drainage when a lower drainage boundary condition is chosen at the bottom, seepage losses to the furrow and potential water harvestable when a no flow boundary condition is chosen at the bottom, and the ratio of the potential to actual transpiration. The latter is an indicator of actual to potential crop yield.

Fertilizer was considered to be applied at the start of the season in a band 0.4 m wide down the centre of the bed for wavy beds and over the whole surface of the bed in the PRB. Rooting depth in both configurations was assumed to extend to 0.3 m depth.

Water balance for Kawo site rice

In the wet year (2002-03) on the wavy beds at the Kawo site November 2002 was dry and results in the lower values for AET in this month (fig. 6.2.8 b,d). The transpiration did not deviate from the potential for rice during the remaining months of the year. The amount of seepage face loss is between 200 and 400 mm. This is the likely maximum seepage loss and potential harvestable water as no drainage losses are assumed in this simulation. This is greater than that found by Robinson et al. (2005) of 130 mm on average for the whole of Lombok. When deep drainage is simulated the drainage losses are more than seepage face losses, due to less storage of water in the soil profile.

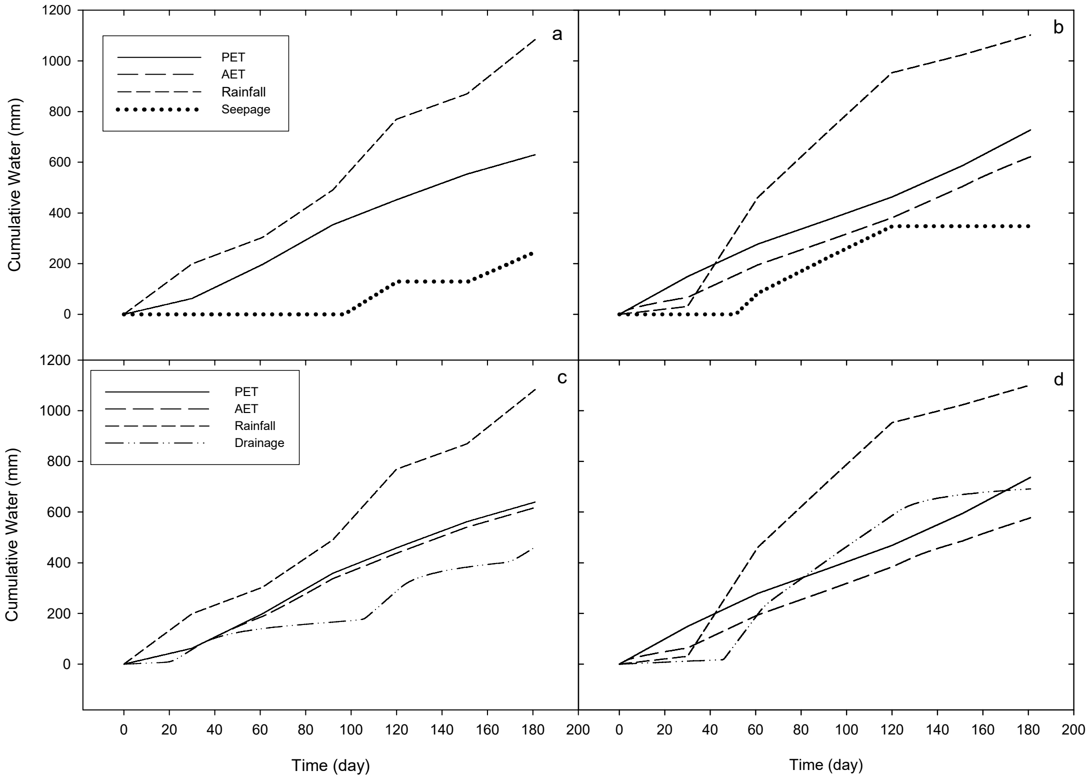

Figure 6.2.8. Simulation results for rice on Kawo soil on wavy beds during the wet season (November to April): a) dry year (2001-02), crop rice no drainage and seepage face; b) wet year (2002-03) crop rice no drainage and seepage face; c) dry year, crop vegetables, deep drainage d) wet year, crop vegetables, deep drainage. Potential evapotranspiration, actual evapotranspiration (AET), rainfall, seepage losses and drainage are shown.

For the Kawo soil there is little difference in the wet year and dry year total rainfall but there is an increase in simulated seepage and drainage losses in both wavy or PRB beds in the wet year (figs 6.2.8 & 6.2.9). This is due to the timing of the rainfall compared to the potential evapotranspiration. In the wet year the most rainfall occurs when the evapotranspiration is low causing more seepage and drainage.

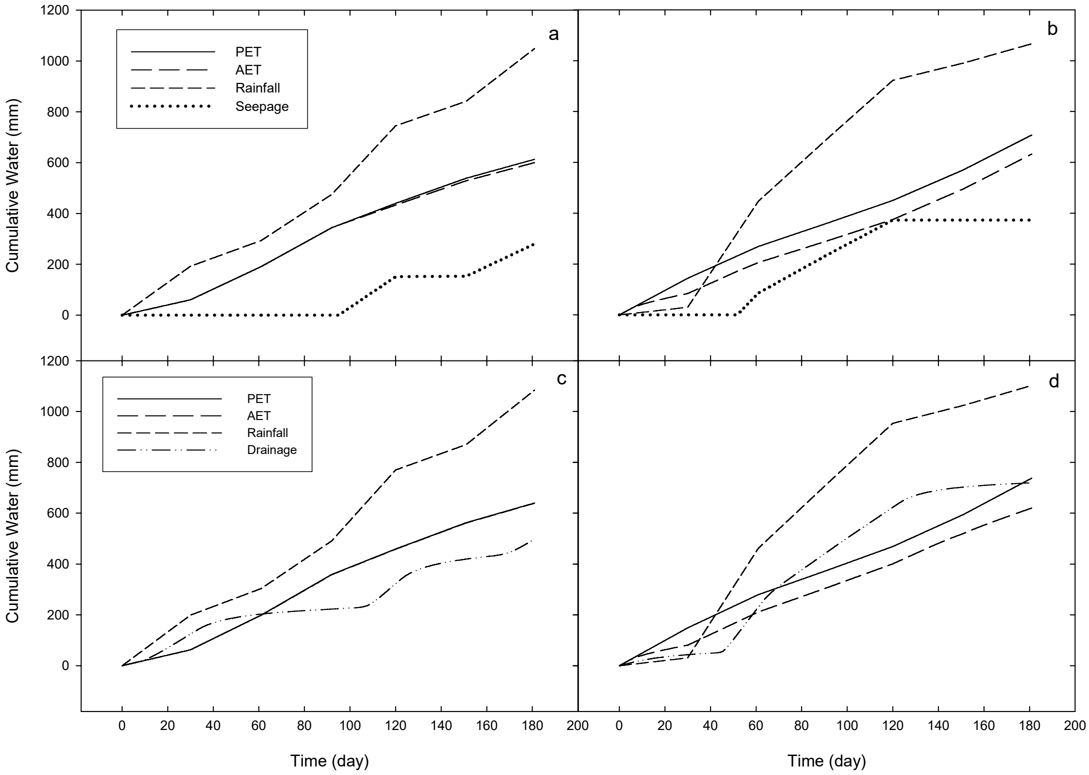

Figure 6.2.9. Simulation results for rice on Kawo soil on PRB beds during the wet season (November to April): a) dry year (2001-02), crop rice no drainage and seepage face; b) wet year (2002-03) crop rice no drainage and seepage face; c) dry year, crop vegetables, deep drainage d) wet year, crop vegetables, deep drainage. Potential evapotranspiration, actual evapotranspiration (AET), rainfall, seepage losses and drainage are shown.

In the wet year the actual evapotranspiration (AET) is less than the potential evapotranspiration (PET) for both wavy and PRB beds. This is due to November 2001 being dry and resulting in reduced evaporation, as the simulation assumes no crop until December. The PET and AET values are then almost equal in all other months suggesting no reduction in crop yield for rice would be expected.

Water balance for Kawo site vegetables

For the vegetable crops at the Kawo site the results for the wavy beds indicate a reduction in AET, but this is again due to the dry period in November and is unlikely to result in a yield reduction (fig. 6.2.10b). The water potential at which aeration problems would reduce transpiration was chosen as -0.10 m which means these results are applicable to vegetable crops that are not greatly affected by lack of aeration. Given the tropical temperatures the reductions in vegetable crop yield may be even worse than these simulations suggest (Cook and Knight, 2003).

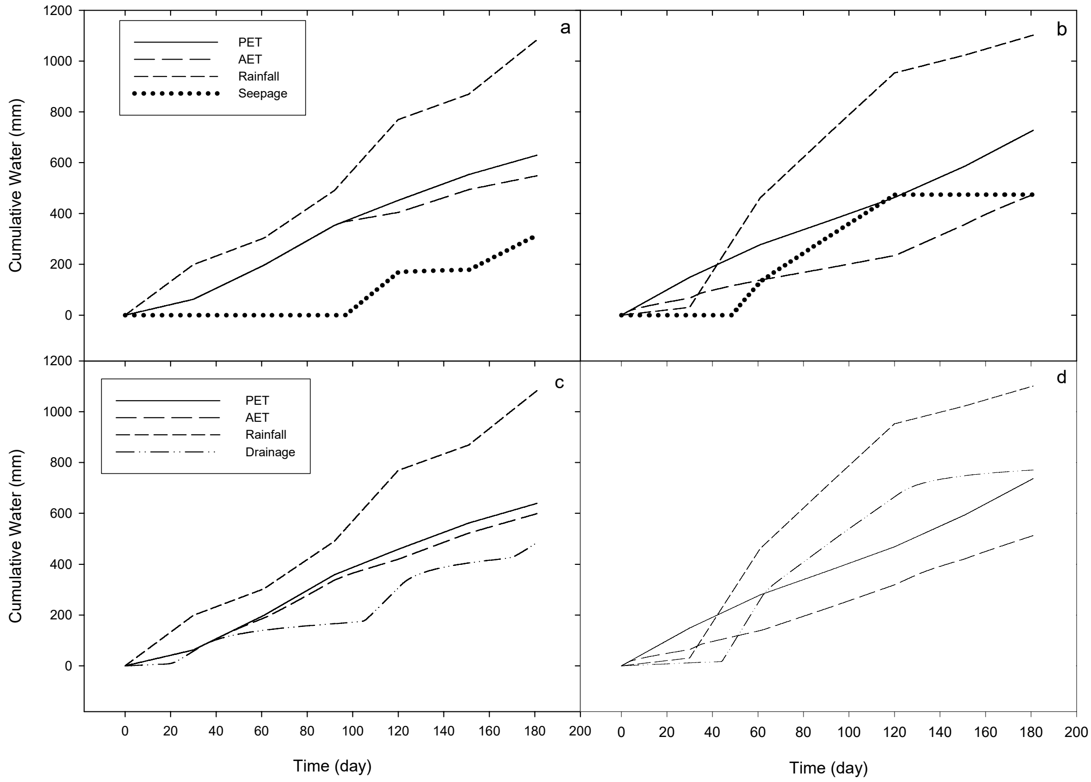

Figure 6.2.10. Simulation results for vegetables on Kawo soil on wavy beds during the wet season (November to April): a) dry year (2001-02), crop vegetables no drainage and seepage face; b) wet year (2002-03) crop vegetables no drainage and seepage face; c) dry year, crop vegetables, deep drainage d) wet year, crop vegetables, deep drainage. Potential evapotranspiration, actual evapotranspiration (AET), rainfall, seepage losses and drainage are shown.

For the PRB beds the simulations suggest that the vegetable crop yield may be worse in wet years (fig. 6.2.11b,d), and especially if seepage is the only means of draining the beds. In the dry year some reduction in yield is indicated in the latter part of the season, by the AET being lower than the PET, but only when seepage is the only means of draining the beds (fig. 6.2.11a). Seepage losses are predicted to be over 400 mm in the wet year, but only about 200 mm in the dry year. The actual water harvestable yield will be less than this due to some drainage occurring.

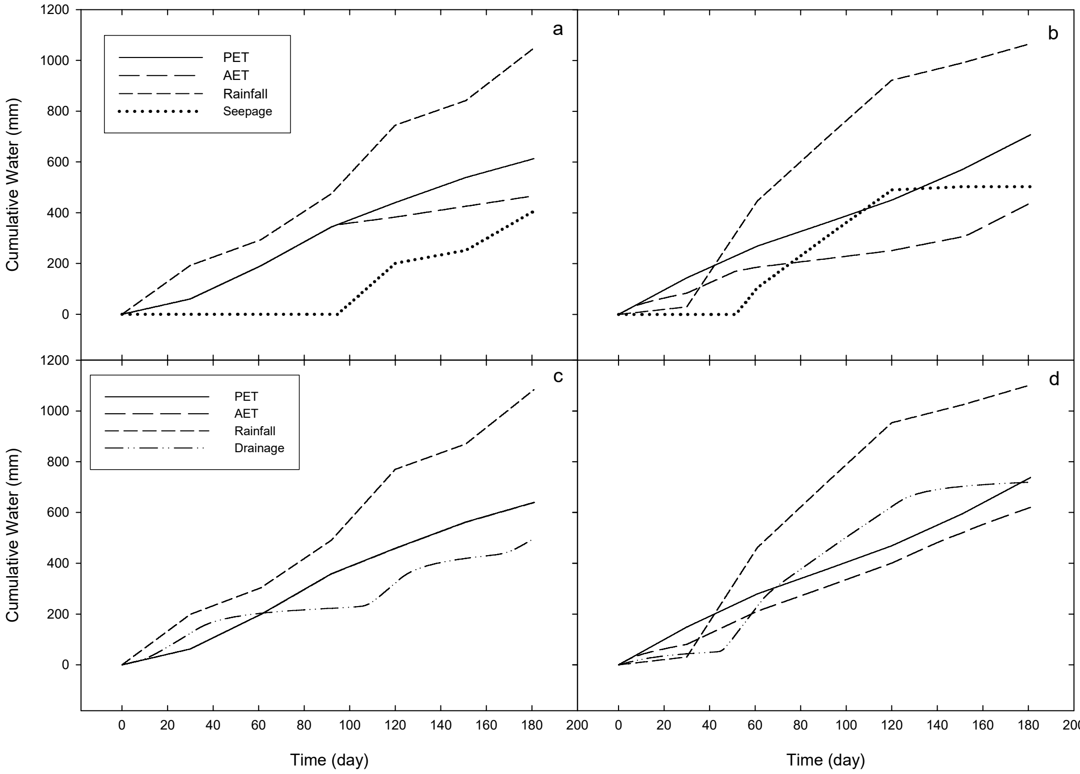

Figure 6.2.11. Simulation results for vegetable on Kawo soil on PRB beds during the wet season (November to April): a) dry year (2001-02), crop rice no drainage and seepage face; b) wet year (2002-03) crop rice no drainage and seepage face; c)dry year, crop vegetables, deep drainage d) wet year, crop vegetables, deep drainage. Potential evapotranspiration, actual evapotranspiration (AET), rainfall, seepage losses and drainage are shown.

Water balance for Wakan site rice

The Wakan site shows some slight differences to the Kawo site. Firstly there is a much bigger difference in the rainfall between the wet and dry years at the Wakan site. This has the effect of suggesting in the dry year (2001-02) that the rice yield could have been reduced due to lack of water in the middle of the wet season in the wavy beds (fig. 6.2.12a,c). The seepage losses are predicted to be small in the dry year which has implications if this water is the source of irrigation in the dry season.

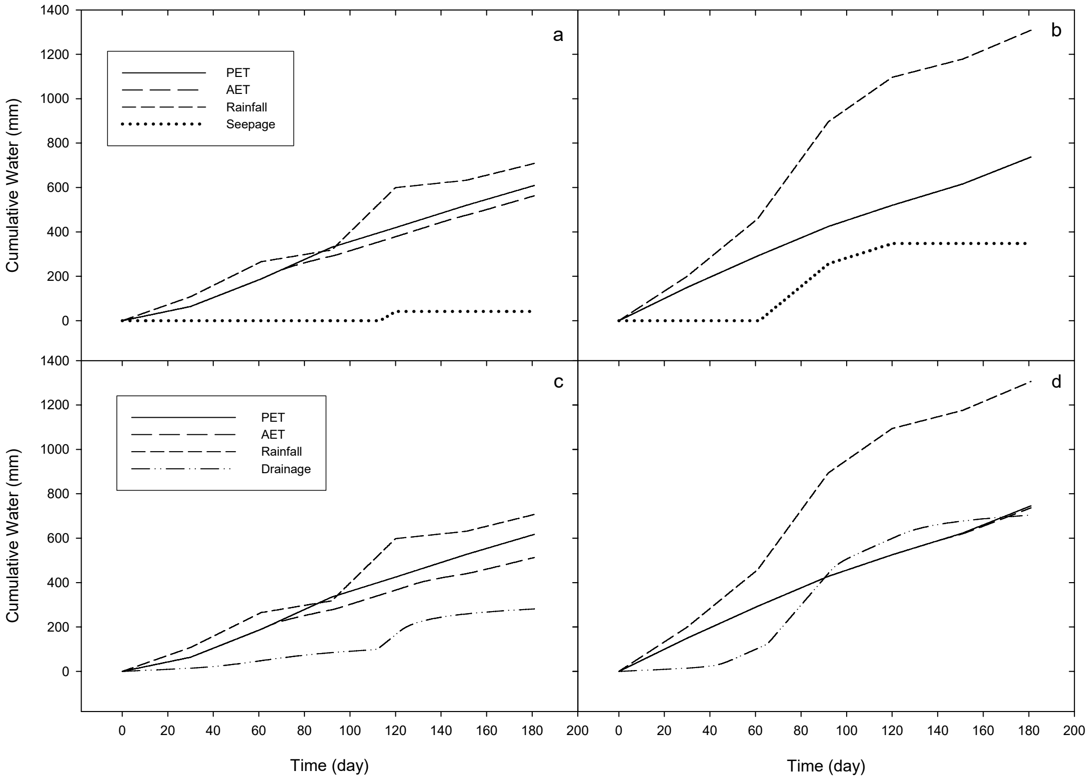

Figure 6.2.12. Simulation results for rice on Wakan soil on wavy beds during the wet season (November to April): a) dry year (2001-02), crop rice no drainage and seepage face; b) wet year (2002-03) crop rice no drainage and seepage face; c) dry year, crop vegetables, deep drainage d) wet year, crop vegetables, deep drainage. Potential evapotranspiration, actual evapotranspiration (AET), rainfall, seepage losses and drainage are shown.

The simulations show a possible yield reduction in the dry year with deep drainage in the PRB beds (fig. 6.2.13). The seepage face loss for the Wakan site in the dry year for PRB beds, similar to the wavy beds is small. This suggests that water harvesting from this site for dry season cropping could be a problem during dry years. At this site the simulations suggest that more water will be lost by seepage face losses on PRB beds compared to wavy beds.

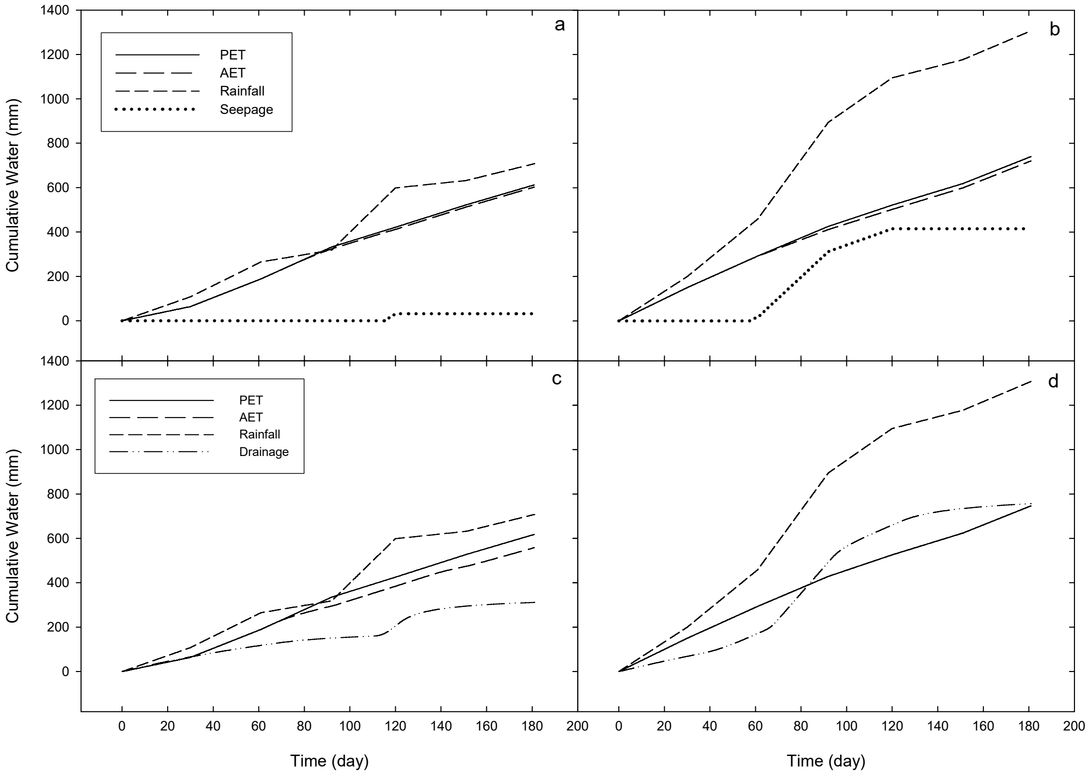

Figure 6.2.13. Simulation results for rice on Wakan soil on PRB beds during the wet season (November to April): a) dry year (2001-02), crop rice no drainage and seepage face; b) wet year (2002-03) crop rice no drainage and seepage face; c) dry year, crop vegetables, deep drainage d) wet year, crop vegetables, deep drainage. Potential evapotranspiration, actual evapotranspiration (AET), rainfall, seepage losses and drainage are shown.

There is a suggested reduction in yield shown at the Wakan site for rice in the dry year also due to lack of water but not as pronounced as in the higher wavy beds (figs 6.2.12, 6.2.13). The marked difference in the wet and dry years results in a marked difference in the drainage and seepage losses from the soil at this site. In particular the simulations suggest that there could be only limited seepage losses in dry years which could be a problem at this site for dry season irrigation.

Water balance for Wakan site vegetables

The simulations predict that on the wavy beds the vegetable crop yield would be reduced for all combinations of wet and dry years and seepage face or drainage as the process for water loss (fig. 6.2.14). This is mainly due to aeration restricting transpiration during a period of high rainfall between 80 and 100 days.

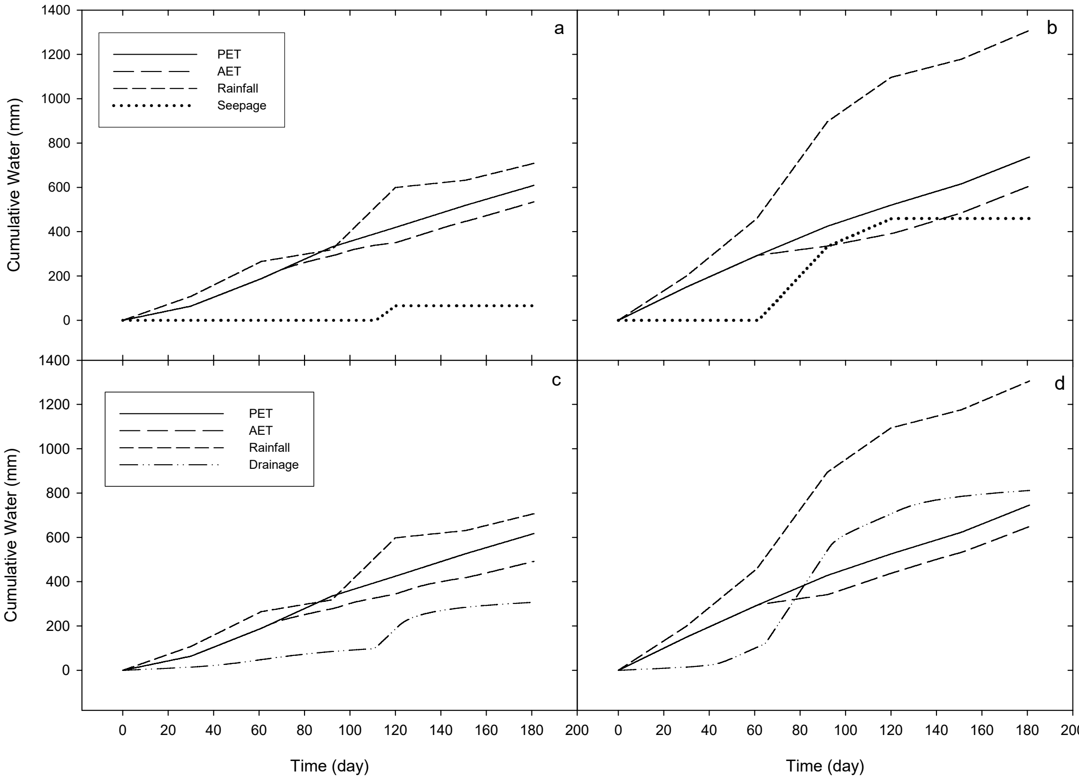

Figure 6.2.14. Simulation results for vegetables on Wakan soil on wavy beds during the wet season (November to April): a) dry year (2001-02), no drainage and seepage face; b) wet year (2002-03) no drainage and seepage face; c) dry year, deep drainage d) wet year, deep drainage. Potential evapotranspiration, actual evapotranspiration (AET), rainfall, seepage losses and drainage are shown.

The PRB results for the vegetables suggest that only in the wet year with only seepage face drainage will the AET be significantly reduced from the PET with possible yield reduction (fig. 6.2.15).

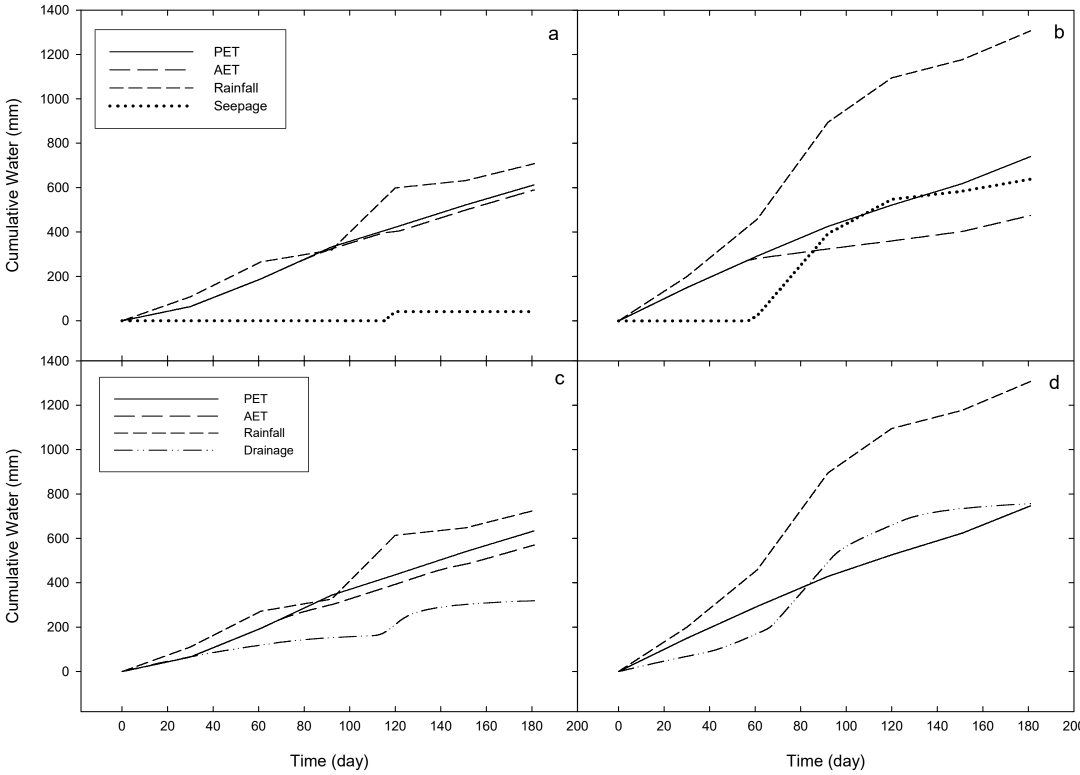

Figure 6.2.15. Simulation results for vegetables on Wakan soil on PRB beds during the wet season (November to April): a) dry year (2001-02), no drainage and seepage face; b) wet year (2002-03) no drainage and seepage face; c) dry year, deep drainage d) wet year, deep drainage. Potential evapotranspiration, actual evapotranspiration (AET), rainfall, seepage losses and drainage are shown.

Water harvesting and solute losses

The seepage face drainage and maximum potential harvestable water available for storage for supplementary irrigation is shown in table 6.2.5. This also represents the maximum irrigation depth that would be available to use in the dry season on the same area. We can clearly see that there is more water consistently available at the Kawo site. However, the highest seepage loss occurs at the Wakan site on a PRB for a vegetable crop during the wet year.

Robinson et al. (2005) simulated the water balance for Lombok using climate data for the period of 26 years from 1973 to 1998. They presented their results as runoff (excess water) and drainage and assumed that only the runoff was potential harvestable. The average annual values for excess water was simulated as ranging from 138 to 97 mm depending on crop by Robinson et al. (2005) and drainage rates from 135 to 88. Combining the excess water and drainage together to give a value comparable to those in table 6.2.5 gives annual average values of 238 to 218 mm, which is less than the average of the values in Table 6.2.5 of 312 mm. They also indicated that the maximum excess water in the 26 years of their simulation from 1973 to 1998 was 760 mm and the lowest was ‘virtually no excess water’. This would suggest that the values presented here are consistent with the results of Robinson et al. (2005).

Table 6.2.5. Yield of water from seepage face during the wet season. The wet and dry years are defined above.

Soil	Bed Type	Crop	Year	Seepage loss (mm)
Kawo	Wavy	Rice	Wet	348
			Dry	246
		Vegetable	Wet	474
			Dry	315
	PRB	Rice	Wet	373
			Dry	280
		Vegetable	Wet	503
			Dry	407
Wakan	Wavy	Rice	Wet	348
			Dry	42
		Vegetable	Wet	460
			Dry	66
	PRB	Rice	Wet	416
			Dry	32
		Vegetable	Wet	639
			Dry	41

The amount of solute taken up by the plant roots or lost to seepage or drainage is shown in table 6.2.6. The simulations showed that the solute gets pushed beyond the depth of the root system in the wet season. The timing of the wettest period during the wet season is important in determining the amount of solute that was taken up. If the wettest period occurred early then solute was transported below the root zone before the plants were able to extract it, as occurred with rice at the Kawo site on the dry year. This can be seen in fig. 6.2.16 where after 15 days the solutes have either discharged through the seepage face or been transported to near the base of the bed.

The mass balance for the solute in a number of simulations was poor and these are excluded from the data in table 6.2.6. Attempts were made to obtain better mass balances but were unsuccessful and took considerable time and effort. The wavy beds where the fertilizer was applied nearer to the centre of the bed showed better proportional root uptake of solute than in the PRB beds where the solute was spread across the bed. This was particularly so when seepage discharge occurred. This suggests that on these soils placement of the fertilizer away from the furrow will have a positive effect on fertilizer utilisation and reduction fertilizer loss to runoff water. The simulations that did not maintain mass balance occurred mainly in the wet season when the soil was excessively wet. These simulations would be likely to produce data that indicated lower solute uptake and high rates of salt leaching.

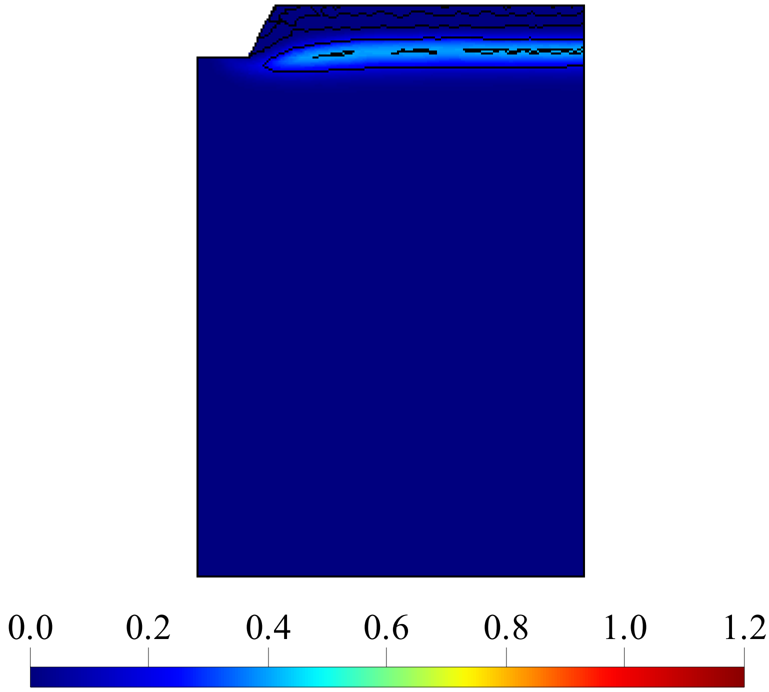

Figure 6.2.16. Solute concentrations at day 15 at the Kawo site, during the dry year for the wet season with a crop of rice. Concentrations are mmol m^{-3}.

Table 6.2.6. Proportion of solute taken up ((M(t)/Mi)) by roots or loss from the soil via seepage or deep drainage during from rice or vegetable crops during the wet season. The S or D after wet or dry in the year column indicates whether no drainage and seepage was the boundary conditions or deep drainage.

Soil	Bed Type	Crop	Year	Root uptake (M(t)/Mi)	Seepage loss (M(t)/Mi)	Drainage loss (M(t)/Mi)
Kawo	Wavy	Rice	Wet	nd	nd	nd
			Dry S	0.3310	0	
			Dry D	0.5574		0
		Vegetable	Wet	nd	nd	nd
			Dry S	0.3227	0	
			Dry D	0.5496		0
	PRB	Rice	Wet	nd	nd	nd
			Dry S	0.0421	0.4444	
			Dry D	0.0746		0
		Vegetable	Wet S	0.9237	0	
			Wet D	nd		nd
			Dry S	0.0421	0.5456	
			Dry D	0.7809		0
Wakan	Wavy	Rice	Wet S	0.3124	0.0284	0
			Wet D	0.5554		
			Dry S	0.8605	0	0
			Dry D	1.0004		
		Vegetable	Wet	nd	nd	nd
			Dry S	0.8517	0	0
			Dry D	0.9926		
	PRB	Rice	Wet S	0.1392	0.4898	
			Wet D	0.1817		0.002
			Dry S	0.7143	0.002	
			Dry D	0.7627		0
		Vegetable	Wet S	0.1392	0.4898	
			Wet D	0.1817		0.002
			Dry S	0.7125	0.003	
			Dry D	0.7627		0

6.2.4 Irrigation application method

No irrigation of the rice or vegetable crops is required in the wet season. Vegetable crops are irrigated in the dry season, mainly by hand watering. Simulations to determine how best to apply the water were carried out. Simulations were also performed to determine if furrow irrigation was viable with the present bed sizes. For these simulations the moisture characteristics in table 6.2.3 are used to estimate the amount of water required.

Furrow irrigation

Simulations to determine the penetration of the wetting front into the beds and to depth with time were performed with a head of water in the furrow of 0.1 m for both wavy and PRB beds. For comparison an irrigation run with the 2 m high PRB was also run. In this run the height of the wetting front on the front face of the bed was also monitored.

The simulations predict more rapid penetration of the wetting front in the wavy bed due to the smaller volume of soil close to the furrow (fig. 6.2.5). The horizontal and vertical wetting front penetration is almost identical for the both the PRB and high PRB configurations (fig. 6.2.5). The height of infiltration rise into the high (2 m) PRB would mean that wetting of this bed could not be achieved with only 0.1 m depth of water in the furrow. The results for the 2 m bed are useful in that they show that PRB beds would need to be less than 0.3 m in height above the water level in the furrow if wetting to the bed surface is required. For the wavy and PRB configurations the wetting front reaches the surface of the beds.

Penetration of the wetting front into the PRB is predicted to take > 2 days to reach the centre of a 1.2 m wide bed but in less that 1 day for wavy beds. For PRB beds of half the width (0.6 m) the wetting front would penetrate in < 1 day. If furrow irrigation was to be used for irrigation in the dry season then PRB width, these simulations suggest that PRB beds would need to be narrower.

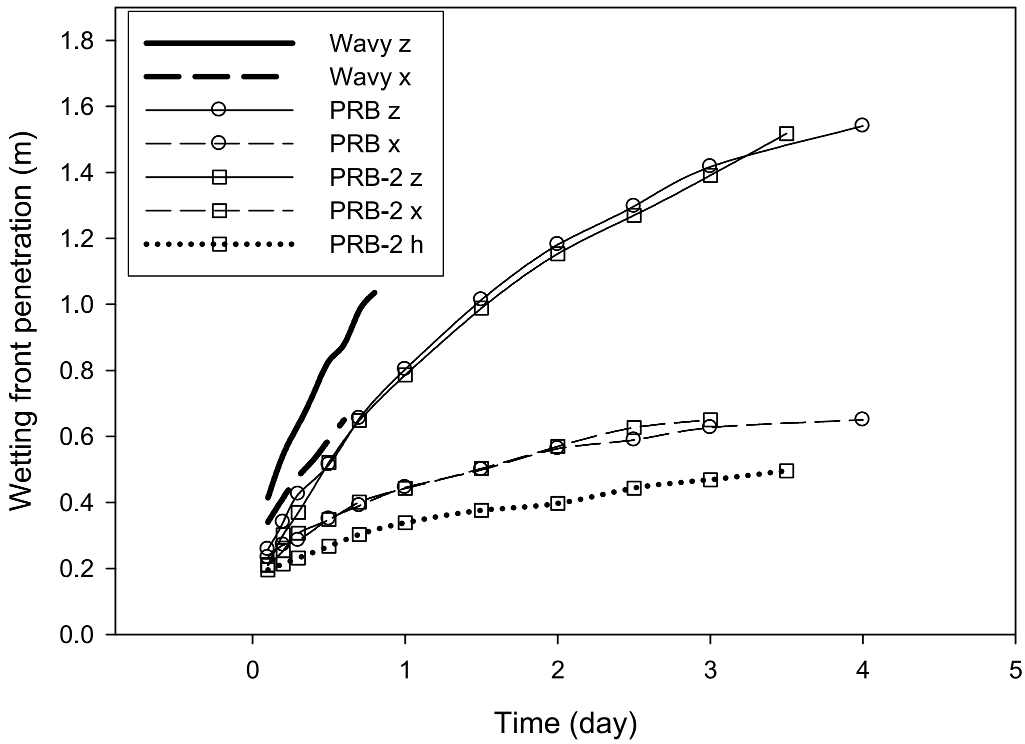

Figure 6.2.5. Penetration of wetting front into beds during infiltration from the furrow with a head of 0.1 m. The initial potential is -10 m. The various bed configurations are described in the legend with; *z* for depth, *x* for width and *h* for height.

Dry season irrigation

The final set of simulations is related to the dry season irrigation. Given the plant available water capacity of 0.06 m^3 m^{-3} and an assumed rooting depth of 0.3 m then the depth of water to be applied per irrigation will be 18 mm. For a bed width of 1.2 m this requires a volume of 21.6 L per m length of bed. From calculations of the potential water balance (rainfall – evapotranspiration) such irrigation would be required every second day at both sites during the driest part of the season. Applying 18 mm in one day to these soils is approximately equivalent to a flow rate which is 0.1 of their saturated hydraulic conductivity, so is feasible. Thus we investigated the infiltration pattern if this water was applied in a strip 0.2 and 0.4 m wide down the middle of the beds (equivalent to 0.1 and 0.2 m strips in the simulation domain). This is equivalent to applying 108 and 54 mm respectively to these strips. The results show that applying water in this way the infiltration will not wet all the PRB bed even when the infiltration strip is 0.4 m wide (fig. 6.2.6 1 b). The wider strip in the PRB bed does result in more horizontal and less depth of penetration of the wetting front (fig. 6.2.6 a,b) For the wavy bed due to the shape of the bed most of the bed will be wetted by a strip 0.4 m wide (fig. 6.2.6 d).

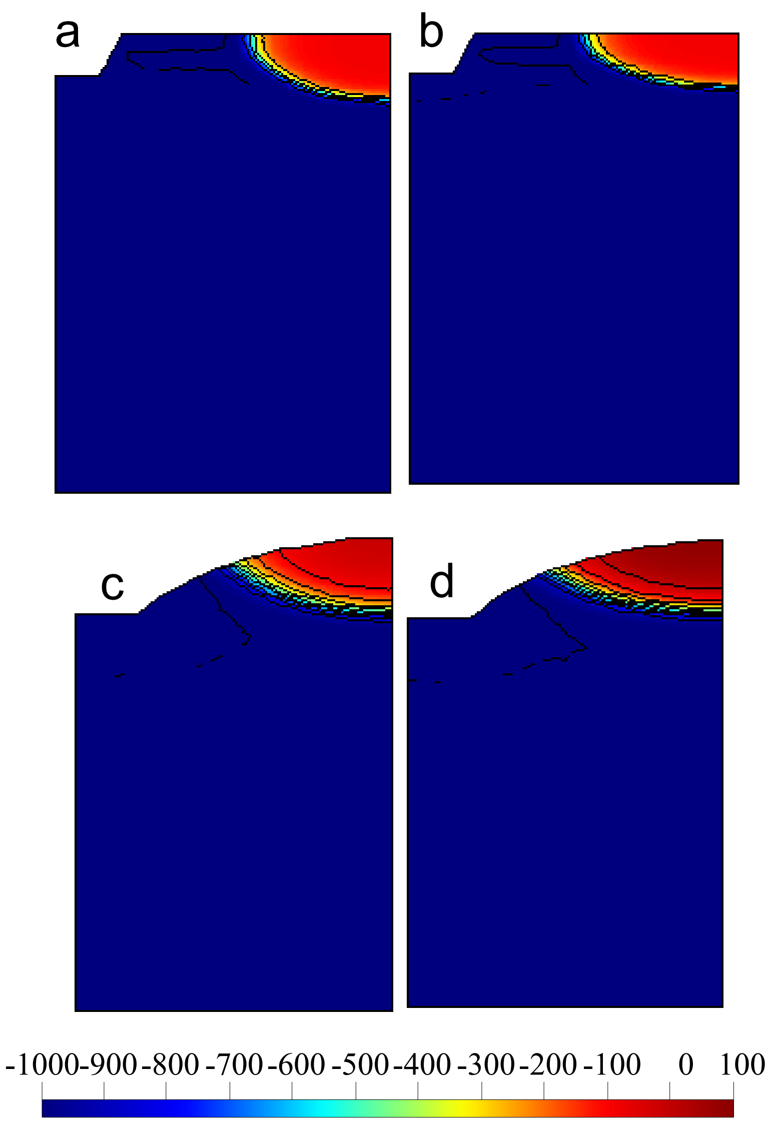

Figure 6.2.6. Wetting fronts after infiltration of the 10.8 L per m (for half bed space) into the Wakan soil initial at a potential of -10 m from; a) a strip 0.1 m wide at the centre of the bed for a PRB, b) a strip 0.2 m wide at the centre of the bed for a PRB, c) a strip 0.1 m wide at the centre of the bed for a wavy bed and d) a strip 0.2 m wide at the centre of the bed for a wavy bed. Note the 0.1 and 0.2 m wide strips at the centre correspond to double this width for a full bed.

Further simulations were carried out with three strips, one 0.2 m wide in the middle of the bed and two 0.1 m wide at the mid-point between the middle of the bed and the furrow edge. This configuration results in two strips of 0.1 m width in the simulation domain. In these strips the application depth is 54 mm. What these simulations show is that for this configuration, the entire bed will wetted (fig. 6.2.7).

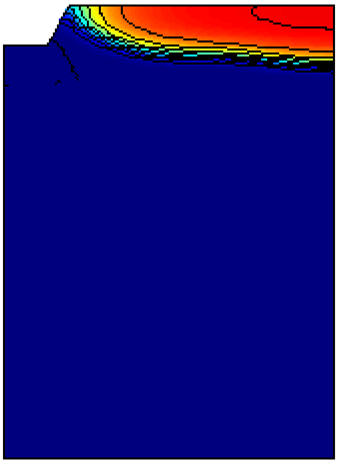

Figure 6.2.7. Wetting pattern in a PRB with two wetting strips (in the simulation domain) as described above. Initial conditions are the same as in figure 6.2.6.

The amount of irrigation water described above is equivalent to applying approximately 2 L every 100 mm of bed length. This may be difficult to achieve with hand watering but some simple applicators could be developed.

6.2.5 Dry season irrigation volumes

The irrigation regime for the dry season vegetables simulations was calculated as follows. A wetting depth of 0.3 m was chosen. The ready available water storage of 0.06 m^3 m^{-3} from table 6.2.3 was used as the water storage. The equivalent depth of water to be applied per irrigation was then calculated from these values as 18 mm. This corresponds to a volume over the whole bed (1.2 m) of 21.6 L for every 1 m of bed length.

For the climate data from both sites for the same wet (May - October 2003) and dry May - October 2002) years the potential soil water deficit was calculated on a daily basis until it reached 18 mm and then 18 mm of irrigation was added. If rainfall occurred on the day scheduled for irrigation then this rainfall was in addition to the irrigation. Using this method the total number of irrigations and total depth of water require was calculated (table 6.2.6).

Table 6.2.7. Number of irrigations and total volume applied for summer vegetable crops and highest seepage loss for site and year from table 6.2.5.

Site	Year	No. of Irrigations	Total Irrigation (mm)	Highest seepage loss (mm)
Kawo	2002 (Dry)	43	630	407
	2003 (Wet)	35	774	503
Wakan	2002 (Dry)	39	702	66
	2003 (Wet)	48	864	639

The total volumes applied are always greater than the highest seepage face loss. This would indicate that irrigation of the total area planted to rice is unlikely in the dry season even if all the water could be harvested and stored. In a dry year at the Wakan site it is likely that there would be only enough water to irrigate dry season crops on less than 10% of the area. Robinson et al. (2005) estimated irrigation requirements of on average 250 mm, but this was calculated using soil data based on Queensland vertosols and much larger water storage figures due to both the soil storages and rooting depths. The values in table 6.2.7 were estimated using observed (much shallower, J. Tisdal pers. comm.) rooting depths and lower by approximately 1/3 soil water storagevalues.

The water was applied to the surface of the beds as if it was rainfall. This maybe different to the actual application method. The irrigation water was considered to contain 1 mmol m^{-3} of salt to determine if accumulation of salt in the bed would be a problem. The results gave similar patterns in all simulations. Typical results for both wavy and PRB beds show that by the end of the dry season salt will have build up in the middle of the bed at the base of the root zone (fig. 6.2.17).

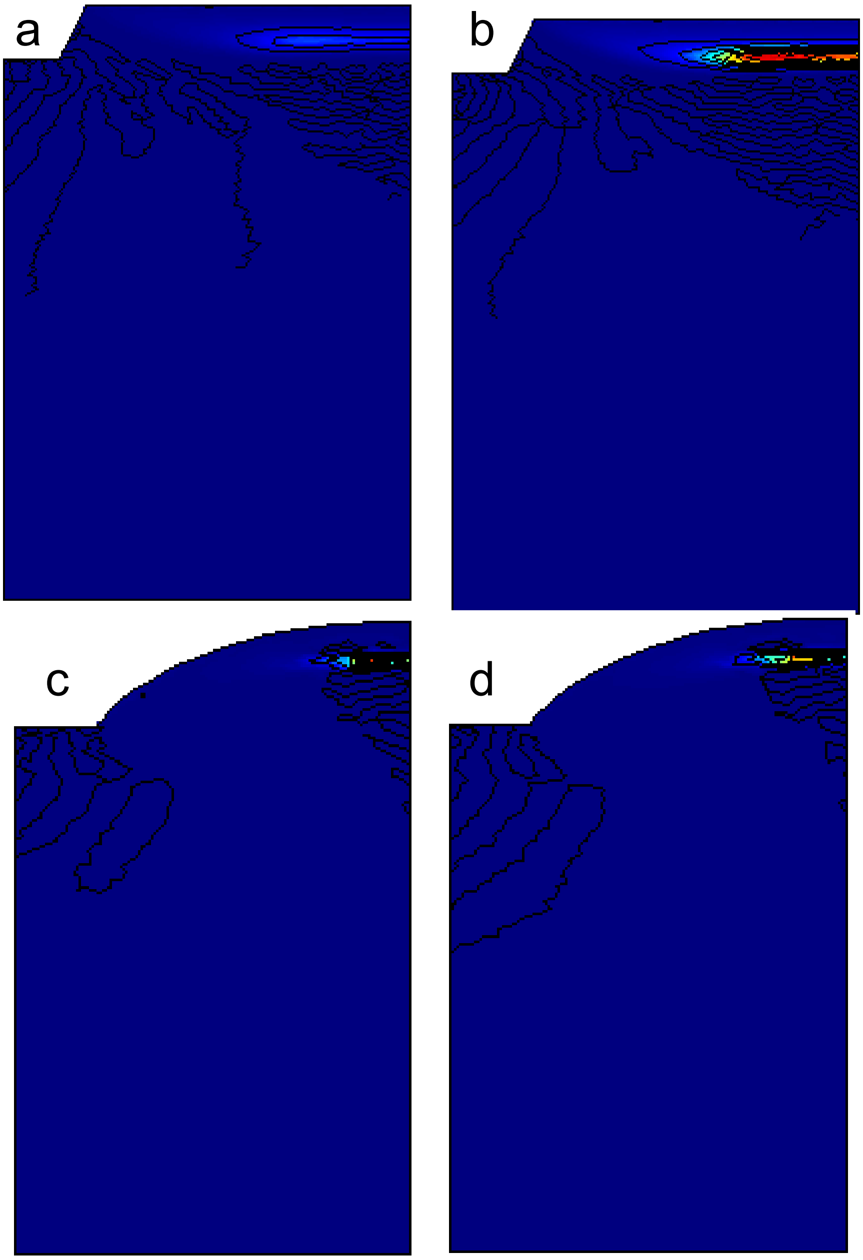

Figure 6.2.17. Solute concentrations at the end of the dry season following irrigation with water with 1mmol m^{-3} solute concentration for a) PRB on wet year at Kawo site, b) PRB on wet year at Wakan Site, c) wavy bed on dry year at Kawo site, and d) wavy bed on dry year at Wakan site. The scale is not shown as a different range is generated for each simulation.

The highest concentrations of 600 mmol m^{-3} occurred with the wavy beds (figure 6.2.17). The concentration was not as extreme for the PRB beds with the highest concentration at about 100 mmol m^{-3}. These values can be used to estimate the likely ratio of solute concentration that is likely. The amount of concentration shown in the wavy beds would suggest that some monitoring of salinity in the centre of the beds during the dry season would be a sensible precaution. However, given the seepage and/or drainage losses during the wet season this is unlikely to be a long term problem.

6.3 China case study

The raised beds project used for this case study is situated in China's northwestern Province of Gansu. The experimental sites of this project are located near the city of Zhangye, which lies in the middle reach of the Hexi Corridor (for more details on the project see http://www.aciar.gov.au/project/LWR/2002/094). The Hexi Corridor is situated in an arid zone with deep water tables and with permeable, Loess-like alluvial soils. The winter is cold and no crops are grown during this period. The main crops are wheat and maize which are grown in the summer. In the past, reliable snowmelt water from the adjacent Qianlian Mountains has sustained the irrigated agricultural areas along the length of the valley. In more recent times, reduced snowmelt water has led to significant reductions in available surface water, whilst over extraction and decreased recharge has lowered water tables in groundwater driven systems. As a consequence, severe water restrictions are being placed on farmers (up to 50% reduction in allocations), and the introduction of PRBs is seen as a key strategy for farmers to cope with reduced irrigation allocations. In addition to assessing the water savings potential of PRBs in this case study, other important issues investigated relate to the potential for build up of salts as the amount of irrigation is reduced, and the fates of fertilisers, particularly nitrate.

Information on the soils is relatively good compared to the other case studies and the derived functions and parameters used in the simulations mean the results should be reasonably close to experimental data that will be collected during this project's life. Simulations will also be carried out for a flat soil condition. This will act as the control situation for the simulations.

Infiltration and solute transport into the beds as a function of bed width will be simulated without considering the climatic conditions initially. The salinisation and leaching of the beds will be the main issue that will be investigated when using the climate data.

6.3.1 Soil properties

The soils data for this site shows that there is little difference in the soil properties with depth or between the soil in the flat paddocks and beds. On the basis of the bulk density data (table 6.3.1) three layers were chosen for both flat and bed configurations. Extensive bulk density data (table 6.3.1) was available on two dates and these were used along with moisture characteristic and particle size distribution data to estimate the soil properties.

Table 6.3.1. Soil bulk density with depth for flat fields and beds.

Depth (m)	Bulk density (Mg m-3)			
	Flat 4/4/2006	Flat 2/8/2006	Bed 4/4/2006	Bed 2/8/2006
0.10	1.23	1.45	1.17	1.39
0.20	1.47	1.42	1.38	1.53
0.30	1.47	1.40	1.43	1.37
0.40	1.40	1.40	1.44	1.49
0.50	1.44	1.47	1.40	1.45
0.60	1.37	1.35	1.40	1.38
0.70	1.35	1.35	1.34	1.39
0.80	1.42	nd	1.33	nd
0.90	1.37	nd	1.42	nd
1.00	1.42	nd	1.46	nd

From the moisture release data and using the bulk densities estimates of the saturated water content the van Genuchten parameters were obtained by fitting the data to eqn (5.1). The saturated hydraulic conductivity was estimated from a combination of the bulk density data, particle size data (table 6.3.2) and moisture release data using Rosetta (Schaup and Feike, 1998). These values are less that those of Zhang et al. (2006) but these were considered more consistent with the field infiltration data.

Table 6.3.2. Particle size for soil at Zhangye (Hexi Corridor, Gansu).

Texture	Particle size (mm)	Proportion of mass (%)
Sand	1 - 0.05	39.5
Coarse silt	0.05 - 0.02	15.6
Fine silt	0.02 – 0.002	33.4
Clay	< 0.002	11.5

The soil physical parameters used in the simulations are presented in table 6.3.3. The main difference between the layers is in the value of α which is related to the draining of the beds. The values of α suggest that the beds do not have to be of great height in this soil to provide adequate drainage.

Table 6.3.3. Soil hydraulic properties for loess soils at Gansu for permanent raised beds (PRB) and conventional tilled plots at two different dates. The differences on the two dates are derived from bulk density data.

Depth (m)	θ_r (m3 m-3)	θ_s (m3 m-3)	α (m-1)	n	K_s (m s-1)
PRB1 (4/04/06)					
0 – 0.20	0.0296	0.5	8.117	1.302	8.14x10-6
0.1 – 0.2	0.0403	0.48	3.441	1.320	2.71x10-6
0.20 - 2.0	0.0437	0.47	2.868	1.329	4.04x10-6
PRB2 (2/08/06)					
0 – 0.20	0.0253	0.475	4.567	1.277	4.36x10-6
0.1 – 0.2	0.0468	0.424	1.537	1.328	2.22x10-6
0.20 - 2.0	0.0288	0.465	3.708	1.284	3.94x10-6
Conventional tillage (4/04/06) (Con 1)					
0 – 0.20	0.033	0.54	8.766	1.321	7.58x10-6
0.1 – 0.2	0.0409	0.485	3.622	1.337	4.89x10-6
0.20 - 2.0	0.048	0.461	2.315	1.356	3.68x10-6
Conventional tillage (2/08/06) (Con 2)					
0 – 0.20	0.0632	0.4	1.142	1.405	1.73x10-6
0.1 – 0.2	0.0467	0.438	2.423	1.347	3.00 x10-6
0.20 – 2.0	0.04	0.459	3.589	1.329	3.78x10-6

The fit of the moisture characteristic function derived from the data to eqn (5.1) is good with r^2 regression coefficients of > 0.99. The water storage properties were then derived using eqn (6.2) for each layer (table 6.3.4)

Table 6.3.4. Water storage properties for PRB and conservation tillage soils using eqn (6.2).

Soil	Depth (m)	$\Delta\theta_I(\psi_e$ = -10 m)	$\Delta\theta_I(\psi_e$ = -154 m)
PRB1	0 - 0.1	0.121	0.190
	0.1 - 0.2	0.141	0.235
	0.2 - 2	0.144	0.223
PRB2	0 - 0.1	0.130	0.212
	0.1 - 0.2	0.140	0.243
	0.2 - 2	0.133	0.229
Con 1	0 - 0.1	0.128	0.149
	0.1 - 0.2	0.149	0.163
	0.2 – 2.0	0.150	0.170
Con 2	0 - 0.1	0.143	0.225
	0.1 - 0.2	0.147	0.226
	0.2 – 2.0	0.139	0.217

The rooting depth for soils at Gansu is considered to be 1m (J. McHugh pers comm., 2006).

The bed dimensions and modelling domain are shown in figure 6.3.1. This domain was used for all of the crop modelling and standard infiltration modelling.

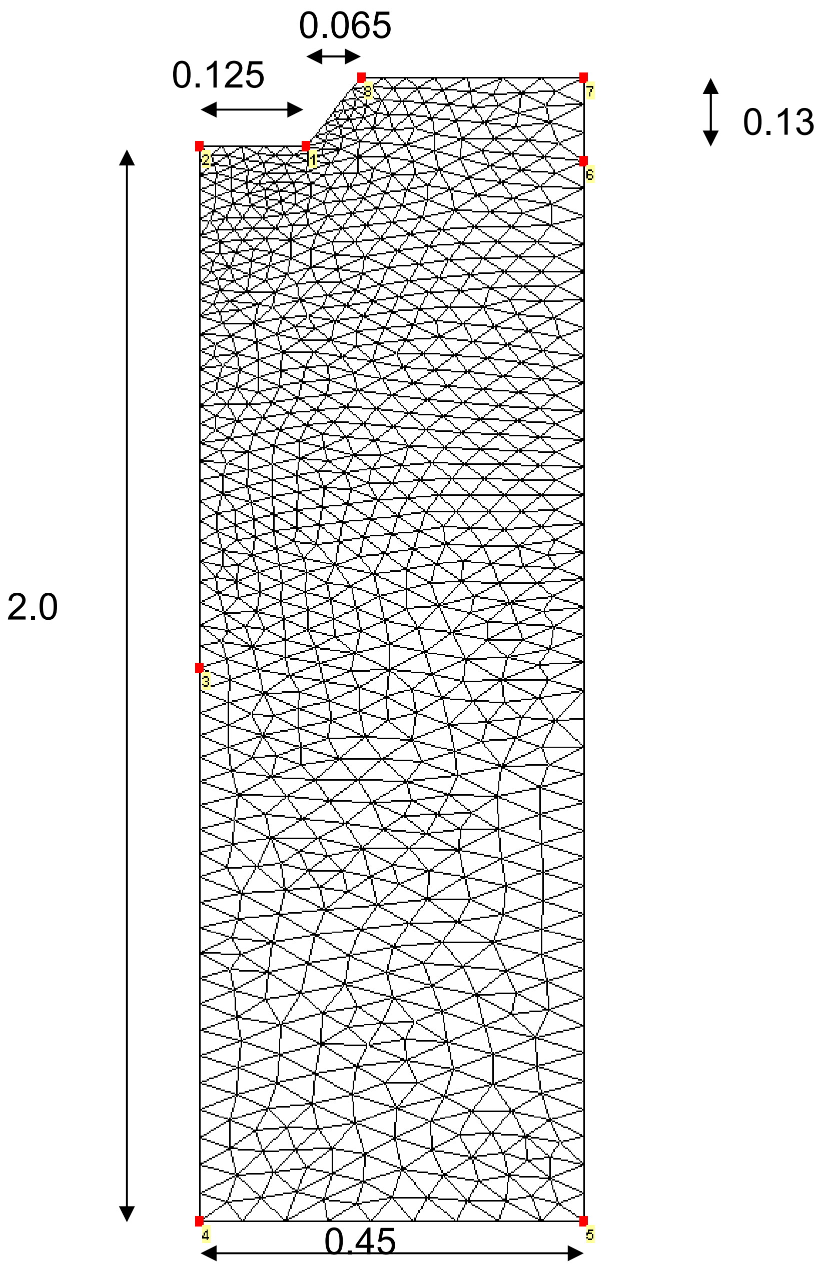

Figure 6.3.1. Domain used for 2-D simulations. The grid shown is not that used in the simulations, as the actual grid is too dense to show clearly.

The volume of water to be depleted from the soil prior to irrigation was calculated using the assumed rooting depth the bed dimensions (fig. 6.3.1) and the data in table 6.3.4 for ψ_e = -10 m, is 141 mm for PRB1 and 133 mm for PRB2. For the conventional tillage the volume was also calculated and is 147 and 140 mm for Con1 and Con2 respectively. These data were used along with the climate data to predict when irrigation was required based on the potential deficit. Given the similarity of the storage values a value of 140 mm was used for estimating when to irrigate.

6.3.2 Infiltration

Infiltration into a standard bed, wide bed and flat soil were simulated. The initial water potential was set at -10 m. In these simulations the latest versions of HYDRUS1D and HYDRUS2/3D were used in these simulations. The wetting front for the 1D simulations show that the wetting front penetrates similarly to a depth of approximately 0.1 m and then deviates due to in particular the lower hydraulic conductivity of the top soil layer (fig. 6.3.2).

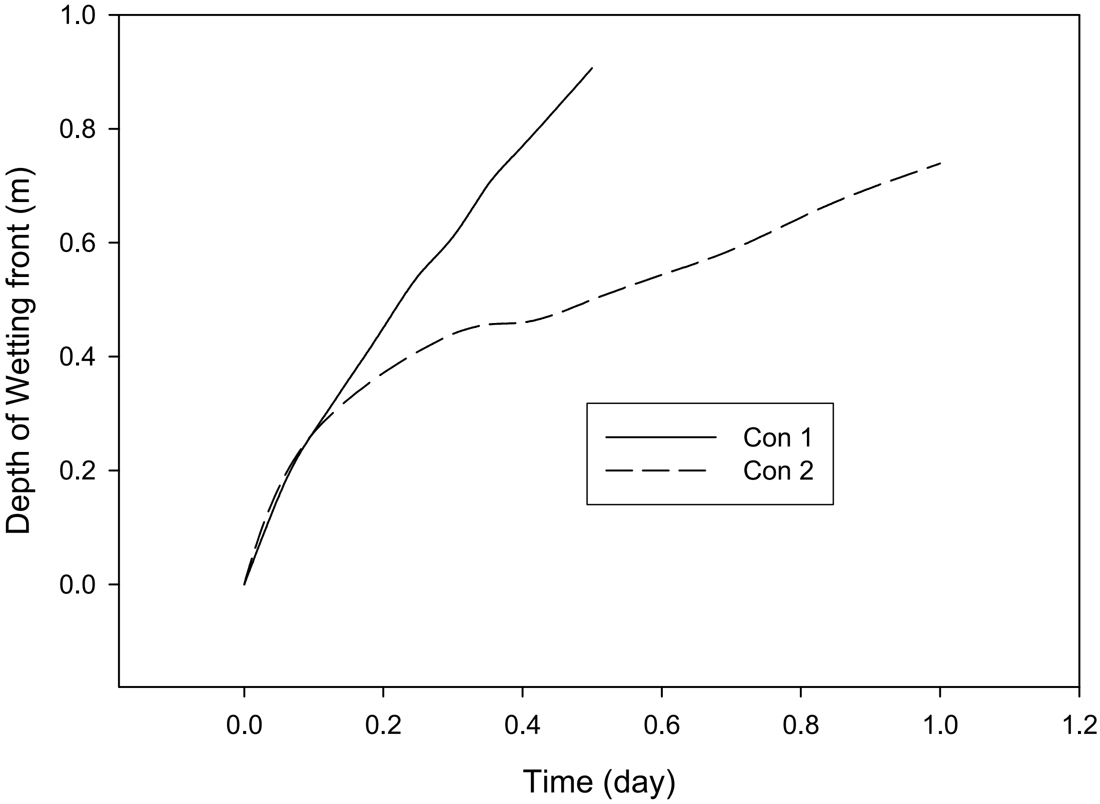

Figure 6.3.2. Depth of wetting front versus time for the conventional tillage soils at two different dates designated by Con 1 and Con 2 in table 6.3.3.

For simulated infiltration into the bed when the amount required for an irrigation of 140 mm has been applied the wetting front has reached the centre of the bed at the depth of the furrow for PRB2 but not for PRB1 soil properties. For neither soil has the wetting front reached the centre at the surface and the depth of penetration is similar (fig. 6.3.3). Complete wetting of the beds is predicted during redistribution of the water following infiltration for PRB but does take up to 3 days. PRB1 a small volume of soil near the centre of the bed is predicted to remain dry. These simulations are for a water height in the furrow of 0.065 m. Raising the water height to nearer the bed height does overcome the penetration to the centre of the bed. Further simulations and experimental studies could be justified.

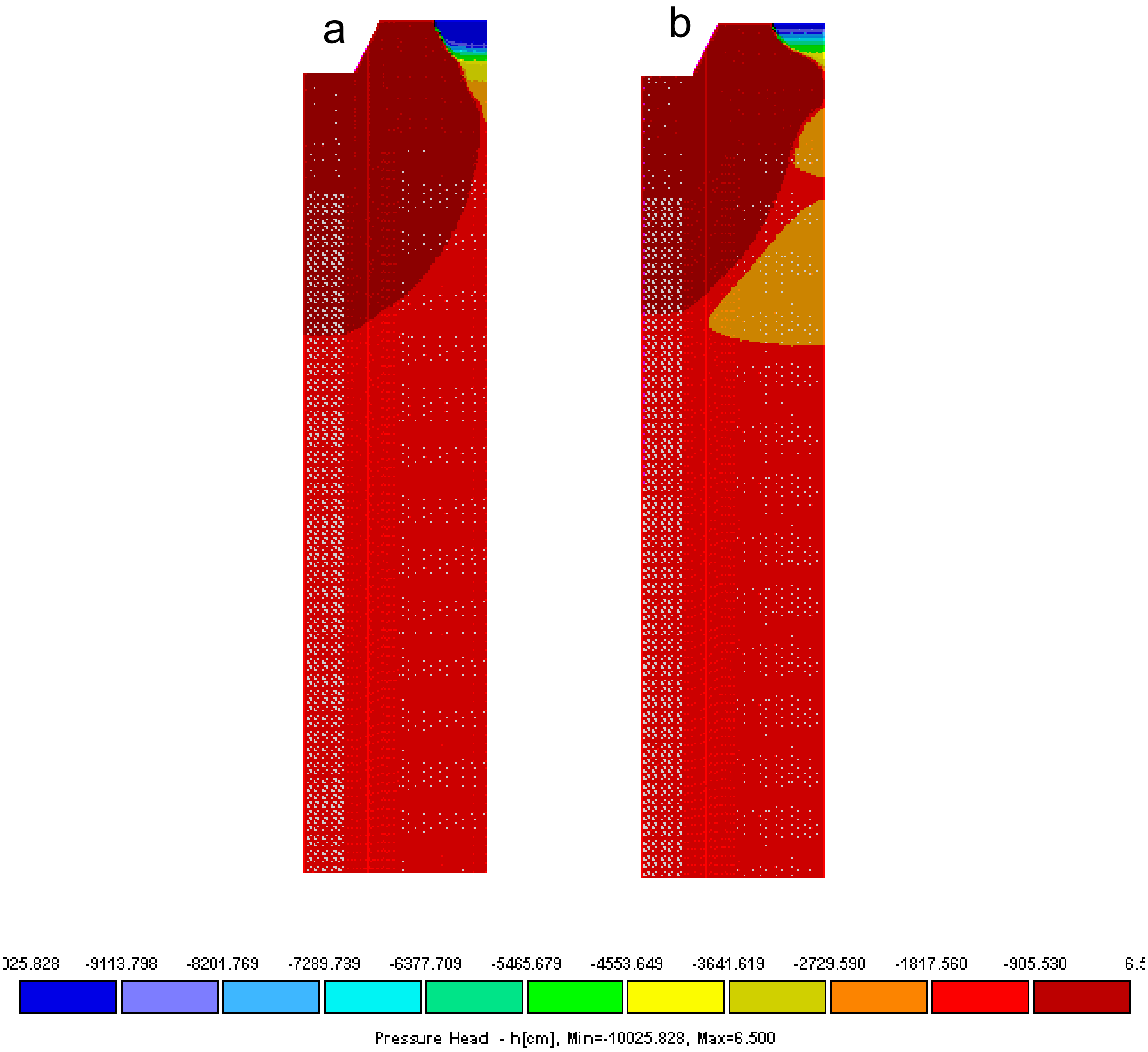

Figure 6.3.3. Simulated water potential distribution at the end of infiltration of 140 mm of water for a) PRB1 and b) PRB2 soil properties.

6.3.3 Water balance

The climate data and water balance for PRB1 show how little rainfall (3.6 mm) occurs during the growing season of 2006. The amount of irrigation applied in the simulations was 548 mm which is consistent with the target amount of between 400 and 533 mm (fig. 6.3.4a). This amount of irrigation is predicted to result in 0.2 mm of drainage. The transpiration by the crop is simulated to be very close to the potential transpiration which means that if crop nutrition is optimal then the crop yield should be close to the potential yield. The evaporation is not shown as it is the same as the potential evaporation. For PRB2 slightly less water was applied of 486 mm, due to the lower storage value and this produced 0.13 mm of drainage (fig. 6.3.4b). The results for the both plots are very similar for evaporation and transpiration and suggest only slight decreases from potential for both of these water balance components.

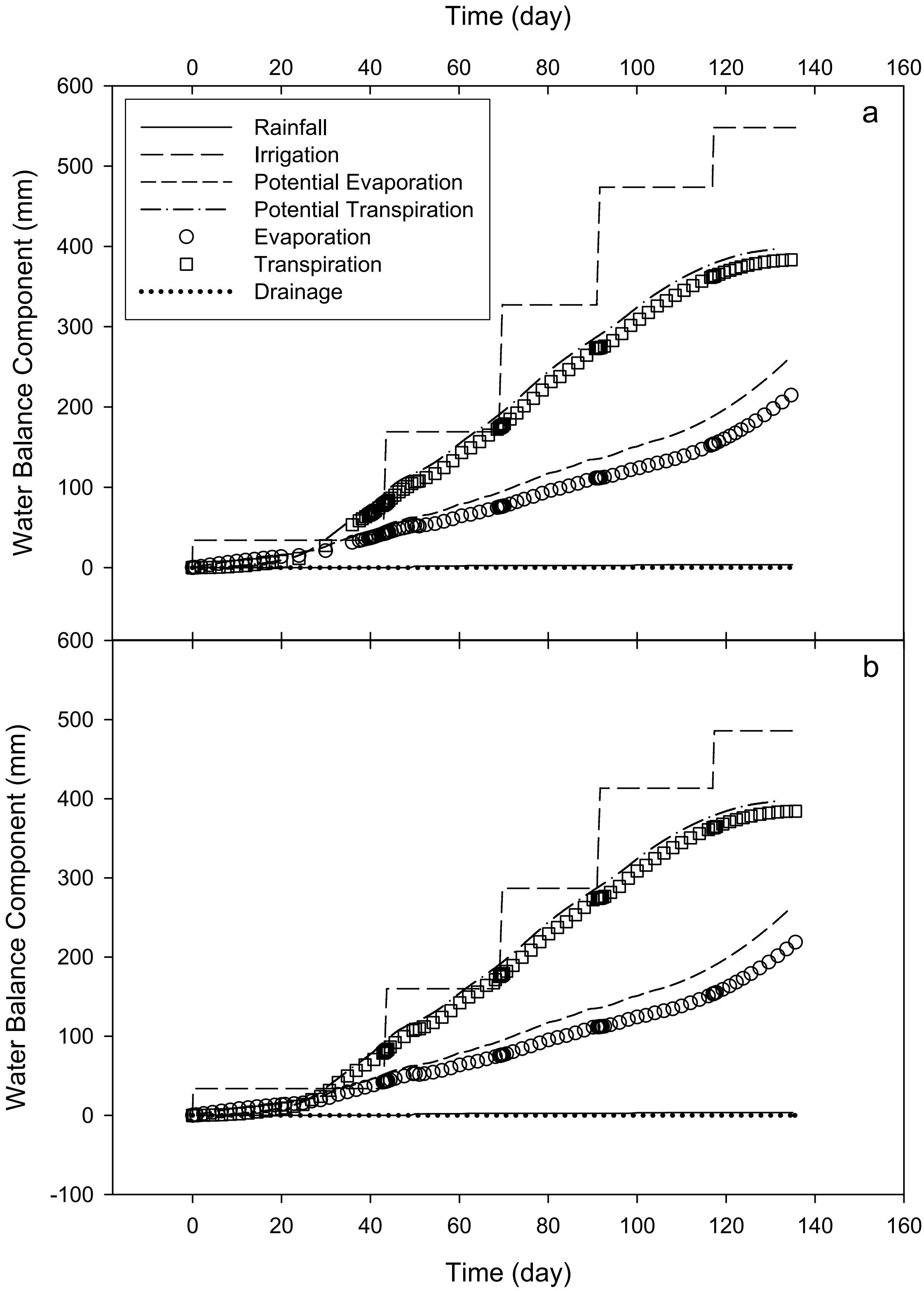

Figure 6.3.4. Simulated water balance for a) PRB1 and b) PRB2 during 2006 cropping season.

The results for the flat plot simulations do show some differences between the Con1 and Con2 simulations with regard to water balance (fig. 6.3.5). In particular there are two changes one to the drainage and the other to the evaporation. The greater drainage in Con1 is somewhat surprising as more irrigation water, 97 mm (639 - 542), was applied to Con2 than Con1. This difference in the total amount of irrigation occurred as the first irrigation event for Con2 was based on the water storage to a depth of 1 m, rather than to a depth of 0.3 m as in PRB1, PRB2 and Con1. The rooting depth information suggested

that the roots were only present to 0.3 m in the first 20 days of growth, hence the smaller first irrigation for most of the simulations.
The drainage in Con1 was 167 mm, while that for Con 2 was 0.1 mm. This difference is due mainly to the higher evaporation that occurred in Con1 as a result of the large α values for the Con1 soil. These higher α values mean that the falling rate stage in the soil evaporation occurs much sooner than for the Con2 soil. This can be seen in the rapid decrease in evaporation following irrigation for the Con1 soil compared to the Con2 soil. This suggests that mulching of the soil surface to reduce evaporation could be a good option for increasing drainage.

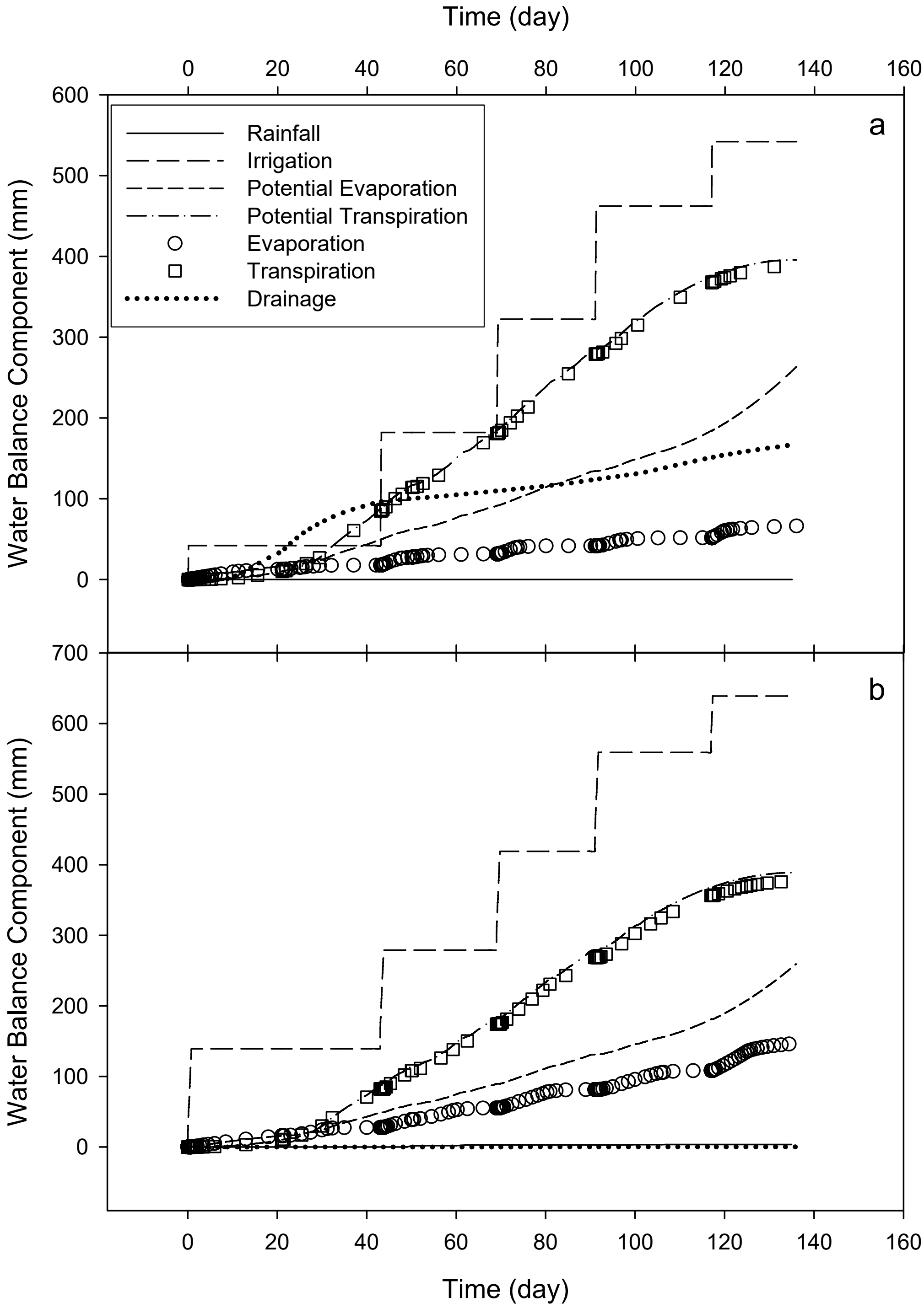

Figure 6.3.5. Water balance components for a) Con1 and b) Con2 for 2006 season.

A further simulation with the PRB1 soil but without any evaporation (perfect mulch) was simulated to see if this would result in increased drainage. The results show that during the growing season the drainage does not increase, yielding a value of 0.2 mm (fig. 6.3.6).

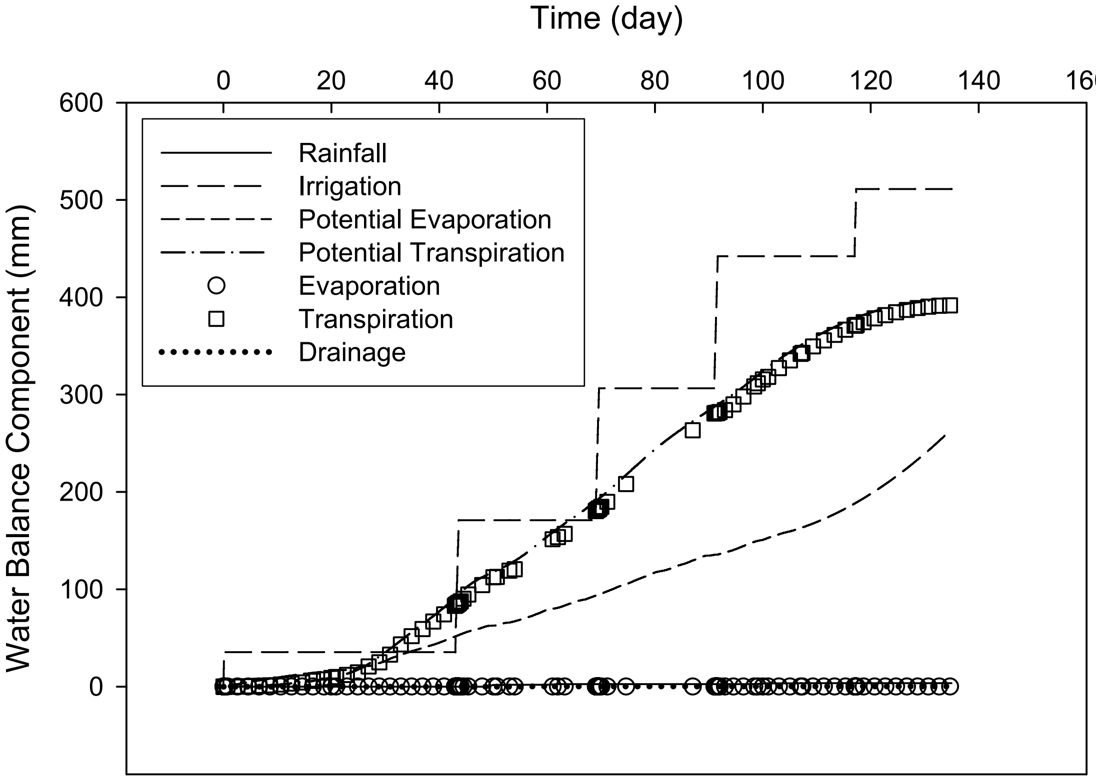

Figure 6.3.6. Water balance components for PRB1 with a perfect mulch (no evaporation).

This at first glance would indicate that the mulch has had no effect on improving drainage. However, if the potential profiles for the three raised bed simulations are plotted, then this shows that the wetting front for the no-evaporation simulation has just reached 2 m and will result in drainage beyond this depth during the next growing season (fig. 6.3.7). This figure also shows that in the PRB1 and PRB2 simulations some water has penetrated below the rooting depth of 1m and will also be lost to deep drainage in the future. The mulch has also resulted in only a small potential gradient towards the surface of the soil which will also result in a greater drainage component in the future. These results also indicate that some drainage is likely to occur when the simulations are extended to time frames greater than 1 year. Further simulations and experimental work is required to fully explore the required leaching fraction to prevent salinisation at this site. These results do show that inclusion of mulch will be highly beneficial in management of salinity at this site.

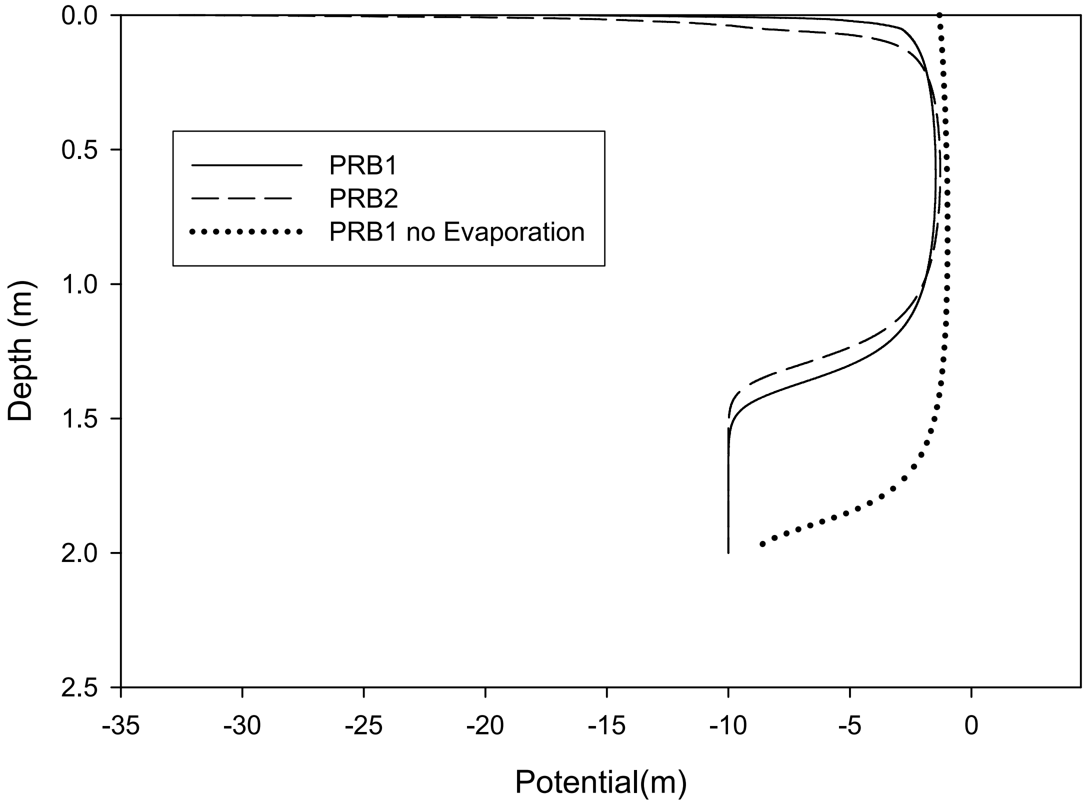

Figure 6.3.7. Potential profiles for the three raised bed simulations at the centre of the furrow at the end of the simulations (day 136).

6.3.4 Solutes

Simulations of two tracers were performed. The first tracer is only applied in the irrigation and had a concentration of 16 mol m^{-3} which is the equivalent of the concentration of salts in the irrigation water used at Gansu. This tracer was applied to determine where solutes may accumulate in the soil and if salinisation could occur.

The second tracer was used to simulate the possible fate of nitrate fertilizers applied at a depth of 50 mm below the bed surface (fig. 6.3.8).

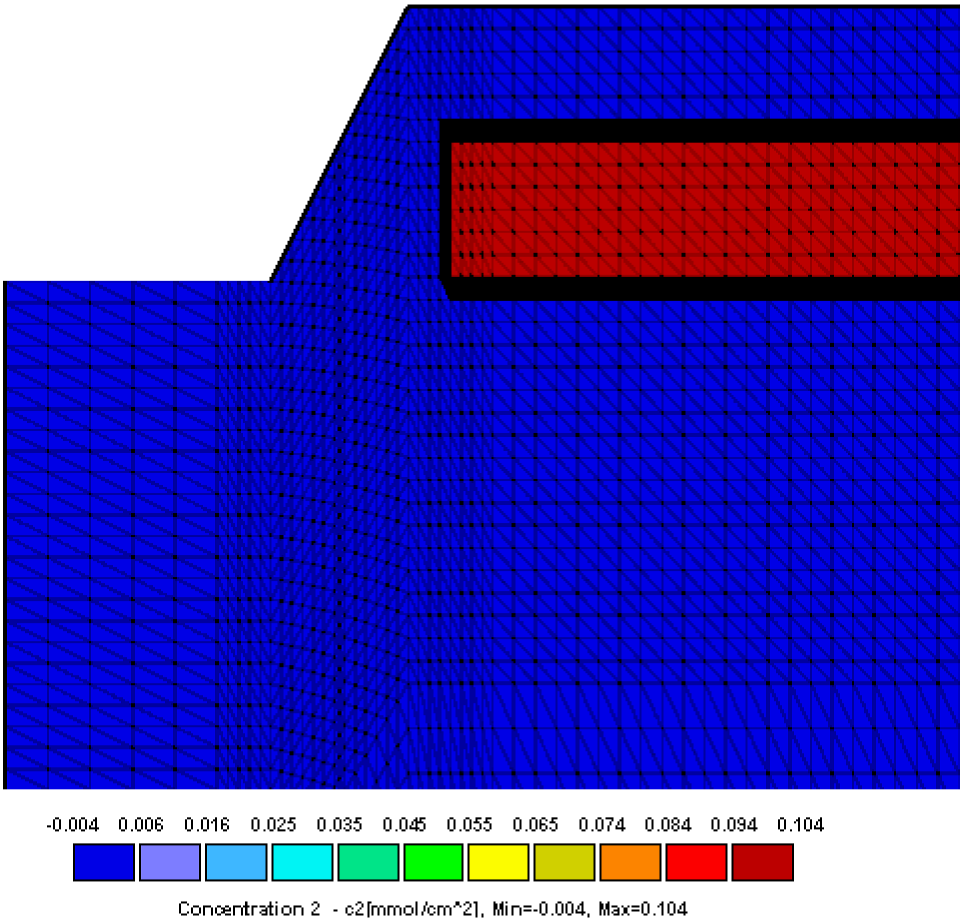

Figure 6.3.8. Fertilizer placement within the beds prior to simulation. Note the profile is truncated to 0.51 m depth.

Unfortunately instabilities and oscillations occurred with the simulations as the simulations proceeded and mass balance was not maintained. However, some understanding can be gained from both the early simulations and the drainage component of the water balance.

The fertilizer is predicted to get pushed towards the middle of the bed and due to evaporation a high concentration zone is predicted at the soil surface at about ¼ of the bed width (fig. 6.3.9). This leads to the high concentrations that cause the numerical instabilities and should be tested experimentally to see if it is actually occurring.

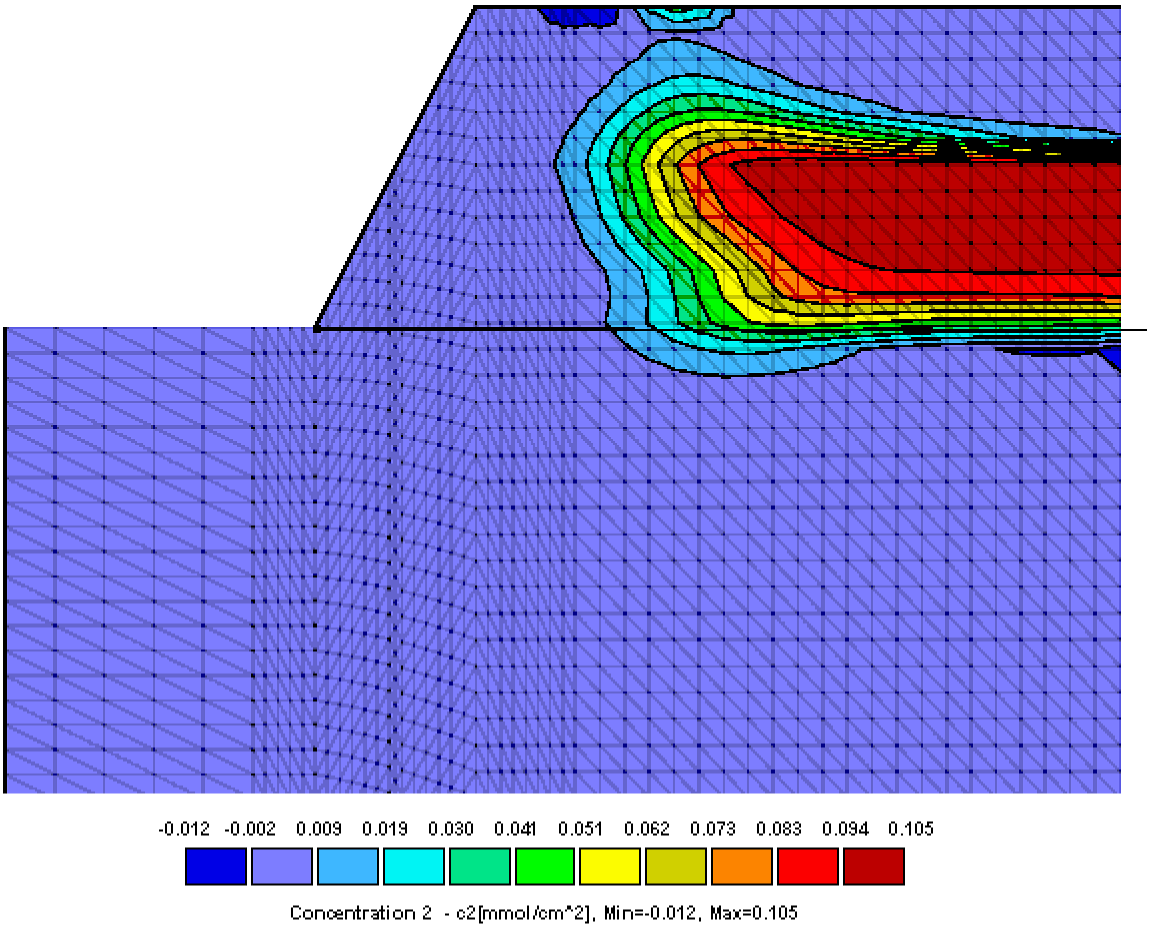

Figure 6.3.9. Simulated fertilizer distribution after 20 days since planting of the crop for PRB1. This time corresponds to the solute distribution after the first irrigation on day 1 and a further 20 days of plant growth following this. Note the soil profile shown is truncated to a depth of 0.51 m.

The simulations show that with this placement of the fertilizer, little fertilizer is transported to below the rooting depth. This indicates that good utilization of the fertilizer is likely. But plants on the edge of the beds though may have lower nutritional status due to the fertilizer being pushed towards the centre of the bed. By the end of the third irrigation the remaining fertilizer is concentrated near the centre of the (not shown). This suggests that after a few cropping seasons the soil fertility across the bed should be checked to see if fertilizer management needs adjusting.

For the solute in the irrigation water some understanding can be gained by looking at the distribution following the first and second irrigations (fig. 6.3.10).

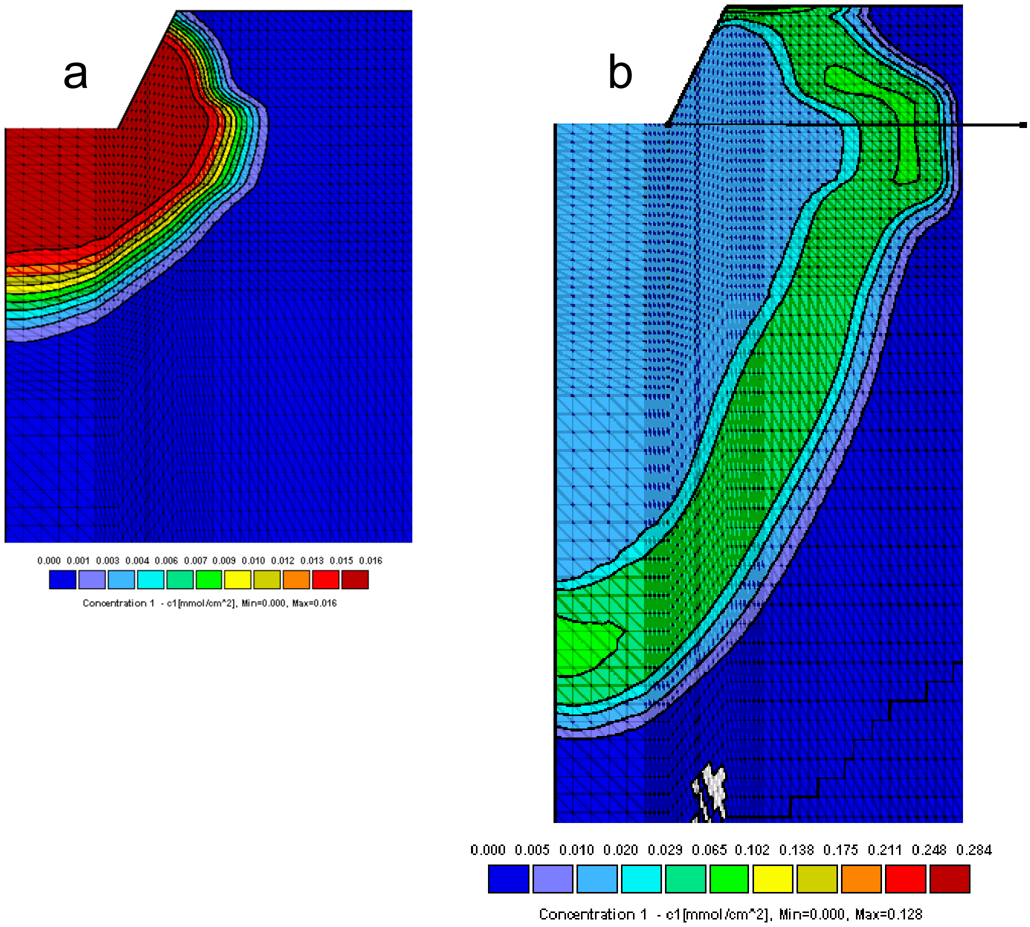

Figure 6.3.10. Simulation of solute (salt) distribution following a) the first and b) second irrigations.

The solute applied by the first irrigation gets concentrated by evaporation and then displaced downward and towards the centre of the bed by the second irrigation. This is shown in fig. 6.3.10b where the salt initially applied in the first irrigation (fig. 6.3.10a) now forms the green band behind the solute front. Back beyond this green band is the solutes added in the second irrigation. This process is likely to continue with each successive irrigation, with the salt added in the first irrigation being pushed down and towards the middle of the beds.

Salinity is likely to build up in the soil unless irrigations are included to flush the salt out. Experimental results are already indicating the salinity is increasing in the middle of the beds (McHugh, pers. comm. 2007). The requirement to consider the drainage of salts as part of the management of irrigation is reviewed by Cook et al. (2007). Further evidence to support this is gained from the simulations with perfect mulch, where mass balance is maintained for the salt until the fourth irrigation (day 91)). These simulations clearly show the concentration bulges due to evapotranspiration concentration of the salt from two earlier irrigations that have been displaced down the profile (fig. 6.3.11).

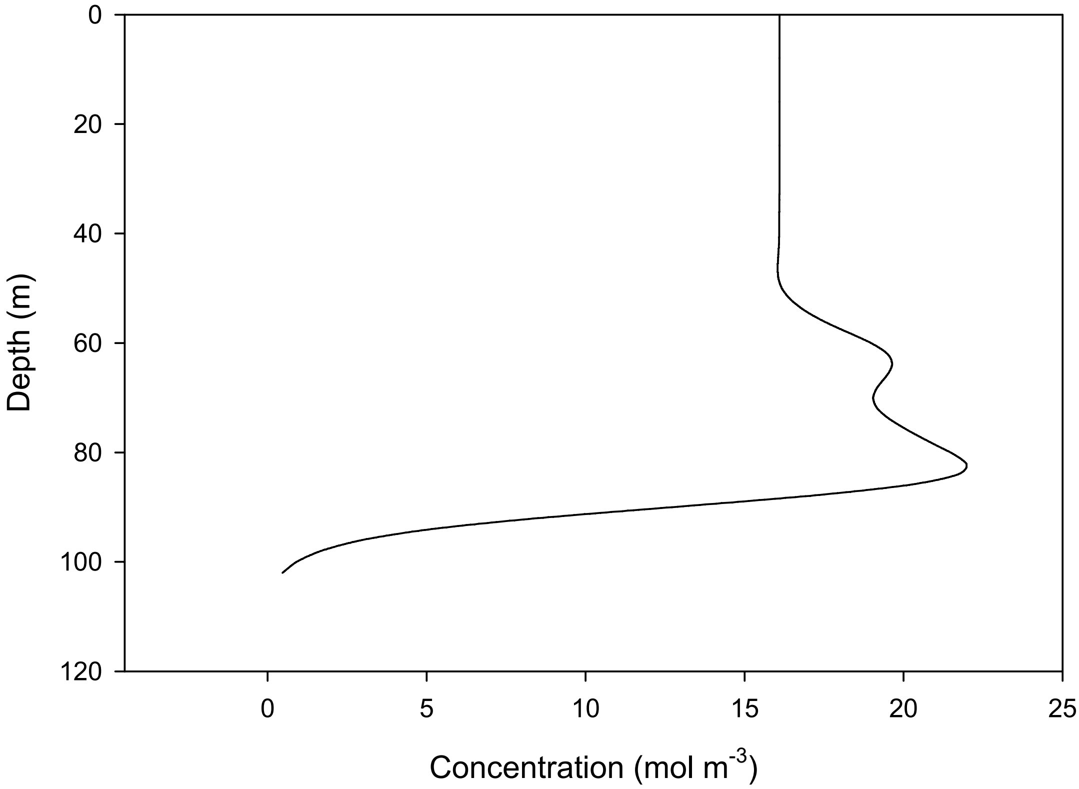

Figure 6.3.11. Solute profile for salt (tracer 1) at the end of the third irrigation on day 91 for the simulations with a perfect mulch at the soil surface. Note the bulges which represent the previous two irrigations.

The concentration across the bed also shows that salt is simulated to accumulate at about ¼ of the width of the bed (fig. 6.3.12). Experimental investigations should be undertaken to determine if this is occurring. These results suggest that occasional flooding of the whole bed may be required to push this salt down the soil profile. Careful management on salt at this site will be required if irrigation is to be a long term activity.

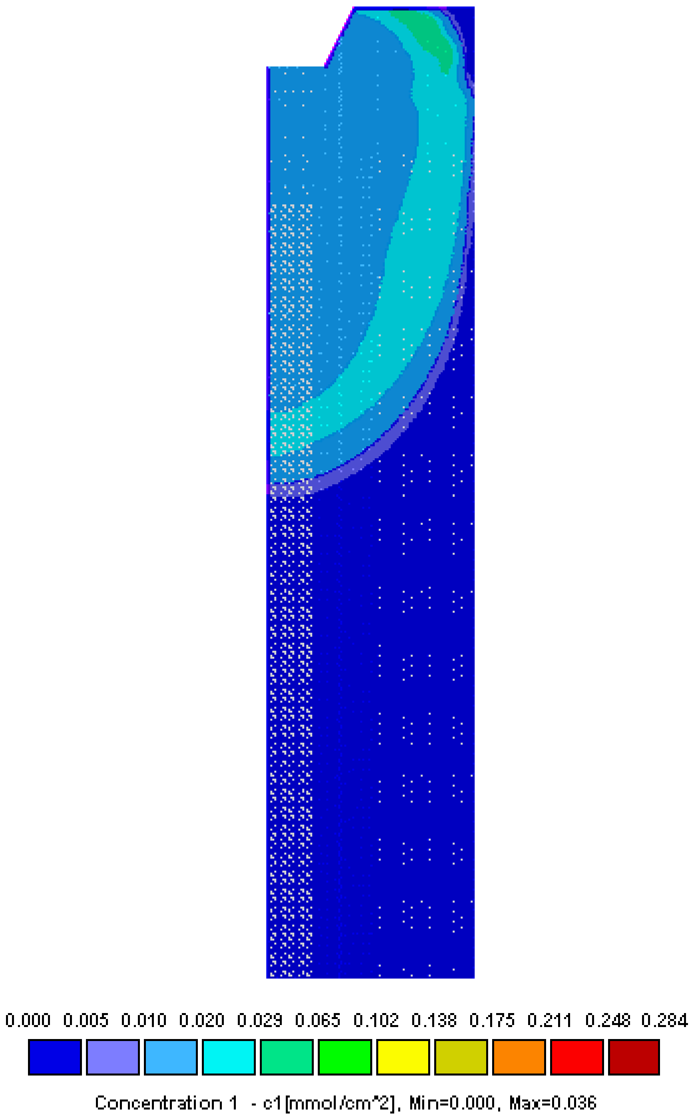

Figure 6.3.12. Concentration contours of salt at the end of the fourth irrigation on day 91 for the simulations with a perfect mulch at the soil surface. The data in figure 6.3.11 is derived from this data along the centre line of the furrow.

For the simulations of the conventional tillage sites the same overall trends occur and only the concentration profiles from the last simulation period (117-136 days) are presented. These show that the salt (concentration 1) has reached much higher concentrations near the surface for the Con 2 soil compared to the Con 1 and both soils have a bulge at about 0.5 m (fig. 6.3.13). For the fertilizer although this shows a similar bulge the mass balance data indicated that all was taken up by the plants (101% for Con1 and 102% for Con2). Similar good mass balances were maintained for the salt (concentration 1) with 100% of the salt applied for Con1 stored in the soil and 102% for Con2.

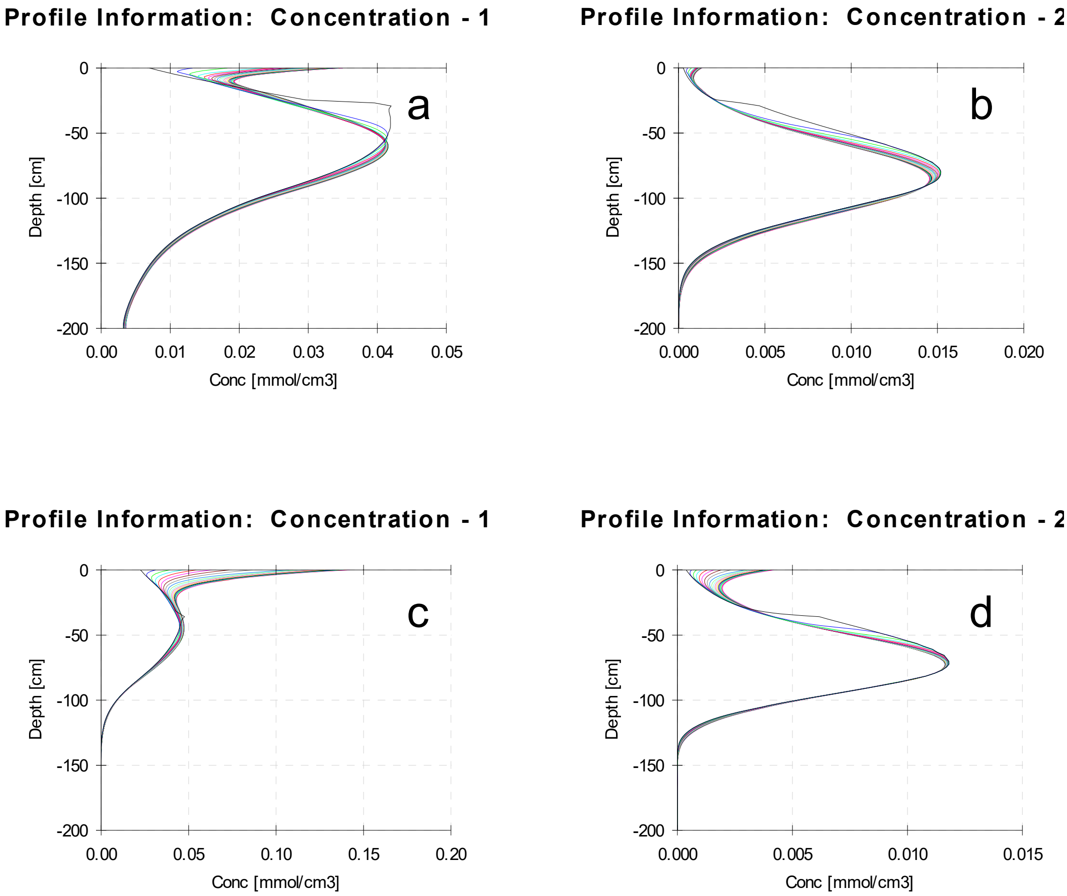

Figure 6.3.13. Concentration profiles during the last simulation runs (117-136 days) for a) Con1 concentration 1 (salt), b) Con1 concentration 2 (fertilizer), c) Con2 concentration 1 (salt) and d) Con2 concentration 2 (fertilizer). Note these figures are from HYDRUS1D and the units are cm for depth and mmol cm^{-3} for concentration.

6.4 Pakistan case study

The experimental sites of this raised beds project are located near the town of Mardan, in the Northwest Frontier Province of Pakistan. Mardan lies in Peshawar valley and from 34° 05′ to 34° 32′ North and 71° 48′ to 72° 25′ East. The climate is monsoonal with ~300 mm of rainfall in the monsoon and ~150 mm in cool (Rabi) season. The evaporation rates are high with 6-15 mm day^{-1} in the monsoon and 2-7 mm day^{-1} in the cool season. The cropping consists of two crops per year, i.e wheat during the cool season and maize during the monsoon season. Sowing for wheat occurs in mid-November and harvesting in early-May and for maize sowing is in early June and harvesting in early September. More details on this project can be obtained from Hassan et al. (2005) or http://www.aciar.gov.au/project/LWR/2002/034.

The project is situated in an area where the water table is at 3 m and the soils are permeable in the topsoil but have denser and less permeable subsoils. Good information exists on sorptivity, infiltration rates and bulk density of the soil. From these and data supplied by on some van Genuchten parameters used in previous HYDRUS simulations (G. Hamilton, pers. comm., 2006) the soil properties were estimated.

The main issues to be studied in this case study were whether infiltration into the wide beds was attained, whether there was a risk of salt accumulation and the overall water dynamics of PRB in comparison to flat fields (basin irrigated) and the fate of soluble fertilisers. As irrigation water savings are a crucial motivation for establishing PRB, an additional aspect of this case study was to model the water balance. Infiltration and solute transport into the beds as a function of bed width will be simulated without considering the climatic conditions initially. The salinisation and leaching and consolidation of the beds will be the main issue that will be investigated.

6.4.1 Soil properties

From the bulk density data the soil was divided into three layers. The bulk density data and estimates already derived for the van Genuchten parameters were used to initialise HYDRUS1D (Simunek etal., 1998). The sorptivity data from G. Hamilton (pers. comm..) (table 6.4.1) was then used to generate horizontal infiltration data for a period of up to four hours. This time was chosen as sorptivity behaviour dominates infiltration for up to 4 hours (G. Hamilton, pers. comm..).

Table 6.4.1. Sorptivity of the surface soils in the Permanent Raised Bed and Basin treatments at Mardan, Pakistan (G. Hamilton, pers. comm.).

	Raised beds			Basin
	Unconsolidated	Consolidated	Furrows	
Sorptivity (mm h-1)	52.5	48	7.5	18.0

The infiltration data generated was then used to with HYDRUS1D to inverse model the soil properties and the results are presented in table 6.4.2 below. The value of n in the van Genuchten parameters was found not to affect the results and was not included in the inverse modelling after some initial runs.

Table 6.4.2. Soil hydraulic properties for the Basin and Permanent Raised Bed (PRB) treatments for soils in consolidated and unconsolidated states.

Depth (m)	θ_r (m3 m-3)	θ_s (m3 m-3)	α (m-1)	n	K_s (m s-1)
Basin					
0 – 0.15	0.067	0.5	3.145	1.41	1.52x10-6
0.15 – 0.3	0.067	0.41	3.145	1.41	8.04x10-7
0.30 - 2.0	0.067	0.37	3.145	1.41	8.04x10-7
PRB unconsolidated					
0 – 0.15	0.067	0.54	0.50	1.41	5.21x10-6
0.15 – 0.3	0.067	0.44	0.50	1.41	3.70x10-6
0.30 - 2.0	0.067	0.37	0.50	1.41	8.04x10-7
PRB consolidated					
0 – 0.15	0.067	0.5	0.77	1.41	3.68x10-6
0.15 – 0.3	0.067	0.39	0.77	1.41	3.24x10-6
0.30 - 2.0	0.067	0.37	0.77	1.41	8.04x10-7

The fit of the infiltration data derived from the sorptivity for the unconsolidated PRB with the HYDRUS1D simulations is shown in figure 6.4.1. The regression coefficients were always greater than 0.995 for all fits.

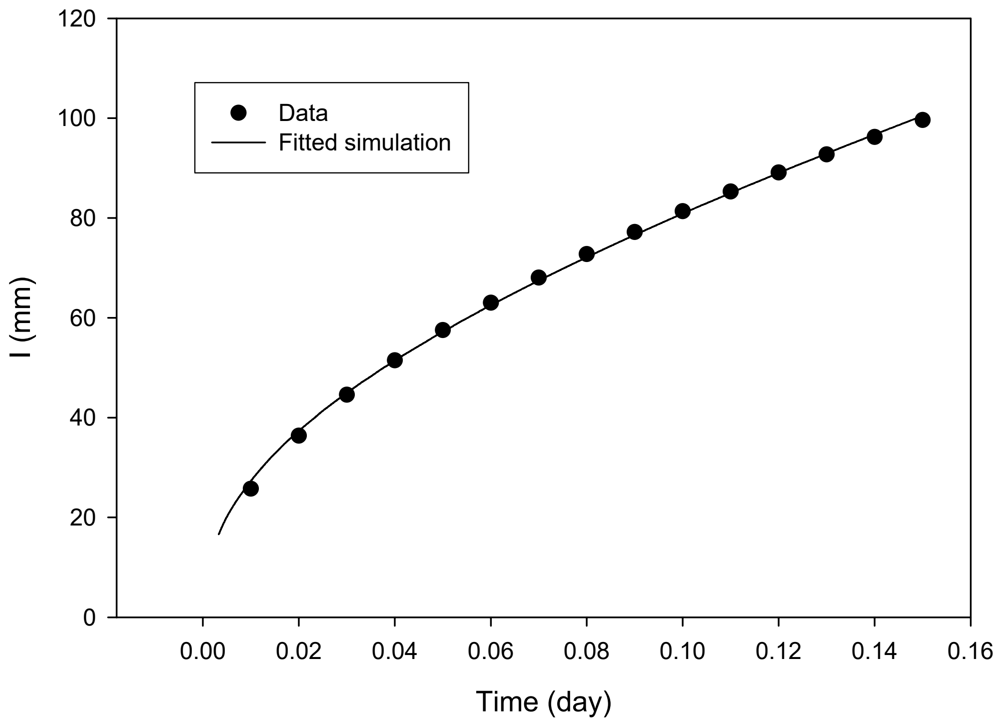

Figure 6.4.1. Cumulative horizontal infiltration (I) for the unconsolidated PRB treatment with time. The data points are generated from the sorptivity data in table 5.4.1 and the line is from HYDRUS1D after inverse fitting to the data.

The water storage properties were calculated using eqn (6.2) and the data in table 6.4.2, which results in the values shown in table 6.4.3. These were used along with the dimensions of the beds (fig. 6.4.2) to calculate the amount of irrigation water required.

Table 6.4.3. Water storage properties for PRB and conservation tillage soils using eqn (4.2.1).

Soil	Depth (m)	$\Delta\theta_I(\psi_e$ = -10 m)	$\Delta\theta_I(\psi_e$ = -154 m)
Basin	0 - 0.15	0.151	0.222
	0.15 - 0.3	0.120	0.176
	0.3 - 2	0.141	0.156
PRB unconsolidated	0 - 0.15	0.193	0.351
	0.15 - 0.3	0.153	0.277
	0.3 - 2	0.124	0.225
PRB consolidated	0 - 0.15	0.187	0.310
	0.15 - 0.3	0.140	0.232
	0.3 – 2.0	0.131	0.217

The maximum rooting depth for these soils was considered to be 0.45 m giving an irrigation application of 57 mm for the basin if the lower limit is taken as the water content at a ψ_e = -10 m. This is slightly less than that for the basin. For the beds estimates for the unconsolidated beds using the same criteria above the irrigation required is 69 mm and 70 mm for the consolidated beds. This is similar to the experimental values used in the beds.

Two different bed configurations were simulated: wide beds (fig. 6.4.2a) and narrow beds (fig. 6.4.2b). A fine spatial grid was used in these simulations as the soil properties meant the solution was stable and simulations could be performed within a reasonable time with the new HYDRUS2/3D version.

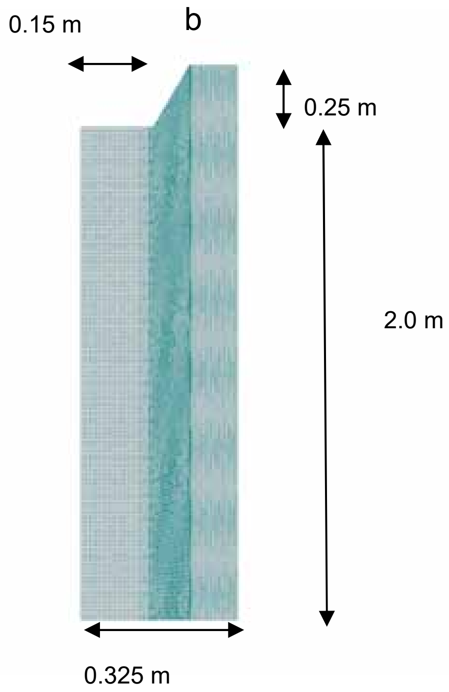

Figure 6.4.2. Domain for raised bed simulations for a) wide and b) narrow beds. The finite element grid cannot be clearly seen due to the high density of the grid.

6.4.2 Infiltration

Infiltration into a standard bed, wide bed and flat soil were simulated. The initial water potential was set at -10 m. In these simulations the latest versions of HYDRUS1D and HYDRUS2/3D were used. The wetting fronts for the 1D simulations show that the wetting front penetrates almost linearly with time, with only a slightly faster rate initially. With a rooting depth of 0.45 m the amount of irrigation required to wet the soil to a potential of -1 m is 57 mm.

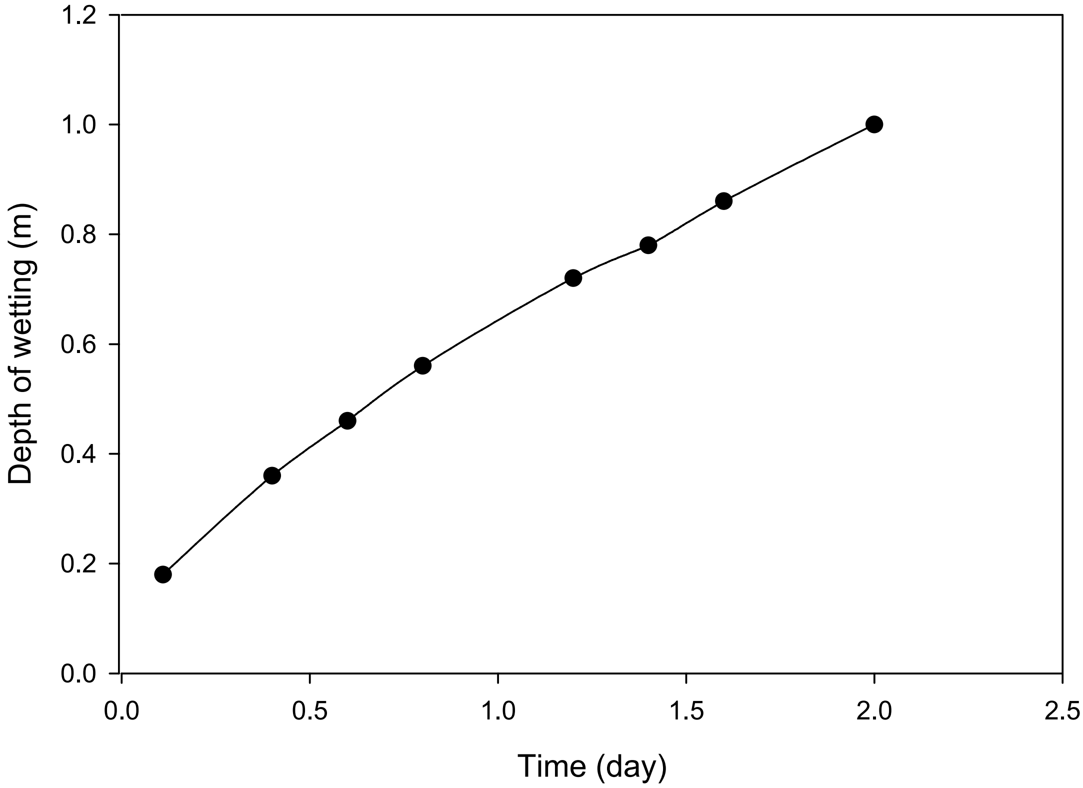

Figure 6.4.2. Depth of wetting front versus time for the basin, with soil initially at a potential of -10 m.

For simulated infiltration into the bed when the amount required for an irrigation of 70 mm has been applied the wetting front has almost reached the centre of the bed for the wide bed (fig. 6.4.3a) and has reached the centre for the narrow bed (fig. 6.43b). For both bed configurations wetting of the beds should not be a problem but the beds should not be made much wider than the present wide beds. The estimated bed width using the simple model would suggest that the beds could be almost double their present width at 1.7 m for the unconsolidated and 2.7 m for the consolidated beds. These results seem unlikely for the consolidated bed.

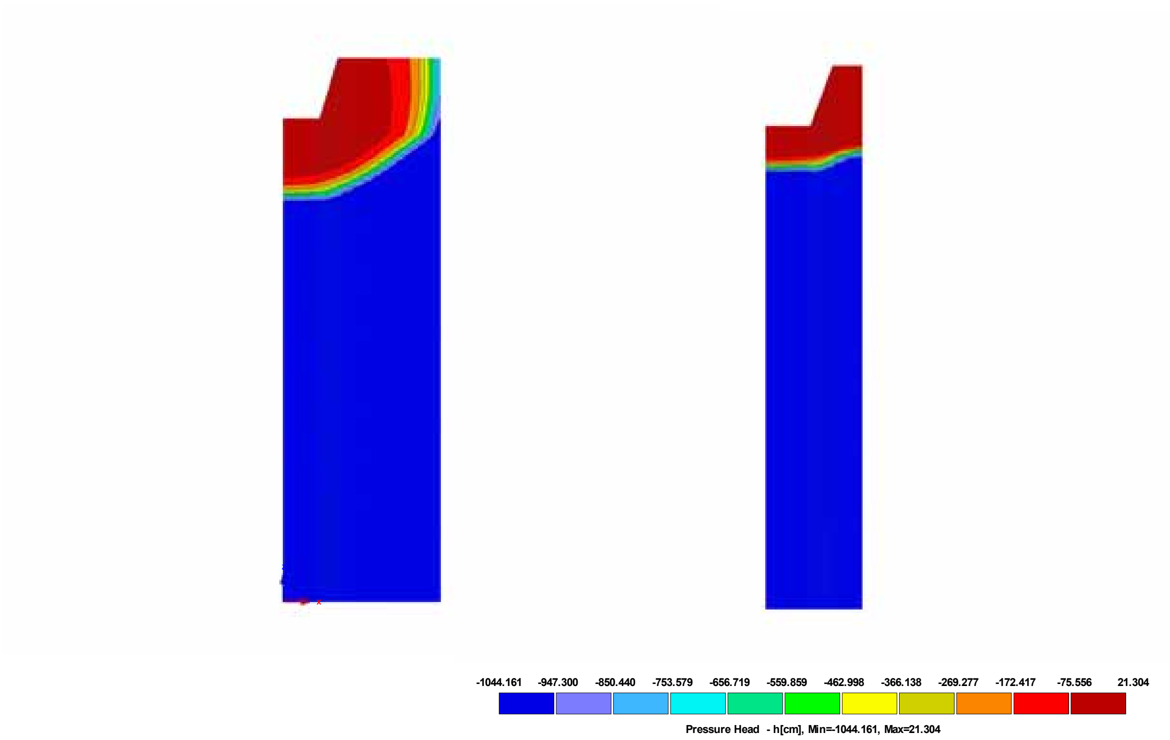

Figure 6.4.3. Simulated water potential distribution at the end of infiltration of 70 mm of water for a) wide and b) narrow bed.

6.4.3 Water balance

The simulations were split into the two cropping periods and simulations were performed for both crops for basin and wide beds. Initial simulations showed very little difference between results using consolidated and unconsolidated soil properties in the beds thus only data associated with simulations using the unconsolidated data will be shown. These simulations take considerable time to run and analyse, so the narrow bed simulations were only performed for the wheat crop, as this crop requires a lot less post processing of the data and the results give insights into the behaviour of the narrow beds that are applicable to the maize crop.

Maize

The maize crop although grown during the monsoon season still requires a lot of irrigation if it is to grow at an optimal rate. For the basin soil there is little difference shown between the potential and simulated evaporation and transpiration and little drainage (< 0.1 mm) is predicted to occur (fig. 6.4.4). The total irrigation applied in the simulations was 725 mm which is higher than is in practice applied (table 6.4.4).

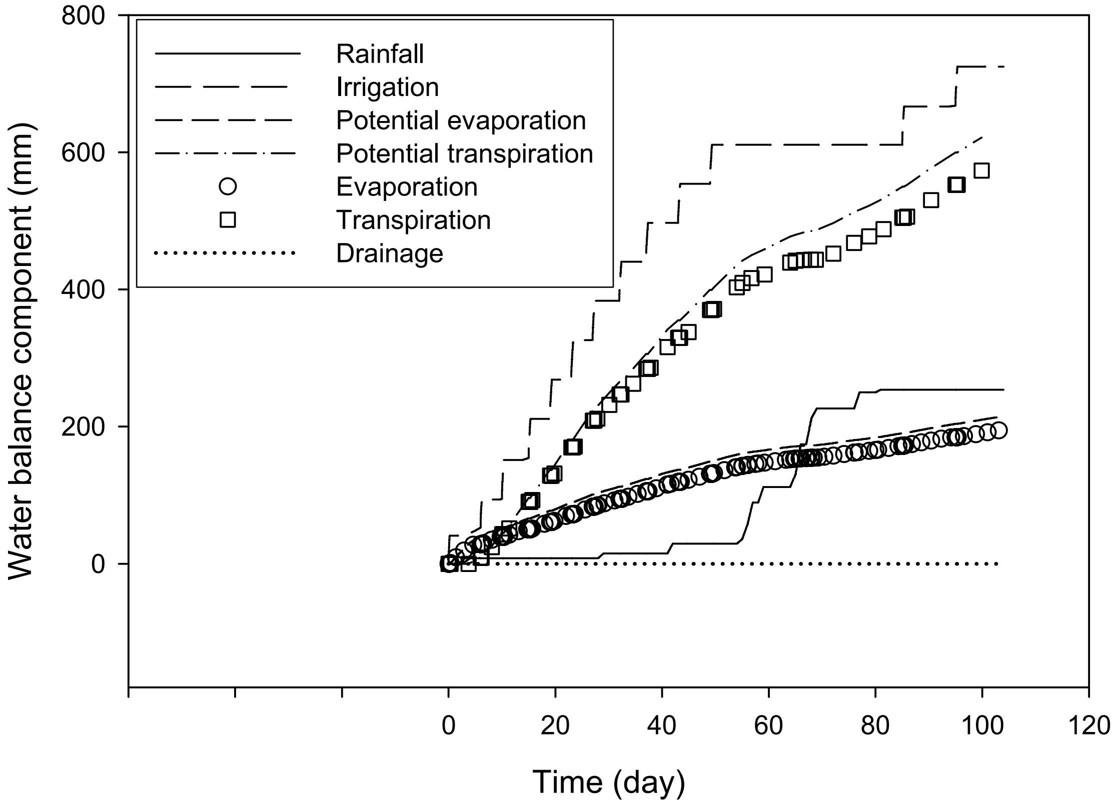

Figure 6.4.4. Water balance components during the growing season for maize for the basin simulations.

The last two irrigations may not in practice occur which would reduce the irrigation to 611 mm, but the lack of drainage is concerning. The water content profiles at the start and end of the simulations show that water has moved beyond the root zone and is travelling to depth (fig. 6.4.5). At least some of this water is likely to continue its downward journey.

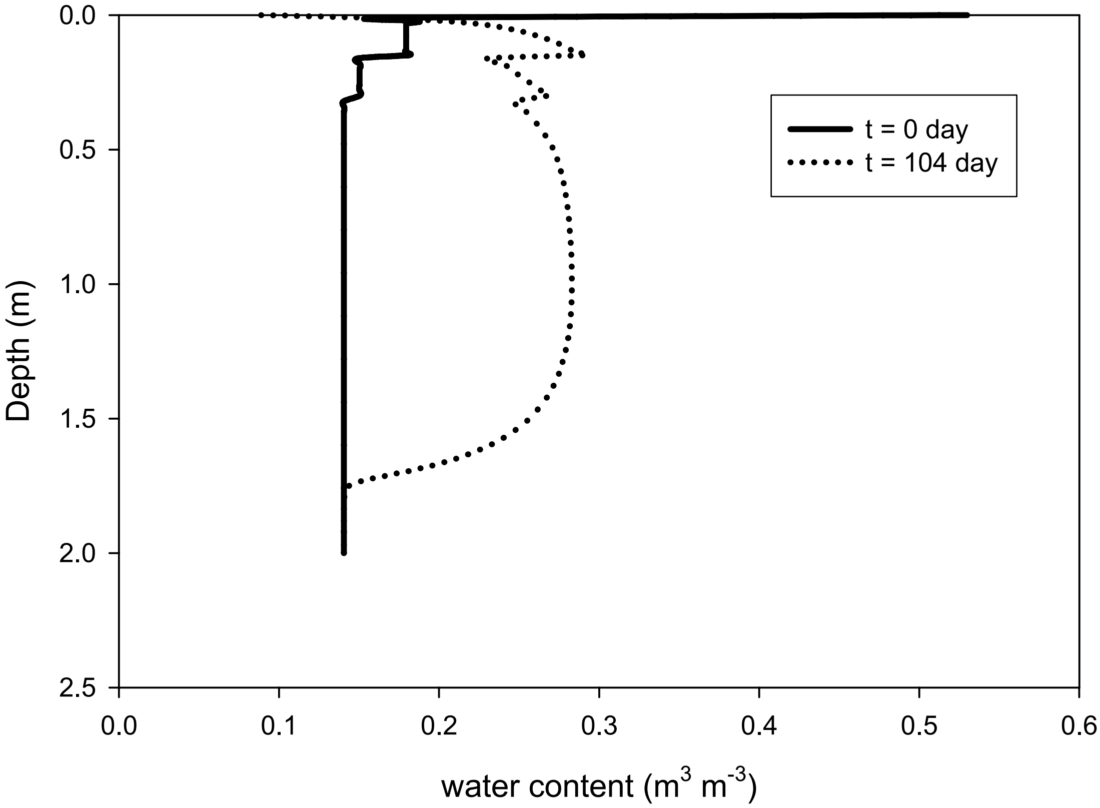

Figure 6.4.5. Water content profiles at the start and end of the simulation period for maize growing for a basin.

The water balance for the PRB treatment with the wide beds does show that some drainage below 2 m does occur during the maize growing season (fig. 6.4.6). The total irrigation added was 751 mm which is greater than double the 298 mm applied in 2006 (table 6.4.4). The climatic data supplied are from the Sugar Research Institute located 20 km north and the total rainfall during the growing season based on this data was 254 mm. The site data supplied for the experimental site was 356 mm (table 6.4.4). These differences in rainfall account for some of the differences in simulated and actual irrigation, but suggest that too little irrigation water may have been applied at the experimental sites. This may have resulted in lower yields than could have occurred and is also likely to lead to salinisation as we will discuss below. Further combined efforts with modelling and experimental measurements are likely to give insight into possible management changes.

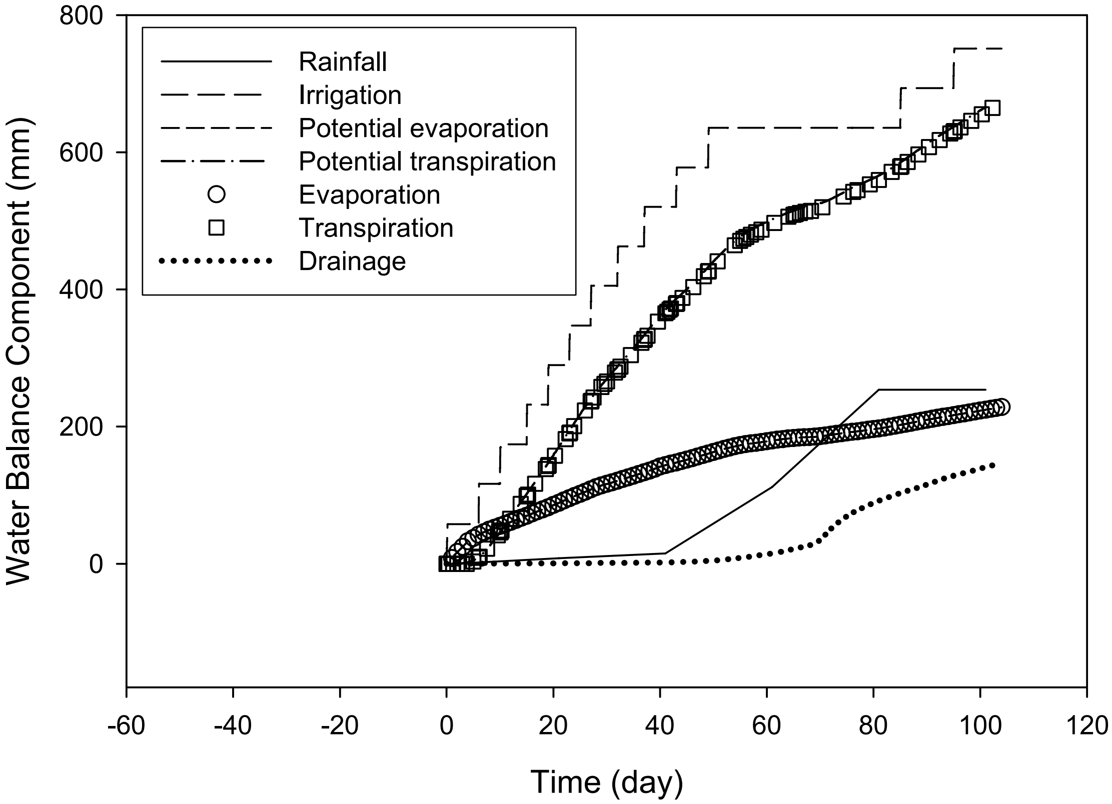

Figure 6.4.6. Water balance components for maize simulations on wide beds.

The simulations also suggest that potential evaporation and actual evaporation are equal. Thus mulching of the beds could be useful in reducing evaporation loses for both wide and narrow beds and for the basin also. The potential and actual transpiration are also simulated to be equal suggesting that if nutrient supply is optimal the wide beds should yield close to potential yield. The basin simulations suggest that actual transpiration will be less than potential, mainly due to aeration problems during large rainfall events. This is likely to result in a yield penalty. In reality the yield difference between the basin and beds is likely to be greater as the experimental data suggest that more water is applied at each irrigation than is optimal and the poor aeration is likely to occur for longer than is simulated.

Wheat

The wheat crop is grown during the dry cool winter. The results show that the rainfall and evaporation are almost the same, as are the irrigation and transpiration. The evaporation is simulated to be slightly less than the potential evaporation, while the potential and actual transpiration are almost identical (fig. 6.4 7). This results in no simulated drainage beyond 2 m depth.

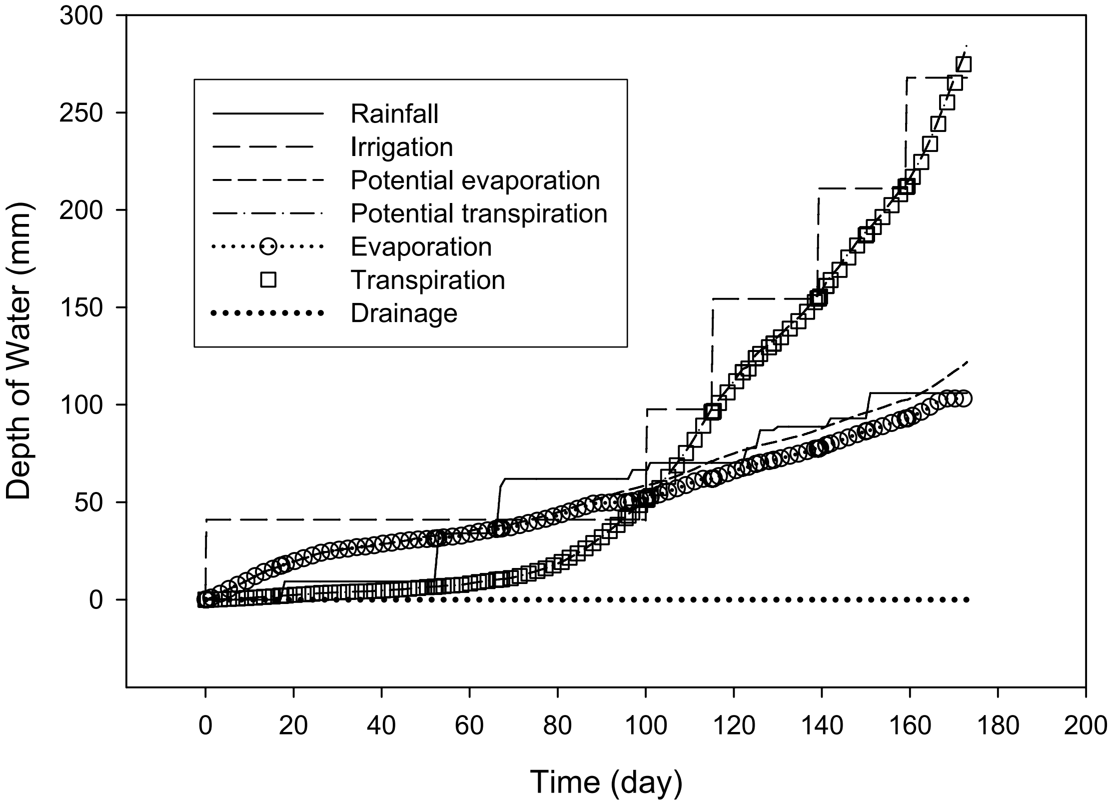

Figure 6.3.7. Simulated water balance basin soil with wheat as the crop.

The water content profiles at the start and end of the wheat crop suggests that there has been little movement of water down the soil profile (fig.6.4.8). This lack of leaching in winter means that any salt that is added in the drainage water is likely to accumulate in the soil profile.

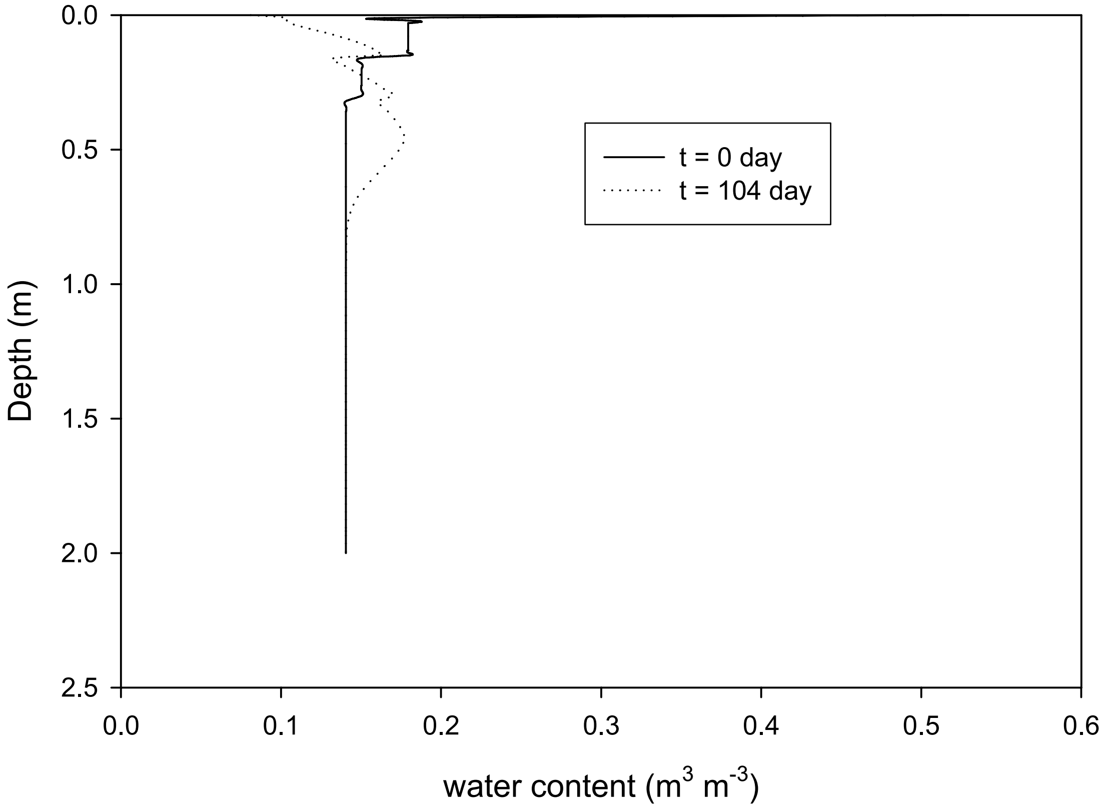

Figure 6.4.8. Water content profiles at the start (t = 0) and end (t = 104 day) of the wheat cropping season for the basin.

The wide and narrow raised beds were simulated for the wheat crop and allow a comparison of these two configurations. The water balance for the narrow beds (fig. 6.4.9a) suggests that less irrigation is applied than in the wide beds. This occurs because of the different ratio of the bed volume to the furrow and hence the storage properties of the soil. The amount of irrigation for the narrow beds was 210 mm while for the wide beds was 282 mm (fig. 6.4.9). The irrigation estimated to have been applied experimentally was 227 mm for the narrow bed and 149 mm for the wide beds. Comparing the experimental results to the modelled results indicates that possibly the correct irrigation water is applied to the narrow beds and too little to the wide beds to meet evpotranspirational needs (table 6.4.4). The simulations irrigation amount is calculated on the basis of per unit surface area of the bed and furrow. For the wide beds the surface area is 0.836 m^2 per m length of bed and for the narrow beds this is 0.511 m^2 per m length of bed. The surface area at the top of the beds is 0.425 m^2 per m length of bed for the wide beds and 0.1 m^2 per m length of bed for the wide beds. Thus if the irrigation is expressed compared to the area of the top of the bed than the irrigation amount of the narrow beds increases to 555 mm for the wide and 1073 mm for the narrow beds. The surface area used in calculating the irrigation depth applied can dramatically change the results with regard to apparent irrigation and water use efficiencies. However, the water is infiltrating into the furrow bottom and side of the bed during irrigation, so the surface area that should be used in calculating the irrigation is debatable,

Table 6.4.4 Measured total irrigation and rainfall during growing season for crops in 2004 to 2006 growing seasons, for wide and narrow beds and basin sites.

Crop and Season	Rainfall (mm)	Irrigation – Basin (mm)	Irrigation – wide Bed (mm)	Irrigation – narrow bed (mm)
Wheat 2004-05	318	163	109	117
Maize 2005	274	551	330	575
Wheat 2005-06	121	213	149	227
Maize 2006	356	474	298	415

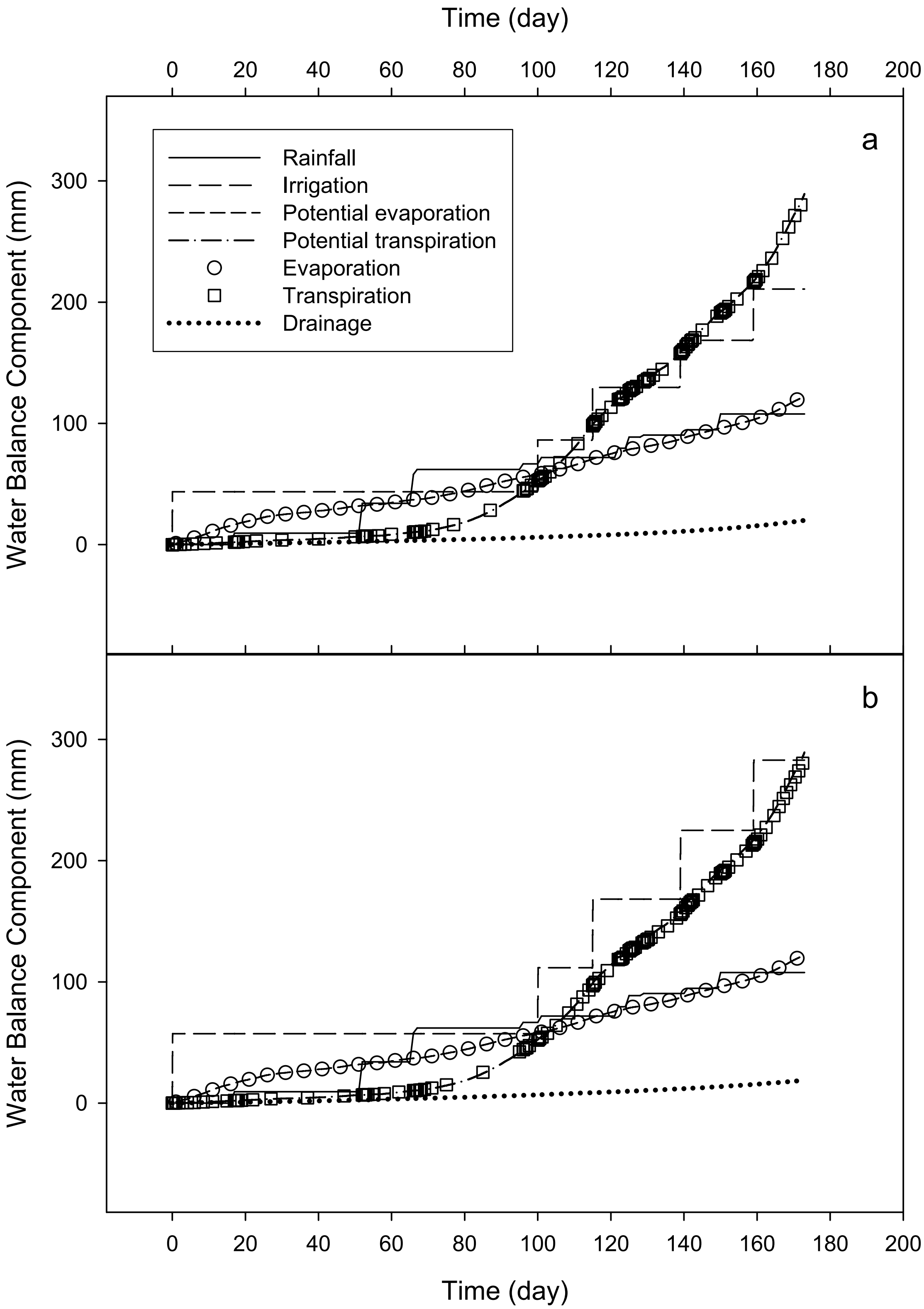

Figure 6.4.9. Simulated water balance components for a) narrow beds and b) wide beds for wheat cropping season at Mardan.

The actual evaporation and transpiration amount is the same as the potential for both the narrow and wide beds. This suggests that if this amount of water was applied, then yield reduction due to either aeration or water deficits are unlikely. Drainage of 2 mm is predicted for both narrow and wide beds but there is a bulge in the water content profiles suggesting that some further drainage could occur (fig. 6.4.10) especially under the narrow beds.

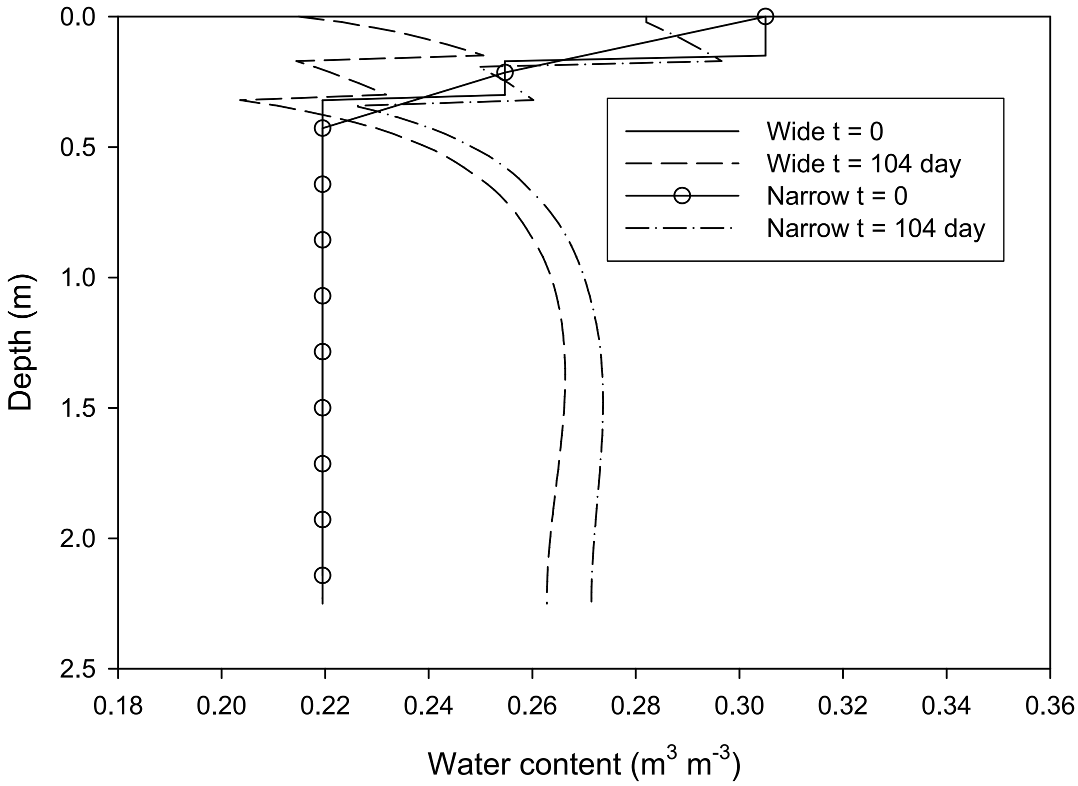

Figure 6.4.10. Simulated water content profiles for the middle of the plots for both wide and narrow beds. The initial (t = 0) profiles are identical and only every tenth point is plotted for the narrow beds.

6.4.4 Solutes

Simulations of two tracers were performed. The first tracer is only applied in the irrigation (S1) and had a concentration of 1 mol m^3 as the actual concentration is unknown. This tracer was applied to determine where solutes may accumulate in the soil and if salinisation could occur.

The second tracer (S2) was used to simulate the possible fate of nitrate fertilizers applied at the surface and incorporated to a shallow depth (fig. 6.4.11). The concentration profile is considered to decrease linearly from 1 at the surface to 0 at a depth of approximately 100 mm.

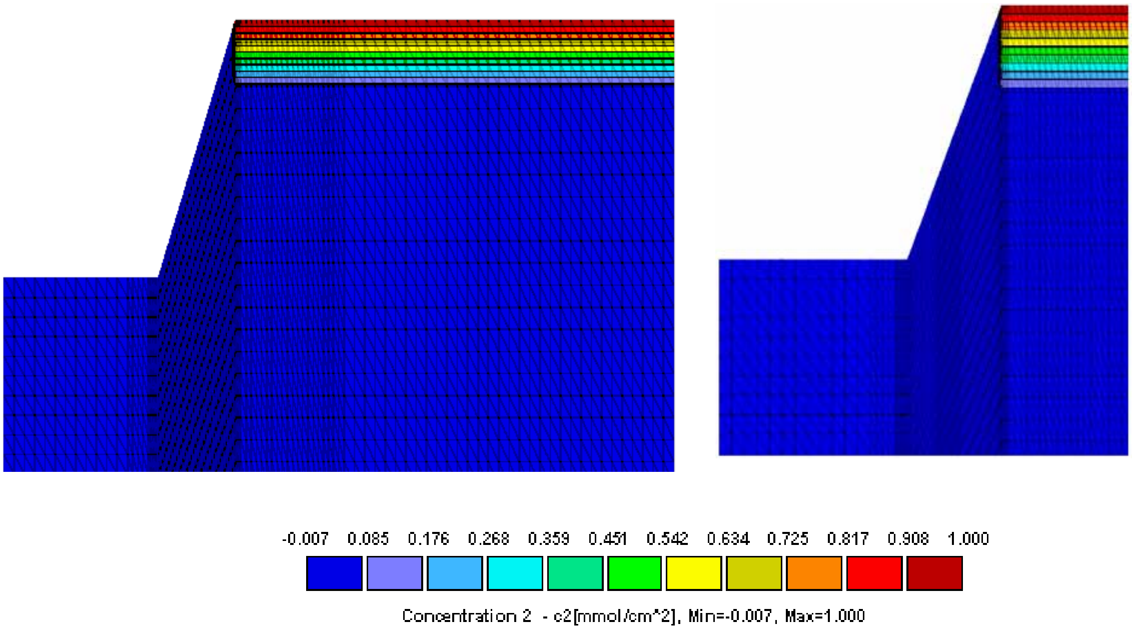

Figure 6.4.11. Fertilizer placement within the beds prior to simulation. Note profiles truncated to a depth of 0.45 m

Basin

Similarly the fertilizer (solute S2) was applied for the basin soil (fig. 6.4.12) but unlike beds the mass balance was not good for the 1-D basin simulation. This was illustrated by there being more of solute S2 in the soil at the end of the simulation than was present at the start of the simulations for the wheat crop (fig. 6.4.12a). The maize crop profiles show much deeper penetration of the salt into the profile indicating that some leaching of the salt may occur each year during the monsoonal maize cropping season. These profiles do however suggest that if water was applied as per these simulations accumulation of solute would be expected within the profile and further multi-year simulations are warranted. Given that the irrigation applied in the simulations is generally less for the wide beds than was actually applied this suggests that salinisation in the wide beds is a possibility.

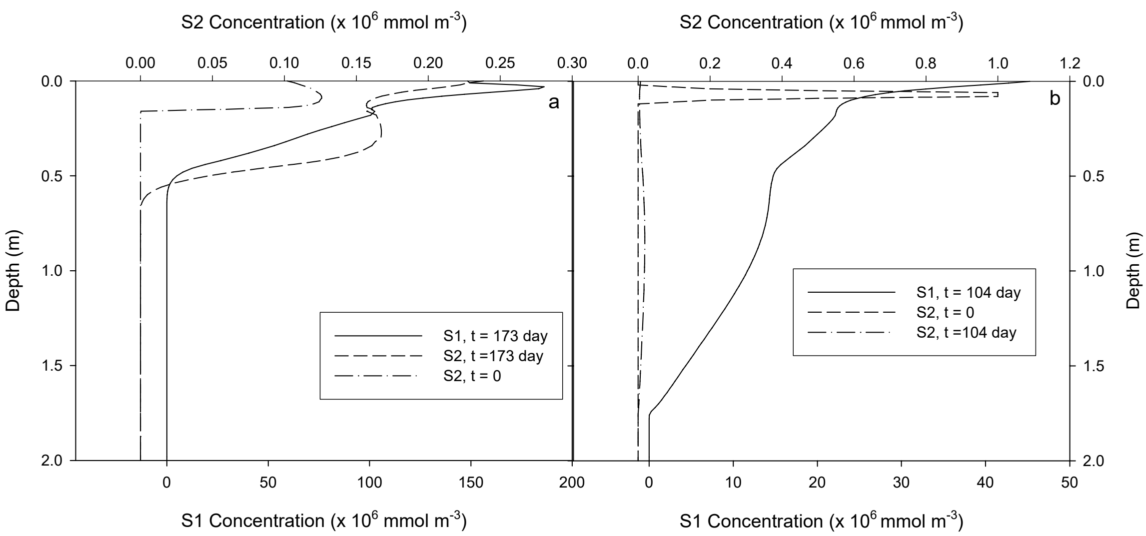

Figure 6.4.12. Solute concentration profiles from simulations with HYDRUS1D for the basin a) wheat crop and b) maize crop. The solute S1 is the salt applied in the irrigation water and accumulated with time. The solute S2 is the fertilizer and the initial and final concentration profiles are shown.

Experimental data from the sites at Mardan, indicate that an accumulation of salt could be occurring (fig. 6.4.13) near the soil surface. The shape of the profile is similar to the simulations but the experimental data is limited in the depth of the profile. It would seem prudent to measure the salinity profile in more detail and to continue monitoring while strategies to control the salinity are trialled both by modelling and experimentation. For the basin treatment the amount of irrigation applied is greater than that applied in the simulations; thus the salt may have been transported further down the soil profile.

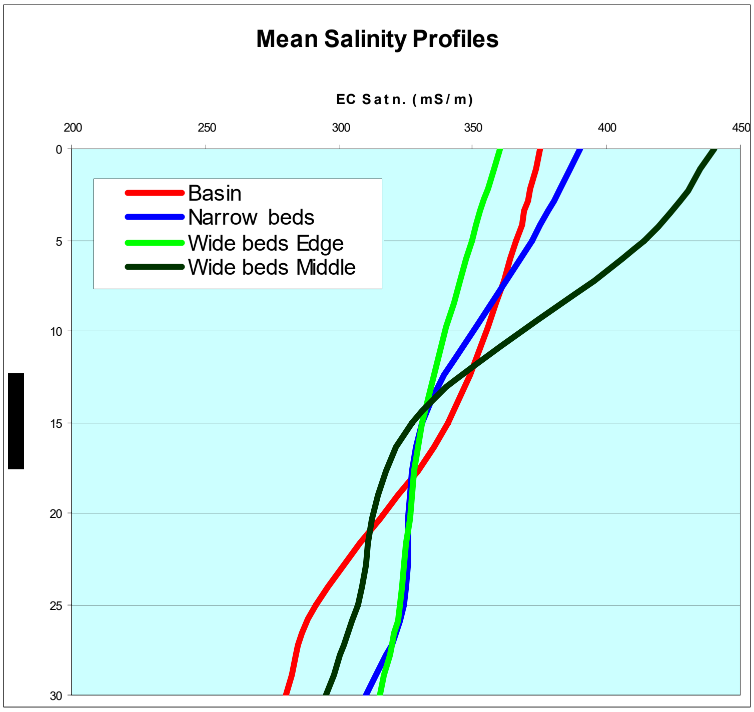

Figure 6.4.13. Profiles of salinity forum in the soil for the various irrigation options at Mardan (figure supplied by G. Hamilton).

Raised beds, wheat crop

The solute simulations were relatively well behaved for both the narrow and wide beds. The mass balances were for all simulations except the fertilizer for the narrow bed (solute

S2) within ± 4% (table 6.4.5). The simulations for the fertilizer simulations estimate more mass being taken up by roots than the change in mass storage in the soil. This discrepancy is likely to arise from a combination of factors such as rounding errors and numerical dispersion.

Table 6.4.5. Mass balance and components of solute transport in narrow and wide raised bed simulations for wheat crop at Mardan.

Solute	Input	Root Uptake	Drainage	Storage change	Mass balance (%)
Narrow Bed (mmol)					
S1 (salt)	690.6	0	<0.1	711.7	103
S2 (fertilizer)	0	4.66	<0.1	3.5	77
Wide Bed (mmol)					
S1 (salt)	1912.7	0	<0.1	1898	99
S2 (fertilizer)	0	26.1	<0.1	24.5	96

The small amount of drainage both from the water balance data above and for the solutes mass balance suggests that solutes are accumulating in the soil. The depth to which the solutes have been displaced and concentration profiles show that the highest concentration occurs in the centre of the wide beds (fig. 6.4.14a). This is the same result as was obtained experimentally. These results suggest that monitoring of the salinity in the centre of the wide beds will be required and that strategies to deal with the salinity will be necessary.

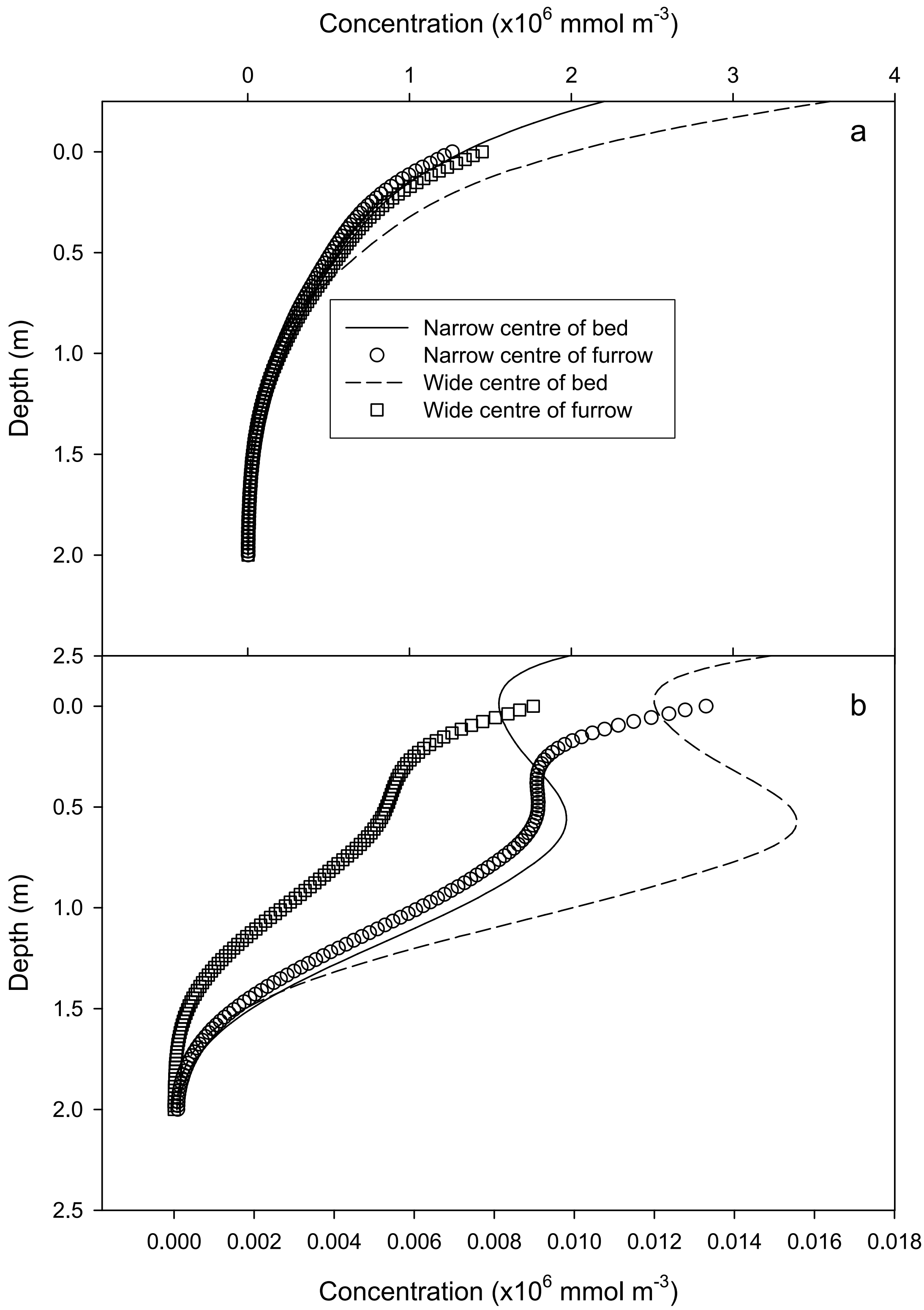

Figure 6.4.14. Concentration profiles at the centre of bed and furrow for narrow and wide bed simulations at day 173 for a) salt and b) fertilizer.

The profile plots give only a one dimensional view of the solute profiles at the end of the wheat cropping season. When a two dimensional view is taken (fig. 6.4.15) it can be seen that for the fertilizer there is a bulge near the centre of the bed at a depth of a 0.5 m. Since the rooting depth for this soil is 0.45 m this solute is now probably going to leach and will eventually reach the water table. Again this suggests that monitoring of the solutes with either suction cups or other means would be a sensible precaution. The simulations show that for narrow beds the solute distribution is more one-dimensional than the wide beds and the concentrations do not reach as high values especially for the fertilizer concentrations in the centre of the bed.

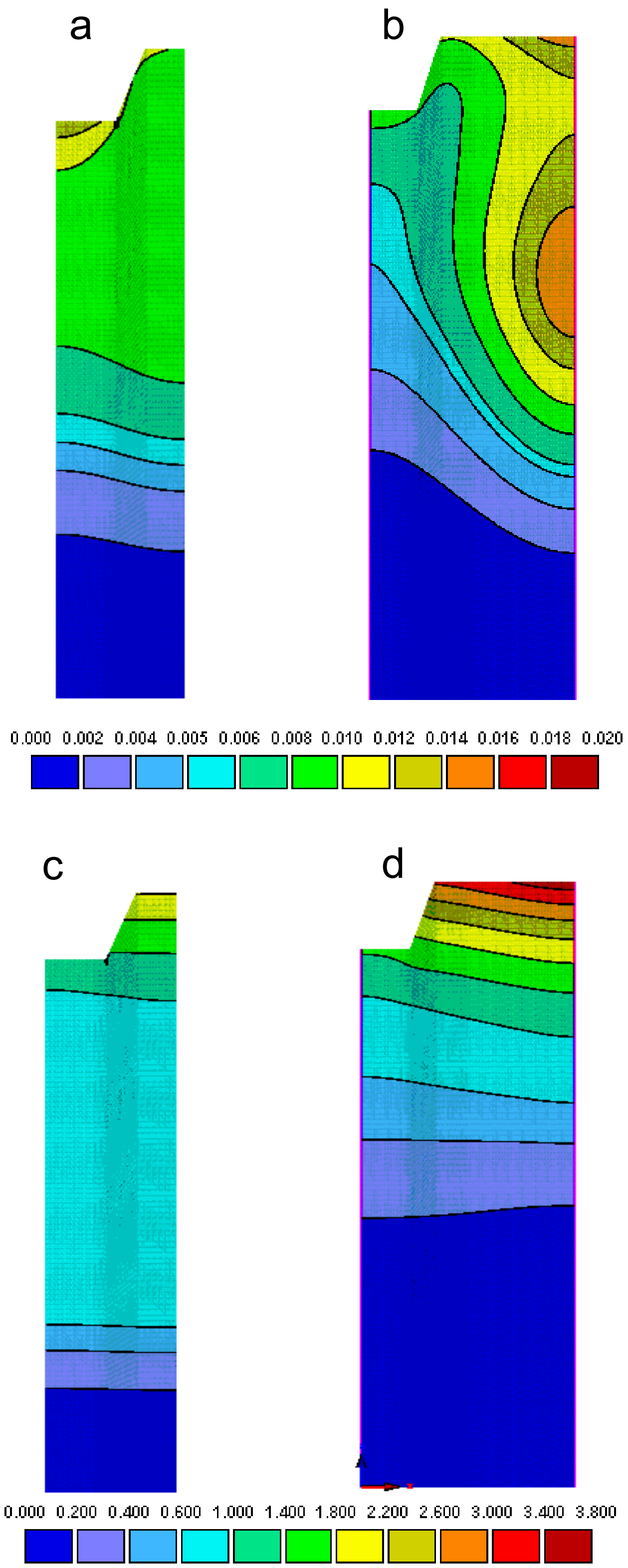

Figure 6.4.15. Solute concentrations for cross-section of beds on day 173 of the simulations for a) narrow bed for solute S2 (fertilizer), b) wide bed for solute S2, c) narrow bed for solute S1 (salt) and d) wide bed for solute S1.

Raised beds, maize crop

The maize crop with wide beds was also successfully simulated. The mass balance data was not as good as that for the wheat crop (table 6.4.5) but still good enough to gain insight into the solute processes. The amount of drainage represents 3.6% of the added solute for the fertilizer and 5.8% for the salt. The lower proportion for the fertilizer is due to the root uptake as the solute passed through the root zone.

Table 6.4.5. Mass balance and components of solute transport in wide raised bed simulations for maize crop at Mardan.

Solute	Input	Root Uptake	Drainage	Storage change	Mass balance (%)
Wide Bed (mmol)					
S1 (salt)	4882.3	0	255.4	4431.4	86.3
S2 (fertilizer)	0	45.8	1.3	36.0	76.6

The combination of irrigation and rainfall during the maize cropping period has resulted in the solutes being transported further down the soil profile and in the case of the residual from the fertilizer again the concentration is higher near the centre of the bed (fig. 6.4.16). However, the concentration is still low as 127% has been taken up by the roots. This suggests that for maize the fertilizer use could be very efficient. The nutrient of plants on the furrow/bed edge could have reduced nutrient due to the lower fertilizer concentrations that could occur there.

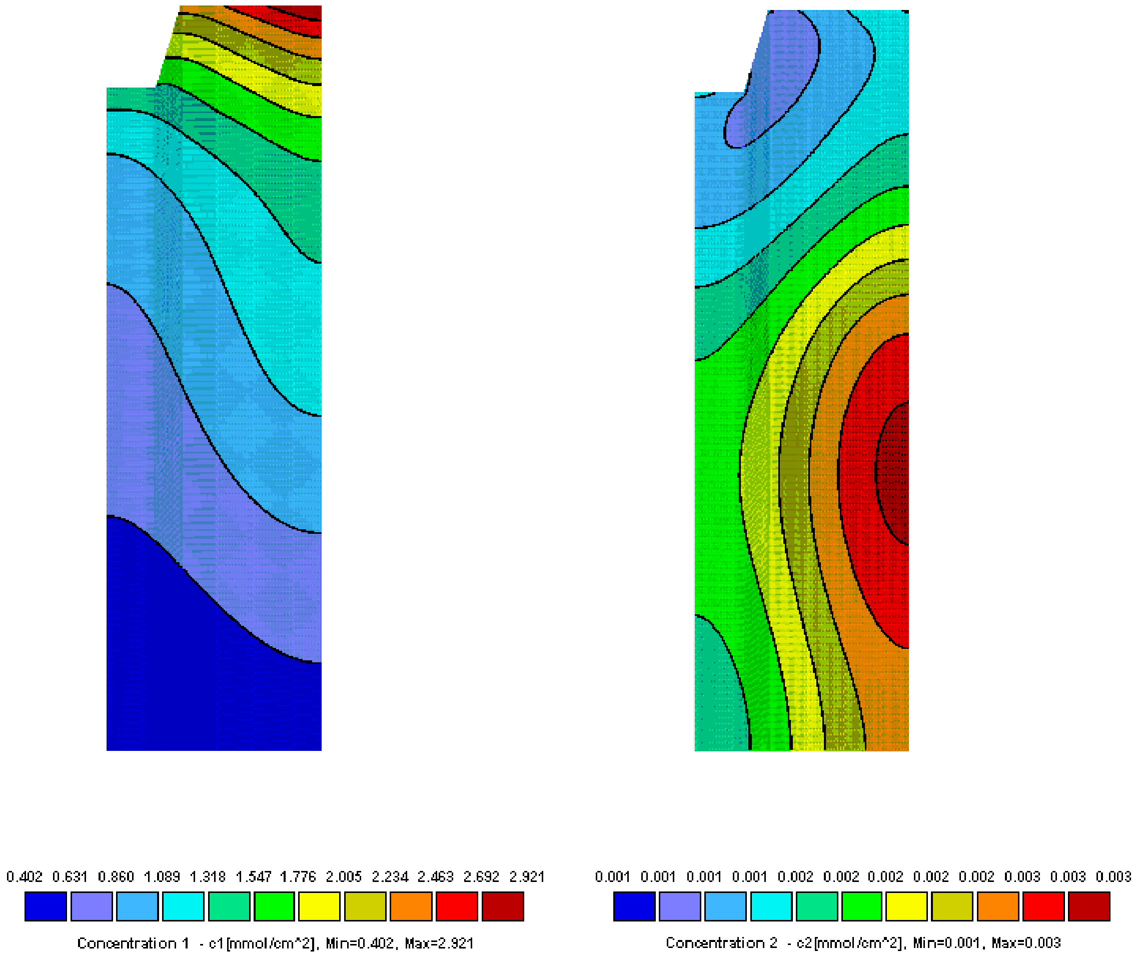

Figure 6.4.16. Simulated solute concentrations in a cross-section of a wide bed at the end of the maize cropping period (day 104) for a) salt and b) fertilizer. The concentration is in mmol cm^{-3}. Note the black bars are due to higher mesh density in the band which appears black. The depth of the bulge in the fertilizer concentration is at approximately 1.4 m.

Although the narrow beds were not simulated we can gain an insight from the wheat results. The solutes are likely to be transported even further down the soil profile for both solutes with narrow beds. This will assist with control of salinisation but could result in pollution of the groundwater. Drainage of and long term management of salt will need to be considered for sustainable irrigated agriculture to persist (Cook et al., 2007). Given that the experimental results show that less irrigation was applied than in the simulations the salinisation of the beds is likely.

7 Conclusions and recommendations

This report constitutes considerable efforts in: assimilation of data, estimate of soil properties, collation of climate data, estimation of crop rooting patterns, simulation of water and solute transport and post-processing of the simulation data. The report is quite extensive but there is a considerable amount of information in the simulations that may still be useful to extract. This work has highlighted some potential advantages and disadvantages of permanent raised beds and the need for further modelling and experimental work on permanent beds. The combined effort of modelling and experimental work together is considered to offer the best way to move forward with future research on permanent raised beds.

The main advantages found for permanent raised beds in this work are:

- Good utilisation of water and fertilizers are possible if bed configuration is correct
- Beds can provide much better aeration for all soils following irrigation and especially clay soils.

The main disadvantages for permanent raised beds that will need careful scrutiny are:

- Bed width and wetting of the bed
- Salt build up in the centre of beds
- Leaching of salts and agro-chemicals to the groundwater.

7.1 Generic results

The results of this generic research on modelling of raised beds have shown that a simple model developed for estimating bed width from soil properties to provide adequate irrigation from furrows is not useful unless the sorptivity is known. The numerical modelling of infiltration suggests that compaction below the furrow does not greatly increase lateral penetration of water into beds, but a no flow bottom boundary condition at a shallow depth below the bed does greatly enhance lateral wetting. This suggests that low permeability layers within the soil could enhance lateral wetting of the beds.

Drainage of the beds when such a no flow boundary condition (low permeability layer) occurs will be achieved by seepage into the furrow. A simple model was developed to determine the water potential with depth in the beds and this could be useful to estimate bed height to achieve adequate aeration of the beds. This simple model was shown to work well.

Studies of solute washout from the beds suggest that for soluble agro-chemicals placement away from the furrow should occur if irrigation is not going to leach these from the beds. These simulations are only for uniform soils with irrigation from the furrow. Rainfall was found in simulations for the case studies to cause the solutes to be transported downward and into the pathway of the water flow from the irrigation. This resulted in placement being shown to be less important with regard to solute transport. Soil layering within real soils will also affect the solute transport especially if a less conductive layer occurs at a depth below where the solute is placed. This lower conductivity layer tends to reduce the leaching of solutes..

Salinisation is simulated to occur when the water table is within 0.5 m for sands and 1.5 m for loams and clays of the soil surface (or bottom of root zone). These results maybe useful in already salinised sands where permanent beds may offer a means to recover productive use of these soils, so long as the salt leached from them to the furrows can be managed.

HYDRUS2D has proved to be a useful tool for simulating the water solute transport in raised beds. However, it is not a straightforward tool to use and considerable 'art' is required to get a combination of the spatial discretisation and time stepping that will give a stable solution. Sometimes even when the Peclet number (ratio between diffusion and advection of solute transport) is in a range where oscillations should not occur in the solute transport they still do. HYDRUS2D does not include precipitation reactions which can result in extremely high and unrealistic solute concentrations on the soil surface due to evaporative concentration. These high concentrations create instabilities in the numerical solutions and result in poor mass balance found in some of the simulations.

The new version of HYRUS2/3D used in the latter simulations is more stable that the earlier version. HYDRUS has the ability to simulate complicated flow regimes with respect to boundary conditions and spatial distributions of soil properties. It is a tool that can be used to explore different scenarios and will be very useful for designing and interpreting experimental results from raised beds. For its full potential to be utilised good soil property definition is required, which was not always possible here.

A modelling tool like HYDRUS is particularly useful if used in an adaptive procedure (fig 7.1). This process allows for continuous use of modelling for experimental design and interpretation and model improvement.

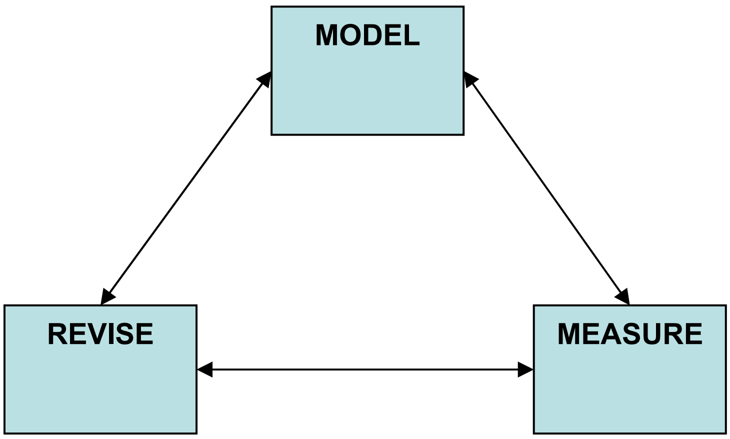

Figure 7.1. Apative framework for experimentation and modelling.

7.2 Case study results

7.2.1 India case study

- The simulations have provided some useful soil property estimates for the soils at the two sites. These data were based on a combination of experimental data and estimation using existing pedotransfer functions.
- The infiltration simulations suggest that the present width of the beds could be increased for both soils and still allow thorough wetting of the beds. Experiments in the field would be required to confirm this.
- The simulations indicate excessive infiltration and drainage for the rice crops on both soils occurs using the present flooding regime. Excess water use is particularly bad for the sandy loam soil, but this is unrealistic as the puddling of the soil experimentally reduces the infiltration rate of this soil considerably. The results are instructive as to what would happen if puddling was not undertaken.
- The solute simulations show that fertilizer placement is unlikely to make much difference to fertilizer losses. This is due to rainfall transporting the solute down and into the zone where it can be transported to depth by the irrigation water.

- The simulations suggest that salt is likely to accumulate during the wheat cropping season but then be flushed out during the rice growing season.
- Fertilizer losses to the groundwater during the rice cropping season could be excessive due to excessive drainage.

7.2.2 Indonesia case study

- Soil properties were only based on particle size distributions and there was almost no difference between the predicted soil properties at both sites.
- Drainage of the beds to a depth of air-filled porosity of 8% if drainage is only by seepage from the bed face would require a bed height of ≈ 2 m.
- Furrow irrigation of the PRB bed configuration would take > 2 days for wetting to the centre of the 1.2 m wide beds, while beds half the width would wet in less that 1 day.
- To wet the bed from the surface in the dry season at least three strips, one 0.2 m in width down the middle of the bed and two 0.1 m wide at the mid-point between the middle and edge of the bed, would be required on PRB configurations, but one strip 0.4 m wide down the middle of the bed would be sufficient for wavy beds. Calculations also showed that an irrigation of 18 mm would be required and for the 1.2 m wide beds this represents a volume of water of 21.6 L per one meter length of bed.
- Rice yields should be unaffected by drainage via deep drainage or seepage from all sites and bed configurations.
- Potential water yield for all sites, crops and bed configurations in the wet is unlikely to provide sufficient water for full irrigation in the dry season.
- Fertilizer uptake in the wet season is best at Wakan site.
- Salt accumulation is possible from irrigation at the centre of beds especially for the wavy configuration.

7.2.3 China case study

- The soil properties data for this project are the best of any of the projects with only the hydraulic conductivity data having to be estimated using pedotransfer functions. This means that these simulations should be the most reliable.
- The management of solutes, both fertilizer and salt will be critical to the success of this project.
- Irrigation to displace salt from the beds and to depth may be required, but these simulations are only for one growing season. Further multi-year simulations should be undertaken to get a better understanding of the long-term consequences of irrigation at this site.
- Careful monitoring of the solute concentrations within the soil with time will be required if this project is to be a long-term success.
- The salt that will be displaced to deep drainage in this project may also constitute a longer term problem with regard to pollution of the groundwater.
- Crop yields should be close to optimum using the present irrigation practices.

7.2.4 Pakistan case study

- Good measurements of some soil properties existed for this project. This meant that the properties that had to be estimated with pedotransfer functions were well bounded and the soil properties presented should be sound. The hydraulic conductivity values should be close to the field values as they are based on measured infiltration or values estimated from sorptivity.
- The management of solutes, both fertilizer and salt will be critical to the success of this project. Simulations indicate salt accumulation will occur in the centre of wide beds.
- Irrigation to displace salt from the beds and to depth may be required.
- Careful monitoring of the solute concentrations within the soil with time will be required if this project is to be a long term success, especially in the centre of wide beds.
- The salt that will be displaced to deep drainage in this project may also constitute a longer term problem with regard to pollution of the groundwater.
- Excessive fertilizer if applied is likely to be transported to below the rooting depth especially in the monsoonal maize cropping season.
- Crop yields should be close to optimum if optimal irrigation practices are used.
- Even with optimal irrigation practices basin irrigation may cause a yield decline due to poor aeration post-irrigation.
- The present wide beds are adequately wetted by irrigation even after some consolidation.
- Narrow beds are wetted well by irrigation with water and solute transport becoming close to 1-dimensional.

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