Agricultural Water Management 115 (2012) 242–251

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Minimizing nitrogen leaching from furrow irrigation through novel fertilizer placement and soil surface management strategies

Altaf A. Siyal[a,b,*], Keith L. Bristow[c], Jirka Šimůnek[d]

[a] Department of Land and Water Management, Faculty of Agricultural Engineering, Sindh Agriculture University, Tandojam, Sindh, Pakistan
[b] Endeavour Foundation Fellow with CSIRO Land and Water, PMB Aitkenvale, Townsville, QLD 4814, Australia
[c] CSIRO Sustainable Agriculture National Research Flagship and CSIRO Land and Water, PMB Aitkenvale, Townsville, QLD 4814, Australia
[d] Department of Environmental Sciences, University of California Riverside, Riverside, CA 92521, USA

ARTICLE INFO

Article history:
Received 8 April 2012
Accepted 12 September 2012

Keywords:
Irrigation efficiency
Water and nutrient use efficiency
Water savings
Solute transport
Nitrate leaching
HYDRUS

ABSTRACT

Inappropriate soil, water and fertilizer management in irrigated agriculture can result in environmental problems, including groundwater pollution with nitrates. Furrow irrigation is widely used around the world and is considered as a major source of nitrate leaching. Improved soil, water and fertilizer management practices are needed to improve the production and environmental performance of furrow irrigated agriculture. This paper describes results of a simulation study using HYDRUS-2D to assess opportunities to improve irrigation efficiency and reduce the risk of nitrate leaching from furrow irrigated systems. It focuses on the commonly used practice in Pakistan where irrigation water supply is turned off once the water level in the furrow has reached a pre-determined depth. The study involved analysing the impact of fertilizer placement on nitrate leaching from a loamy soil subjected to three different soil surface treatments. Fertilizer placements included placing the fertilizer on the bottom of the furrow (P_1), sides of the furrow (P_2), bottom and sides of the furrow (P_3), on the sides of the furrow near to the ridge top (P_4), and on the surface in the middle of the ridge top (P_5). The soil surface management treatments included the original soil (S_o), compacting the bottom of the furrow (S_c) and placing a plastic sheet on the bottom of the furrow (S_p). Results showed water savings varied with application rate and soil surface management, with soil surface management strategies S_c and S_p yielding water savings of 17% and 28% relative to S_o for a water application rate of 1800 L h^{-1} for a 100 m long furrow. Leaching of nitrogen for this case was reduced from 33% for S_o with fertilizer placement P_1 to 1% by compacting the bottom of the furrow (S_c) and to zero loss by placing a plastic sheet on the bottom of the furrow (S_p). By changing the fertilizer placement for S_o from P_1 to P_2, P_3, P_4, and P_5, nitrogen leaching was reduced from 33% to 2%, 15%, 0%, and 0%, respectively. Results of this study demonstrate that placing nitrogen fertilizer on the sides of the furrow near the ridge top (P_4) or on top of the furrow at the centre of the ridge (P_5) maximize the retention of nitrogen fertilizer within the root zone. Results of this study also demonstrate that enhancements in irrigation efficiency, particularly in coarser soils with high infiltration rates can be achieved through compacting the bottom of the furrow or by placing a plastic sheet on the bottom of the furrow before applying irrigation.

1. Introduction

The wide spread occurrence of high levels of nitrate in surface and groundwater is of growing concern (Angle et al., 1993; Mailhol et al., 2001; Gärdenäs et al., 2005; Liu et al., 2005; Waddell and Weil, 2006). This has resulted in increasing scrutiny of and pressure to improve agricultural practices, especially in irrigated systems to reduce the amount of nitrogen entering our water systems (Bar-Yosef, 1999; Gärdenäs et al., 2005; Jones and Olson-Rutz, 2011). The quality of soils, ground and surface water resources is always at risk in areas where agricultural production is dominated by irrigation such as in Pakistan and many other semiarid and arid regions of the world. Excessive and improper application of nitrogenous fertilizers with irrigation water leads to an increase in nitrate concentration in the ground and surface water in these areas (Hayens, 1985; Waskom, 1994; Mitchell et al., 1994). One of the most common contaminants found in groundwater worldwide is nitrate (NO_3^-), an oxidized form of dissolved nitrogen.

Traditional cropping practices in Pakistan, as in many other regions of the world, involve application of significant quantities

* Corresponding author at: Department of Land and Water Management, Faculty of Agricultural Engineering, Sindh Agriculture University, Tandojam, Sindh, Pakistan. Tel.: +92 343 835 8031.
E-mail address: siyal@yahoo.com (A.A. Siyal).

0378-3774/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agwat.2012.09.008

of nitrogenous fertilizers and large quantities of irrigation water, which can result in significant leaching of nitrate due to excess deep drainage. This not only decreases the availability of nitrogen to plants but also creates environmental problems by degrading the quality of the groundwater. The problem of nitrate leaching is aggravated in agricultural areas when soils are coarse textured (Waddell and Weil, 2006).

In about 90% of the irrigated area of the world, crops are irrigated with surface irrigation methods, most often using furrow irrigation (Tiercelin and Vidal, 2006), which is considered as a more water use efficient method than basin and border irrigation methods. Furrow irrigation is commonly used in arid, semiarid and subhumid regions of the world to irrigate vegetables and row crops. Wylie et al. (1994) reported furrow irrigated corn as a major source of nitrate leaching and groundwater pollution. As much as 40% of the available nitrate can leach out of the root zone from a clay loam soil (Artiola, 1991). Hence, there is a need to improve water, fertilizer and soil surface management strategies for furrow irrigation to increase irrigation efficiency and reduce nitrogen losses by leaching to groundwater (Bar-Yosef, 1999).

Leaching of nitrate below the root zone can be affected by a range of factors, including application rates and timing of applications (Robbins and Carter, 1980). A field study conducted by Benjamin et al. (1998) showed that placing fertilizer in the non-irrigated furrow in alternate furrow irrigated systems increased water use efficiency and reduced fertilizer leaching. However, Musick and Dusek (1974) and Crabtree et al. (1985) found a decrease in yield of different crops when alternate furrow irrigation systems were compared with conventional furrow irrigation systems. Mailhol et al. (2001) reported that fertilizer application near the top of the ridge followed by heavy irrigation has a beneficial impact on both yield and nitrogen leaching. Kemper et al. (1975), Hamlett et al. (1990), Clay et al. (1992) and Waddell and Weil (2006) also found that by placing fertilizer near the top of the ridge, corn crop yields increased and the risk of nitrogen leaching decreased. Most of the research to date on reducing leaching of nitrogen from furrow irrigation has focused on fertilizer placement (Benjamin et al., 1998; Lehrsch et al., 2000; Mailhol et al., 2001; Waddell and Weil, 2006) and managing water application and water depth (Abbasi et al., 2003, 2004; Mailhol et al., 2007). Little work has been done on reducing deep drainage and solute leaching from furrow irrigation using a combination of soil surface management and fertilizer placement strategies.

When the water infiltration rate is very high and advancement of the furrow wetting front is slow (often a problem in coarse textured soils), the bottom of the furrows (but not the sides) is sometimes compacted before irrigation to reduce the infiltration rate (Yonts, 2007). Compaction of the bottom of the furrow can be achieved in a number of ways, including driving a tractor along the furrows to decrease porosity (increase soil density). Another way to minimize (and mostly eliminate) infiltration and deep drainage directly below the furrow is to place impermeable plastic sheets on the bottom of the furrow. This will increase irrigation efficiency by diverting the direction of water flow directly into the side walls of the furrow, thereby eliminating direct downward flow below the plastic cover and providing maximum opportunity for water to infiltrate into the side of the furrow and be drawn up into the ridge by capillarity.

Placement of fertilizer plays an important role in nutrient uptake by plants and leaching of nutrients below the root zone. In Pakistan, nitrogen fertilizers, in granular form, are usually broadcast manually onto the bottom of the furrow and sides, which can result in leaching of nitrate below the root zone before it can be extracted by plants. Normal furrow irrigation practice in Pakistan involves diverting water from a watercourse or field canal to the furrow until the water level reaches a particular depth in the furrow at which point the water supply is turned off. In this paper we refer to this depth as the 'switch-off depth'.

The main objective of precision fertilizer placement is to make nutrients easily accessible to roots but without causing damage to the young seedlings, especially during the early stages of plant growth (Jones and Jacobsen, 2009). Achieving this requires careful placement of fertilizer within furrow irrigated systems to retain as much nitrogen as possible within the root zone for as long as possible to maximize plant uptake. The objective of this study therefore was to evaluate different strategies to improve irrigation efficiency and minimize deep drainage and nitrogen leaching from furrow-irrigated systems. To do this we used the HYDRUS-2D model (Šimůnek et al., 2008) to analyze different nitrogen fertilizer placements in combination with modifications of the soil surface at the bottom of the furrow. Computer modelling is an efficient methodology for analysing alternative water and fertilizer management options for different irrigation systems (Abbasi et al., 2003), and HYDRUS-2D has been widely used as an effective tool for modelling water and solute transport in a variety of soil geometries and irrigation systems (Mailhol et al., 2001; Cote et al., 2003; Gärdenäs et al., 2005; Crevoisier et al., 2008; Siyal et al., 2009; Siyal and Skaggs, 2009). We did not include plants and root water uptake in this study, which allowed us to assess the worst case scenario in terms of fertilizer placement and soil surface modification on deep drainage and nitrate leaching.

2. Materials and methods

The HYDRUS-2D software package, which includes a user friendly interactive graphics-based interface (Šejna et al., 2011), uses numerical methods to solve the Richards' equation for saturated–unsaturated water flow and the convection–dispersion equation for solute transport. We used HYDRUS-2D in the present study to analyze water flow and nitrogen transport through a cross-sectional furrow subjected to different fertilizer placements and soil surface management strategies.

2.1. Governing equations for water and solute transport

For Darcian two-dimensional water flow in a variably saturated medium, the Richards' equation can be expressed as:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}\frac{\partial h}{\partial x_j} + K_{iz}\right)\right] \qquad (i, j = 1, 2) \tag{1}$$

where x_i ($i = 1, 2$) are the spatial coordinates (L), t is time (T), θ is water content ($L^3\,L^{-3}$), h is the pressure head (L), K is the hydraulic conductivity ($L\,T^{-1}$), and K_{ij} are components of the hydraulic conductivity anisotropy tensor. Since we assume isotropic porous media with $x_1 = x$ and $x_2 = z$ being the horizontal and vertical coordinates, respectively, the conductivity tensor is diagonal with the entries K_{xx} and K_{zz} equal to one.

Solute transport was described using the advection–dispersion equation:

$$\frac{\partial\theta c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right) - \frac{\partial q_i c}{\partial x_i} \qquad (i, j = 1, 2) \tag{2}$$

where c is the solution concentration ($M\,L^{-3}$), q_i represents water flux density ($L\,T^{-1}$), and D_{ij} is the dispersion tensor ($L^2\,T^{-1}$), with standard expression for the longitudinal (ε_L) and transverse (ε_T) dispersivities (L) (e.g. Bear, 1972). Eq. (2) is valid for non-reactive transport, so adsorption and precipitation/dissolution of the solutes are ignored.

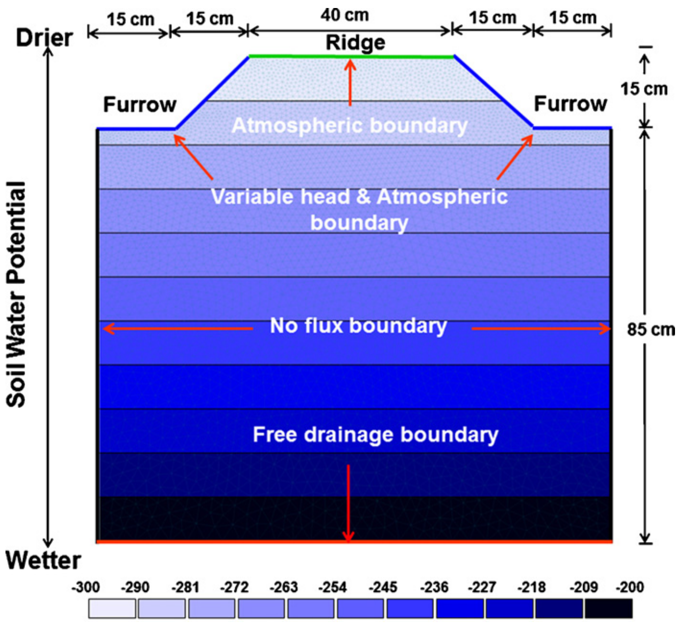

Fig. 1. Initial soil water pressure head (cm) in the flow domain and boundary conditions imposed on the flow domain during simulations.

2.2. Soil hydraulic properties

The soil hydraulic properties (water retention $\theta(h)$ and hydraulic conductivity $K(h)$) needed in Eq. (1) are described using the van Genuchten–Mualem model (van Genuchten, 1980; Mualem, 1976):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (3)$$

$$K(h) = K_s S_e^{\ell}[1-(1-S_e^{1/m})^m]^2 \quad (4)$$

where θ_r and θ_s denotes the residual and saturated water contents ($L^3\,L^{-3}$), respectively; K_s ($L\,T^{-1}$) is the saturated hydraulic conductivity, α (L^{-1}) and n are empirical coefficients affecting the shape of the hydraulic functions, ℓ is a pore connectivity parameter, $m = 1 - 1/n$, and S_e is effective saturation:

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \quad (5)$$

The HYDRUS-2D soils catalogue contains hydraulic property parameters for a wide range of soil types and we used a medium textured loam for this study. The soil hydraulic parameters for the loam soil were $\theta_r = 0.078$, $\theta_s = 0.43$, $K_s = 1.04\,cm\,h^{-1}$, $\alpha = 0.036\,cm^{-1}$, $n = 1.56$ and $\ell = 0.5$ (Carsel and Parish, 1988).

2.3. Flow domain

We simulated water flow and solute transport in the root zone of a furrow irrigation system represented by a flow domain 100 cm wide (representing two halves of a 60 cm furrow and a complete 40 cm ridge at the upper boundary) and 100 cm deep (Fig. 1). A finite element mesh was generated using the MESHGEN module within HYDRUS-2D. Total number of nodes and triangular elements in the flow domain were 4437 and 8651, respectively. The finite element grid was adjusted such that the size of the elements were smaller near the soil surface and the furrows where water fluxes (infiltration and surface evaporation) were most rapid, and larger near the no-flow and free drainage boundaries along the sides and the bottom of the flow domain.

2.4. Initial conditions

The initial conditions were specified in terms of the soil water pressure head h(x, z) and were set to decrease linearly with depth, from −300 cm at the top of the flow domain ($z = 0$) to −200 cm at the bottom of the flow domain ($z = -100$) (Fig. 1).

2.5. Boundary conditions

The boundary conditions used to simulate water and solute transport in the furrow irrigated system are given in Fig. 1. We did not consider the effect of a water table so nodes at the bottom of the flow domain ($z = -100$ cm) were assigned a free drainage boundary condition (unit hydraulic gradient in the z direction). Due to symmetry, the nodes representing the left and right boundary of the flow domain were set as 'no flux boundaries' as no flow or solute transport occurred across these boundaries. The ridge surface and the unsubmerged sides of the ridge were specified as 'atmospheric boundaries' (Šejna et al., 2011). Here water evaporates from the soil surface at a constant potential rate (= 0.016 cm h^{-1}) as long as the surface soil water pressure head is above a certain threshold value (= −15,000 cm in our study), and then switches to a constant pressure head (−15,000 cm) when the soil surface dries out to the threshold value.

The bottom and both sides of the furrow were assigned a special boundary condition, newly implemented into HYDRUS-2D for this study. The actual conditions along this boundary were adjusted dynamically depending upon the water level in the furrow and conditions in the flow domain (root zone). The part of the furrow that was below the water level was assigned a pressure head boundary condition and the part that was above the water level was assigned either a seepage face or atmospheric boundary condition, depending upon the saturation conditions in the ridge (see Appendix for a detailed description of this boundary condition).

The initial water level in the furrow was set to zero, and it increased once water flowed into the furrow. A water application rate of 1800 L h^{-1} furrow^{-1} for a 100 m long furrow was used. This corresponds with a Q_s flux of 90 cm^2 h^{-1} in Fig. A1 and an area based application rate of 18 mm h^{-1}. Once water entered the furrow it started infiltrating into the soil from the bottom and sides of the furrow. The criterion for controlling irrigation was based on the commonly used practice in Pakistan, where once the furrow fills to a particular depth, 10 cm in this study, water flow into the furrow is switched off. Infiltration then continued until all of the water in the furrow had entered the soil. When water infiltration ceased, the boundary condition switched from the pressure head boundary condition to the atmospheric condition.

2.6. Initial and boundary conditions for nitrogen transport

The flow domain was considered nitrogen free at the beginning of the simulations, i.e. $c(x, z) = 0$, except for those areas where fertilizer was placed to simulate the effects of different fertilizer placements (see next section for detail about actual placement of the fertilizer). Nitrogen was applied at 150 kg N ha^{-1}, which is typical of what is commonly practiced in furrow irrigated systems in many parts of the world, including Pakistan (FAO, 2004). The irrigation water was nitrogen free. Solute flux out of the flow domain could occur only from the bottom free drainage boundary. A third-type (Cauchy) boundary condition was specified at the seepage, atmospheric and free drainage boundary conditions.

The diffusion coefficient D_o of nitrate in solution at 25 °C was taken as 0.068 cm^2 h^{-1} as reported by Beven et al. (1993) and used by Mailhol et al. (2001, 2007) in their simulations with HYDRUS-2D. The longitudinal dispersivity (ε_L) is usually considered equal to one-tenth of the profile depth and transverse dispersivity (ε_T) equal

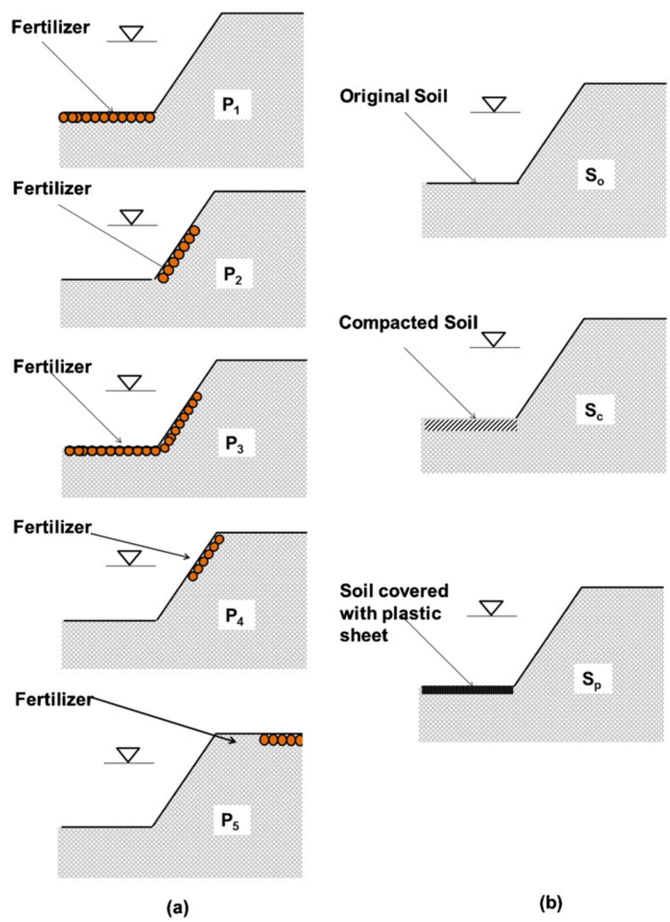

Fig. 2. Schematic showing (a) the different fertilizer placements (P_n) and (b) soil surface management treatments (S_i) analysed in this study (P_1, fertilizer at the bottom of furrow; P_2, fertilizer on the sides of furrow; P_3, fertilizer on the bottom and sides of the furrow; P_4, fertilizer on the furrow sides near the ridge top; P_5, fertilizer on the top at the centre of the ridge and S_o, original soil; S_c, compacted soil; S_p, plastic covered soil).

to one-tenth of ε_L (Beven et al., 1993; Cote et al., 2003; Phogat et al., 2011). For the present study longitudinal and transverse dispersivities were therefore set at 10 cm and 1 cm, respectively. Nitrogen volatilisation and adsorption by the soil matrix was not considered in this study (Huygens et al., 2007).

2.7. Soil surface management and fertilizer placement strategies

Opportunities to maximize nitrogen retention in the flow domain (root zone) and hence minimize leaching were analysed for five different fertilizer placements. These involved placing the fertilizer at the bottom of furrow (P_1), on the sides of the furrow (P_2), on the bottom and sides of the furrow (P_3), on the furrow sides near the ridge top (P_4) as suggested by Kemper et al. (1975), Mailhol et al. (2001) and Waddell and Weil (2006), and on the top at the centre of the ridge (P_5) (Fig. 2(a)). The nitrogen fertilizer was mixed into the top 1–3 cm of soil to ensure that the same concentration and total amount of nitrogen (150 kg N ha^{-1}) was applied to each of the P_1–P_5 treatments.

We also analysed different soil surface management strategies in combination with the fertilizer placement strategies. These included original soil (S_o) as the control, compaction of the bottom of the furrow (S_c) and placement of a plastic sheet on the bottom of the furrow (S_p) as shown in Fig. 2(b).

The saturated soil hydraulic conductivity for the original soil (S_o) was 1.04 cm h^{-1}. For the compacted soil (S_c) the saturated hydraulic conductivity of the top 2 cm of soil was decreased to 1/5th of the original uncompacted value (i.e. 0.208 cm h^{-1}) (Douglas and Crawford, 1993; Schwen et al., 2011). Soil compaction in the field can be achieved in a number of ways, including by tractor wheels or with the Eversman v-shaped wheel as suggested by Yonts (2007).

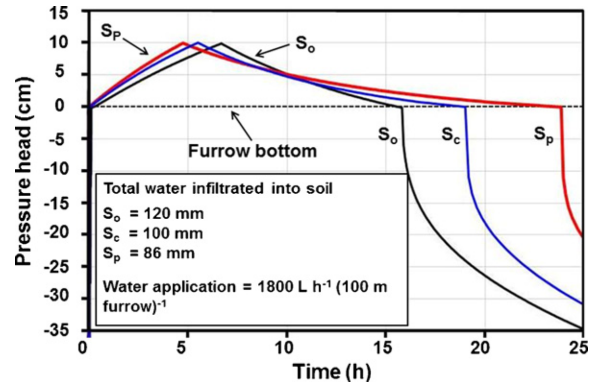

Fig. 3. Water pressure head at the bottom of the furrow following initiation of irrigation for the different soil surface management strategies (S_o, original soil; S_c, compacted soil; S_p, plastic covered soil).

Placement of plastic on the bottom of the furrow (S_p) was simulated by setting a no flux boundary condition at the bottom of the furrow, so that infiltration occurred only through the sides of the furrow. The simulations were run for 120 h (5 days) for all treatments.

3. Results and discussion

3.1. Water application

The soil water pressure head at the bottom of the furrow for the different soil surface management strategies with an application rate of 1800 L h^{-1} (100 m furrow)$^{-1}$ is given in Fig. 3. The plots show that the water level in the furrow starts rising following initiation of irrigation. When the water level reaches the target depth of 10 cm (after 6.7 h for S_o) the irrigation is switched off. Water remaining in the furrow continued to infiltrate into the soil, with the furrow emptying after 16 h. Similarly, for S_c and S_p, water application continued until the water level in the furrow reached 10 cm after 5.6 and 4.8 h respectively, at which time the irrigation is switched off. Water remaining in the furrow continued to infiltrate, with the furrow emptying after 18.7 and 23.8 h for S_c and S_p, respectively.

As expected, the plastic covered furrow (S_p) took the least time to reach the 10 cm switch-off depth (4.8 h) while the S_c treatment took 5.6 h and the S_o treatment took 6.7 h. These relatively short differences in application times resulted in significant savings in terms of water applied, with the depth equivalents of water infiltration for S_o, S_c and S_p equalling 120, 100 and 86 mm, respectively. This demonstrates water savings of 17% and 28% for the compacted and plastic covered soil scenarios, respectively, compared with the original soil (Table 1). These water savings mean less water was taken from the water supply, leaving more water to be used elsewhere, either as environmental flows or for other productive purposes.

Fig. 4 shows the time periods for irrigation, infiltration and redistribution for the different soil surface management strategies up to 120 h. It shows that the irrigation periods are 6.7, 5.6 and 4.8 h for S_o, S_c and S_p, respectively. Infiltration starts at the beginning of the irrigation event and continues after irrigation has been turned off until all the water residing in the furrow has infiltrated. The infiltration periods were 15.8, 18.7 and 23.8 h for S_o, S_c and S_p, respectively. Even though the least amount of water is applied in the S_p treatment (Table 1), this treatment retains water within the furrow the

Table 1
The impact of application rate on millimeter equivalent of water applied, drained and retained in the flow domain and the % savings in water applied under the compacted (S_c) and plastic covered (S_p) soil surface management strategies compared to the original (S_o) practice. The highlighted row is the 1800 L h^{-1} (100 m furrow)$^{-1}$ flow rate used as the base case in this study.

Application rate (L h^{-1} (100 m furrow)$^{-1}$)	S_o			S_c				S_p			
	Applied (mm)	Drained (mm)	Retained (mm)	Applied (mm)	Drained (mm)	Retained (mm)	% Saved relative to S_o	Applied (mm)	Drained (mm)	Retained (mm)	% Saved relative to S_o
1200	187	58.0	129.0	136	12.5	123.5	27.3	106	0.38	105.6	43.3
1400	150	25.0	125.0	117	3.5	113.5	22.0	96	0.20	95.8	36.0
1600	132	12.0	120.0	107	1.3	105.7	18.9	90	0.18	89.8	31.8
1800	120	5.5	114.5	100	0.6	99.4	16.7	86	0.18	85.8	28.3
2000	112	3.5	108.5	95	0.4	94.6	15.2	84	0.18	83.8	25.0

longest (Fig. 3) as there is no vertically downward infiltration from the bottom of the furrow. Redistribution continues to take place after all water has infiltrated from the furrow in response to gravity (mostly vertically downwards) and capillarity (mostly horizontally and vertically upwards into drier parts of the flow domain, and especially into the ridge).

Further investigation of the effect of evaporation losses from the water remaining in the furrow until it has all infiltrated into the soil is needed in follow up studies. One way to minimize these evaporative losses would be to irrigate in the evening or at night to avoid irrigating during daylight hours when evaporative demand is highest.

3.2. *Water flux and soil water content*

Fig. 5 shows the water fluxes at the bottom boundary (free drainage boundary) of the flow domain as a function of time from initiation of irrigation under the different soil surface management strategies. It shows that for soil surface management strategy S_o water started draining from the bottom of the flow domain 35 h after initiating irrigation, with the drainage flux increasing to 1.11 cm^2 h^{-1} after 120 h. For S_c, water started draining from the bottom of the flow domain 57 h after initiating irrigation with the drainage flux increasing to 0.21 cm^2 h^{-1} after 120 h. For S_p, water started draining from the flow domain after 89 h with the drainage flux increasing to 0.017 cm^2 h^{-1} after 120 h. The drainage fluxes after 120 h were 5 and 65 times smaller for S_c and S_p, respectively, than for S_o. This, together with the reduced water input, resulted in total water savings of 17% and 28% over the 120 h for the S_c and S_p treatments, respectively, when compared with S_o (Table 1).

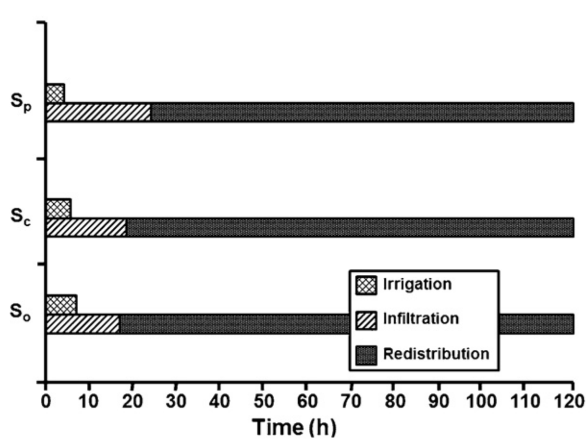

Fig. 4. The time duration of irrigation, infiltration and redistribution under different soil surface management strategies (S_o, original soil; S_c, compacted soil; S_p, plastic covered soil).

The movement of the wetting front horizontally into the ridge and vertically downwards is shown in Fig. 6. It is clear from this figure that for the S_o scenario gravitational forces combine strongly with the capillary forces to cause downward vertical flow of water to dominate compared with horizontal flow. The wetting front in this case reached a depth of 83 cm 30 h after initiation of irrigation. For the S_c scenario, flow in the vertical and horizontal directions is similar early on (up to 5 h), but gravitational forces again start dominating over capillary forces as irrigation progresses. For this scenario, water reached a depth of 70 cm after 30 h, compared to 83 cm for the S_o scenario. There is thus a reduction of about 16% in the vertical water movement in S_c compared to S_o.

Placing plastic on the bottom of the furrow (S_p) prevents direct vertical infiltration from the bottom of the furrow. This forces the water to first flow horizontally into the ridge before it can flow downwards in response to gravitational forces. This exposes more of the infiltrating water to capillary forces associated with drier soil in the ridge and can reduce the vertical downward movement of water. In this case the wetting front reached a depth of 55 cm after 30 h, which is a reduction of about 21% in the vertical water movement compared to S_c. It is worth highlighting that the different soil surface treatments had a bigger effect on the downward vertical flow than the horizontal flow (Fig. 6), with some of this effect reflecting the different total amounts of water applied. These results are consistent with those of Cook et al. (2009)

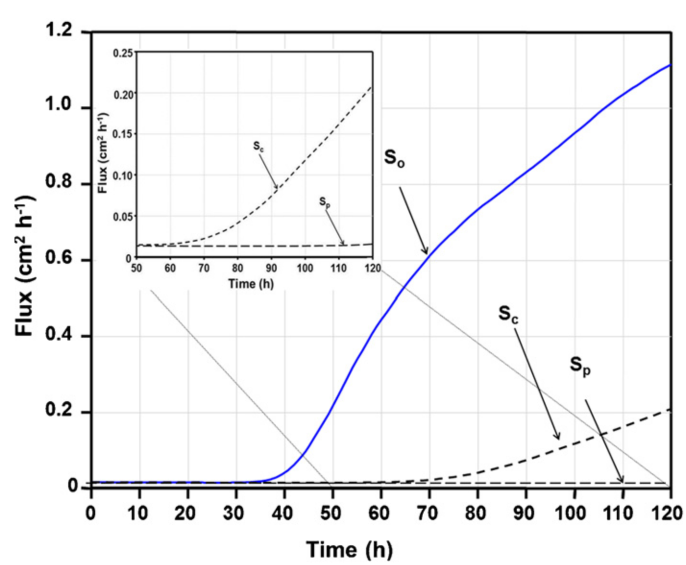

Fig. 5. Water flux (cm^2 h^{-1}) from the bottom free drainage boundary as a function of time from initiation of irrigation under the different soil surface management strategies (S_o, original soil; S_c, compacted soil; S_p, plastic covered soil).

who analysed water flow in permanent raised beds and showed that the horizontal wetting front extended further into the bed when the base of the furrow was compacted compared with no compaction.

We calculated the effect of the 17% and 28% reductions in water applied for treatments S_c and S_p compared with S_o by assessing the total drainage from the flow domain and total water remaining within the flow domain 120 h after initiation of irrigation (Table 1). The initial water held in the flow domain was 180 mm for all treatments. Fig. 7 shows the soil water content distribution within the flow domain at 0 h (initial water content) and 120 h after initiation of irrigation for each of the soil surface treatments. The S_o treatment has the highest level of non-uniformity with wetter zones below the furrows and drier zones below the ridge. The S_c and S_p treatments show much more uniform distributions of water with depth across the flow domain. These data together with that in Table 1 confirm that compacting the base of the furrow or placing a plastic sheet on the bottom of the furrow can deliver significant water savings without major reductions in total soil water held within the flow domain.

Furrow irrigation efficiencies, which can vary from 30% (Fahong et al., 2004) to 65% (Arabiyat et al., 1999) are very low compared to well managed hi-tech subsurface drip irrigation systems (Ayars et al., 1999). Furrow irrigation is however still considerably cheaper than subsurface drip systems and is therefore likely to remain a major form of irrigation for many years to come. Given this reality it is essential that every effort is made to keep improving the efficiency of furrow irrigation and as we have shown there are real and practical opportunities to do this. An advantage of the strategies presented here is that they could be easily implemented by farmers around the world, including those with limited resources.

3.3. Effect of rate of water application

As the criterion for applying water to the furrow was set by filling the furrow to a preset depth, 10 cm in this study, the rate of water application (and amount of infiltration) will be affected by the time needed to reach this switch-off depth. The lower the rate of water application, the more time it will take to reach the switch-off point and hence the more time there will be for infiltration. The effect of application rates of 1200, 1400, 1600, 1800 and 2000 L h^{-1} (100 m furrow)$^{-1}$ on the total amount of water applied, drained and retained within the flow domain was also analyzed, with results given in Table 1. It shows that with increasing rates of water application the percent water savings of S_c and S_p compared with S_o decreases.

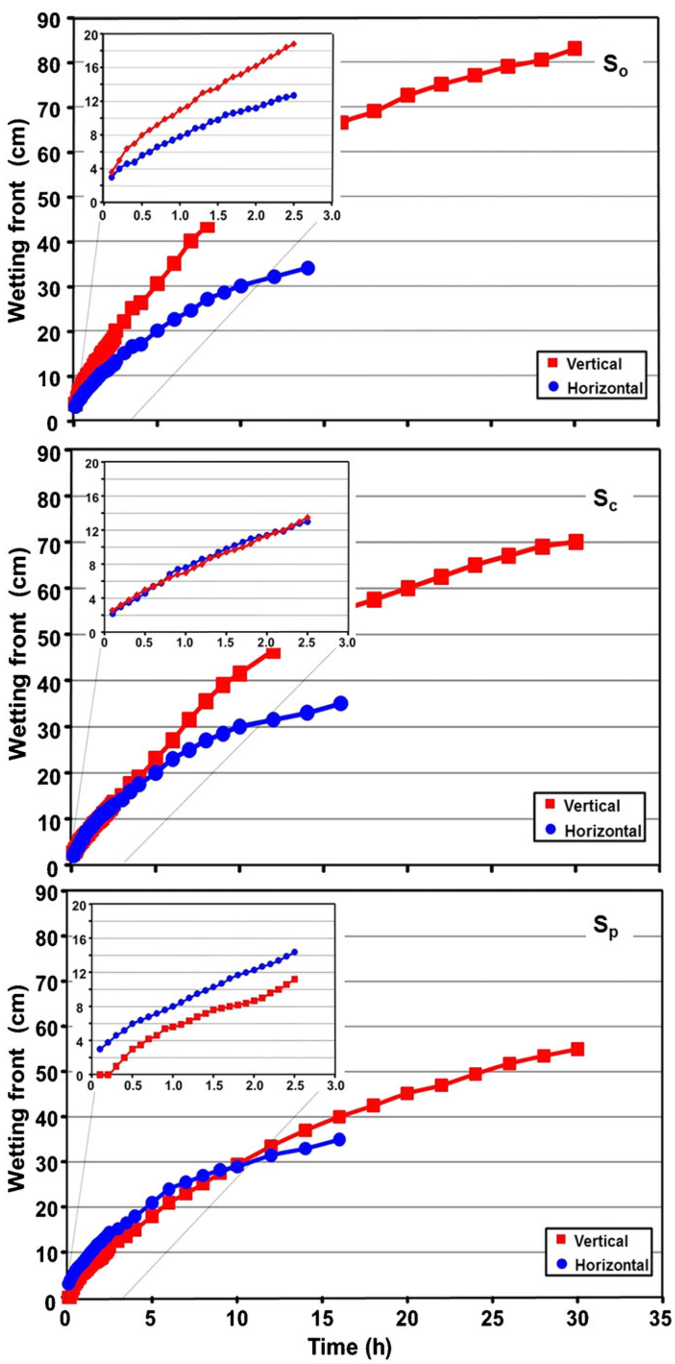

Fig. 6. Horizontal and vertical movement of the wetting front as a function of time following initiation of irrigation for the different soil surface management strategies (S_o, original soil; S_c, compacted soil; S_p, plastic covered soil).

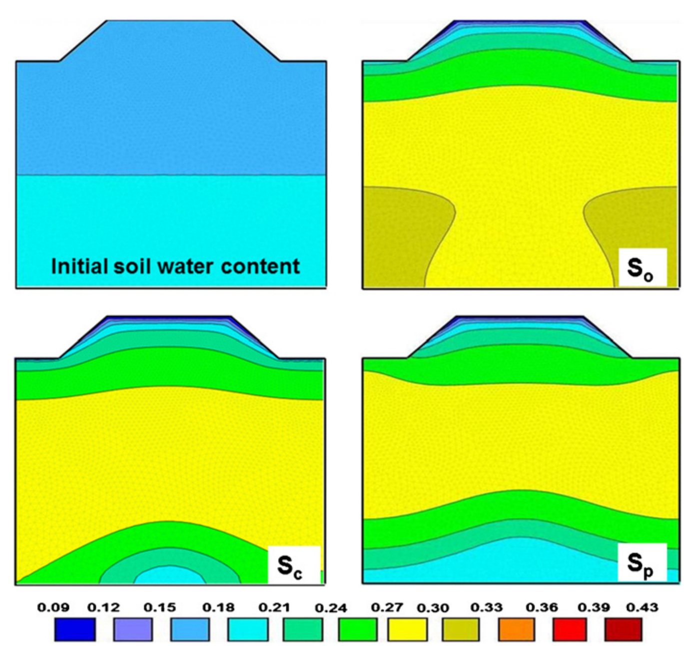

Fig. 7. Soil water content ($cm^3\ cm^{-3}$) distributions within the flow domain (root zone) initially and 120 h after initiation of irrigation for soil surface treatments S_o, S_c and S_p (see text for further explanation).

Table 2
Effect of fertilizer placement on the total amount of nitrogen leached from the bottom boundary (100 cm) of the flow domain 120 h after the initiation of irrigation. Fertilizer placements P_1–P_5 and soil surface management strategies S_o, S_c and S_p are described in the text.

Fertilizer placement	Original soil (S_o) (kg N ha^{-1})	Compacted soil (S_c) (kg N ha^{-1})	Plastic covered soil (S_p) (kg N ha^{-1})
P_1 (furrow bottom)	50.00	1.40	0.00
P_2 (furrow sides)	3.00	0.05	0.00
P_3 (furrow bottom & sides)	23.00	0.62	0.00
P_4 (furrow sides near the ridge top)	0.00	0.00	0.00
P_5 (centre of ridge)	0.00	0.00	0.00

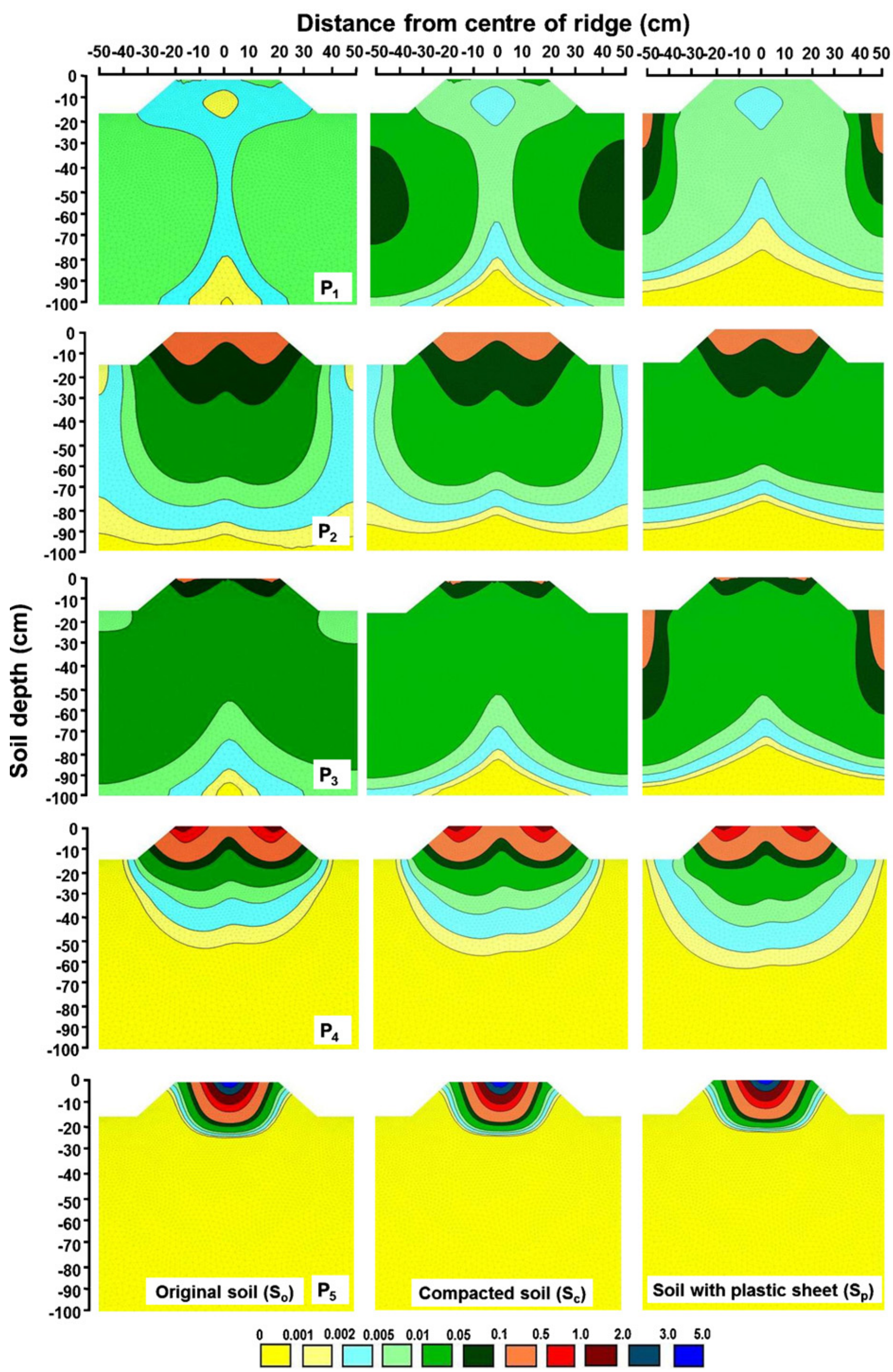

Fig. 8. Nitrogen concentration (mg cm^{-3}) distributions within the flow domain for different soil surface management strategies and fertilizer placements.

3.4. Nitrogen leaching

3.4.1. Effect of nitrogen fertilizer placement and soil surface management strategies on nitrogen leaching

The effect of nitrogen fertilizer placement and soil surface management strategies on nitrogen leaching is summarized in Table 2. Results show that for S_o the maximum amount of nitrogen leached (50 kg ha^{-1}) occurred from fertilizer placement P_1 (nitrogen at furrow bottom) followed by fertilizer placement P_3 (nitrogen on furrow bottom and side) (23 kg ha^{-1}). The least amount of nitrogen loss occurred from fertilizer placements P_4 and P_5 (nitrogen on side or top of the ridge). Similar trends were observed for soil surface management strategy S_c. This demonstrates that direct contact of the fertilizer with infiltrating water such as in P_1, P_2 and P_3 will lead to more nitrogen leaching. Minimising direct contact will therefore reduce the risk of nitrogen leaching as has been previously reported (Lehrsch et al., 2000, 2008). In terms of soil surface management strategy S_p, there is little impact of fertilizer placement on nitrogen leaching. This is because most of the water that infiltrated stayed in the flow domain (root zone), with very little of the water that came in contact with the nitrogen leaving the flow domain.

3.4.2. Nitrogen concentration remaining within the flow domain

The effects of soil surface management and fertilizer placement strategies on nitrogen leaching are demonstrated graphically by plotting the spatial distribution of nitrogen concentration (mg cm^{-3}) in the flow domain 120 h after initiation of irrigation (Fig. 8). This figure shows that nitrogen in the P_1/S_o treatment is most vulnerable to leaching, with very little nitrogen migrating towards the central plane of the flow domain and up into the ridge. This contrasts strongly with the P_1/S_p treatment where most of the nitrogen is retained directly below the plastic covered furrow and the zero concentration at the bottom of the flow domain highlights that no nitrogen has reached this depth and leached from the flow domain.

Fertilizer placement P_2 highlights the benefit of having slightly drier conditions in the ridge prior to irrigation in all three soil surface management treatments, with capillary forces pulling water and hence nitrogen up into the ridge. The spatial distribution of nitrogen with higher concentrations in and immediately below the ridge and very low concentrations directly below the furrow highlights the effect of the dominant downward movement of water below the furrow in P_2/S_o. This contrasts with treatment P_2/S_p where water has to first flow into the ridge then down and around the plastic, resulting in high concentrations of nitrogen in the ridge but a much more uniform distribution of nitrogen with depth across the flow domain.

Nitrogen concentration profiles show that all the nitrogen fertilizer is retained within and below the ridge to depths of 50–60 cm for all soil surface treatments with fertilizer placement P_4. Treatment P_4/S_p shows the greatest lateral and vertical spread compared with P_4/S_c and P_4/S_o, which again highlights the potential benefit of using plastic on the bottom of the furrow. The nitrogen concentration profiles also show that all the nitrogen fertilizer is retained within the ridge for all soil surface treatments with fertilizer placement P_5.

The above results demonstrate that the alternative soil surface management strategies involving compaction and use of plastic on the bottom of the furrow not only save water but also play a key role in retaining greater amounts of nitrogen within the flow domain for longer periods of time. The benefits of these practices are particularly noticeable when fertilizer is placed at the bottom of the furrow (P_1) or at the bottom and sides of the furrow (P_3).

4. Conclusions

Results of this study demonstrate the effect of soil surface management and fertilizer placement strategies on nitrogen leaching from furrow irrigated systems and highlight practical opportunities for improvement in water and fertilizer use efficiency. They show that a 30–35% loss of nitrogen from the root zone for the original soil (S_o) with fertilizer placement P_1 (fertilizer placed just beneath the surface of the soil on the bottom of the furrow) can be reduced to 1–2% by compacting the bottom of the furrow and to zero loss by placing a plastic sheet on the bottom of the furrow. Similarly, a 30–35% loss of nitrogen from the flow domain for the original soil (S_o) with fertilizer placement P_1 can be reduced to 2%, 15%, 0% and 0% by changing fertilizer placement to P_2, P_3, P_4 and P_5 respectively. Placing fertilizer on the furrow sides near the ridge top (P_4) and on the top at the centre of the ridge (P_5) have the lowest risk of nitrogen leaching. This demonstrates the importance of minimising the exposure of nitrogen fertilizer to downward flowing water.

Irrigation efficiency of furrow irrigated systems, especially on coarse textured soils, can be improved by compacting or placing a plastic sheet on the bottom of the furrow. For the soil and irrigation application rates used in this study compacting the bottom of the furrow can result in water savings as high as 25%, while placing a plastic sheet on the bottom of the furrow can lead to water savings as high as 40%. Implementing combined fertilizer placement and soil surface management strategies as outlined in this study will improve the production and environmental performance of furrow irrigated systems and thereby contribute to meeting both environmental and food security objectives.

We purposely focussed on one irrigation cycle and omitted plants and root water uptake in this study to explore the interactions and differences between the soil surface conditions and fertilizer placements and the role of gravity versus capillarity with as few 'complicating' factors as possible. This allowed us to focus on soil surface modifications that are likely to provide the most opportunity for improving water and nutrient use efficiency. The impact of soil type, furrow design, different switch-off depths and other strategies for turning off irrigation water, multiple irrigation cycles, plant water uptake and evaporation from water ponded in the furrow along with other aspects will be addressed in follow up studies.

Acknowledgments

This work was supported in part by the Sindh Agriculture University, Tandojam, Pakistan, CSIRO Sustainable Agriculture National Research Flagship and CSIRO Land and Water. We thank in particular the Australian Government Department of Education, Employment and Workplace Relations (DEEWR) for providing an Endeavour Research Fellowship to Professor Altaf Ali Siyal and the Sindh Agriculture University, Tandojam, Pakistan, for approving leave to allow Prof. Siyal to undertake his fellowship with CSIRO Land and Water in Townsville, Australia.

Appendix A. Special boundary condition at the bottom and sides of the furrow, implemented for this study

Analyzing furrow irrigation with a special boundary condition that accounts for changes in the water depth in the furrow required adjustments to the HYDRUS code and an additional input file. This boundary condition is shown schematically in (Fig. A1).

HYDRUS calculates the volume of water in the half furrow (S) and its rate of change (dS/dt) depending on inflow and outflow to

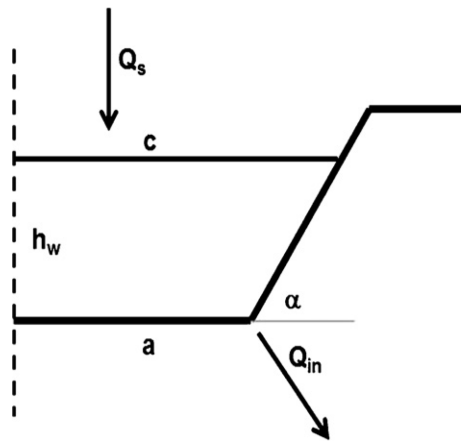

Fig. A1. Schematic showing a half furrow and implementation of a special boundary condition accounting for variable water depth in the furrow (a is the half-width of the bottom of the furrow, h_w is the water level in the furrow, Q_{in} the water infiltration from the furrow into the soil, Q_s is the water supply rate, α is the slope of the ridge side and c is the half-width of the water surface).

determine the water level in the furrow (h_w) via the following mass balance equations:

$$S = \frac{1}{2}h_w(a+c) = \frac{1}{2}h_w\left(a + a + \frac{h_w}{\tan\alpha}\right) = h_w a + \frac{h_w^2}{2\tan\alpha} \quad \text{(i)}$$

$$\frac{dS}{dt} = Q_s(t) - Q_{in}(t) \quad \text{(ii)}$$

$$a\frac{dh_w}{dt} + \frac{h_w}{\tan\alpha}\frac{dh_w}{dt} = \left(a + \frac{h_w}{\tan\alpha}\right)\frac{dh_w}{dt} = Q_s(t) - Q_{in}(t) \quad \text{(iii)}$$

This can be expressed in its finite difference form as:

$$\left(a + \frac{h_w}{\tan\alpha}\right)\frac{h_w^{j+1} - h_w^j}{\Delta t} = Q_s(t) - Q_{in}(t) \quad \text{(iv)}$$

$$h_w^{j+1} = h_w^j + \frac{\Delta t\ \tan\alpha}{h_w^j + a\tan\alpha}(Q_s - Q_{in}) \quad \text{(v)}$$

where a is the half-width of the bottom of the furrow, Q_{in} the water infiltration from the furrow to the soil profile across the furrow walls, Q_s is the water supply rate, Δt is the time step, and h_w^j and h_w^{j+1} are water levels in the furrow at the previous and current time steps. The relevant parts of the boundary below and above the water level in the furrow were then assigned the time–variable pressure head (Dirichlet) and seepage face boundary conditions, respectively. HYDRUS then calculated which part of the seepage face boundary was active (with prescribed zero pressure head) and which was inactive (with prescribed zero flux or atmospheric boundary conditions). The supply rate (Q_s) and the maximum water level that can be reached before water supply is stopped are specified by the user.

References

Abbasi, F., Adamsen, F., Hunker, J., Feyen, J., Shouse, P., van Genuchten, M.Th., 2003. Effects of flow depth on water flow and solute transport in furrow irrigation: field data analysis. Journal of Irrigation and Drainage Engineering 129 (4), 237–245.

Abbasi, F., Feyen, J., van Genuchten, M.Th., 2004. Two dimensional simulation of water flow and solute transport below furrows: model calibration and validation. Journal of Hydrology 290 (1–2), 63–79.

Angle, J.S., Cross, C.M., Hill, R.L., McIntosh, M.S., 1993. Soil nitrate concentrations under corn as affected by tillage, manure, and fertilizer applications. Journal of Environment Quality 22, 141–147.

Arabiyat, T.S., Segarra, E., Willis, D.B., 1999. Sophisticated irrigation technology and biotechnology adoption: impacts on ground water conservation. AgBioForum 2 (2), 132–136, Available on the World Wide Web: http://www.agbioforum.org

Artiola, J.F., 1991. Non-uniform leaching of nitrate and other solutes in a furrow-irrigated, sludge amended field. Communications in Soil Science and Plant Analysis 22, 1013–1030.

Ayars, J.E., Phene, C.J., Hutmacher, R.B., Davis, K.R., Schoneman, R.A., Vail, S.S., Mead, R.M., 1999. Subsurface drip irrigation of row crops: a review of 15 years of research at the Water Management Research Laboratory. Agricultural Water Management 42, 1–27.

Bar-Yosef, B., 1999. Advances in fertigation. Advances in Agronomy 65, 1–75.

Bear, J., 1972. Dynamics of Fluids in Porous Media. Elsevier, New York.

Benjamin, J.G., Porter, L.K., Duke, H.R., Ahuja, L.R., Butters, G., 1998. Nitrogen movement with furrow irrigation method and fertilizer band placement. Soil Science Society of America Journal 62, 1103–1108.

Beven, K.J., Henderson, D.E., Reeves, A.D., 1993. Dispersion parameters for undisturbed partially saturated soil. Journal of Hydrology 143, 19–43.

Carsel, R.F., Parish, R.S., 1988. Developing joint probability distributions of soil water retention characteristics. Water Resources Research 24, 755–769.

Clay, S.A., Clay, D.E., Koskinen, W.C., Malzer, G.L., 1992. Agrichemical placement impacts on alachlor and nitrate movement through soil in a ridge tillage system. Journal of Environment Science and Health, Part B: Pesticides 27, 125–138.

Cook, F.J., Knight, J.H., Humphreys, E., McHugh, A.D., Tisdall, J., Hamilton, G., Roth, C.H., 2009. Modelling of water and solutes in permanent raised beds. In: Proceedings of the 18th World IMACS/MODSIM Congress, Cairns, Australia, July 13–17, 2009, pp. 505–511, http://mssanz.org.au/modsim09

Cote, C.M., Bristow, K.L., Charlesworth, P.B., Cook, F.J., Thorburn, P.J., 2003. Analysis of soil wetting and solute transport in subsurface trickle irrigation. Irrigation Science 22, 143–156.

Crabtree, R.J., Yassin, A.A., Kargougou, I., McNew, R.W., 1985. Effects of alternate furrow irrigation: water conservation on the yields of two soybean cultivars. Agricultural Water Management 10, 253–264.

Crevoisier, D., Popova, Z., Mailhol, J.C., Ruelle, P., 2008. Assessment and simulation of water and nitrogen transfer under furrow irrigation. Agricultural Water Management 95, 354–366.

Douglas, J.T., Crawford, C.E., 1993. The responses of a ryegrass sward to wheel traffic and applied nitrogen. Grass Forage Science 48, 91–100.

Fahong, W., Xuqing, W., Sayre, K., 2004. Comparison of conventional, flood irrigated, flat planting with furrow irrigated, raised bed planting for winter wheat in China. Field Crops Research 87 (1), 35–42.

FAO, 2004. Fertilizer Use by Crop in Pakistan. Land and Water Development Division. Food and Agriculture Organization of the United Nations, Rome, p. 17.

Gärdenäs, A.I., Hopmans, J.W., Hanson, B.R., Šimůnek, J., 2005. Two-dimensional modelling of nitrate leaching for various fertigation scenarios under micro-irrigation. Agricultural Water Management 74 (3), 219–242.

Hamlett, J.M., Baker, J.L., Horton, R., 1990. Water and anion movement under ridge tillage: a field study. Transactions of the ASAE 33, 1859–1866.

Hayens, R.J., 1985. Principles of fertilizer use for trickle irrigated crops. Fertilizer Research 6 (2), 235–255.

Huygens, D., Rutting, T., Boeckx, P., van Cleemput, O., Godoy, R., Muller, C., 2007. Soil nitrogen conservation mechanisms in a pristine south Chilean Nothofagus forest ecosystem. Soil Biology and Biochemistry 39, 2448–2458.

Jones, C., Jacobsen, J., 2009. Fertilizer placement and timing. In: Nutrient Management Module No. 11. Montana State University, Bozeman, USA.

Jones, C., Olson-Rutz, K., 2011. Crop and fertilizer management practices to minimize nitrate leaching. Agriculture and Natural Resources (Fertilizers). MontGuide. MT201103AG New 1/11.

Kemper, W.D., Olsen, J., Hodgdon, A., 1975. Fertilizer or salt leaching as affected by subsurface shaping and placement of fertilizer and water. Proceedings – Soil Science Society of America 39, 115–119.

Lehrsch, G.A., Sojka, R., Westermann, D., 2000. Nitrogen placement, row spacing and furrow irrigation water positioning effects on corn yield. Agronomy Journal 92, 1266–1275.

Lehrsch, G.A., Sojka, R., Westermann, D., 2008. Nitrogen placement, row spacing and water management for furrow-irrigated field corn. In: Proceedings of the Idaho Nutrient Management Conference, vol. 4, pp. 42–48.

Liu, A., Ankumah, M.J., Ramble, O., 2005. Nitrate contamination in private wells in rural Alabama, United States. Science of the Total Environment 346, 112–120.

Mailhol, J.C., Ruelle, P., Nemeth, I., 2001. Impact of fertilisation practices on nitrogen leaching under irrigation. Irrigation Science 20, 139–147.

Mailhol, J.C., Crevoisier, D., Triki, K., 2007. Impact of water application conditions on nitrogen leaching under furrow irrigation: experimental and modelling approaches. Agricultural Water Management 87 (3), 275–284.

Mitchell, A.R., Shock, C.C., Barnum, J.M., 1994. Furrow irrigation modelling and management for reduced nitrate leaching. ground water quality management. In: Proceedings of the GQM 93 Conference, (IAHS Publ. No. 220).

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resources Research 12 (3), 513–522.

Musick, J.T., Dusek, D.A., 1974. Alternate furrow irrigating of fine textured soils. Transactions of the ASAE 17, 289–294.

Phogat, V., Mahadevan, M., Skewes, M., Cox, J.W., 2011. Modelling soil water and salt dynamics under pulsed and continuous surface drip irrigation of almond and implications of system design. Irrigation Science 30 (4), 315–333.

Robbins, C.W., Carter, D.L., 1980. Nitrate-nitrogen leached below the root zone during and following alfalfa. Journal of Environment Quality 9, 447–450.

Schwen, A., Ramirez, G., Smith, E., Sinton, S., Carrick, S., Clothier, B., Buchan, G., Loiskandl, W., 2011. Hydraulic properties and the water-conducting porosity as affected by subsurface compaction using tension infiltrometers. Soil Science Society of America Journal 75, 822–831.

Šejna, M., Šimůnek, J., van Genuchten, M.Th., 2011. The HYDRUS Software Package for Simulating the Two- and Three-dimensional Movement of Water, Heat, and

Multiple Solutes in Variably-Saturated Media. User Manual. Version 2.0. PC Progress, Prague, Czech Republic, 280 pp.
Šimůnek, J., van Genuchten, M., Šejna, Th.M., 2008. Development and applications of the HYDRUS and STANMOD software packages, and related codes. Vadose Zone Journal 7 (2), 587–600.
Siyal, A.A., Skaggs, T.H., 2009. Measured and simulated wetting patterns under porous clay pipe subsurface irrigation. Agricultural Water Management 96 (6), 893–904.
Siyal, A.A., van Genuchten, M.Th., Skaggs, T.H., 2009. Performance of pitcher irrigation systems. Soil Science 174 (6), 312–320.
Tiercelin, J.R., Vidal, A., 2006. Traiteĭ d'Irrigation, 2nd ed. Lavoisier, Technique and Documentation, Paris, France.
van Genuchten, M.Th., 1980. A close-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal 44, 892–898.
Waddell, J.T., Weil, R.R., 2006. Effect of fertilizer placement on solute leaching under ridge tillage and no till. Soil and Tillage Research 90, 194–204.
Waskom, R.M., 1994. Best management practices for nitrogen fertilization. Colorado State University Cooperative Extension. Bulletin # XCM-172.
Wylie, B.K., Shaffer, M.J., Brodahl, M.K., Dubois, D., Wagner, D.G., 1994. Predicting spatial distributions of nitrate leaching in northeastern Colorado. Journal of Soil and Water Conservation 49, 288–293.
Yonts, C.D., 2007. Firming Irrigation Furrows to Improve Irrigation Performance. NebGuide. The Board of Regents of the University of Nebraska, USA.