Journal of Hydrology 513 (2014) 504–516

Contents lists available at ScienceDirect

Journal of Hydrology

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

Seasonal simulation of water, salinity and nitrate dynamics under drip irrigated mandarin (*Citrus reticulata*) and assessing management options for drainage and nitrate leaching

V. Phogat [a,*], M.A. Skewes [a], J.W. Cox [a,b], G. Sanderson [c], J. Alam [d], J. Šimůnek [e]

[a] South Australian Research and Development Institute, GPO Box 397, Adelaide, SA 5001, Australia
[b] The University of Adelaide, PMB1, Glen Osmond, SA 5064, Australia
[c] Dareton Agricultural Research and Advisory Station, PO. Box 62, Dareton, NSW 2717, Australia
[d] Rural Solutions SA, GPO Box 1671, Adelaide, SA 5001, Australia
[e] Department of Environmental Sciences, University of California, Riverside, CA 92521, USA

ARTICLE INFO

Article history:
Received 9 January 2014
Received in revised form 31 March 2014
Accepted 4 April 2014
Available online 16 April 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Markus Tuller, Associate Editor

Keywords:
Modelling
HYDRUS
Mandarin
Fertigation
Nitrate leaching
Soil salinity

SUMMARY

Estimation of all water fluxes temporally and spatially within and out of the crop root zone, and evaluation of issues like salinity and nutrient leaching, are necessary to fully appraise the efficiency of irrigation systems. Simulation models can be used to investigate these issues over several seasons when the cost of long term monitoring is prohibitive. Model results can be used to advise growers if improvements are required to various aspects of irrigation system operations. In this study, HYDRUS-2D was used to evaluate data measured during one season in a young mandarin (*Citrus reticulata*) orchard, irrigated with an intensive surface drip fertigation system. Water contents, salinities, and nitrate concentrations measured weekly in the field were compared with model predictions.

The temporal mean absolute error (*MAE*) values between weekly measured and simulated water contents ranged from 0.01 to 0.04 $cm^3\,cm^{-3}$. However, modelling error (*MAE*) was slightly larger at 10 cm depth (0.04 $cm^3\,cm^{-3}$), as compared to greater depths (0.02–0.03 $cm^3\,cm^{-3}$). Similarly, the errors were larger in the surface soil layer (25 cm depth) for nitrate–nitrogen, NO_3^-–N (1.52 $mmol_{(c)}\,L^{-1}$), as compared to greater depths. The spatial and temporal soil solution salinity (EC_{sw}) and NO_3^-–N data showed accumulation of salts and nitrate within the soil up until day 150 of the simulation (December, 2006), followed by leaching due to high precipitation and over irrigation at later times. Only 49% of applied water was used by the mandarin trees, while 33.5% was leached. On the other hand, the simulation revealed that a significant amount of applied nitrogen (85%) was taken up by the mandarin trees, and the remaining 15% was leached. The results indicate that the irrigation and fertigation schedule needs modifying as there was overwatering from December onwards.

Different permutations and combinations of irrigation and fertigation scheduling were evaluated to optimise the water and nitrogen uptake and to reduce their leaching out of the crop root zone. Slightly higher nitrogen uptake (1.73 $kg\,ha^{-1}$) was recorded when fertigation was applied second to last hour in an irrigation event, as compared to applying it earlier during an irrigation event. Similarly, a 20% reduction in irrigation and N application produced a pronounced reduction in drainage (28%) and N leaching (46.4%), but it also decreased plant N uptake by 15.8% and water uptake by 4.8%, and increased salinity by 25.8%, as compared to the normal practice. This management would adversely impact the sustainability of this expensive irrigation system. However, reducing only irrigation by 30% during the 2nd half of the crop season (January to August) reduced drainage and N leaching by 37.2% and 50.5%, respectively, and increased N uptake by 6.9%. Such management of irrigation would be quite promising for the sustainability of the entire system. It is concluded that judicious manipulations of irrigation and fertilizer applications can be helpful in designing drip irrigation schedules for perennial horticultural crops to achieve improved efficiency of irrigation and fertigation applications and reduced contamination of receiving water bodies.

* Corresponding author. Tel.: +61 8 83039567; fax: +61 8 83039473.
E-mail address: vinod.phogat@sa.gov.au (V. Phogat).

http://dx.doi.org/10.1016/j.jhydrol.2014.04.008
0022-1694/

1. Introduction

Micro-irrigation has become the optimal standard for irrigation and fertigation of horticultural crops in Australia, due to increased water scarcity and higher costs of fertilizers over the last decade. Intensive fertigation schedules have been developed to increase yield and quality of many permanent horticultural crops, including mandarin. This combines drip irrigation and fertigation to deliver water and nutrients directly to the roots of the crop, with the aim of synchronizing the applications with crop demand (Assouline, 2002; Gärdenäs et al., 2005) and maintaining the desired concentration and distribution of ions and water in the soil (Bar-Yosef, 1999). The overall aim of these interventions is to develop an irrigation and nutrient management program that increases yield and fruit quality, while reducing leaching. The fundamental principle of drip fertigation is to apply water and nutrients regularly to a small volume of soil at a low application rate and at a high frequency to closely meet crop demand (Falivene et al., 2005). However, the potential for movement of water and mineral nutrients, especially nitrogen (as nitrate), below the root zone and into the ground- and then surface-waters using these approaches is still high. This is due to a number of factors: amount and intensity of precipitation, the large amounts of water and nutrients being applied, the limited capacity of roots to take up these nutrients, and to the ability of irrigators to manage drainage and hence leaching.

Citrus is one of the important horticultural crops being grown under intensive fertigation systems in Australia. The vast majority of citrus plantings are oranges (73%), with the rest split between mandarins (20%), lemons and limes (5%), and grapefruit (2%) (Horticulture Australia Limited, 2008). About 75% of the Australian citrus industry is located in the Murray-Darling Basin, utilising the lighter-textured free-draining soils adjacent to the Murray, Darling and Murrumbidgee rivers, and thus potential off-site effects of poorly managed fertigation may have wider implications.

Irrigated horticulture has, in general, been identified as the major source of nitrogen in drainage waters in the Murray Darling Basin (Harrison, 1994). A significantly high nitrate level has been reported in drainage water ($60\ mg\ L^{-1}$) and soil solution ($100\ mg\ L^{-1}$) under grapevines (Correll et al., 2010) in the Murray Darling Basin. These values are significantly higher than the Australian environmental trigger value ($0.5\ mg\ L^{-1}$ for lowland rivers) for nitrate (ANZECC and ARMCANZ, 2000). Leaching of nitrates from soils under perennial horticulture may pose a potential threat to groundwater.

The main sources of nitrate in mandarin production are mineral fertilizers. Nitrate is removed from the soil by plant uptake or through decomposition by micro-organisms in the process of denitrification. In well-aerated soils typical of this region, denitrification is often negligible because of a lack of favourable conditions (Alva et al., 2006). Nitrate, being an anion, moves freely in these mineral soils, and hence has the potential to leach into groundwater and waterways if fertigation is not well scheduled (Paramasivam et al., 2002; Gärdenäs et al., 2005; White, 2006). Several researchers have reported substantial leaching (6–45%) of applied N in citrus cultivation under field conditions (Wang and Alva, 1996; Paramasivam and Alva, 1997; Paramasivam et al., 2002; Sluggett, 2010). Syvertsen and Jifon (2001) found that N leaching was higher under weekly fertigated orange trees than under daily or monthly fertigated trees. Syvertsen and Sax (1999) reported that increasing the number of fertigation events could significantly reduce N leaching. However, they observed 38–52% leaching of N from fertilizer, and the nitrogen use efficiency ranging between 25% and 44% in Hamlin orange trees. Other researchers (Clothier et al., 1988; Li and Liu, 2011) have reported that nitrate accumulates toward the boundary of the wetted volume for most combinations of drip emitter discharge, input concentrations, and volumes applied. These studies suggest that there is a need for efficient tools, capable of describing and quantifying nitrate leaching, as well as nitrate uptake by crops, which in turn would help in designing and managing drip irrigation systems and achieving a high N fertilizer use efficiency, thereby limiting the export of this nutrient as a pollutant to downstream water systems.

In addition to nitrate leaching, salinity is also an important factor influencing the sustainability of the citrus production worldwide, as citrus species are relatively salt sensitive. The reported value of the average threshold electrical conductivity of saturation extract (EC_e) and slope for oranges (*Citrus sinensis*) are $1.7\ dS\ m^{-1}$ and 16%, respectively (Maas and Hoffmann, 1977). Salt damage is usually manifested as leaf burn and defoliation, and is associated with accumulation of toxic levels of Na^+ and/or Cl^- in leaf cells. Under drip irrigation there are many factors influencing the distribution of soil water and salts, and hence the water use efficiency (WUE), such as water quality, dripper discharge rate (Liu et al., 2012), irrigation water depth (Hanson et al., 2006), and irrigation frequency (El-Hendawy et al., 2008).

Simulation models have been valuable research tools in studies involving complex and interactive processes of water flow and solute transport through the soil profile, as well as the effects of management practices on crop yields and the environment (Pang and Letey, 1998; Li et al., 2003). HYDRUS-2D (Šimůnek et al., 2011) has been used extensively in evaluating the effects of soil hydraulic properties, soil layering, dripper discharge rates, irrigation frequencies, water quality, and timing of nutrient applications on wetting patterns and solute distribution (e.g., Cote et al., 2003; Lazarovitch et al., 2005; Gärdenäs et al., 2005; Hanson et al., 2006; Ajdary et al., 2007; Phogat et al., 2009; Šimůnek and Hopmans, 2009; Li and Liu, 2011; Phogat et al., 2012a,b, 2013a,b; Ramos et al., 2011, 2012). Although these studies demonstrate well the importance of numerical modelling in the design and management of irrigation and fertigation systems for various crops, most studies involving salinity and nitrate leaching are based on either an analysis of hypothetical scenarios, or are carried out for annual crops. Hence, there is a need to carry out modelling studies for perennial horticultural crops such as mandarin, using experimental results from field studies involving modern irrigation systems such as drip.

The objectives of the present investigation were to evaluate water, salt (EC_{sw}), and nitrate (NO_3^-–N) movement in soil below young mandarin tree using HYDRUS-2D, and to evaluate various irrigation and fertigation strategies for controlling deep drainage and nitrate leaching, whilst maintaining soil salinity below the threshold for mandarin. This approach will help us understand the best irrigation and fertigation management practices to be adopted in future practical applications, with the goal to increase root water and nutrient uptake.

2. Materials and methods

2.1. Field experiment

The field experiment was conducted at the Dareton Agricultural and Advisory Station (34.10°S and 142.04°E), located in the Coomealla Irrigation Area, 3 km from Dareton and 10 km from Wentworth in New South Wales (NSW). The research station forms part of the Sunraysia fruit growing district of NSW and Victoria located in the Murray Darling Basin.

An experimental site with an intensive fertigation system, consisting of various mandarin (*Citrus reticulata*) varieties budded onto a number of rootstock varieties (Volkameriana, C35, Cleopatra Mandarin, Trifoliata, Swingle Citrumelo and Citrange), was established in October 2005. The trees were planted at a spacing of 5 m × 2 m. The actual monitoring and measurements were initiated in August 2006. The trees were managed and fertilized following current commercial practices, although the amounts of applied fertilizer varied. The soils of the site are alkaline (Class IIIA), with red sandy loam from the surface to 90-cm depth, and loam below (90–150 cm). The total organic carbon content is very low (0.4%) in the first 30 cm, and below 0.25% in the remainder of the root zone. The climate is characterized as dry, with warm to hot summers and mild winters. The total rainfall during the experimental period from 21 August 2006 (DOY 233) to 20 August 2007 (DOY 232) was 187 mm (Fig. 1), which was slightly below average for the area. Potential evapotranspiration is normally high and equal to 1400 mm per year. Mild frost conditions occur during the winter months. Weather data were collected from an automated weather station located within the research station.

2.2. Irrigation, fertigation and measurements

Irrigation water was supplied through a surface drip irrigation system, with drip lines placed on both sides of the tree line at a distance of 60 cm. Laterals had 1.6 L h^{-1} pressure compensating online drippers spaced at 40 cm, resulting in 10 drippers per tree. Irrigation was performed weekly/bi-weekly, depending on the plant requirement, and the total seasonal irrigation was 432.8 mm.

The crop was irrigated to replace estimated crop evapotranspiration ($ET_{C.}$) for previous days. Reference crop evapotranspiration (ET_0) was calculated using the FAO 56 method (Allen et al., 1998). $ET_{C.}$ was calculated using the equation:

$$ET_C = ET_0 \cdot K_c \cdot A_c \quad (1)$$

where K_c is the crop coefficient and A_c is the crop age coefficient. The K_c values were compiled by the Irrigated Crop Management Service (ICMS) at Rural Solutions, South Australia. K_c values were taken from the FAO 56 report and adjusted for the Southern Hemisphere. A_c was used to correct ET_0 for the age of the crop and its impact on canopy area (RMCWMB, 2009). Mandarin is an evergreen tree that requires nitrogen throughout the year. Nitrogen fertilizer was applied as ammonium nitrate and mono ammonium phosphate. The amount and timing of fertilizers injected into the irrigation water during the crop growth season is shown in Fig. 2. Total seasonal amounts of applied ammonium nitrate and mono ammonium phosphate fertilizers were equal to 508.1 and 139.4 kg ha^{-1}, respectively. While irrigation was applied continuously during multiple hours, fertigation was applied during a one hour interval.

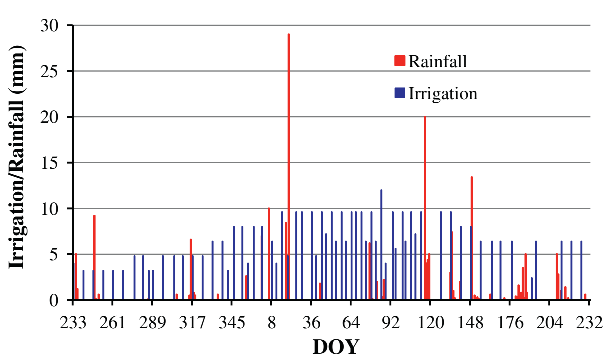

Fig. 1. Rainfall received (red bars) and irrigation applied (blue bars) during the experimental period (21 August 2006 to 20 August 2007). DOY represents the Julian day of the year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

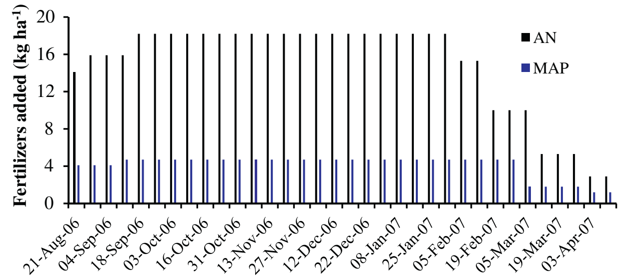

Fig. 2. Fertigation schedule followed during the experimental period (21 August 2006 to 20 August 2007) (AN represents Ammonium nitrate, black bars; MAP represents Mono-ammonium phosphate, blue bars). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Water for irrigation was pumped directly from the Murray River. The salinity of the irrigation water (EC_w) was monitored daily, and ranged between 0.09 and 0.19 dS m^{-1}, well below the EC_w threshold for irrigation of orange, a close relative of mandarin (1.1 dS m^{-1}; Ayers and Westcot, 1989).

Daily soil water content measurements were collected using Sentek® EnviroSCAN® logging capacitance soil water sensors, installed adjacent to the drip line (approximately 10 cm away from the dripper) at depths of 10, 25, 50, 80, and 110 cm. The EnviroSCAN probes were calibrated for the experimental site by the gravimetric method.

Soil water was sampled on a weekly basis using SoluSAMPLERs™ (Biswas, 2006; Biswas and Schrale, 2007). The SoluSAMPLER is a porous ceramic cup connected to a PVC sample reservoir and the tubing from the reservoir to the soil surface, which is used to apply suction and then extract soil solution within 24 h. The experimental site had SoluSAMPLERs located at depths of 25, 50, 100, and 150 cm at a horizontal distance of 10 cm from the drip emitter. The SoluSAMPLERs used in this study were developed at the South Australian Research and Development Institute (SARDI) and are distributed by Sentek Pty, Ltd.

The extracted soil solution was analysed to determine EC_{sw} and the NO_3^-–N content. Nitrate was determined by the Auto-analyser (cadmium reduction) procedure of Maynard and Kalra (1993).

2.3. Modelling software

The HYDRUS-2D software package (Šimůnek et al., 2011) was used to simulate the transient two-dimensional movement of water and solutes in the soil. This program numerically solves the Richards' equation for variably-saturated water flow, and advection–dispersion equations for both heat and solute transport. The model additionally allows specification of root water uptake, which affects the spatial distribution of water, salts and nitrate between irrigation cycles. The solute transport equation considers the advective–dispersive transport in the liquid phase, as well as diffusion in the gaseous phase. The theoretical part of the model is described in detail in the technical manual (Šimůnek et al., 2011) and in Šimůnek et al. (2008).

2.4. Input parameters

2.4.1. Soil hydraulic properties

Soil hydraulic properties were described using the van Genuchten–Mualem constitutive relationships (van Genuchten, 1980). The parameters for these constitutive relationships (except for the 120–150 cm soil depth) were optimised using data from a lysimeter experiment (Phogat et al., 2013b) (Table 1) involving similar soils as in the current study.

Table 1
Soil hydraulic parameters used in the modelling study (the residual water content θ_r, the saturated water content θ_s, van Genuchten shape parameters (α, n and l), and the saturated hydraulic conductivity K_s).

Soil depth (cm)	Texture	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s (cm day^{-1})	l
0–30	Loamy sand	0.060	0.37	0.0294	1.92	116.88	0.5
30–60	Loamy sand	0.060	0.36	0.0268	1.91	107.04	0.5
60–90	Loamy sand	0.050	0.34	0.0308	1.99	113.28	0.5
90–120	Loam	0.050	0.33	0.0300	1.85	79.20	0.5
120–150	Loam	0.046	0.36	0.0346	1.41	27.89	0.5

2.4.2. Root water uptake

The spatial root distribution is defined in HYDRUS-2D according to Vrugt et al. (2001a):

$$\Omega(x,z) = \left[1 - \frac{z}{z_m}\right]\left[1 - \frac{x}{x_m}\right] e^{-\left(\frac{p_z}{z_m}|z^* - z| + \frac{p_x}{x_m}|x^* - x|\right)} \quad (2)$$

where x_m and z_m are the maximum width and depth of the root zone (cm), respectively, z^* and x^* describe the location of the maximum root water uptake, from the soil surface in the vertical direction (z^*) and from the tree position in the horizontal direction (x^*), and p_x and p_z are empirical coefficients.

We considered a simple root distribution model, in which the roots of young mandarin trees expanded horizontally into all available space between tree lines (x_m = 200 cm), were concentrated mainly below the drip emitter (x^* = 60 cm, z^* = 20 cm) where water and nutrients were applied, and extended to a depth of 60 cm (z_m = 60 cm). The parameters defining the maximum root water uptake in vertical and horizontal directions (z^* and x^*) were also based on our earlier experience in similar studies (Phogat et al., 2012a,b, 2013a,b). No significant volume of roots was found outside of the specified area in field observations.

The reduction of root water uptake due to the water stress, $\alpha_1(h)$, was described using the well-known piecewise linear relation, developed by Feddes et al. (1978):

$$\alpha_1(h) = \begin{cases} 0, & h > h_1 \text{ or } h \leqslant h_4 \\ \frac{h - h_1}{h_2 - h_1}, & h_2 < h \leqslant h_1 \\ 1, & h_3 < h \leqslant h_2 \\ \frac{h - h_4}{h_3 - h_4}, & h_4 < h \leqslant h_3 \end{cases} \quad (3)$$

where h_1, h_2, h_3, and h_4 are the threshold parameters. Water uptake is at the potential rate when the pressure head is between h_2 and h_3, decreases linearly when $h > h_2$ or $h < h_3$, and becomes zero when $h < h_4$ or $h > h_1$. The following parameters of the Feddes et al. (1978) model were used: h_1 = −10, h_2 = −25, h_3 = −200 to −1000, h_4 = −8000 cm, which were taken from Taylor and Ashcroft (1972) for orange.

The reduction of root water uptake due to the salinity stress, $\alpha_2(h_\phi)$, was described by adopting the Maas and Hoffmann (1977) salinity threshold and slope function. The salinity threshold (EC_T) for orange (closely related to mandarin) corresponds to a value for the electrical conductivity of the saturation extract (EC_e) of 1.7 dS m^{-1}, and a slope (s) of 16%. As required by HYDRUS-2D, these values were converted into EC_{sw}, assuming that the EC_{sw}/EC_e ratio was 2, which is a common approximation used for soil water contents near field capacity in light-textured soils (U.S. Salinity Laboratory Staff, 1954; Skaggs et al., 2006).

Plant uptake of non-adsorbing nutrients such as nitrate is controlled mainly by mass flow of water uptake (Barber, 1995). Therefore, it was assumed that nitrate was either passively taken up by the tree with root water uptake (Šimůnek and Hopmans, 2009) or moved downward with soil water.

2.4.3. Solute parameters

Soil solution salinity (EC_{sw}) distribution in soil was modelled as a nonreactive solute (e.g., Skaggs et al., 2006; Ramos et al., 2011; Wang et al., 2014). These studies demonstrated that this approach can be successfully used in environments under intensive irrigation and fertigation management. Additionally, Ramos et al. (2011) reported that similar salinity distributions were obtained when this simple approach of EC modelling using HYDRUS was compared with much more complex predictions involving consideration of precipitation/dissolution and ion exchange as done with UNSATCHEM, particularly when the soil solution is under-saturated with calcite and gypsum.

Nitrogen transport was simulated by means of a sequential first-order decay chain, implemented in HYDRUS-2D. Hence, N reaction or transformation processes, other than nitrification, were not considered. Similar assumptions have also been made in previous studies involving modelling of the nitrate transport is soil (Ramos et al., 2011, 2012). We also assumed that inherent soil organic N was mineralised directly into NO_3^-–N, consistent with other studies (Wang et al., 2010; Tafteh and Sepaskhah, 2012).

Nitrate (NO_3^-–N) was assumed to be present only in the dissolved phase (with the distribution coefficient, K_d = 0 cm^3 g^{-1}). Ammonium (NH_4^+–N) was assumed to adsorb to the solid phase with a K_d value of 3.5 cm^3 g^{-1} (e.g., Hanson et al., 2006; Ramos et al., 2012). The nitrification of NH_4^+–N to NO_3^-–N thus acts as a sink for NH_4^+–N and as a source for NO_3^-–N. First-order rate constants for solutes in the liquid and solid phases were set to be 0.2 d^{-1}. These were taken from a review of published data presented by Hanson et al. (2006), and represent the centre of the range of reported values.

The longitudinal dispersivity (ε_L) was considered to be 20 cm and the transverse dispersivity (ε_T) was taken as one-tenth of ε_L. These values have been optimised in similar studies involving solute transport in field soils (e.g., Cote et al., 2003; Mallants et al., 2011).

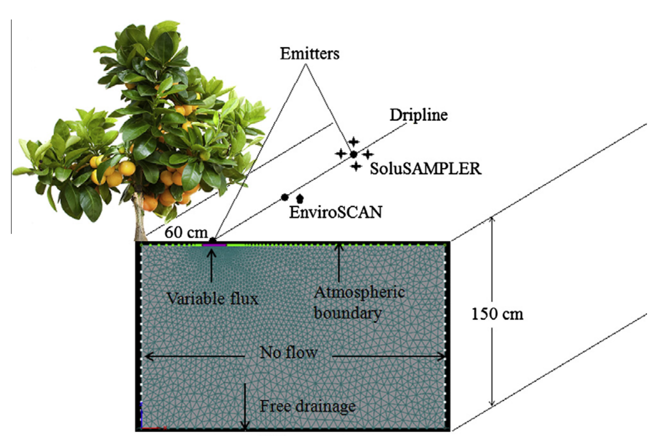

Fig. 3. A schematic view of the model domain (2D) showing considered boundary conditions based on the experimental layout, plant and drip spacing, and locations of monitoring equipments.

2.4.4. Initial and boundary conditions

A time-variable flux boundary condition was applied to a 20 cm long boundary directly below the dripper, centred on 60 cm from the top left corner of the soil domain (Fig. 3). The flux boundary condition with a flux q was defined as:

$$q = \frac{volume\ of\ water\ applied/day}{surface\ wetted\ area} \quad (4)$$

where the volume of water applied (L^3) varied for different irrigation events and was calculated by multiplying the dripper discharge rate by irrigation time, and the surface wetted area (L^2) was approximately 800 cm^2 (i.e., 20 cm × 40 cm). The length of the boundary was selected to ensure that all water could infiltrate into the soil without producing positive surface pressure heads, because positive pressure heads at the flux boundary could make the numerical code unstable. During irrigation, the drip line boundary was held at a constant water flux, q. The atmospheric boundary condition was assumed for the remainder of the soil surface during periods of irrigation, and for the entire soil surface during periods between irrigation. A no-flow boundary condition was established at the left and right edges of the soil profile, to account for flow and transport symmetry. A free drainage boundary condition was assumed at the bottom of the soil profile. All these boundary conditions are illustrated in Fig. 3. The mathematical details of applying the boundary conditions to a domain similar to the current one can be obtained from Phogat et al. (2012a).

The initial soil water content distribution was based on EnviroSCAN measured values and varied from 0.1 to 0.25 $cm^3\ cm^{-3}$ in the soil domain (0–150 cm). Measured values of EC_{sw} and NO_3^-–N in the soil were used as initial conditions in the model. The EC_{sw} varied from 0.8–1.5 $dS\ m^{-1}$ and NO_3^-–N concentrations ranged between 0.16 and 1.07 $mmol_{(c)}\ L^{-1}$ in the soil profile (0–150 cm).

The third-type Cauchy boundary conditions were imposed at the soil surface and at the free drainage boundary for solute transport (EC_{sw}, NH_4^+–N and NO_3^-–N) and no flux boundary was imposed on the sides of the domain.

2.4.5. Flow domain and simulation

In this approach, the drip tubing can be considered as a line source (Fig. 3), because in a twin line drip irrigation system with closely spaced drippers the wetted pattern from adjacent drippers merges to form a continuous wetted strip along the drip lines (Falivene et al., 2005). Water movement was therefore treated as a two-dimensional (in the vertical plane) process (Skaggs et al., 2004). Our field observations of the wetting pattern on the soil surface during experiments also supported this approach. The transport domain was set as a rectangle with a width of 250 cm (half of the lateral spacing between tree rows) and a depth of 150 cm. The transport domain was discretised into 2172 finite element nodes, which corresponded to 4191 triangular elements (Fig. 3). Observation nodes corresponded to the locations where EnviroSCAN probes (depths of 10, 25, 50, 80, 100, and 110 cm) and SoluSAMPLERs (depths of 25, 50, 100, and 150 cm) were installed, at a distance of 10 cm from the emitter source (Fig. 3).

2.4.6. Estimation of potential evaporation and transpiration

HYDRUS-2D requires daily estimates of potential evaporation (E_s) and transpiration (T_p). In this study, these parameters were obtained by combining the daily values of reference evapotranspiration (ET_0), determined by the FAO Penman–Monteith method, and the dual crop coefficient approach (Allen et al., 1998; Allen and Pereira, 2009), as follows:

$$ET_C = (K_{cb} + K_e)ET_0 \quad (5)$$

where $ET_{C.}$ is the evapotranspiration (LT^{-1}), K_{cb} is the basal crop coefficient, which represents the plant transpiration component, and K_e is the soil evaporation coefficient. Standard mandarin K_{cb} values (Allen et al., 1998) were adjusted for the local climate, taking into consideration crop height, wind speed, and minimum relative humidity averages for the period under consideration. The values of daily potential transpiration (T_p) and soil evaporation (E_s) thus obtained (Fig. 4) were used as time-variable boundary conditions (see Fig. 3) in the model, along with the precipitation received at the site during the experimental period. The seasonal T_p amounted to 696 mm and E_s to 174 mm. The maximum T_p of 4.4 mm occurred on 10th January 2007 (DOY 10), when the most adverse weather conditions occurred.

2.5. Scenario analysis for controlling deep drainage and N losses

The nitrogen balance for the mandarin crop was evaluated for two fertigation strategies. First, the fertigation pulse was applied at the beginning of each irrigation event (Fert A). Second, the fertigation pulse was applied near the end of each irrigation event (Fert B). It is a common practice that irrigation water is initially and at the end free of fertilizer, to ensure a uniform fertiliser application and flushing of the drip lines (Gärdenäs et al., 2005). Therefore, fertigation applications were simulated to either start one hour after irrigation started or to end one hour before irrigation stopped.

Nitrate management strategies also include a judicious manipulation of irrigation and N fertilizer applications, and increasing or decreasing the frequency of applications. These interventions should improve N uptake by plants and reduce N leaching out of the plant root zone (Harrison, 1994). The evaluated scenarios are described in Table 2. Scenario, S1, illustrates the impact of applying the same volume of water in small irrigation events (<5 mm). Scenarios S2 and S3 then represents the reduction of the irrigation volume application by 10% and 20%, respectively. Scenarios S4 and S5 are based on decreasing the nitrogen application by 10–20%, respectively, while scenarios S6 and S7 represent a combined reduction in irrigation and fertigation by 10–20%, respectively. Five scenarios (S8 to S12) were executed, in which irrigation was reduced during the second half of the crop season, i.e., between January and August, by 10%, 20%, 30%, 40%, and 50%, respectively.

2.6. Statistical analysis

A mean absolute error (MAE) has been reported (Willmott and Matsuura, 2005) to be a good parameter for comparing modelling results with observed values. It was calculated by comparing weekly measured (M) and corresponding HYDRUS-2D simulated (S) values of water contents, electrical conductivities of soil solution (EC_{sw}), and nitrate concentrations (NO_3^-–N) in soil as follows:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|M_i - S_i| \quad (6)$$

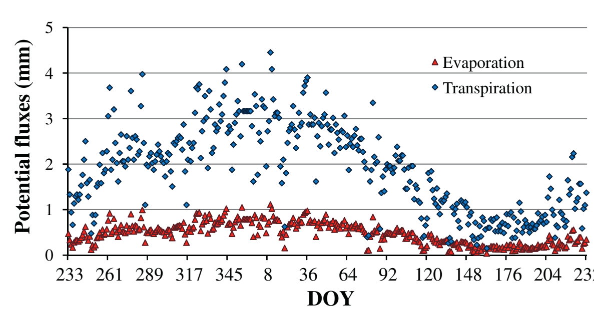

Fig. 4. Daily potential transpiration (T_p) and potential soil evaporation (E_s) estimated using the dual crop coefficient approach during the study period. DOY represents the Julian day of the year 2006–2007.

Table 2
Various scenarios evaluated for optimising irrigation and fertigation of a mandarin orchard.

Scenario	Reduction in irrigation (I) and/or fertigation (F)
S1	All irrigation events ⩽5 mm
S2	10% less I during the entire season
S3	20% less I during the entire season
S4	10% less F during the entire season
S5	20% less F during the entire season
S6	10% less I and F during the entire season
S7	20% less I and F during the entire season
S8	10% less I during January–August, 2007
S9	20% less I during January–August, 2007
S10	30% less I during January–August, 2007
S11	40% less I during January–August, 2007
S12	50% less I during January–August, 2007

Here, *N* is the number of comparisons.

3. Results and discussion

3.1. Moisture distribution

The water contents measured weekly by EnviroSCAN at different depths (10, 25, 50, 80 and 100 cm) at a horizontal distance of 10 cm from the dripper, and corresponding values simulated by HYDRUS-2D during the entire growing season are illustrated in Fig. 5. The measured water contents remained similar at 10 (0.2 $cm^3 cm^{-3}$) and 80 cm (0.1 $cm^3 cm^{-3}$) cm, fluctuated between 0.1 and 0.2 $cm^3 cm^{-3}$ at 25 and 50 cm, and stayed higher than 0.2 $cm^3 cm^{-3}$ at 110 cm soil depths throughout the growing season, indicating a favourable moisture regime in the crop root zone. However, the simulated water contents were lower than the measured values during the initial period at a depth of 10 cm and during the mid period at a depth of 110 cm. The simulated values matched the measured values more closely at soil depths of 25 and 50 cm, which is the most active root zone for water and nutrient uptake for citrus (Mikhail and El-Zeftawi, 1979). However, the profile average water distribution matched well.

The *MAE* between weekly measured and simulated moisture content values across all locations varied from 0.01 to 0.04 $cm^3 cm^{-3}$, indicating a good agreement between the two sets of values (Table 3). Slightly higher temporal *MAE* values during the mid-season agreed well with the variation shown in Fig. 5. Similarly, the *MAE* values at 10, 25, 50, 80, and 110 cm soil depths (Table 3) at a 10 cm lateral distance from the dripper also revealed that the variation between measured and simulated water contents remained between 0.02 and 0.04 $cm^3 cm^{-3}$. However, the differences were slightly higher at 10 cm depth (0.04 $cm^3 cm^{-3}$) as compared to greater depths (0.02–0.03 $cm^3 cm^{-3}$). Higher variations at the surface depth (10 cm) are to be expected because this part of the soil profile is influenced by soil evaporation, which peaks in day time and is low at night time, while the assumption of a constant atmospheric boundary flux for daily time steps in the model (Ramos et al., 2012) deviated from the actual transient conditions existing at the surface boundary. Other studies (Vrugt et al., 2001b; Skaggs et al., 2010; Phogat et al., 2012a,b, 2013a,b; Ramos et al., 2012) also showed a similar magnitude of variations between measured and predicted water contents.

3.2. Soil solution salinity distribution

Comparison of simulated electrical conductivities of soil solution (EC_{sw}) with weekly measured values at different depths (25, 50, 100 and 150 cm) are shown in Fig. 6. Despite of low irrigation water salinity (0.09–0.2 dS m^{-1}) and low initial soil salinity (0.8–1.5 dS m^{-1}), the measured EC_{sw} increased in the soil with the onset of irrigation at all depths, except at 150 cm where the increase in salinity occurred only after December 2006. Subsequently, a decreasing trend was observed in EC_{sw} later in the season. The higher amount of irrigation compared to ET_C and an significant amount of precipitation (Fig. 1) during this period resulted in a reduction in soil solution salinity.

On the other hand, the model over-predicted EC_{sw} at a depth of 25 cm from October to December 2006 and under-predicted it at a depth of 100 cm during the same period. However, at a depth of 150 cm, simulated values remained constant till January 2007, indicating a delayed response. The increase in simulated EC_{sw} values was delayed at 100 and 150 cm depths as compared to measured values. Both set of values matched well at a depth of 50 cm and the profile average of EC_{sw} also showed a close match.

It is significant to note that irrigation with good quality water (EC_w < 0.2 dS m^{-1}) in our study led to the development of significant levels of measured EC_{sw} (0.34–2.32 dS m^{-1}; mean 1.17 dS m^{-1}). However, the EC_{sw} values remained below the threshold of salinity tolerance (EC_e = 1.7 dS m^{-1} or EC_{sw} = 3.4 dS m^{-1}) of orange throughout the season (Ayers and Westcot, 1989; ANZECC and ARMCANZ, 2000).

The (temporal) *MAE*s between weekly measured and simulated EC_{sw} in the soil ranged from 0.08 to 0.76 dS m^{-1} (Table 3), which are acceptable for a complex and highly dynamic soil system, with the exception of a few divergent values obtained between mid October and December (DOY 290-365). The disagreement in EC_{sw} values during this period was correlated with corresponding fluctuations and low values of water contents, especially at soil depths of 10 and 25 cm and this variability was transferred to

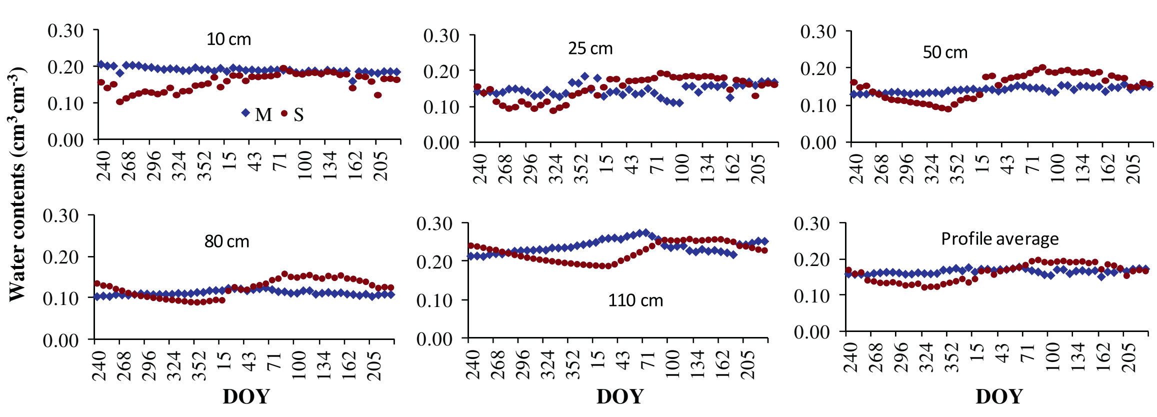

Fig. 5. Comparison of weekly measured (M) and simulated (S) water contents at indicated depths in the soil profile under a mandarin tree.

Table 3
Temporal and spatial mean absolute error (*MAE*) values between measured and simulated water contents, soil solution salinities (EC_{sw}), and nitrate–nitrogen (NO_3^-–N) concentrations.

N^b	Water content		N^b	EC_{sw}		N^b	NO_3^-–N	
	Mean	Range		Mean	Range		Mean	Range
	($cm^3\ cm^{-3}$)			($dS\ m^{-1}$)			($mmol_{(c)}\ L^{-1}$)	
Temporal MAE values[a]								
48	0.03	0.01–0.04	47	0.34	0.08–0.76	48	0.89	0.10–1.97
Spatial MAE values								
n^c	Depth (cm)	Error ($cm^3\ cm^{-3}$)	n^c	Depth (cm)	Error ($dS\ m^{-1}$)	n^c	Depth (cm)	Error ($mmol_{(c)}\ L^{-1}$)
353	10	0.04	47	25	0.36	48	25	1.52
353	25	0.03	47	50	0.47	48	50	0.64
353	50	0.02	47	100	0.36	48	100	0.73
353	80	0.02	47	150	0.19	48	150	0.63
353	110	0.03	–	–	–	–	–	–

[a] MAE for temporal data were calculated across 5 depths (i.e. $n = 5$) at weekly interval of the trial.
[b] Represents the number of weekly comparisons.
[c] Represents number of values in each error calculation.

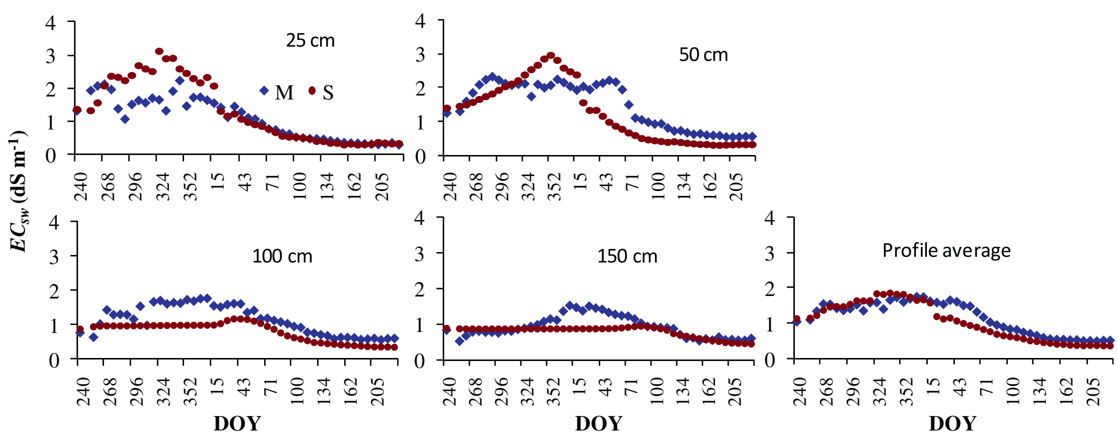

Fig. 6. Comparison of measured (M) and simulated (S) values of soil solution salinity (EC_{sw}) at indicated depths in the soil profile under a mandarin tree.

the EC_{sw} values. Differences between measured and simulated EC_{sw} values at 50 cm depth were relatively higher ($MAE = 0.47$ dS m^{-1}) than at other depths (Table 3). The mean *MAE* at 25, 100, and 150 cm depths ranged from 0.19 to 0.36 dS m^{-1}, showing a good agreement with the measured values at these depths.

The spatial distribution of EC_{sw} in the soil profile at various dates is depicted in Fig. 7. It can be seen that salts remained restricted to roughly the upper 50 cm of the soil profile until December (between 28/11/2006 and 17/01/2007 in Fig. 7). The salts mass was later pushed deeper due to high rainfall (55 mm in January, 29% of seasonal rain). The downward movement of salts continued in February and March (8/03/2007 in Fig. 7), because in March the amount of irrigation was higher than ET_C (Fig. 2). It is pertinent to note here that the EC_{sw} distribution under the dripper remained lower as compared to the adjoining soil at all times, because a continuous water application in this region pushes the

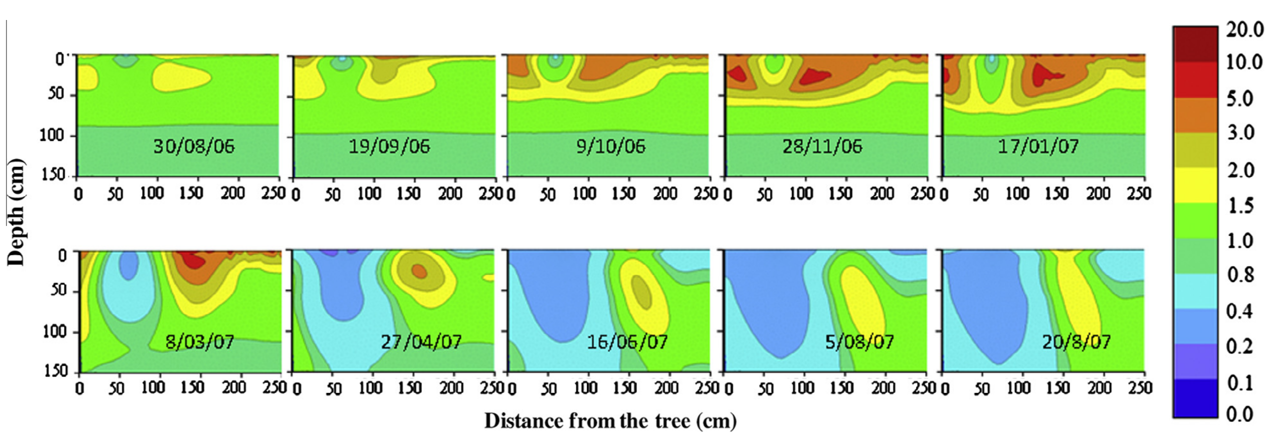

Fig. 7. Spatial distribution of simulated soil solution EC (EC_{sw}, dS m^{-1}) in the soil profile at indicated times.

salts towards the outer boundary of the wetting front. The drainage flux during and after March transported salts vertically downwards, thereby making the soil directly beneath the dripper relatively salt free by the end of the season. Applying additional water at the end of the season could be a strategy to create a salt free rootzone which may encourage vigorous root development, and assist the plant growth in the ensuing season.

3.3. Nitrate nitrogen distribution

Comparison of weekly measured and daily simulated nitrate–nitrogen (NO_3^-–N) concentrations at different depths (25, 50, 100 and 150 cm) in the soil profile is illustrated in Fig. 8. Over-prediction was observed at a depth of 25 cm from October to November 2006, which coincided with similar over-prediction for salinity. Similarly, both measured and simulated values matched well at a depth of 50 cm, while a delayed response in predicted nitrate contents was observed at lower depths. However, a fairly good correspondence was observed between profile averaged NO_3^-–N contents. The temporal *MAE* values for NO_3^-–N ranged from 0.1 to 1.97 $mmol_{(c)}\ L^{-1}$ (Table 3). Similar differences between measured and HYDRUS-2D simulated values were also reported in another study (Ramos et al. (2012) involving simulations of nitrogen under field cropped conditions. Additionally, MAE at a 25 cm depth (Table 3) had a higher value (1.52 $mmol_{(c)}\ L^{-1}$) than at greater depths (0.63–0.73 $mmol_{(c)}\ L^{-1}$). A similar match of nitrate distributions has been reported in other studies as well (Ajdary et al., 2007; Ramos et al., 2012; Tournebize et al., 2012).

The reason for differences in EC_{sw} and NO_3^-–N values may be partially due to the fact that model reports point values, whereas the SoluSAMPLER draws in solution from a sampling area of a certain volume, the size of which depends on the soil hydraulic properties, the soil water content, and the applied suction within the ceramic cup (Weihermuller et al., 2005; Ramos et al., 2012; Phogat et al., 2012a). Hence the measured parameters considered in modelling may not represent the inherent spatial variability of the soil. In addition, while a homogeneous soil environment is assumed by the model, the field site could be far more heterogeneous and anisotropic. Also, the model simulations considered only a 2D movement of nitrogen and the nitrification process, while more complex nitrate processes (e.g., mineralisation, ammonification, denitrification, immobilization through carbon–nitrogen complex formation and microbial interaction) were not taken into account. Ramos et al. (2012) documented numerous factors influencing the correspondence between measurements and simulations of water contents and solute concentrations in the soil under drip irrigation conditions and these factors are relevant also for the present investigation. These factors, including those mentioned above, may modify the error in the simulated NO_3^-–N values.

The simulated movement of nitrate–nitrogen (NO_3^-–N) in the soil under a mandarin tree at various dates is shown in Fig. 9. Nitrate fertigation increased the nitrogen content in the soil with time, as is evident from an increasing size of the concentration plume below the dripper as the season progressed. This indicates that the plant was not able to take up all nitrogen added through fertigation, and thus nitrogen built up in the soil over time, leading to a maximum concentration values in January (17/01/07 in Fig. 11). Ultimately, nitrogen started moving downwards after late January, when there was high rainfall and total water additions exceeded ET_C. Alva et al. (2006) also detected greater variations in NO_3^-–N concentrations in the 0–15 cm depth horizon, as compared to greater depths in a field experiment involving citrus. The seasonal NO_3^-–N concentrations in the domain varied from 0.01–7.03 $mmol_{(c)}\ L^{-1}$. Hutton et al. (2008) reported higher mobilization of nitrate at a shallower depth under drip irrigation of grapevine, and seasonal root zone nitrate concentrations ranging between 0 and 11.07 $mmol_{(c)}\ L^{-1}$ in the Murrumbidgee Irrigation Areas in Australia.

As the season continued and plant uptake was reduced, excess water further mobilised nitrate–nitrogen out of the root zone, as is evident from 27/04/07 and beyond (Fig. 9). At the end of the crop season, little nitrogen remained in the soil system, and what did remain was well beyond the reach of the plants. This nitrogen is expected to continue leaching downwards over time and become a potential source of nitrate–nitrogen loading to the ground water.

Additionally, peak NO_3^-–N concentrations in the soil profile (7.03 $mmol_{(c)}\ L^{-1}$) and in drained water (NO_3^-–N concentration at the 150 cm depth, 2.14 $mmol_{(c)}\ L^{-1}$) were significantly higher than the Australian environmental standard (ANZECC and ARMCANZ, 2000) for protection of 80% (17 mg $NO_3\ L^{-1}$ = 0.27 $mmol_{(c)}$ NO_3^-–N L^{-1}) and 95% of species (0.7 mg $NO_3\ L^{-1}$ = 0.01 $mmol_{(c)}$ NO_3^-–N L^{-1}). The NO_3^-–N concentrations in the soil solution also occasionally exceeded the level of Australian drinking water quality standard (NRMMC, 2011) for nitrate (100 mg NO_3 L^{-1} = 1.61 $mmol_{(c)}$ NO_3^-–N L^{-1}). High levels of nitrate–nitrogen below the crop root zone are undesirable, as some recharge to groundwater aquifers can occur, in addition to flow into downstream rivers, which are used for drinking water and irrigation. These findings are consistent with other studies (Barlow et al., 2009; Correll et al., 2010), in which high nitrate concentrations in drainage water under drip and furrow fertigated irrigation systems have been reported.

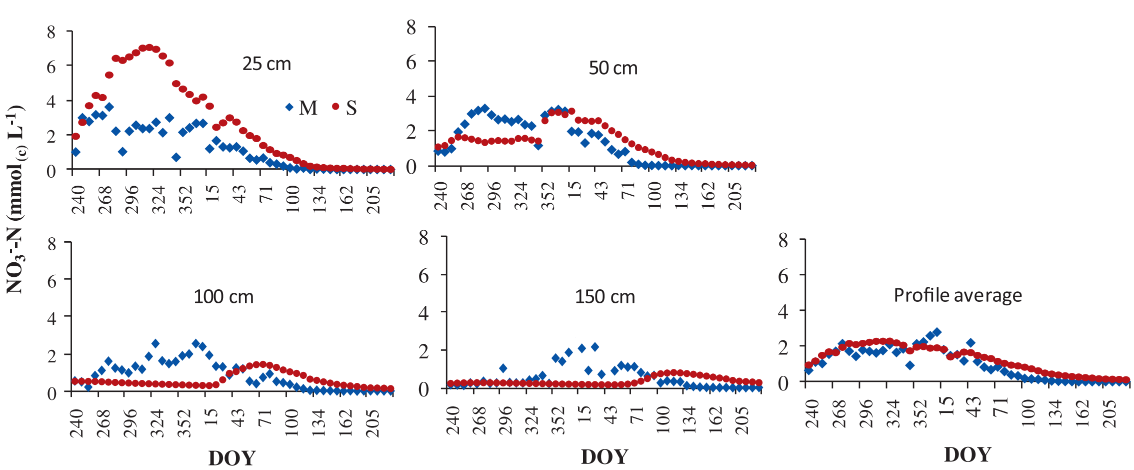

Fig. 8. Comparison of measured (M) and simulated (S) values of soil solution nitrate–nitrogen (NO_3^-–N) at indicated depths in the soil profile under a mandarin tree.

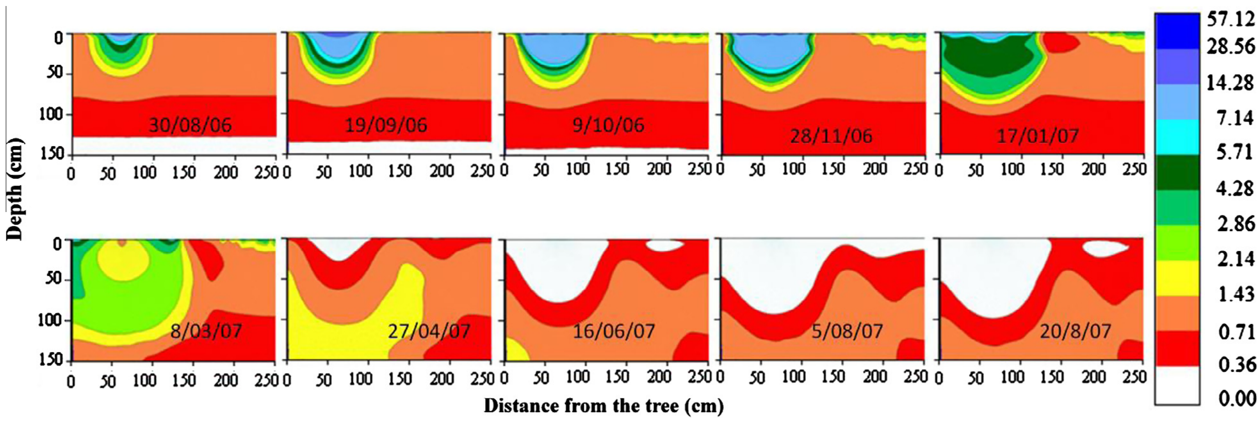

Fig. 9. Spatial distribution of simulated soil solution NO_3^-–N ($mmol_{(c)}\ L^{-1}$) in the soil profile at indicated times.

3.4. Water and nitrogen balance

The seasonal water balance was computed from cumulative fluxes calculated by HYDRUS-2D. Estimated water balance components above and below the soil surface under a mandarin tree are presented in Table 4. It can be seen that in a highly precise drip irrigation system, a large amount of applied water (210.9 mm) drained out of the rootzone, even though the amount of irrigation applied was based on estimated ET_C. This drainage corresponded to 33.5% of applied water, and occurred because highly permeable light textured soils, such as those found in this study, are prone to deep drainage whenever the water application exceeds ET_C. The drainage amount in our study falls within the range of recharge fluxes to groundwater reported by Kurtzman et al. (2013) under citrus orchards in a semiarid Mediterranean climate. Mandarin root water uptake amounted to 307.3 mm, which constitutes about 49% of applied water. Root water uptake slightly increased (3.5%) when the model was run without considering solute (salt) stress (not shown here), which is not a significant difference. It further substantiates the results obtained for seasonal EC_{sw} in Fig. 6, where salinity remained below threshold (3.4 dS m^{-1}) over the season. Evaporation accounted for 17.7% of the total water applied through irrigation and rainfall. The modelling study overestimated the sink components of the water balance by 4.79 mm (0.77%, Table 4).

There were major differences between water input and output from January 2007 onwards (Fig. 10). During this period, irrigation (I) and precipitation (P) significantly exceeded tree water uptake (S_W), which eventually resulted in deep drainage (Dr_W) from March 2007 onwards. Therefore, current irrigation scheduling requires adjustment during this period. This illustrates how simulations were helpful in evaluating the overall water dynamics in soil under the mandarin tree.

Table 4
Simulated components of the seasonal water balance under a young mandarin tree.

Components	(mm)	(%)
Sources		
Irrigation	432.68	69.16
Rainfall	171.13	27.35
Soil depletion	21.80	3.48
Sinks		
Root water uptake	307.3	48.80
Drainage	210.94	33.50
Evaporation	111.56	17.70
Water balance error	−4.79	−0.77[a]

[a] Water balance error (%) = $\left(\frac{\sum W_{source} - \sum W_{sink}}{\sum W_{source}}\right) \times 100$.

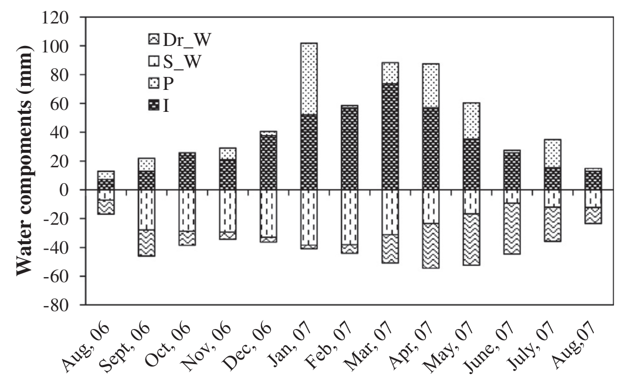

Fig. 10. Monthly irrigation (I, mm), precipitation (P), water uptake (S_W) by a mandarin tree, and deep drainage (Dr_W) from the soil during the study period (from August 2006 to August 2007).

The nitrogen balance is presented in Table 5. The nitrogen fertilizer was applied either in the form of NH_4^+ or NO_3^-, but NH_4^+ transforms quickly to NO_3^- through the process of nitrification. Model simulations showed that nitrification of NH_4^+ was very rapid and most of the NH_4^+–N converted to NO_3^- before it moved to a depth of 20 cm, and no traces of NH_4^+ were observed below this depth. It is apparent that the nitrification of NH_4^+ took place in the upper soil layer, which contains organic matter and moisture that supports microorganisms (*Nitrosomonas* and *Nitrobactor*), facilitating the nitrification of NH_4^+. Though NH_4^+ was initially nitrified to NO_2^- and consequently to NO_3^-, NO_2 was short-lived in the soil and

Table 5
Components of the nitrogen balance under a mandarin crop for fertigation at the beginning (Fert A) and at the end (Fert B) of an irrigation event.

N source	N balance (kg ha^{-1})	Fert A	Fert B
NH_4^+–N	$Soil_{initial}$	0	0
	Added	105.6	105.6
	Adsorbed on soil	0	0
	Uptake	0.71	0.71
	Leached	0	0
	Nitrification	104.9	104.9
	$Soil_{end}$	0	0
NO_3^-–N	$Soil_{initial}$	22.8	22.8
	Added	88.8	88.8
	Uptake	167.11	168.84
	Leached	31.3	31.1
	$Soil_{end}$	20.21	20.09
Mass balance error[a]		−0.98	−1.63

[a] Mass balance error (%) = $\left(\frac{\sum W_{input} - \sum W_{output}}{\sum W_{input}}\right) \times 100$.

decayed to NO_3^- quickly. Therefore, the simulated plant NH_4^+–N uptake was only 0.71 kg ha^{-1}. Hence, the NO_3^-–N form was responsible for most of the plant uptake, corresponding to about 85% of the applied nitrogen. The monthly N applications were slightly higher than plant uptake during the flowering (August–October) and fruit growth (January–March) periods (Fig. 11). However, the monthly uptake was slightly higher than the N application between these periods.

High frequency of N applications in small doses resulted in similar nitrogen uptake efficiency (61–75%) in citrus as in other studies (Syvertsen and Smith, 1995; Quiñones et al., 2007). Similarly, Scholberg et al. (2002) reported doubling of nitrogen use efficiency as a result of frequent application of N in a dilute solution. Slightly higher uptake (1.73 kg ha^{-1}) was recorded when fertigation was applied in second last hour of an irrigation event (Fert B), as compared to when it was applied early in the irrigation event (Fert A, Table 5). Hence, it can be concluded that timing of fertigation does not have a major impact in a normal fertigation schedule with small and frequent N doses within an irrigation event in light textured soils. Similar results were also obtained in our earlier study in a lysimeter planted with an orange tree (Phogat et al., 2013b), which revealed that timing of fertilizer N applications in small doses in an irrigation event with a low emitter rate had little impact on the nitrogen uptake efficiency.

Nitrate–nitrogen leaching accounted for only 15% of the applied nitrogen (Table 5). Monthly N balance (Fig. 11) revealed that most of the N leaching happened between March 2007 and August 2007, which was correlated with the extent of deep drainage occurring during this period. NO_3^-–N losses ranging from 2% to 15% were illustrated by Paramasivam et al. (2002) and Alva et al. (2006), attributable in part to an improved management of N, which could be a contributor in the current estimation.

3.5. Strategies for controlling water and nitrogen losses

In our study, it is evident that there were significant deep drainage (33%) and nitrate–nitrogen leaching losses (15%), which could be reduced by appropriate management. Hence, different simulations involving the reduction of irrigation and fertigation applications during the whole or part of the crop season were conducted, to optimize water and nitrogen uptake and to reduce their losses from the soil (Table 6).

Increasing the irrigation frequency with short irrigation events (S1) while maintaining the same irrigation volume, had no impact on deep drainage (Dr_W) and N leaching (Dr_N). However, the seasonal salinity increased by 11% compared to the standard practice. This confirms that the current irrigation schedule followed with respect to the irrigation frequency seems to be optimal under the

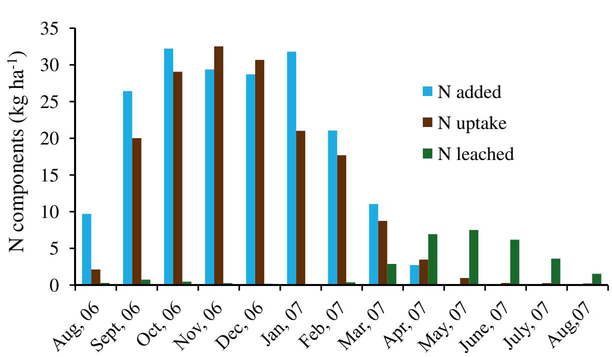

Fig. 11. Simulated monthly values of nitrogen added (N added), nitrogen uptake (N uptake) by a young mandarin tree, and nitrogen leached (N leached) from the soil during the study period (from August 2006 to August 2007).

experimental conditions. In S2, Dr_W and Dr_N were reduced by 14.4% and 19%, respectively, but salinity increased by 11%. However, a sustained reduction in irrigation by 20% (S3) eventually reduced the Dr_W and Dr_N by 28.1 and 38.3%, respectively, at the expense of a 4.9% decline in plant water uptake, but with a 4% increase in N uptake. However, salinity increased by 25.8% compared to the normal practice, which would likely have a significant impact on plant growth.

Scenarios S4 and S5 were based on decreasing the nitrogen application by 10% and 20%, resulting in a decrease in N leaching by 7.4% and 14.8%, respectively, along with a much higher reduction in plant N uptake (10.4% in S4 and 19.7% in S5), suggesting that the reduction in the fertilizer application alone is not a viable option to control N leaching under standard conditions. A combined reduction in irrigation and fertigation by 10% (S6) further reduced N leaching by 5.5%, compared to reducing irrigation alone (S2), but at the same time plant N uptake was reduced by 5% more than in S2. Similarly, reducing irrigation and N application by 20% (S7) produced a pronounced reduction in N leaching (46.4%) and water drainage (28%), but it also resulted in a decrease in plant N uptake by 15.8% and water uptake by 4.8%, compared to normal practice. At the same time, salinity increased by 25.8%, which is similar to S3. The reduction in plant water and N uptake would have a major impact on plant growth and yield, and would adversely impact the sustainability of this expensive irrigation system. Hence, reducing fertilizer applications does not seem to be a good proposition under the current experimental conditions, as it results in an appreciable decline in plant N uptake. However, Kurtzman et al. (2013) reported that a 25% reduction in the application of N fertilizer is a suitable agro-hydrological strategy to lower the nitrate flux to groundwater by 50% under different environmental conditions. Rather, reducing irrigation alone seems to be a better option to control the deep drainage and N leaching losses under the conditions encountered at the experimental site.

Additionally, it is worth noting that in S3 and S7 the salinity (EC_{sw}) during a period between October and December at a depth of 25 cm, and during December at a depth of 50 cm, increased considerably, and was higher than the threshold level (Fig. 12), confirming that a sustained reduction in irrigation (S3) and fertigation (S7) is not a viable agro-hydrological option for controlling water and N leaching under the mandarin orchard.

However, it seems unnecessary to reduce irrigation applications uniformly across the season as suggested by Lidón et al. (2013). Rather, irrigation could more profitably be reduced only during a particular time period when excess water was applied. The water and N balance data in our study revealed that an imbalance between water applications and uptake happened during the second half of the crop season, i.e., from January till August 2007, resulting in maximum drainage (Fig. 10) and N leaching (Fig. 11), coinciding with the fruit maturation and harvesting stage. Hence, there is a need to reschedule irrigation within this period, rather than reducing water applications throughout the entire season. Keeping this in mind, the following 5 scenarios (S8 to S12, Table 6) were executed, in which irrigation was reduced during the second half of the crop season, i.e., between January and August, by 10%, 20%, 30%, 40%, and 50%, respectively.

Scenarios S10, S11, and S12 showed an enormous potential for reducing water and N losses. In S10, Dr_W and Dr_N were reduced by 8% and 4% more than in S7, N uptake was increased by 6.9% (compared with a reduction in S7), and salinity was also 4% less than in S7, which seems quite promising. On the other hand, in S11 and S12, the Dr_W and Dr_N were reduced to a greater extent (50–58% water and 70–80% N leaching) than in S10, and soil salinity increased substantially (40.3% and 58.7% higher than normal practice), due to a considerable reduction in the leaching fraction. This is also shown in Fig. 12, which shows that monthly soil

Table 6
Percent increase (+)/decrease (−) in water uptake (S_W), drainage (Dr_W), N uptake (S_N), N leaching (Dr_N), and electrical conductivity of the soil solution (EC_sw) in different scenarios of water and fertilizer applications, compared to the normal practice.

Scenario	Reduction in irrigation (I)/fertigation (F)	S_W	Dr_W	S_N	Dr_N	EC_sw
S1	Irrigation events ⩽5 mm	−0.25	−1.16	−1.01	0.06	11.29
S2	10% I, full season	−2.17	−14.40	2.64	−19.07	11.29
S3	20% I, full season	−4.88	−28.15	4.07	−38.29	25.81
S4	10% F, full season	0.18	0.06	−10.38	−7.40	0.00
S5	20% F, full season	0.21	0.03	−19.72	−14.76	0.00
S6	10% I and F, full season	−2.06	−14.25	−7.05	−24.60	11.29
S7	20% I and F, full season	−4.83	−28.18	−15.66	−46.43	25.81
S8	10% I, January–August, 2007	−0.30	−12.74	1.90	−15.53	5.65
S9	20% I, January–August, 2007	−0.87	−25.41	4.36	−32.97	13.71
S10	30% I, January–August, 2007	−1.66	−37.16	6.89	−50.52	21.77
S11	40% I, January–August, 2007	−2.68	−49.89	9.79	−69.53	40.32
S12	50% I, January–August, 2007	−4.11	−57.91	12.76	−80.51	58.87

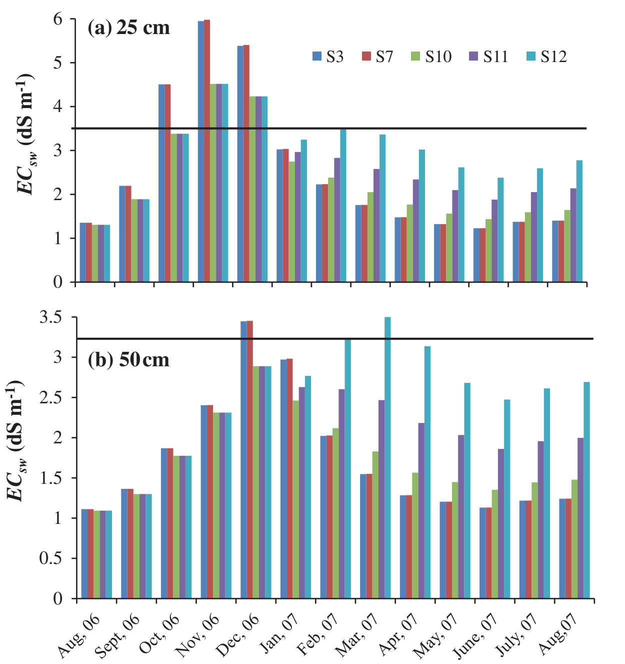

Fig. 12. Monthly average soil solution salinity (EC_{sw}, dS m^{-1}) at (a) 25 cm depth and (b) 50 cm depth in the soil profile under different scenarios (see Table 6). Horizontal lines show the threshold salinity level for citrus (3.4 dS m^{-1}).

solution salinity (EC_{sw}) in S11 and S12 at the 25 and 50 cm soil depths increased dramatically between January and August. Although EC_{sw} remained below the threshold level, except at a 50 cm depth in S12 during March 2007, there is a significant likelihood of it increasing further in subsequent seasons, which would ultimately impact the growth and yield of mandarin trees. Hence, under current conditions, Scenario S10 represents the best option to control excessive water and N losses, and high salinity, and to increase the water and N efficiency for mandarin trees. Other permutations and combinations, involving fertilizer reductions along with S10, did not provide further improvements in controlling water and N leaching. It is concluded that simulations of irrigation and fertilizer applications, using HYDRUS, can be helpful in identifying strategies to improve the water and N efficiency for drip irrigation systems of perennial horticultural crops.

4. Conclusions

This study demonstrates the importance of combining strategic monitoring with numerical modelling to assess water movement, salinity distribution, and nitrogen management under drip irrigation systems in young mandarin orchards in Australia. HYDRUS-2D was used to predict seasonal water, salt, and nitrate dynamics in soils. Modelling results were compared with measured values of moisture content, soil solution salinity (EC_{sw}), and nitrate–nitrogen (NO_3^-–N) in the soil profile during the complete season.

Graphical and statistical comparisons of measured and simulated values of water contents, EC_{sw}, and NO_3^-–N concentrations in the soil under a mandarin tree showed a consistent performance of HYDRUS-2D for modelling water, salinity, and nitrogen transport. The temporal mean absolute errors (*MAE*) for water contents, EC_{sw}, and NO_3^-–N concentrations were within acceptable limits. However, *MAE* showed divergent values at shallow depths (10–25 cm) due to the assumption of a constant surface boundary flux during a particular daily time step, which deviated from normal diurnal fluctuations in the real-time evaporation flux. Other reasons for deviations between predicted and observed NO_3^-–N contents were attributed to the model considering only a simple linear movement of nitrogen, rather than considering all complex processes (e.g., mineralisation, ammonification, denitrification, immobilization through carbon–nitrogen complex formation, and microbial interactions).

The simulated water and nutrient balances showed that the irrigation scheduling at the experimental site from December onwards needed to be modified in order to control deep drainage (33.5% of applied water) and nitrate leaching (15% of applied NO_3^-–N). Sustained reduction of irrigation and/or fertilization by 10–20% reduced water (14–28%) and NO_3^-–N (19–46%) losses appreciably, but these strategies reduced the leaching fraction and/or plant N uptake to a level where root zone EC_{sw} increased to substantially higher values than the recommended threshold (3.4 dS m^{-1}) and plant N uptake was reduced (7–20%), both of which may affect plant growth and yield, and in turn would adversely impact the sustainability of expensive irrigation systems.

Other evaluated scenarios focused on reducing irrigation (by 10–50%) between January and August, when a mismatch between irrigation applications and plant uptake was observed. A 30% reduction in irrigation during this period provided the best scenario, in which both water and NO_3^-–N leaching were reduced by 37% and 52%, respectively, and plant N uptake was increased by 7%, compared to the normal practice. However, a further reduction in irrigation by 40 and 50% reduced the water (50–58%) and NO_3^-–N (70–80%) losses to a great extent, but increased salinity in the root zone to a level much higher than the tolerance threshold of mandarin.

This study forms the basis for future evaluation of irrigation, salinity, and nitrate–nitrogen dynamics under drip fertigation systems in fields with horticultural trees, and for future exploration of ways to fine-tune irrigation schedules in order to better control excessive drainage and N losses. However, there is a need to further improve the modelling estimates by considering all processes of the nitrogen cycle in the soil system. It is concluded that such studies would help in improving irrigation and fertigation programs for horticultural crops irrigated with drip irrigation systems, and would lead to more efficient and less environmentally detrimental crop management practices.

Acknowledgements

The authors wish to thank Dr. Tapas Biswas for initiating the experimental set up and Dareton Agricultural Research and Advisory Station farm staff for managing the site and plantings. The financial support of the National Program for Sustainable Irrigation is gratefully acknowledged.

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