Simulation of Water and Salinity Dynamics under Different Irrigation Applications to an Almond Tree in Pulsed and Continuous Mode

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Abstract

The quantification of the components of water balance is essential for designing strategies for improving irrigation efficiency and water productivity of crops under different irrigation systems and for minimizing the offsite movement of nutrients out of the rhizosphere. HYDRUS-2D was used to simulate seasonal water balance and salinity distribution under full pulsed (FI p), sustained deficit pulsed (SDI p; 65% ETc), and full continuous (FI c) irrigation of an almond tree using a surface drip. The weekly measured and predicted values of moisture content at different distances from the dripper and at different soil depths matched well, showing only a small variation in RMSE values. The sap flow underestimated almond water uptake by 31% as compared to the modeled value in SDI p. Water uptake efficiency under SDI p (68%) was higher compared to full water application conditions under FI p and FI c (54-55%). The leaching fraction was estimated to be 0.14 under SDI p and 0.25 in FI p and FI c treatments. The higher irrigation amounts under 100% ETc treatments (FI p and FI c) largely contributed to non-productive water fluxes (deep drainage losses and evaporation). The seasonal water uptake by almond under pulsed (FI p) and continuous irrigation (FI c) remained almost at par, indicating that pulsing didn't provide any added advantage, although it is a viable alternative to slow discharge continuous irrigation. The average modeled soil solution salinity (ECsw) of the soil profile also remained below the threshold for the yield reduction during the growing season in all treatments. The irrigation water productivity (WPI) increased substantially (37%), yield was reduced by 8% and about 35% of irrigation water was saved under sustained deficit irrigation (SDI p) as compared to full irrigation (FI p). It was concluded that SDI p is a promising deficit irrigation strategy for almond cultivation in Australia. These outcomes can be utilized to improve irrigation efficiency and system design for drip irrigation of almond trees.

1. Introduction

Fierce competition among water users, frequent droughts, and scarce water resources in Australia put enormous pressure on irrigation systems and drive a requirement for more efficient irrigation practices. Hence, 90% of almond plantation in Australia is under a high efficiency drip system of irrigation. Various water saving interventions, like pulsing of irrigation and sustained deficit irrigation, are being followed for managing water efficiently and increasing the water productivity. However, dynamics of water fluxes above and in the soil exert a pronounced impact on plant water uptake, deep drainage, and solute distribution in the soil profile and thus significantly influence processes of water and solute movement in the rhizosphere (Phogat et al., 2013). Therefore, evaluating seasonal dynamics in plant water uptake and deep drainage is
needed, so that improvements in the usage of scarcely available water can be attained and to enhance water productivity.

The temporal and spatial dynamics of water fluxes through the soil-plant-atmosphere continuum can be better understood using numerical simulation models, provided that the precisely measured values of input parameters are used for modeling simulations. Out of the numerous models, varying in degree of sophistication and complexity and presently available for evaluating the soil water movement (Subbaiah, 2013), HYDRUS has been extensively used for the analysis of micro irrigation systems involving a varied range of soil, water, and crop conditions (Gardenas et al., 2005; Hanson et al., 2006; Kandelous et al., 2012; Phogat et al., 2012ab, 2013; Ramos et al., 2012). Although modeling has been done extensively for problems related to drip irrigation systems using the HYDRUS software, only a few studies have been substantiated with field validation.

The present study uses HYDRUS-2D modeling and the field data recorded for an almond tree over a season to evaluate the water balance and salinity dynamics under full irrigation and stress conditions, and to evaluate the impact of pulsing and continuous drip irrigation on the dynamics of water fluxes, including plant water uptake and deep drainage. Understanding the daily water fluxes during the crop season under high frequency irrigation would have large implications for devising the irrigation scheduling and improving water productivity of almond under stress conditions.

2. Materials and Methods

2.1. Details of Field Experiment

The experiment was conducted at Clark Taylor farms, a commercial almond [Prunus dulcis (Mill.) Webb] orchard in Berri, South Australia (34°20'S and 140°35'E) from July, 2009 to May, 2010. The orchard was planted in 1998 with the rows oriented north–south and a spacing of 6.7 m between rows and 6.1 m within a row. Since the soil was more or less uniform, a mean soil particle size distribution of 88.5% sand, 1.9% silt, and 9.6% clay, and a bulk density of 1,610 kg m⁻³ were considered in this study. The trees were managed and fertilized following current commercial practices. The total rainfall received during the study period was 220 mm. The daily \( \text{ET}_C \) for the irrigation purpose was calculated from \( \text{E}_{\text{pan}} \) values of the previous day multiplied with suitable crop factors.

The orchard was surface drip irrigated, with a pulsed irrigation treatment of 100\% \( \text{ET}_C \) (\( \text{FI}_p \)), sustained deficit irrigation of 65\% \( \text{ET}_C \) (\( \text{SDI}_p \)), and a continuous irrigation treatment of 100\% \( \text{ET}_C \) (\( \text{FI}_c \)), covering an area of 1.89, 0.97, and 0.7 ha, respectively. The treatments were initiated from 20\textsuperscript{th} August, 2009 after one month of a profile establishment stage. Profile establishment resulted in the application of an equal amount of irrigation (85 mm) in each treatment. The seasonal salinity of irrigation water ranged between 0.2 to 0.52 dS m⁻¹.

Each row of trees had two laterals, one on either side of the row at 1 m offset from the tree trunk. The pulsed treatments (\( \text{FI}_p \) and \( \text{SDI}_p \)) were irrigated with a cycle of one hour on and one hour
off, with an average flow rate of the drippers of 3.87 l h⁻¹. For continuous treatment (Flc), the measured flow rate was 2.00 l h⁻¹ per dripper. The number of drippers per tree was approximately 12 for the pulsed treatments and 15 for the continuous treatment, as the dripper distance in pulsed and continuous treatments was 100 cm and 80 cm, respectively.

Neutron probe access tubes were installed at a lateral distance of 0, 20, 40, 60, 80, and 100 cm from the dripper (Fig. 1) to a depth of 160 cm to monitor the profile soil water distribution at weekly intervals, at every 10 cm depth up to a depth of 100 cm, and then every 20 cm between depths of 100 and 160 cm.

![Figure 1](image-url). A schematic view of a model domain, plant spacing, and measuring gadgets.

Sap flow measurements were performed on two trees under pulsed treatments (SDIp and Flp) and were based on the heat pulse method outlined by Green et al. (2003) to quantify the water uptake by an almond tree. However, the sap flow installation was delayed and measurements were obtained only from 25th November onward.

2.2. Numerical Modeling

Soil water and soil water salinity distributions below the drip line were simulated with the version 2.x of the computer simulation model HYDRUS (2D/3D). This new HYDRUS software module can simulate two- and three-dimensional variably saturated water flow, heat movement, and transport of solutes involved in sequential first-order decay reactions. In addition, the model allows for specification of root water uptake, which affects the spatial distribution of water and soil water salinity between irrigation cycles. The details about the model can be obtained from Šimůnek et al. (2011) and Šejna et al. (2011).

2.3. Input Parameters

Though seasonal irrigations of almond were based on $E_{pan}$ and crop factors, the potential $ET_C$ was calculated from the reference evapotranspiration ($ET_0$) values collected from the
Bookpurong meteorological station, situated 150-200 m away from the experimental site, following the dual crop coefficient method (Allen et al., 1998), to serve as an input for the model. The seasonal potential transpiration ($T_{pot}$) amounts to 1,380 mm, and potential evaporation ($E_t$) for the same period was 414 mm. The estimates of optimized soil hydraulic parameters used for the modeling simulations were: $\theta_r = 0.06$, $\theta_s = 0.37$, $K_s = 276.6$ cm day$^{-1}$, $\alpha = 0.0316$ cm$^{-1}$ and $n = 2.52$. The value of $l$ was taken as 0.5 as recommended.

The almond root distribution was described using the Vrugt et al. (2001) two-dimensional model adapted in HYDRUS. The parameters used in the model for almond were: $z_m = 150$ cm, $z^* = 30$ cm, $x_m = 335$ cm, $x^* = 25$ cm, $p_x = 2.918$, $p_z = 3.214$. The values of empirical coefficients were taken from Vrugt et al. (2001), and were optimized for almond.

The reducing effects of both soil water pressure head and osmotic head on root water uptake were included, assuming their effects were multiplicative. The following parameters of the model were used: $h_1 = -10$, $h_2 = -25$, $h_{3\text{max}} = -500$, $h_{3\text{min}} = -800$, $h_4 = -8000$ cm; $r_{2, \text{high}} = 0.5$ cm d$^{-1}$, and $r_{2, \text{low}} = 0.1$ cm d$^{-1}$. The threshold model was used to describe osmotic effects using a threshold $EC_e = 1.5$ dS m$^{-1}$ and a slope of 19%.

Spatial distribution of salinity in the transport domain was simulated using the convection–dispersion equation for a nonreactive tracer. Such simulations cannot account for complex processes such as precipitation or dissolution of solid phases (e.g., gypsum or calcite) or cation exchange. Longitudinal dispersivity was considered to be 20 cm and transverse dispersivity was 2 cm.

The water content initial conditions were based on values measured by the neutron probe, which varied from 0.05 to 0.08 cm$^3$cm$^{-3}$ in F1p, 0.07-0.14 cm$^3$cm$^{-3}$ in SDIp, and 0.04-0.06 cm$^3$cm$^{-3}$ in continuous (F1c) drip irrigation. Similarly, the initial soil solution salinity ($EC_{swi}$) in the soil profile varied from 3.89 to 7.22 dS m$^{-1}$, 3.63-8.3 dS m$^{-1}$, and 4.55-7.95 dS m$^{-1}$ in F1p, SDIp, and F1c treatments, respectively. Initial soil water salinities were based on field measurements made at the start of the experiment and estimated from measurements of the saturated soil extract ($EC_e$). The water flow boundary conditions are shown in Figure 1. In the case of solute transport, the boundary condition representing salinity is a third-type Cauchy boundary condition that prescribes the salt movement during defined irrigation intervals.

Simulations were made for hourly pulsed and continuous irrigation treatments during a period of 316 days. The simulated surface drip irrigation system design characteristics were typical of the drip systems used for the field experiment on almond, as shown in Figure 1. The model domain was 200 cm deep and 335 cm wide (one fourth of the bed spacing used for the almond production). The domain was discretized into 5,087 finite elements with a very fine grid around the dripper (0.3 cm) and gradually increasing elements farther from the drip (up to 9.8 cm). The measured salinity of irrigation water ($EC_{iw}$) was used as a time variable boundary condition. The drip irrigation was simulated assuming an infinite line source to be a good representation of the drip irrigation system. The root mean square error (RMSE) was calculated to compare the experimental and predicted values of water content.
3. Results and Discussion

The model-produced, weekly values of water content were compared with measured values at various horizontal and vertical locations in the domain in all treatments. For example, the measured and simulated water contents in full pulsed treatment (FI_p) at a distance of 20 cm from the dripper, averaged for all depths is shown in Figure 2. The simulated water content values matched the neutron probe measured data well, except within a short period during midseason of the crop. The RMSE values ranged from 0.01 to 0.08, 0.01-0.06, and 0.01-0.05 cm$^3$cm$^{-3}$ in full pulsed (FI_p), pulsed deficit (SDI_p), and full continuous (FI_c) irrigation, respectively. Similar variations between measured and simulated moisture regimes have also been reported in other modeling studies (Phogat et al. 2012ab, 2013). This comparison confirms that the model successfully captured the dynamics of water movement in the soil throughout the cropping season under both scenarios of the water application. However, the small differences between measured and simulated water contents are likely due to model errors caused by restrictive assumptions regarding the geometry of the rooting system, homogeneity of soil hydraulic properties within the spatial domain, and the prescribed root water uptake model.

Simulated water balance components obtained for different treatments are shown in Table 1. Seasonal water uptake in sustained deficit treatment (SDI_p) was reduced by 13.9%, compared to full pulsed irrigation. However, water uptake under full pulsed (FI_p) and full continuous (FI_c) irrigations remained almost equal. On the other hand, root water uptake efficiency under stress treatment (68%) was much higher compared to normal water application conditions (54-55%) in FI_p and FI_c treatments.

![Figure 2. The comparison of weekly measured and simulated water contents in full pulsed irrigation (FI_p) at a distance of 20 cm from the dripper.](image)

A significant reduction was observed in deep drainage flux for scenarios under stress, which was drastically reduced under SDI_p as compared to full irrigation (Table 1). Only 14% of total water applied escaped the crop root zone in SDI_p, compared to 25% in full irrigation treatments (FI_p and FI_c). However, among full irrigation scenarios, pulsing had a little impact on the deep drainage because it was slightly higher (13 mm) under pulsing (FI_p), and the soil storage was 20 mm higher under continuous irrigation (FI_c). Apparently, large changes in the soil storage (53
and 73 mm) reflected the depth of the soil in the model domain (200 cm) and the fact that the soil was quite dry at the beginning of the simulation, and uniformly wet across the model domain at the end of the simulation, as a result of irrigation and rainfall events.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>SDI_p</th>
<th>FI_p</th>
<th>FI_c</th>
<th>Difference (FI_p &amp; FI_c)</th>
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<td>1668</td>
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<tr>
<td>Rainfall</td>
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<td>220</td>
<td>220</td>
<td>-</td>
</tr>
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<td>1051</td>
<td>1026</td>
<td>25</td>
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<tr>
<td>Evaporation</td>
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<td>311</td>
<td>-1</td>
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<tr>
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<td>489</td>
<td>476</td>
<td>13</td>
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<td>Soil storage</td>
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<td>53</td>
<td>73</td>
<td>-20</td>
</tr>
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</table>

Daily root water uptake rates calculated by HYDRUS-2D were compared with the sap flow measured transpiration by almond during 25th Nov, 2009 to 31st May, 2010 in full pulsed (FI_p), as well as for stress (SDI_p) treatments. The comparison for full irrigation has been illustrated in Figure 3. It can be seen that HYDRUS very well sensed the diurnal fluctuations in the water uptake driven by the evapotranspirational demand, and the model also predicted water uptake fluctuations very well, in accordance with the sap flow measurements. However, the magnitude of modeled water uptake was higher than the sap flow measurements until the almond harvest and, subsequently, both matched well. Sap flow measurements estimated 492 mm water uptake during this period, compared to 659 mm predicted by the model, and compared with the 1,167 mm of water applied through irrigation and rainfall. Hence, sap flow measurements underestimated water uptake by almond by about 25% under full irrigation and 31% under the stress treatment. We believe that the assumption of wood thickness, and wood and sap composition for the estimation of the correction factor may have resulted in the underestimation of water uptake by sap flow. Several other reasons for underestimations are also outlined in Phogat et al. (2013).

Figure 3. Comparison of simulated daily water uptake and sap flow water uptake by almond in full pulsed (FI_p) irrigation.
The deep drainage was not evenly distributed over the season (Figure 4). There was higher leaching early in the season (August) and after harvest in Feb-April, together amounting to 50% of the total seasonal leaching in FI_p and FI_c treatments, whereas more than 50% drainage in SDI_p occurred in July-August (a profile establishment stage), and thereafter the drainage volume was drastically reduced to negligible amounts during the midseason, increasing again during March-April after the harvest of kernels. Hence, during the July-August and Feb-April periods, the water requirement of almond was less than the water application. This implies that there is a need to revise the used crop coefficients ($K_c$), and reschedule irrigation applications during these periods so that these unnecessary water losses can be controlled.

Model simulations were also performed for the seasonal salinity distribution in the soil profile, and average soil solution salinity ($EC_{sw}$) data is presented in Figure 5. The $EC_{sw}$ values remained similar in both full irrigation treatments (FI_p and FI_c) because the salt transport in a light-textured soil is predominantly governed by the dynamics of water movement, which was similar in both treatments. The average $EC_{sw}$ values in the soil below the dripper ranged from 0.47 to 3.38 dS m\(^{-1}\) and 0.49 to 3.67 dS m\(^{-1}\) in FI_p and FI_c treatments, respectively.

![Figure 4. Simulated deep drainage (mm) under pulsed deficit (SDI_p), full pulsed (FI_p), and full continuous (FI_c) drip irrigation of almond.](image)

![Figure 5. Simulated soil solution salinity ($EC_{sw}$) distribution in pulsed deficit (SDI_p), full pulsed (FI_p) and continuous (FI_c) drip irrigation of almond.](image)
The soil solution salinity ($EC_{sw}$) under SDI$_p$ was initially lower because the initial soil water content was substantially higher compared to FI$_p$ and FI$_c$ treatments and consequently, higher leaching was observed during the profile establishment and early growth period. However, from September onward the salinity in SDI$_p$ was much higher and continued to increase until December, when it reached a maximum value of 3.55 dS m$^{-1}$, after which it decreased continuously until April, 2010. This occurred due to relatively lower water content in the soil under stress conditions in SDI$_p$ up until December, and then dilution due to increased soil water contents after December, although little drainage was evident until March. However, the salinity remained below the threshold for almond ($EC_e$ 1.5 dS m$^{-1}$) throughout the growing season in all the treatments.

HYDRUS-2D-calculated values of actual monthly evaporation and transpiration were summed up to calculate the monthly crop coefficients of almond (Figure 6). The midseason $K_c$’s of 1.23, 1.22, 1.31, and 1.11 for October, November, December, and January, respectively, were significantly higher than the FAO 56 value of 0.9, which is applied to a temperate climate and no-stress conditions. However, the values of $K_c$ obtained in the present study matched well with those reported by Stevens et al. (2012) for a sprinkler-irrigated almond in this region. They reported that higher $K_c$ values for midseason were due to the prevalence of non standard weather conditions and high advective conditions in the region.

Experimental and simulated values of water balance were utilized to calculate the water productivity of almonds under full and deficit irrigation (Figure 7). It can be seen that irrigation water productivity ($WP$) under stressed conditions (SDI$_p$) increased substantially (37%) as compared to full irrigation (FI$_p$). It is inferred that almonds are among the species capable of maintaining high gains in the water productivity under increasing soil water deficit (Girona et al., 2005). The estimated irrigation water productivity ($WP$) in this investigation was appreciably higher than that reported in several other studies, where it varied from 0.20-0.33 kg m$^{-3}$ (Egea et al., 2010). The data indicates that, for regions with a severe water scarcity, SDI$_p$ appears to be a promising deficit irrigation strategy for almond trees, as it increased $WP$ by 37%, reduced yield only by 8%, and saved about 34.5% of irrigation water in comparison to full irrigation (FI$_p$).
Figure 7. Almond water productivity under full irrigation (FIp) and stress conditions (SDIp).

4. Conclusions

The study concludes that HYDRUS-2D simulated water fluxes and soil salinity dynamics under drip-irrigated almond very well. This work identifies significant drainage during the months of August and Feb-April, when the tree water demand was less than had previously been assumed. The model-produced values of evapotranspiration were utilized to evaluate the monthly crop coefficients and the crop water productivity. Recalculations of crop coefficients ($K_c$) as a result of this work have the potential to lead to significant water savings and water efficiency improvements. The study also revealed that SDIp seems to be one of the most promising reduced irrigation application options available for improving irrigation efficiency.

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References


