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# Modelling water and salinity distribution in soil under advance fertigation systems in horticultural crops

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**Abstract:** New generation irrigation and fertilizer application methods have revolutionised input applications in agriculture, leading to significant savings of scarce resources like water. These systems are highly capital intensive, and apply water at suitable locations, facilitating their maximum uptake by crops. However there is still a need to evaluate these systems for water and salinity dynamics on a long term basis, to further finetune them and come to terms with the high cost involved, and to control the possible deep drainage of water which transports solutes below the root zone endangering the quality of groundwater. But the soil-plant-atmosphere system evaluation in respect of water and salt distribution involves very complex processes which are unable to be managed by experimentation alone. The numerical models offer good opportunity to analyse the complex systems if reliable input parameters are available. In this study, HYDRUS-2D model was used to evaluate the seasonal water balance and salinity distribution in soil under surface drip irrigation of two horticultural crops, almond and mandarin which are widely grown in Australia.

Modelling domain represents the plant spacing of the trees in the field studies. Modelling simulations were carried out on daily basis involving daily input of variable flux equivalent to the depth of irrigation. The daily potential transpiration ($T_{pot}$) and potential evaporation ($E_s$) under almond and mandarin trees were estimated by FAO 56 dual crop coefficient method utilizing local weather parameters, soil characteristics and plant estimates. The estimated daily $T_{pot}$ and $E_s$ were then used as daily atmospheric inputs along with rainfall received at the experimental sites. The modelling simulations were carried out for one complete growing season for both crops. The field experiments were equipped with temporal and spatial monitoring of water content and salinity (in mandarin only) distribution following standard procedures. The modelling output on water content and salinity (for mandarin) were compared with the corresponding measured values throughout the growing season. The model was also used for evaluating the impact of water stress and impact of pulsing in irrigation application.

The graphical and statistical comparison of weekly measured and simulated values of moisture content at various depth and distances from dripper revealed fairly good matching. The RMSE values of weekly comparison varied from 0.005 to 0.06 $cm^3cm^{-3}$ in almond and 0.01-0.06 $cm^3cm^{-3}$ in mandarin. The variation of this magnitude generally exists in field measurement of water content. Similarly the comparison between measured and model predicted values of salinity ($EC_{sw}$) under mandarin also matched well and RMSE ranged between 0.09 to 0.93 dS $m^{-1}$ which is well within the acceptable limit in a complex and highly dynamic soil system. The daily $EC_{sw}$ distribution remained below the threshold salinity values of both crops throughout the growing season. Reducing the irrigation application by 35% (65% $ET_C$) in almond increased the seasonal salinity substantially. The average increase was about 2.5 fold particularly during the summer season. Hence, the temporal and spatial soil solution salinity distribution ($EC_{sw}$) obtained from the modelling simulation was very well synchronised with the corresponding moisture regime in the soil under both trees.

The water balance revealed that only 49% of applied water (irrigation and rain) was used by the mandarin tree, allowing a leaching fraction of 34%, while 54-55% water uptake efficiency was recorded in almond under surface drip irrigation. The deep drainage losses in almond accounted for 25% of the total water application. The pulsing of irrigation events produced a similar seasonal water uptake as obtained in continuous irrigation. The modelling simulations revealed that there is a need to further finetune system design and irrigation scheduling so that significant savings of water can be realised.

***Keywords:*** *Modelling, drip irrigation, deep drainage, salinity, almond, mandarin*

## 1. INTRODUCTION

The water resource management and its judicious use have been central to any irrigation development in water scarce regions including South Australia. South Australia has relied on three rain-dependent sources of water – the River Murray, the Mt Lofty Ranges catchment and groundwater resources. However, like much of the southern region of the continent, many areas of South Australia have experienced a decline in surface water flows and groundwater levels over the past decade compared to long term averages (Lamontagne et al., 2012). This has resulted in an increased threat to the security of water supplies to different sectors. Irrigation practices are, therefore, coming under closer scrutiny, driving a requirement for more efficient utilization. Hence, high frequency advance irrigation and fertigation systems have been adopted in agriculture particularly in horticultural crops to save precious water, control offsite solute movement and improve the quality of produce. The advanced fertigation systems combine drip irrigation and fertigation to deliver water and nutrients directly to the roots of the crop with the aim of synchronizing the applications with the crop demand and maintaining the desired concentration and distribution of ions and water in the soil.

Irrigated horticulture has, in general, been identified as the major source of nitrogen in drainage water in the Murray Darling Basin. About 75% of the Australian horticultural industry is located in the Murray-Darling Basin, utilising the lighter-textured free-draining soils adjacent to the Murray, Darling and Murrumbidgee rivers, and so potential off-site effects of these types of approaches may have wider implications. Hence, there is a need to evaluate the performance of these systems by monitoring temporal and spatial water and salt movement within and out of the root zone so that the irrigation scheduling can be improved and suitable measure can be adopted to check the increasing salinity levels of soil profile.

Attempts to address these issues and improving understanding and management of water and chemicals in the vadose zone have led to the development of various models to describe soil water and solute movement. Simulation models have been valuable research tools for assessing water and solute transport through the soil profile, as well as evaluating the effects of management practices on crop yields and on the environment. In fact, models have proved to be particularly useful for describing and predicting transport processes, simulating conditions which are economically or technically impossible to carry out by field experiments. Hence, the present investigation was carried out to evaluate the surface drip irrigation system for water and salinity dynamics under almond and mandarin trees using HYDRUS 2D which in turn would help in designing and managing drip irrigation systems and achieving high water and fertilizer use efficiency, thereby limiting the deep drainage and export of nutrients as a pollutant to downstream water systems.

However, the irrigation through surface drip is a three dimensional process and should have been modelled in 3 D domain. But 3D system would be computationally more demanding and unstable; hence, a simplified 2D mode was chosen assuming a similar water distribution pattern along the y-axis as suggested by Skaggs et al. (2004). Moreover, the surface wetted area and input flux under drippers would be dynamic, an option that we would not be able to model with HYDRUS in 3D. A preliminary analysis of 2D vs 3D on the present experimental data set for water and salinity distribution also revealed uniformity along y axis. Therefore we simplified the problem to 2D based on the facts sited above and field observation of uniform water distribution pattern along drip line.

## 2. MATERIALS AND METHODS

### 2.1. Field experiments

The field experiments on almond and citrus were conducted at Clark Taylor farms, in Berri, South Australia (34°20'S and 140°35'E) from July 2009 to May 2010 and Dareton Agricultural and Advisory Station (34.10ºS and 142.04ºE), in Dareton, NSW from August 2006 to August 2007, respectively. The almond orchard was planted in 1998 with a spacing of 6.1 m between rows and 6.7 m within a row while the spacing in mandarin was 5 m between rows and 2 m between plants. Soil samples were taken from various depths at the start of the experiments and analysed for physical properties. Soil at almond site was loamy sand to sand in texture to 150 cm depth while it was loam to loamy sand at mandarin site. The trees were managed and fertilized following current commercial practices.

The climate at the sites is Mediterranean type characterized by warm to hot, dry summers and mild to cold winters. The weather parameters were taken from nearby observatories for the modelling purpose. The rainfall recorded during 2006-07 and 2009-10 was 187 mm and 220 mm, respectively. The orchards were surface drip irrigated, with two laterals placed on either side of tree line at equi-distance from the tree lines. Water for irrigation was pumped directly from the River Murray with a separate water meter installed for each treatment to account for the volume of water applied. The salinity of the irrigation water ranged between

0.02 to 0.52 dS/m which is well within the permissible limit for irrigation. The average flow rate of the drippers was 3.87 L/h and 1.6 L/h for almond and mandarin, respectively. In almond, neutron probe access tubes were installed to monitor profile soil water distribution at weekly intervals. While in mandarin, Sentek® EnviroSCAN® logging capacitance soil water sensors used to determine daily water content in soil. Soil water samples were extracted on a weekly basis using SoluSAMPLERs™ (only in mandarin) to determine spatial and temporal soil solution salinity ($EC_{sw}$) distribution.

## 2.2. Numerical modelling

Soil water and salinity distributions below the drip line were simulated with the numerical model HYDRUS2.xx (Šimůnek et al., 2011). The governing two-dimensional flow equation is described by a modified form of Richards equation as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K(h)\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z} + K(h)\right) - S(h) \quad (1)$$

where $\theta$ is the soil water content ($L^3/L^3$); t is the time (T); h is the soil pressure head (L); x is the horizontal coordinate; z is the vertical coordinate (positive upwards); K(h) is the hydraulic conductivity and S(h) is the sink term represents root water uptake (1/T). Root water uptake reductions due to water stress, were described using the piecewise linear model proposed by Feddes et al. (1978).

The soil hydraulic parameters were modelled using the water retention and hydraulic conductivity function described by the van Genuchten-Mualem constitutive relationship (van Genuchten, 1980). The governing advection-dispersion equation for the simulation of the transport of a single non-reactive ion in homogeneous medium is described as:

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_i}\right) - \frac{\partial q_i c}{\partial x_i} \quad (2)$$

where $\theta$ is the volumetric water content ($L^3\ L^{-3}$), $c$ is the solute ($EC_{sw}$) concentrations in the liquid phase ($M\ L^{-3}$), subscripts i and j denote either x (horizontal coordinate) or z (vertical coordinate), The first term on the right hand side of the equation represents the solute flux due to dispersion, and the second term the solute flux due to convection with flowing water. Water flux ($q$) is computed from Eq. (1) and Dij is the dispersion coefficient ($L^2T^{-1}$). The presented application neglects molecular diffusion. The detailed information on the model can be obtained from technical manual (Šimůnek et al., 2011).

## 2.3. Estimation of Input parameters

Potential transpiration ($T_{pot}$) and potential evaporation ($E_s$) were calculated separately for both crops from the reference evapotranspiration ($ET_0$) values collected from the Meteorological Stations, following the dual crop coefficient method (Allen et al., 1998), to serve as an input for the model. This method is based on splitting the crop coefficient (Kc) into two separate coefficients, one for crop transpiration, i.e. basal crop coefficient (Kcb) and one for soil evaporation (Ke) as:

$$Kc = (Kcb + Ke)ETo \quad (3)$$

The seasonal $T_{pot}$ for almond amounts to 1380 mm and $E_s$ for the same period was 414 mm. The corresponding numbers for mandarin were 696 mm and 174 mm, respectively.

The soil hydraulic parameters viz. $\theta r$, $\theta s$, $Ks$, $\alpha$, $n$ and $l$ were estimated from ROSETTA, a pedotransfer function software package that uses a neural network model to predict hydraulic parameters from soil texture and bulk density data. The value of $l$ was taken as 0.5 as recommended in many studies. The root distribution was described using the (Vrugt et al., 2001) two dimensional model adapted in HYDRUS. The reducing effects of both soil water pressure head and osmotic head on root water uptake were included, assuming their effects were multiplicative.

Longitudinal dispersivity was considered to be 20 cm which is equal to one-tenth of the profile depth and this was optimised by previous studies (Phogat et al., 2012, 2013). The molecular diffusion was neglected. The $EC_{sw}$ were assumed to be present only in the dissolved phase ($K_d$ = 0 $cm^3\ g^{-1}$). The simulation output included the spatial and temporal variations of soil water content and soil water salinity, soil water pressure head, and the total water and salt mass in the simulated soil profile.

## 2.4. Initial and boundary conditions

The detailed mathematical and graphical descriptions of the boundaries adapted to the two dimensional flow for almond can be obtained from Phogat et al., (2012, 2013). All initial conditions for water content and salinity were based on field measurements done before the start of the experiment. The soil surface was subjected to atmosphere boundary condition with a variable flux imposed by dripper discharge resulting in two dimensional vertical flow. The potential transpiration ($T_{pot}$), potential evaporation ($E_s$) and rainfall were used to represent the atmospheric boundary condition while irrigation events represent time variable boundary condition. The sides perpendicular to the flow direction were no flow boundaries and free drainage conditions occurred at the bottom boundary since the water table was about 20 m deep. In case of solute transport, the boundary condition representing salinity was a third-type Cauchy boundary condition that prescribes the salt movement during defined irrigation intervals. The measured salinity of irrigation water ($EC_w$) was used as a time variable boundary condition.

## 2.5. Flow domain and simulations

Simulations were made during a 316 days period from 20 July 2009 to 31 May 2010 for almond and for 365 days period for mandarin from 21 August 2006 to 20 August, 2007. The simulated surface drip irrigation system design characteristics were typical of the drip systems used for the field experiments. The simulated model domain was 335 cm x 200 cm for almond and 250 cm x 150 cm for mandarin (one fourth of the bed spacing). The transport domain was discretized into finite elements with a very fine grid around the dripper and gradually increasing elements farther from the drip. The drip irrigation was simulated assuming an infinite line source, which was shown previously by many studies to be a good representation of the drip irrigation system. Observation nodes were selected at specific locations in the domain to monitor levels of soil water salinity and content with time as simulated by the HYDRUS model.

## 3. RESULTS AND DISCUSSION

The weekly measured profile averaged water content and corresponding HYDRUS-2D simulated values were compared for the whole growing season as shown in Fig. 1 for mandarin. The measured moisture content remained between 0.15 and 0.2 $cm^3cm^{-3}$ throughout the growing season, indicating a favourable moisture regime in the crop root zone. Similar matching of soil moisture regimes were also obtained in almond. Other studies have also reported similar performance of HYDRUS model (Ramos et al., 2012; Phogat et al., 2012, 2013). These studies have cited a number of reasons for divergence in simulated values of water content such as 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. In spite of these small divergences in water content, it is accepted that the daily irrigation application and discharge variability were very well captured by the modelling simulations in both crops.

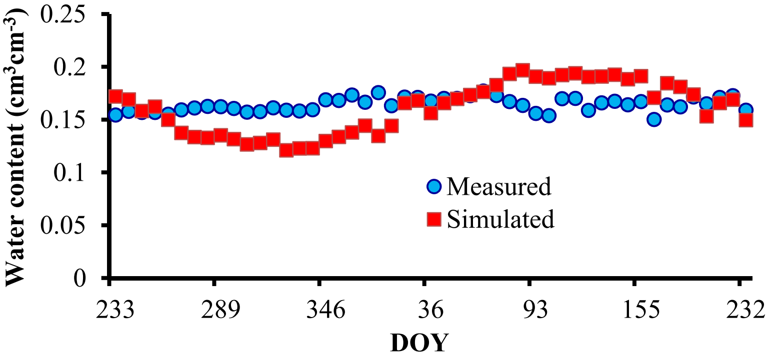

**Figure 1**. Comparison of weekly measured and simulated water content in soil under mandarin tree.

The weekly determined RMSE values between measured and corresponding simulated values were used to draw box plots for both crops as shown in Fig. 2. The RMSE values ranged from 0.005 to 0.06 $cm^3cm^{-3}$ in

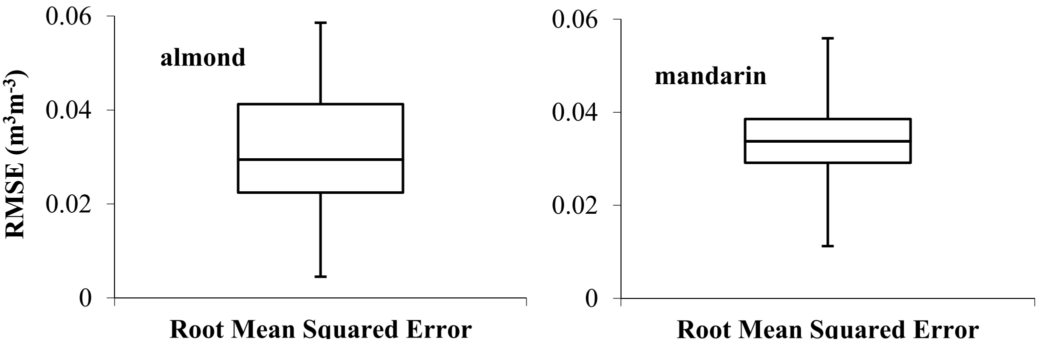

**Figure 2.** RMSE values between measured and simulated water content in almond and mandarin.

almond and 0.01-0.06 cm$^3$cm$^{-3}$ in mandarin. However the inter quartile range in almond was slightly wider than mandarin but the most values falls within 0.02-0.04 cm$^3$cm$^{-3}$ range. The variation of this magnitude in water content is also encountered in field determination of moisture content by neutron probe and EnviroSCAN probes. Similarly, the comparison between measured and model predicted values of salinity (EC$_{sw}$) under mandarin also matched well and RMSE ranged between 0.09 to 0.93 dS m$^{-1}$ which is well within the acceptable limit in a complex and highly dynamic soil system. This statistical comparison further confirms that the HYDRUS 2D was able to capture the process of water movement and salinity distribution in soil under both trees under diverse soil-water-plant-atmospheric conditions throughout the growing season.

The model simulated weekly EC$_{sw}$ averaged for the whole domain under almond and mandarin trees are showed in Fig.3. Initially the salinity was relatively higher under almond which reduced substantially after one month profile establishment period when irrigation was applied irrespective of crop demand to flush the salts out of the soil to facilitate vigorous growth. The EC$_{sw}$ remained equal to 1 dS/m or below after about 2 months of simulation. The maximum salinity (1.41 dS/m) during summer season was observed on 23/12/2010. However in mandarin the EC$_{sw}$ increased as the season progressed and attained a maximum value of 1.85 dS/m during the summer season. Thereafter the EC$_{sw}$ decreased continuously till the end of the season. The EC$_{sw}$ remained below threshold in both trees (almond = 3 dS/m, mandarin 3.4 dS/m) throughout the growing season. The weekly simulated values matched well with the measured values in mandarin (not shown here). Hence HYDRUS 2D produced real time salinity distribution all along the growing season under both trees.

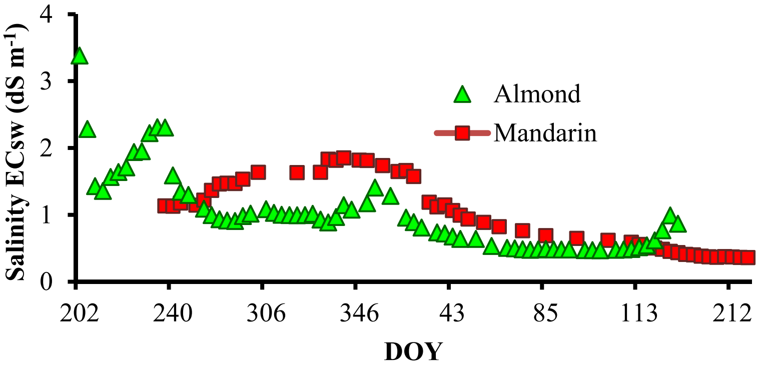

**Figure 3.** Simulated weekly soil water salinity (EC$_{sw}$) under almond (Δ) and mandarin (□). DOY represents the days of the year.

Simulations were also performed for sustained deficit conditions in almond where irrigation application was curtailed by 35% (65% ET$_C$) throughout the growing season. The spatial distribution of moisture content and corresponding EC$_{sw}$ distribution in the domain under 65% irrigation applications on various dates is depicted in Fig. 4. It can be seen that the water content and salinity distribution are highly synchronized e.g. on 23/7/2009 water content plume develops as the heavy irrigations were applied during profile establishment stage resulting in decrease in salinity in the same order in the domain. Similarly during summer season a dry zone extends just below the emitter as shown for 10/12/2009 resulted in increase in the EC$_{sw}$ ranged between 4-6 dS/m. The maximum average salinity of 3.55 dS/m was observed on 23/12/2010 which was more than 2.5 time of salinity observed under full irrigation of almond. The salinity decreased substantially during the post-harvest time due to excess irrigation and rainfall and resultant EC$_{sw}$ was below 1.5 dS/m. Hence, salinity remained under threshold (EC$_{sw}$ = 3 dS/m) value of almond during whole season except few days during summer. Therefore, water flux through drippers acts as a leaching fraction and leached the salts out of the domain, thereby keeping the soil relatively salt free. This in turn encourage vigorous root development, and assist plant growth even under water stress conditions and saline environment in the adjoining region.

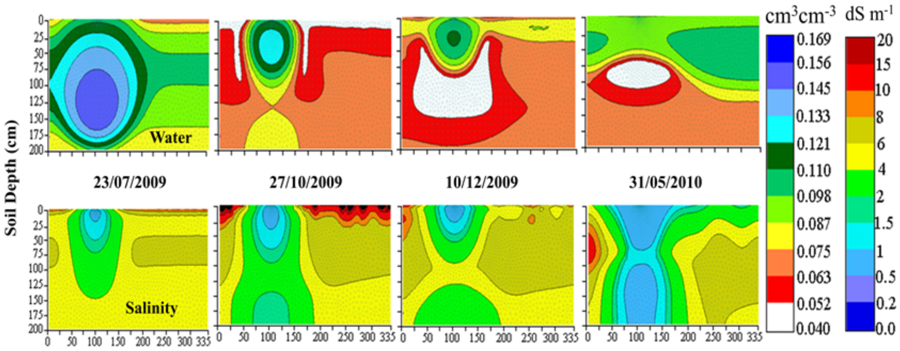

**Figure 4.** Evolution of water content (cm$^3$cm$^{-3}$) and salinity (dS m$^{-1}$) distribution in soil under almond at indicated times.

The seasonal water balance components under almond and mandarin obtained from the modelling simulations are shown in Table 1. The total water uptake by almond was 1050 mm which is 55% of the total water application through irrigation and rain. Almost similar magnitude of water uptake (49% of the applied) was observed in mandarin also which amounts to 307 mm of total water application. However, the drainage component was substantially higher under mandarin than almond which accounted for 34% (211 mm) of the water application. In almond the drainage fraction was 0.25 (488.5 mm). It suggested that there is a room for further finetuning the irrigation scheduling in both crops particularly during post-harvest time where a lot of leaching was happening in both trees. The evaporation losses were almost similar (16-17%) under both trees. The modelling simulation also contained a small error component (0.22- 0.67%) in water balance (Table 1). Hence modelling simulations were helpful in evaluating the overall water dynamics in soil under both trees which may be utilized to improve the irrigation scheduling of these crops so that drainage component can be reduced and irrigation efficiency of crops can be improved.

**Table 1.** Simulated seasonal water balance components under almond and mandarin.

| | Components | Almond | | Mandarin | |
|---|---|---|---|---|---|
| | | (mm) | (%) | (mm) | (%) |
| Sources | Irrigation | 1686.05 | 88.46 | 432.68 | 69.16 |
| | Rainfall | 220.04 | 11.54 | 171.13 | 27.35 |
| | Soil water depletion (-)/ storage (+) | (+) 53.16 | 2.79 | (-) 21.80 | 3.48 |
| Sinks | Root uptake | 1050.50 | 55.11 | 307.3 | 49.12 |
| | Drainage | 488.51 | 25.63 | 210.94 | 33.72 |
| | Evaporation | 309.70 | 16.25 | 111.56 | 17.83 |
| Water balance error (%)* | | 4.22 | 0.22 | -4.79 | -0.67 |

$$^{*}\text{Water balance error (\%)} = \left(\frac{\sum W_{source} - \sum W_{\sin k}}{\sum W_{source}}\right) x100$$

## 4. CONCLUSIONS

This study demonstrates the relevance of numerical modelling in evaluating the water and salt dynamics under drip irrigated horticultural trees. The study revealed that HYDRUS-2D software reproduced the temporal and spatial dynamics of water and salinity distribution in the soil domain, producing comparable values of seasonal moisture distribution equivalent to those measured in field experiments on almond and mandarin. Model produced water balance showed that 55% applied water was lost to the environment through transpirational stream of almond tree. This figure for mandarin was slightly less (49%). A major outcome of the study was the revelations about the deep drainage under highly efficient drip irrigation system which amounted to 25% under almond and 34% under mandarin indicating that there is need to further finetune our irrigation scheduling so that unnecessary flux of water out of the system can be reduced which in turn would help in reducing the danger of movement of solutes out of the system. Seasonal salinity predictions would be helpful in managing the drip irrigation systems for controlling the salinity impact and maintaining the sustainability of the irrigation system. However, there is a need to further improve the modelling estimates, considering all processes of salt dynamics in the soil system and carrying out the simulations in three dimensional mode. It is concluded that such studies would help in improving the irrigation efficiency of horticultural crops irrigated with drip irrigation systems, and would lead to more efficient and less environmentally detrimental crop management practices.

## ACKNOWLEDGMENTS

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