

# Evaluation of crop coefficients, water productivity, and water balance components for wine grapes irrigated at different deficit levels by a sub-surface drip



V. Phogat<sup>a,\*</sup>, M.A. Skewes<sup>a</sup>, M.G. McCarthy<sup>a</sup>, J.W. Cox<sup>a,b</sup>, J. Šimůnek<sup>c</sup>, P.R. Petrie<sup>a,d</sup>

<sup>a</sup> South Australian Research and Development Institute, GPO Box 397, Adelaide SA 5001, Australia

<sup>b</sup> The University of Adelaide, PMB1 Glen Osmond SA 5064, Australia

<sup>c</sup> Department of Environmental Sciences, University of California, Riverside, CA 92521, United States

<sup>d</sup> The Australian Wine Research Institute, GPO Box 197, Adelaide SA 5001, Australia

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## ABSTRACT

Accurate estimation of evapotranspiration ( $ET$ ) and its partitioning into transpiration and evaporation is fundamental for improving water management practices in water-limited environments and under deficit irrigation conditions. This investigation was conducted to estimate the water balance and  $ET$  components of subsurface drip (SDI) irrigated Chardonnay wine grapes for two seasons (2010–2011 and 2011–2012) using a numerical model (HYDRUS-2D). Treatments involved the application of different volumes [51% ( $I_1$ ), 64% ( $I_2$ ), 77% ( $I_3$ ), and 92% ( $I_4$ ) of normal application] of water for irrigation. A modified version of the FAO-56 dual crop coefficient approach was used to generate daily transpiration and evaporation as inputs to the HYDRUS-2D model. The calibrated and validated model produced estimates of actual evapotranspiration ( $ET_{cact}$ ), actual transpiration ( $T_{pact}$ ), and actual evaporation ( $E_{sact}$ ), and deep percolation under varied irrigation applications. The model-simulated values were then used to estimate actual crop coefficients ( $K_{cact}$  and  $K_{cbact}$ ), and water productivity of wine grape under different deficit irrigation conditions.

Seasonal  $ET_{cact}$  simulated by HYDRUS-2D for different treatments varied between 239 and 382 mm. However, seasonal evaporation accounted for 44–59% of seasonal  $ET_{cact}$  losses in different treatments. The modelled daily transpiration rate in  $I_4$  treatment ( $T_{pact}$ ) varied from 0.11–2.74 mm/day. Deep percolation accounted for 35–40% of the total water applied by rainfall and irrigation. The mean value of actual crop coefficient ( $K_{cact}$ ) estimated by HYDRUS-2D simulated  $ET_{cact}$  over the two seasons was 0.27, which matched with other investigations. Similarly, values of  $K_{cbact}$  for initial, mid and end stages were 0.13, 0.27 and 0.14, respectively. Monthly values of evaporation coefficient ( $K_e$ ) ranged from 0.1 to 0.32, with a mean value of 0.18. Water productivity with respect to  $ET$  losses ( $WPET_C$ ) ranged from 5.9 to 6.2 kg/m<sup>3</sup> of water use. However, water productivity for transpiration ( $WPET_T$ ) almost doubled as compared to  $WPET_C$  in all treatments. The impact of deficit irrigation on berry juice composition (Brix, pH and titratable acidity) was lower than the inter-seasonal variability. These results can help develop better irrigation management strategies for SDI irrigated wine grapes under water scarce conditions.

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## 1. Introduction

Seasonal management of irrigation water is the most crucial decision that farmers have to contemplate for sustainable and profitable crop production, particularly in the arid and semiarid regions of the world where water availability for irrigation is not

assured. The majority of high value horticultural orchards and vineyards in Australia are primarily dependent on irrigation. For example, 90% of Australian vineyards rely on some assured irrigation arrangement (Australian Bureau of Statistics, 2012). The allocation of water for irrigation in South Australia is highly influenced by the amount of seasonal rainfall on the eastern Australian high ranges and subsequent storage and flow in the Murray Darling river system. During drought years (2006–2009) the water allocation was severely reduced, to levels as low as 18% of normal allocations, which had serious repercussions on the sustainable

\* Corresponding author.

E-mail address: [vinod.phogat@sa.gov.au](mailto:vinod.phogat@sa.gov.au) (V. Phogat).

production and resilience of vineyards and orchards. Similar conditions with limited availability of irrigation water occur in other arid and semi-arid regions of the world. As a consequence, judicious water use, long-term sustainability and increasing efficiency, i.e., improving the yield to water consumption ratio, become major priorities in viticulture.

Considerable research has been undertaken on various deficit irrigation techniques, such as regulated deficit irrigation (e.g., Costa et al., 2007; Romero et al., 2010, 2013; Santesteban et al., 2011; Edwards and Clingeleffer, 2013; Acevedo-Opazo et al., 2010; Faci et al., 2014), sustained deficit irrigation (e.g., Fereres and Soriano, 2007; Chalmers et al., 2010; Williams, 2010; Williams et al., 2010a,b), and partial root zone drying (e.g., Dry and Loveys, 1998; McCarthy et al., 2000; Intrigliolo and Castel, 2009; Sadras, 2009; Romero et al., 2015), in order to evaluate their impact on water use, yield, berry composition, and wine attributes. However, most of these studies were driven by the need to control vine vigour and maximize fruit quality rather than the need to improve the vineyard water use efficiency (Edwards and Clingeleffer, 2011) and water productivity. Moreover, research results on water use with respect to the application of deficit irrigation techniques under field conditions and the long-term impacts on production have been found to be contradictory (Chaves et al., 2010; Sadras, 2009), which suggests that site specific factors played a major role in evaluating the impact of deficit irrigation in these studies. In addition, most of these studies dealing with deficit irrigation are based on conventional drip or sprinkler irrigation. However, sub-surface drip irrigation (SDI) could have a different impact on water use, potential water losses, and overall vine performance compared to conventional drip and other irrigation methods. A few comparative studies (Fandiño et al., 2012; Cancela et al., 2015) showed slightly higher vine water uptake and crop coefficients under SDI than under conventional drip. Hence, there is need to evaluate the water balance components for wine grapes under SDI, and under varying volumes of irrigation application.

A wide range of methods and techniques have been used for estimating vineyard *ET* and water use, including lysimeter (Williams and Ayars, 2005; Netzer et al., 2009), sap flow (Lascano et al., 1992; Yunusa et al., 1997, 2000, 2004; Ferreira et al., 2012), Bowen ratio (Yunusa et al., 2004; Zhang et al., 2011), surface energy balance (Castellví and Snyder, 2010; Moratíel and Martínez-Cob, 2012), eddy covariance (Ortega-Farias et al., 2010; Rodríguez et al., 2010), soil water balance (Singleton and Maudsley, 1996; Fooladmand and Sepaskhah, 2009), and a combination of field measurements (Trambouze et al., 1998; Cancela et al., 2012; Styles et al., 2015). However, intensive field measurements of these agro-hydrological fluxes require large investment in sensors, labour, and time. On the other hand, precise estimation of the dynamics of evaporation and transpiration could help in judicious management of scarce water resources in drip-irrigated high-value cropping systems (Yunusa et al., 2004; Ortega-Farias et al., 2012). Besides evaporation and transpiration, reliable understanding of the drainage fraction is critical for better identification of productive and unproductive fractions of water for SDI, especially under sustained deficit conditions.

Numerical models are ideally suited to evaluate water balance in drip irrigation systems, and to study the importance of and interaction among various water fluxes under sparse vegetation and for different supplementary irrigation conditions. HYDRUS-2D/3D (Šimůnek et al., 2008, 2016) is a widely used numerical model simulating water flow in soils under cropped conditions. This model has been previously used to study *ET* components, for example, for almond (Phogat et al., 2012, 2013), maize (Ramos et al., 2012), citrus (Phogat et al., 2014), and other crops (Mei-Xian et al., 2013; González et al., 2015). Recently, Kool et al. (2014a) has successfully used this model for the estimation of evaporation losses from a

commercial vineyard in combination with short term above canopy measurements of climatic parameters.

The objectives of this study thus were to (a) calibrate and validate HYDRUS-2D under deficit sub-surface drip irrigation of wine grape, (b) to estimate water balance and actual *ET* components of wine grape, and compare them under different SDI deficit irrigation treatments, (c) to estimate the actual crop coefficients of wine grapes, and (d) to assess yield, wine quality parameters and water productivity of Chardonnay wine grape under SDI under different deficit irrigation treatments, and compare these to other published research.

## 2. Materials and methods

### 2.1. Experimental details

A field experiment was conducted in the Markaranka vineyard (34.08°S and 139.87°E), located near Waikerie in South Australia. The Chardonnay wine grapes (clone Bernard 95) on Ramsey rootstock were planted in November 2004 at a vine spacing of 2.5 m and row spacing of 3.35 m, and were irrigated using subsurface drip (SDI). Monitoring of the experimental site was initiated in November 2010 and continued for two seasons. The soils at the site are predominately light textured, ranging from sand to loamy sand, with the sand content in the range of 84–91%, the clay content from 9 to 13%, and the silt content from 0 to 3%. The climate is characterized as dry, with warm to hot summers and mild winters. The total rainfall during the experimental period from 22 September 2010 to 30 June 2011 was 338 mm (Fig. 1), and from 7 September 2011 to 30 June 2012 was 236 mm. Unusually high precipitations of 95.2 and 68.2 mm occurred on 8 December 2010 and 14 January 2011, respectively, during the first season. Similar heavy summer rainfalls of 58.2 mm and 42 mm occurred on 17 December 2011 and 29 February 2012, respectively, during the second season. The grass reference *ET* ( $ET_0$ ) was calculated using a modified Penman-Monteith equation, which incorporates a number of weather and energy balance parameters, as described in Allen et al. (1998). Estimated  $ET_0$  during 2010–11 and 2011–12 seasons was 904 and 1055 mm, respectively (Fig. 1). The maximum daily  $ET_0$  was estimated to be 8.4 mm on January 1, 2012. Mild frost conditions occurred during the winter months. Weather data were collected from an automated weather station located at Qualco, 4 km from the trial site.

The grapevine growth season at the field site started with budburst in late August–late September. Full leaf cover was attained before flowering, which started in late November and/or early December. The leaves remained active for 3 months till the end of March. The fruit yield and yield attributes (number of bunches per vine, average bunch weight) were recorded for all the treatments plots. Juice from a fresh fifty berry sample was extracted using a small hand-held press and centrifuged at 3000 rpm for 5 min. A bench-top refractometer was used to determine Total Soluble Solids (expressed as °Brix). A 10 mL sample of clear juice was used for the determination of pH and Titratable acid using an automated end-point titrator pH 8.2 with 1 M NaOH (Amerine, 1965).

### 2.2. Irrigation treatments and water content measurements

The irrigation system at the experimental site consisted of a pressure compensated drip system (Toro Drip-In® Rootguard®), with an emitters discharge rate of 1.6 L h<sup>-1</sup> and a spacing of 40 cm. The SDI drip lines were installed at a depth of 25 cm, 25 cm away from the vine line. Water for irrigation was pumped directly from the Murray River. Irrigation treatments were designed to test the

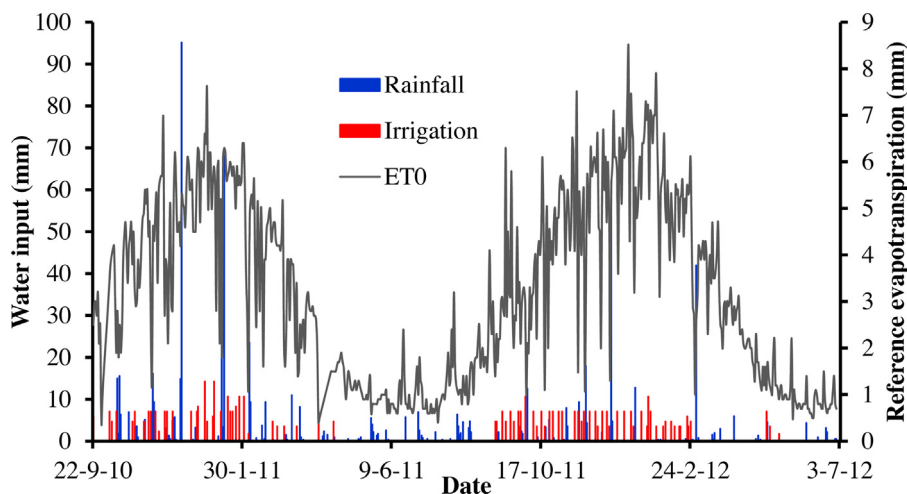


Fig. 1. Rainfall, irrigation (for treatment  $I_4$ ), and reference evapotranspiration ( $ET_0$ ) at the experimental site from 22 September 2010 to 30 June 2012.

impact of different SDI volumes on  $ET$  components, yield and water productivity of Chardonnay wine grape.

Four irrigation treatments with different irrigation event lengths were established, resulting in applications of about 51 ( $I_1$ ), 64 ( $I_2$ ), 77 ( $I_3$ ), and 92 ( $I_4$ )% of the total amount of irrigation applied by the grower to the rest of the Chardonnay vineyard. The irrigation event length in  $I_4$  was similar to full irrigation applied by the grower in the rest of the vineyard. However, different application rates at the experimental area and in the reminder of the vineyard allowed 92% of full irrigation in  $I_4$  treatment. In other treatments ( $I_1$ ,  $I_2$ ,  $I_3$ ), timers were fitted on the drip laterals to apply different deficit irrigations. Each treatment consisted of nine vines irrigated using the same lateral, and all treatments were replicated 5 times. A similar irrigation application rate, timing and schedule was followed for all replicates of different treatments. Total irrigation water applied during 2010–11 amounted to 137, 171, 202, and 240 mm in  $I_1$ ,  $I_2$ ,  $I_3$  and  $I_4$  treatments, respectively. Corresponding values for different treatments during 2011–12 were 155, 195, 232, and 278 mm, respectively. The irrigation depths and timing of irrigations for  $I_4$  are shown in Fig. 1.

The irrigation in the entire vineyard, including the experimental area, was scheduled by the vineyard manager based on biweekly soil moisture monitoring using a portable capacitance sensor (Diviner, 2000, Sentek, Stepney, South Australia). Irrigation was applied when the soil water content reached the refill point, i.e., the soil water content for which the rate of water extraction would start to diminish. This point occurred when total available water in the soil profile (100 cm) ranged between 30 and 35 mm which was estimated using the procedure outlined in McMullen (2000). A regulated deficit irrigation strategy was not applied at any stage of the season. The aggregate irrigation application to the reminder of the vineyard was 260 mm and 302 mm for the 2010–11 and 2011–12 seasons, respectively.

Water content in the soils at the experimental site was monitored at soil depths of 15, 30, 60, and 90 cm. Theta probes were installed in  $I_1$  and  $I_2$  treatments, approximately 10 cm away from the drip line. The Theta probes were manufactured by Delta-T Devices Ltd, and were equipped with TBug loggers manufactured by Measurement Engineering Australia. These probes were calibrated for the experimental site by the gravimetric method. The probes collected water content data at 15-min intervals. However, the last reading of water content for each day was compared with modelling output predicted at the same time at the four monitored depths.

In treatments  $I_3$  and  $I_4$ , gypsum block sensors (GB-Lite) were installed for measuring the spatial and temporal water tension distribution in the soil. These sensors, also known as Watermark sensors, were manufactured by Irrrometer and distributed by Measurement Engineering Australia. The working range for these sensors is from 0 to 200 kPa. Separate sensors were installed for each depth (15, 30, 60 and 90 cm) with a 10 cm horizontal offset along the drip line between adjacent sensors at different depths. These sensors are pre-calibrated and do not require any calibration specific to field conditions. The GB-Lite's were fitted with GBug loggers, and logged the soil tension at an interval of 2 h. The soil tension values were converted to water content using the  $\theta$ - $h$  relation estimated for each depth for the experimental site (Phogat et al., 2016). The water content values thus estimated at different depths and times were compared with the corresponding water content values simulated by HYDRUS-2D.

### 2.3. Numerical modelling

HYDRUS-2D (Šimůnek et al., 2008) software simulates two-dimensional variably-saturated water flow, heat movement, and transport of solutes involved in sequential first-order decay reactions. The governing two-dimensional water flow equation is described as follows:

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

where  $\theta$  is the soil water content ( $L^3 L^{-3}$ );  $t$  is time (T);  $h$  is the soil water pressure head (L);  $x$  is the horizontal coordinate;  $z$  is the vertical coordinate (positive upwards);  $K(h)$  is the hydraulic conductivity ( $LT^{-1}$ ), and  $S(h, x, z, t)$  is the sink term accounting for water uptake by plant roots ( $L^3 L^{-3} T^{-1}$ ).

Root water extraction  $S(h, x, z, t)$  from the soil is computed according to the Feddes macroscopic approach (Feddes et al., 1978). In this method, the potential transpiration rate,  $T_p$ , is distributed over the root zone using the normalized root density distribution function,  $\beta(x, z)$ , and multiplied by the dimensionless water stress response function,  $\alpha_1(h, x, z)$  as:

$$S(h, x, z, t) = \alpha_1(h, x, z) \beta(x, z) T_p(t) * L_p \quad (2)$$

where  $L_p$  is the surface length associated with transpiration (i.e. the lateral extent of the area explored by the roots to access water for transpiration). This model assigns plant root water uptake rates

according to potential transpiration, the spatial root distribution, and the local soil water pressure head,  $h$ , at any point in the root zone. Eq. (2) defines the manner, in which potential transpiration ( $T_p$ ) is reduced below its potential value when the soil is no longer capable of supplying the water required by the plant under the prevailing climatic conditions. In the absence of solute stress, the reduction of root water uptake due to the water stress,  $\alpha_1(h, x, z)$ , is described as:

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

where  $h_1, h_2, h_3$ , and  $h_4$  are the threshold model parameters. Water uptake is at its 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  $h > h_1$ . These critical values of pressure heads for wine grape were taken from [Rallo et al. \(2012\)](#).

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

$$\beta(x, z) = \left[ 1 - \frac{z}{z_m} \right] \left[ 1 - \frac{x}{x_m} \right] e^{-\left( \frac{p_z}{z_m} |z^* - z| + \frac{p_x}{x_m} |x^* - x| \right)} \quad (4)$$

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.

Location of maximum root uptake was assumed to be concentrated mainly near the drip emitter where water and nutrients were applied, although not right at the dripper ( $x^* = 30$  cm,  $z^* = 25$  cm). [Soar and Loveys \(2007\)](#) reported the maximum root density of drip-irrigated vines between soil depths of 25 and 50 cm. Similarly, [Styles et al. \(2015\)](#) reported the maximum root mass density at the 30 cm depth in a drip-irrigated vineyard in South Australia. However, these studies reported variable maximum depth distribution (60–100 cm) of roots in the soil. These parameters ( $x_m, z_m, z^*, x^*, p_x$  and  $p_z$ ) are highly variable in space and time, difficult to measure in the soil, directly influence the water uptake by plants and consequently water content distribution in the soil profile. Hence, parameters except maximum rooting depth ( $z_m = 100$  cm) and maximum horizontal extension ( $x_m = 150$  cm) were optimized during calibration by trial and error and by comparing the measured and simulated water content distribution. No significant volume of roots was found outside of the specified area in field observations.

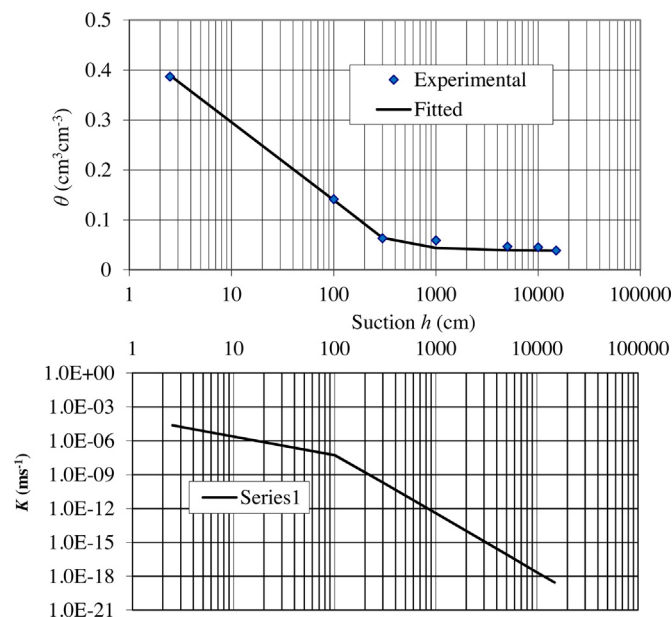
#### 2.4. Input parameters for HYDRUS

Applying HYDRUS to field conditions requires numerous soil, water, crop, and weather parameters, which are discussed in the following sections.

**Table 1**

Soil hydraulic parameters for the van Genuchten-Mualem function ([van Genuchten, 1980](#)) and the bulk density for different soil layers at the experimental site.

Depths (cm)	Soil texture	Soil hydraulic parameters						Bulk density (g cm <sup>-3</sup> )
		$\theta_r$ (cm <sup>3</sup> cm <sup>-3</sup> )	$\theta_s$ (cm <sup>3</sup> cm <sup>-3</sup> )	$\alpha$ (cm <sup>-1</sup> )	$n$	$K_s$ (cm d <sup>-1</sup> )	$l$	
0–15	Sand	0.04	0.41	0.03	2.09	561.60	0.52	1.50
15–30	Loamy sand	0.04	0.39	0.03	2.29	216.00	0.56	1.57
30–60	Loamy sand	0.05	0.38	0.04	1.70	259.20	0.41	1.41
60–100	Loamy sand	0.05	0.37	0.04	1.62	172.80	0.38	1.44



**Fig. 2.** Measured and fitted ([van Genuchten, 1980](#)) relationships between volumetric water content ( $\theta$ ) and pressure head ( $h$ ); and a predicted relationship between hydraulic conductivity ( $K$ ) and pressure head ( $h$ ) for the 15–30 cm soil layer.

#### 2.4.1. Soil hydraulic properties

The soil hydraulic properties are modelled using the water retention and hydraulic conductivity functions described by the van Genuchten-Mualem constitutive relationship ([van Genuchten, 1980](#)):

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^m} \quad h < 0 \quad (5)$$

$$\theta(h) = \theta_s \quad h < 0 \quad (6)$$

$$K(h) = K_s S_e^l \left[ 1 - (1 - S_e^{1/m})^m \right]^2 \quad (7)$$

where  $\theta_s$  is the saturated water content (L<sup>3</sup> L<sup>-3</sup>),  $\theta_r$  is the residual water content (L<sup>3</sup> L<sup>-3</sup>),  $K_s$  is the saturated hydraulic conductivity (LT<sup>-1</sup>),  $l$  is a shape factor, and  $m, \alpha$ , and  $n$  are empirical parameters where  $m = 1 + 1/n$ .  $S_e$  is the relative saturation (dimensionless) and is defined as

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (8)$$

Water content and pressure potential relations for undisturbed soil core samples from different depths (0–15, 15–30, 30–60 and 60–100 cm) at 4 locations were measured in a pressure plate apparatus. Values for each depth were determined as the average of the 4 sites at that depth. The van Genuchten-Mualem constitutive relationship ([van Genuchten, 1980](#)) was fitted to measured soil water retention data and used to predict the unsaturated hydraulic conductivity function. Resulting  $\theta$ - $h$  and  $K$ - $h$  relationships are depicted in [Fig. 2](#) for the 15–30 cm soil depth. The



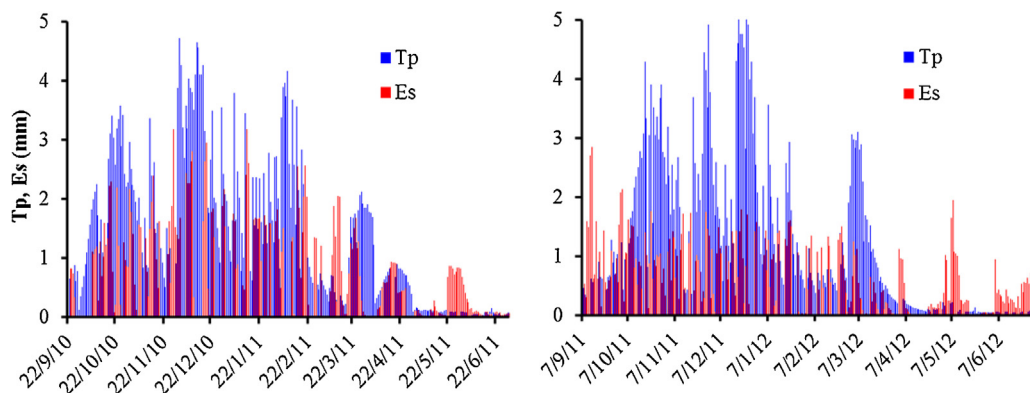


Fig. 3. Daily transpiration ( $T_p$ ) and evaporation ( $E_s$ ) for wine grapes estimated by modified FAO-56 for  $I_4$  irrigation treatment.

saturated hydraulic conductivity ( $K_s$ ) and bulk density were measured on undisturbed cores following standard procedures (Klute, 1986). The soil hydraulic parameters utilized in HYDRUS-2D simulations are given in Table 1 and also described in section 2.3 and Table 1 of Phogat et al. (2016).

#### 2.4.2. Estimation of evaporation ( $E_s$ ) and – transpiration ( $T_p$ )

HYDRUS-2D requires daily estimates of transpiration ( $T_p$ ) and evaporation ( $E_s$ ) as input parameters so that it can simulate corresponding actual values of  $ET$  components ( $ET_{Cact}$ ,  $T_{pact}$ , and  $E_{sact}$ ) for a given soil, climate, crop, and irrigation conditions. In this study, the daily inputs of  $T_p$  and  $E_s$  for HYDRUS-2D were estimated using a modified FAO-56 dual crop coefficient approach (Phogat et al., 2016), in which the evaporation coefficient ( $K_e$ ) for SDI was adjusted by adopting the new fraction representing the amount of irrigation depth that moves to the evaporation zone ( $f_{I,E_s}$ ). Details about the estimation of daily  $E_s$  and  $T_p$  involving soil, water, climate, and vineyard crop parameters for two seasons (2010–11 and 2011–12), are described in section 2.5 of the companion manuscript (Phogat et al., 2016). The daily values of  $T_p$  and  $E_s$  for two seasons (2010–11 and 2011–12) for  $I_4$  treatment are shown in Fig. 3. Similarly, the values of these parameters in other treatments ( $I_1$ ,  $I_2$  and  $I_3$ ) were estimated by varying the amount of irrigation and crop related parameters. A similar strategy has been adopted by González et al. (2015) for modelling soil water dynamics for full and deficit irrigated maize using HYDRUS-1D.

#### 2.4.3. Initial and boundary conditions

The flow domain and prescribed boundary conditions are illustrated in Fig. 4. The simulated domain was 100 cm deep and 335 cm wide (the row spacing at the field site), perpendicular to a vine row. The transport domain was discretized into 16,502 elements with a very fine grid around the dripper (0.3 cm) and gradually increasing element spacing farther from the dripper (up to 3 cm). The drip tubing was depicted as a 1 cm radius circle 25 cm below the surface. SDI irrigation was simulated assuming an infinite line source, which was shown previously (Skaggs et al., 2004; Hanson et al., 2008; Phogat et al., 2012) to be a good representation of the drip irrigation system.

A time-variable flux boundary condition was specified around the drip tubing. During water applications, a constant water flux was imposed on the variable flux boundary equal to the water application rate. Boundary water flux was calculated depending on the emitter discharge rate and a drip line surface area, as described in Phogat et al. (2012).

An atmosphere boundary condition was specified at the soil surface. No flow boundary conditions were prescribed at vertical sides

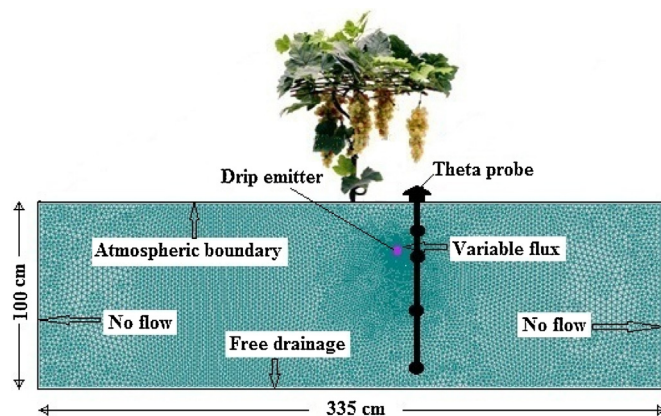


Fig. 4. A schematic view of the simulated domain, displaying boundary conditions, spatial discretization, and the positions of the drip emitter and the theta probe.

and a free drainage boundary condition was specified at the bottom boundary. Daily evaporation,  $E_s$ , transpiration,  $T_p$ , (which were both estimated using the procedure discussed in the previous section) and rainfall were used to define the atmospheric boundary condition. The initial soil water contents were based on values measured by the Theta probes ( $I_1$  and  $I_2$  treatments) and gypsum blocks ( $I_3$  and  $I_4$  treatments).

Utilizing all input parameters described above, HYDRUS-2D was calibrated against measured water contents (Theta probe) in treatment  $I_1$  during the first season (2010–11) by adjusting root water uptake parameters values as described in section 2.3. Since soil hydraulic parameters were estimated directly from measured retention and conductivity values, they were not optimized during calibration. Other studies (e.g. Gonçalves et al., 2006) followed a similar strategy relying on independently measured soil hydraulic parameters. The calibrated model was validated using measured water contents for treatments  $I_2$  (Theta probe),  $I_3$  and  $I_4$  (gypsum blocks) during both seasons (2010–11 and 2011–12) using similar domain characteristics.

#### 2.5. Estimation of crop coefficients and water productivity

Daily values of actual evapotranspiration ( $ET_{Cact}$ ), transpiration ( $T_{pact}$ ), and evaporation ( $E_{sact}$ ) produced by HYDRUS-2D for two seasons were used to compute the monthly actual crop coefficients ( $K_{cact}$ ), basal crop coefficients ( $K_{cbact}$ ), and evaporation coefficient ( $K_e$ ) of wine grape under different deficit irrigation treatments.

Water productivity of grapevine for actual  $ET$  losses ( $WPET_C$ ) and water productivity for actual transpiration ( $WPT_C$ ) were estimated

using the average seasonal  $ET_{Cact}$  and  $T_{pact}$  values, respectively, obtained from HYDRUS-2D simulations for two seasons, and measured average yield data for different treatments. Common equations for estimating  $WPET_C$  and  $WPT_C$  in terms of fruit yield (Perry et al., 2009; Molden et al., 2010) for all treatments are given as:

$$WPET_C = \frac{Y}{ET_{Cact}} \quad (9)$$

$$WPT_C = \frac{Y}{T_{pact}} \quad (10)$$

Where, Y is the average fruit yield (kg/ha), and  $ET_{Cact}$  and  $T_{pact}$  are the average seasonal actual evapotranspiration ( $m^3$  of water/ha) and actual transpiration ( $m^3$  of water/ha), respectively estimated by HYDRUS-2D in different treatments.

### 2.6. Statistical analysis

The modelling output during calibration and validation period was tested by estimating 3 statistical parameters i.e. mean error (ME), mean absolute errors (MAE) and root mean square error (RMSE). These errors were calculated from the measured and simulated water content for both seasons (2010–11 and 2011–12) and at all depths (15, 30, 60 and 90 cm). The following equations were employed to estimate ME, MAE and RMSE by comparing measured (M) and corresponding HYDRUS-2D simulated (S) values of water contents as follows:

$$ME = \frac{1}{N} \sum_{i=1}^N (M_i - S_i) \quad (11)$$

$$MAE = \frac{1}{N} \sum_{i=1}^N |M_i - S_i| \quad (12)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (M_i - S_i)^2} \quad (13)$$

Here, N is the number of comparisons.

## 3. Results and discussion

### 3.1. Comparison of measured and simulated water contents

Water contents simulated by HYDRUS-2D are compared with theta probe measured values during calibration ( $I_1$  treatment, 2010–11) and validation ( $I_1$  treatment, 2011–12) at different depths (15, 30, 60 and 90 cm) in Fig. 5. A similar comparison for validation in  $I_2$  treatment for both seasons is presented in Fig. 6. During calibration a marginal underestimation occurred at 15, 60

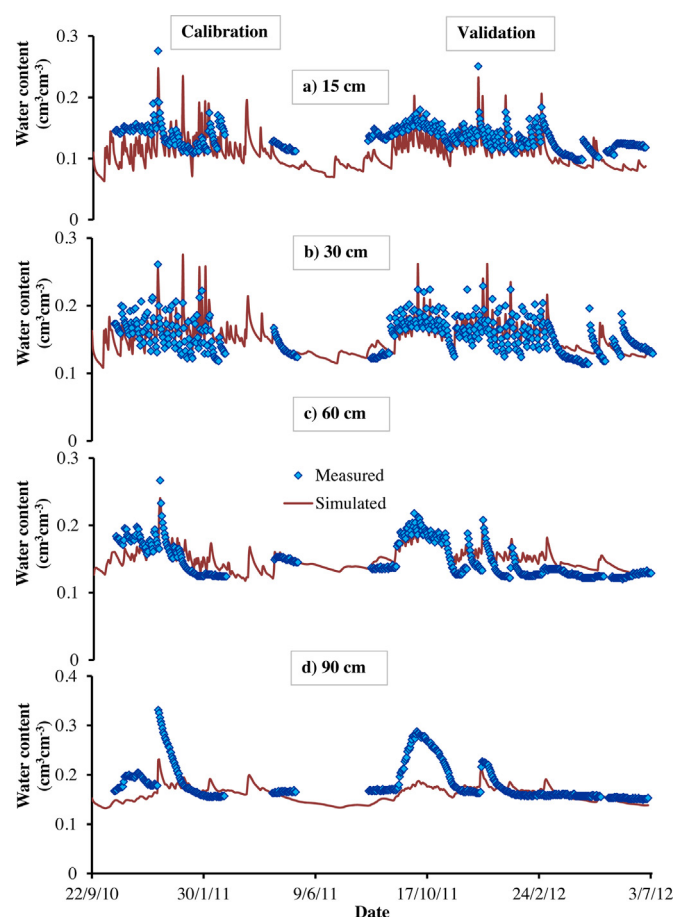


Fig. 5. Comparison of measured and simulated water content during calibration ( $I_1$  treatment, 2010–11) and validation ( $I_1$  treatment, 2011–12) at different soil depths.

and 90 cm during the initial stage, which diminished as the season progressed, while at 30 cm there was good agreement. Close agreement continued thereafter at all locations, except for a small underestimation at 15 and 60 cm. However unusually high values of measured water content at 90 cm persisted during the second half of December 2010 after 100 mm of rainfall from 6–8th December. This condition might have occurred due to local restricted drainage which was not captured by the modelling simulation. A similar mismatch was also observed at an early stage of growth during validation ( $I_1$ , 2011–12). However, it did not follow an excessive rain event. At other depths water content values showed better matching, except for sporadic underestimation at 15 cm during initial and late stages, and a small over-estimation at 60 cm during the latter half of the crop season. Despite these deviations,

Table 2

Range and mean of weekly estimated statistical error parameters (RMSE, MAE and ME) in the measured and simulated water contents during 2010–11 and 2011–12 in different treatments.

Irrigation treatment	Year	RMSE		MAE		ME	
		Range	Mean	Range	Mean	Range	Mean
$I_1$	2010–11	0.01–0.07	0.03	0.01–0.06	0.03	(–)0.05–0.04	0.01
	2011–12	0.01–0.06	0.03	0.01–0.05	0.02	(–)0.03–0.04	0.01
$I_2$	2010–11	0.01–0.05	0.03	0.01–0.05	0.02	(–)0.04–0.04	0.00
	2011–12	0.01–0.04	0.03	0.01–0.04	0.02	(–)0.04–0.02	0.00
$I_3$	2010–11	0.02–0.10	0.05	0.02–0.09	0.04	(–)0.09–0.01	(–)0.04
	2011–12	0.03–0.09	0.05	0.03–0.08	0.05	(–)0.08–0.02	(–)0.03
$I_4$	2010–11	0.03–0.11	0.06	0.03–0.10	0.05	(–)0.10–0.02	(–)0.05
	2011–12	0.03–0.09	0.06	0.02–0.09	0.05	(–)0.09–(–)0.02	(–)0.04

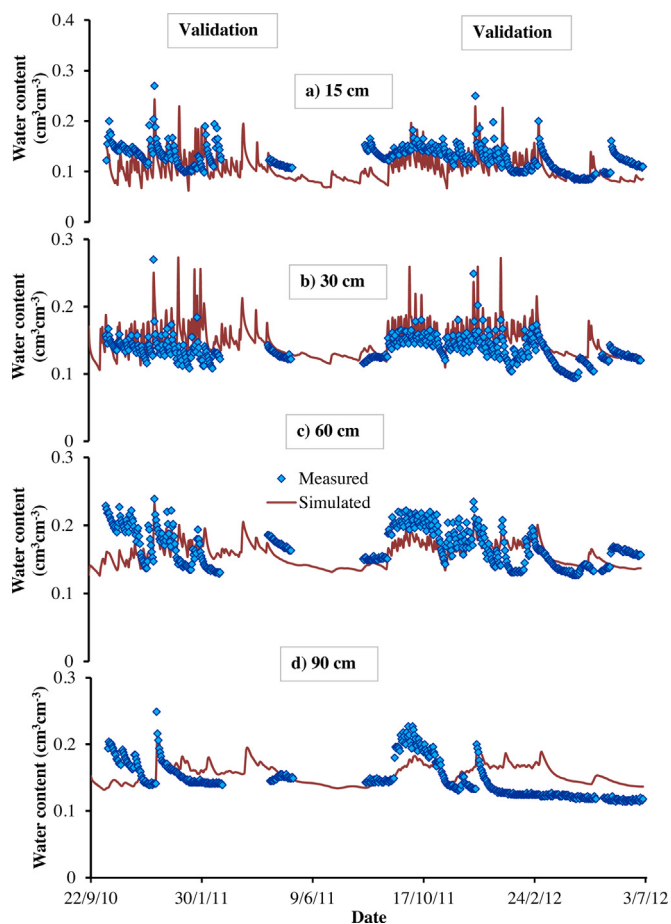


Fig. 6. Comparison of measured and simulated water content during validation ( $I_2$  treatment, 2010–11 and 2011–12) at different soil depths.

**Table 3**  
Statistical error parameters ( $RMSE$ ,  $MAE$  and  $ME$ ) in the measured and simulated water contents at different soil depths in different treatments during 2010–11 and 2011–12.

Error parameters	Year	Soil depth (cm)			
		15	30	60	90
<b>(a) <math>I_1</math> Treatment</b>					
$RMSE$	2010–11	0.03	0.02	0.03	0.04
	2011–12	0.03	0.02	0.03	0.04
$MAE$	2010–11	0.03	0.02	0.03	0.03
	2011–12	0.02	0.01	0.02	0.02
$ME$	2010–11	0.02	0.00	–0.01	0.02
	2011–12	0.02	0.00	–0.02	0.02
<b>(b) <math>I_2</math> Treatment</b>					
$RMSE$	2010–11	0.04	0.03	0.03	0.02
	2011–12	0.03	0.02	0.02	0.03
$MAE$	2010–11	0.03	0.02	0.03	0.02
	2011–12	0.02	0.02	0.02	0.03
$ME$	2010–11	0.02	–0.02	0.01	0.00
	2011–12	0.02	–0.02	0.01	–0.02
<b>(c) <math>I_3</math> Treatment</b>					
$RMSE$	2010–11	0.03	0.05	0.05	0.04
	2011–12	0.04	0.06	0.05	0.06
$MAE$	2010–11	0.03	0.05	0.04	0.04
	2011–12	0.03	0.05	0.05	0.06
$ME$	2010–11	–0.01	–0.05	–0.04	–0.04
	2011–12	–0.02	–0.05	–0.05	–0.06
<b>(d) <math>I_4</math> Treatment</b>					
$RMSE$	2010–11	0.04	0.07	0.05	0.05
	2011–12	0.04	0.07	0.05	0.06
$MAE$	2010–11	0.03	0.06	0.05	0.05
	2011–12	0.03	0.07	0.05	0.06
$ME$	2010–11	–0.02	–0.06	–0.05	–0.05
	2011–12	–0.02	–0.07	–0.05	–0.06

the model has showed fairly good agreement with measured values, as substantiated by the statistical error parameters. The extent of deviation between simulated water content and gypsum block measured values in  $I_3$  and  $I_4$  was marginally higher (not shown), and is statistically compared and discussed below.

The range and mean values of statistical error parameters ( $RMSE$ ,  $MAE$  and  $ME$ ) estimated on a weekly basis for all irrigation treatments ( $I_1$ ,  $I_2$ ,  $I_3$  and  $I_4$ ) during 2010–11 and 2011–12 season are shown in Table 2. Root mean square error ( $RMSE$ ) values of weekly water content during calibration ( $I_1$  treatment during 2010–11 season) ranged from 0.01–0.07  $\text{cm}^3 \text{cm}^{-3}$ , with a mean value of 0.03  $\text{cm}^3 \text{cm}^{-3}$ , while, the weekly  $MAE$  and  $ME$  values during calibration varied from 0.01–0.06  $\text{cm}^3 \text{cm}^{-3}$  and –0.05–0.04  $\text{cm}^3 \text{cm}^{-3}$ , respectively. On the other hand, the error parameters at different depths (15, 30, 60 and 90 cm) during calibration varied within an acceptable range ( $RMSE$  ranged from 0.02–0.04  $\text{cm}^3 \text{cm}^{-3}$ ,  $ME$  varied from –0.01 to 0.02  $\text{cm}^3 \text{cm}^{-3}$  and  $MAE$  showed much lower range of 0.02–0.03  $\text{cm}^3 \text{cm}^{-3}$ ) (Table 3). However, the middle depths of the rootzone (30 and 60 cm) showed slightly lower error parameters as compared to upper and lower depths.

Similarly, weekly  $RMSE$ ,  $MAE$  and  $ME$  during validation ( $I_1$  during 2011–12) ranged from 0.01 to 0.06, 0.01–0.05 and –0.03–0.04  $\text{cm}^3 \text{cm}^{-3}$ , respectively (Table 2). Subsequent validation in  $I_2$  treatment during both seasons (2010–11 and 2011–12) showed similar temporal and spatial variation in error estimates ( $RMSE$ ,  $MAE$  and  $ME$ ) as obtained in  $I_1$  during validation (2011–12). Crevoisier et al. (2008) reported  $RMSE$  values between 0.02 and 0.06  $\text{cm}^3 \text{cm}^{-3}$  during validation at various depths, with higher values at the soil surface. Similarly, Deb et al. (2011) reported  $RMSE$  values similar to our study at various depths for water distribution simulation under a pecan tree. However, Han et al. (2015) recorded higher  $RMSE$  during calibration than validation for cotton.

Comparison between HYDRUS-2D simulated and gypsum block measured values in  $I_3$  and  $I_4$  treatments showed marginally higher values of statistical error parameters (Table 2). The weekly esti-

**Table 4**

Seasonal actual evapotranspiration ( $ET_{Cact}$ ), actual transpiration ( $T_{pact}$ ), and actual evaporation ( $E_{sact}$ ) for wine grape under different irrigation treatments estimated by HYDRUS-2D model.

$ET_{Cact}$ (mm)	2010–11	2011–12	$T_{pact}$ (mm)	2010–11	2011–12	$E_{sact}$ (mm)	2010–11	2011–12
$ET_{C1act}$	289.7	239.2	$T_{p1act}$	134.4	98.1	$E_{s1act}$	155.3	141.1
$ET_{C2act}$	324.9	273.7	$T_{p2act}$	162.6	121.0	$E_{s2act}$	162.3	152.7
$ET_{C3act}$	355.5	305.6	$T_{p3act}$	191.2	144.7	$E_{s3act}$	164.3	160.9
$ET_{C4act}$	382.3	334.1	$T_{p4act}$	213.1	164.2	$E_{s4act}$	169.2	169.9

mated RMSE, MAE and ME values in these treatments varied from 0.02 to 0.11, 0.02–0.10, –0.10–0.02  $\text{cm}^3 \text{cm}^{-3}$ , respectively (Table 2). However, the error estimates at different depths (Table 3) in  $I_3$  and  $I_4$  treatments were well within the reported range e.g. MAE in  $I_3$  and  $I_4$  varied from 0.03–0.05 and 0.03–0.07  $\text{cm}^3 \text{cm}^{-3}$ , respectively (Table 3). Li et al. (2015) reported RMSE between 0.02–0.07  $\text{cm}^3 \text{cm}^{-3}$  for soil water dynamics in drip irrigated tomato-corn intercropping, while, Mei-Xian et al. (2013) showed an RMSE of 0.03–0.05  $\text{cm}^3 \text{cm}^{-3}$  for drip irrigated cotton. The ME values in  $I_3$  and  $I_4$  treatments ranged between –0.10 and 0.02  $\text{cm}^3 \text{cm}^{-3}$  which is similar to González et al. (2015) for water dynamics for full and deficit irrigated maize.

Despite a similar deviation to other studies in  $I_3$  and  $I_4$  treatments, a general overestimation of water content was observed, which is shown by the consistent negative ME values at all depths (Table 3). This can be attributed to various causes, possibly including different root distribution characteristics due to higher water application in  $I_3$  and  $I_4$  compared to treatments  $I_1$  and  $I_2$ , which was assumed constant in all treatments. Modifying these parameters and calibrating the model for each treatment would probably improve HYDRUS-2D predictions. Other causes for deviations between measured and simulated water contents explained by Ramos et al. (2012) relate to field measurement, model input, and model structural errors, and could also be assumed for the current investigation. The measurement of soil water content by sensors is also not free of errors, due to numerous assumptions and inherent complexities in the soil (e.g., Rosenbaum et al., 2010; Ganjegunte et al., 2012; Evett et al., 2012) which may contribute a similar extent of deviations in the water contents as obtained by modelling predictions. Finally, the varied water applications in different treatments could lead to dynamic spatial root growth, which is not considered in the present modelling investigation.

### 3.2. Actual ET components simulated by HYDRUS-2D

Seasonal actual evapotranspiration fluxes of wine grape estimated by HYDRUS-2D ( $ET_{Cact}$ ) for different irrigation treatments during 2010–11 and 2011–12 seasons are shown in Table 4. Total seasonal  $ET_{Cact}$  in the  $I_4$  treatment (92% irrigation) varied from 338 to 382 mm over two seasons, which is between 32 and 42% of  $ET_0$ . Williams (2010) showed similar  $ET_C/ET_0$  relation for Cabernet Sauvignon planted at similar spacing. However, a reduction of irrigation by 15, 28, and 41% in the  $I_3$ ,  $I_2$  and  $I_1$  treatments reduced  $ET_{Cact}$  by only 8, 16, and 26%, respectively. Seasonal  $ET_{Cact}$  of similar magnitude as in  $I_4$  was observed by Cancela et al. (2015) for SDI simulated with the SIMDualKc model under different climate, soil and vine settings. Yunusa et al. (1997) also reported similar ET as in  $I_4$  for own-rooted and grafted Sultana grapevine under surface drip in Australian conditions. However, Williams et al. (2010a) reported much higher  $ET_C$  (574–829 mm) for lysimeter-planted Thompson seedless grape vine under surface drip, with more than double the amount of irrigation applied compared to  $I_4$  in our study.

Simulated average daily  $ET_{Cact}$  rates over two seasons were 1.11, 1.26, 1.39, and 1.50 mm/day in  $I_1$ ,  $I_2$ ,  $I_3$ , and  $I_4$  treatments, respectively. Cancela et al. (2015) reported slightly higher daily  $ET_{Cact}$  (1.7–1.9 mm/day) under SDI than  $I_4$  in our study. However, the

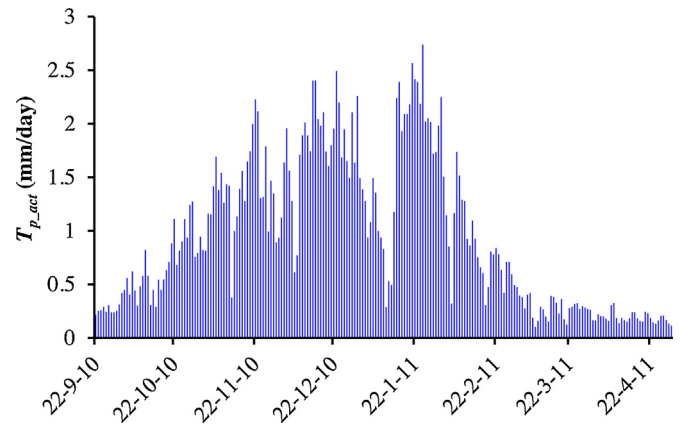


Fig. 7. Simulated daily actual transpiration rates (mm/day) of the Chardonnay wine grape during 2010–11.

average grape vine  $ET$  rate from nine international field experiments is 3 mm/day (Teixeira et al., 2007), which represents varied rootstocks and mostly surface irrigation conditions. Other studies (e.g., Yunusa et al., 1997; Trambouze and Voltz, 2001; Fandiño et al., 2012; Shapland et al., 2012) showed average daily  $ET_C$  varying between 2 and 2.2 mm/day. However, average daily  $ET_C$  rates similar to our study (in  $I_4$  treatment) have been reported by Zhang et al. (2010) and Zhang et al. (2011) under surface drip irrigation. These studies show that the site specific variability in plant water uptake reflects numerous climate, soil, irrigation, and plant parameters, which have tremendous impact on water uptake patterns of wine grape. The average seasonal  $ET_{Cact}$  rate in our study had a strong linear correlation ( $y = 0.003x + 0.475$ ,  $R^2 = 0.99$ ) with the amount of irrigation applied in different treatments.

Simulated annual actual transpiration ( $T_{pact}$ ) ranged from 134.4–213.1 mm during 2010–11 while the corresponding values during 2011–12 were only 98.1–164.2 mm (Table 4). The  $T_{pact}/ET_{Cact}$  ratio ranged from 0.46–0.56 during 2010–11 and from 0.41–0.49 during 2011–12 for different treatments, which compares well with Cancela et al. (2015) for SDI and Yunusa et al. (1997) for surface drip irrigation of Sultana grapevine. The modelled daily transpiration rate in  $I_4$  treatment ( $T_{p4act}$ ) varied from 0.11–2.74 mm/day (Fig. 7). Peak values of  $T_{p4act}$  were observed during the mid-growth period (December–January) while low values were observed during initial and late stages of the vine growth. Similar seasonal variation in daily transpiration was also observed for other treatments (not shown).

Simulated seasonal actual evaporation ( $E_{sact}$ ) ranged from 155.3–169.2 mm during 2010–11 and from 141.1–169.9 mm during 2011–12 (Table 4) in different treatments, indicating a relatively low effect of irrigation treatment. However, seasonal evaporation accounted for 44–59% of seasonal  $ET_{Cact}$  losses in different treatments. For sparse vegetation such as grape vine, evaporation may constitute a large fraction of  $ET$  due to the considerable area exposed to the atmosphere (Kool et al., 2014b). It is worth noting that differences between seasonal values of evaporation in various treatments were low during both years. The seasonal evaporation in  $I_4$  increased by 14.1 and 18–8 mm only as compared to  $I_1$  during



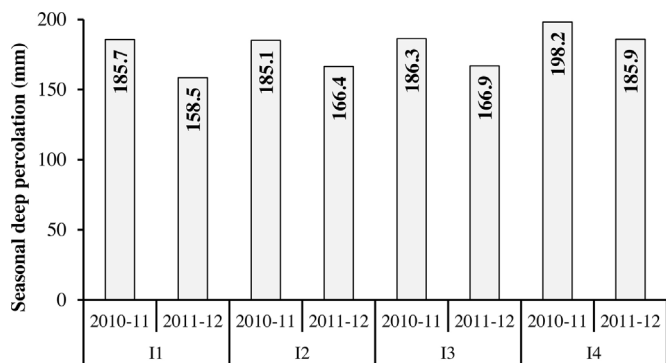


Fig. 8. Simulated seasonal deep water percolation for wine grapes under different irrigation treatments during 2010–11 and 2011–12.

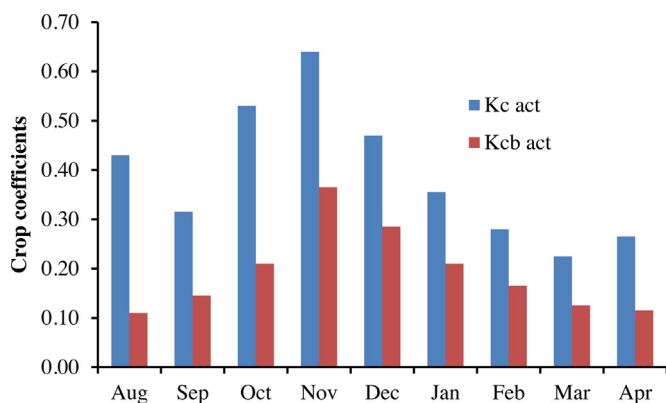


Fig. 9. Monthly values of actual single crop coefficients ( $K_{cact}$ ) and actual basal crop coefficients ( $K_{cbact}$ ) for wine grapes, estimated from HYDRUD-2D simulated actual  $ET_c$  ( $ET_{cact}$ ) and actual  $T_p$  ( $T_{pact}$ ).

2010–11 and 2011–12 season, respectively. This suggests that the effect of deficit irrigations on the evaporation losses under SDI irrigation is relatively minor. Although, evaporation losses of similar magnitude as obtained in  $I_4$  have been observed for vineyards under surface drip in this area with similar vine spacing (Yunusa et al., 1997; Styles et al., 2015) but under different climatic conditions. On the other hand, Fandiño et al. (2012) reported that evaporation was only 8–15% of  $ET$ , while Cancela et al. (2015) observed this fraction to be 27% under SDI. Both studies considered that the wetted fraction of the surface ( $f_w$ ) was only 0.01, compared to 0.22 in our study. Additionally, active ground cover in these studies probably reduced evaporation losses from the soil surface.

HYDRUS-2D simulated annual deep percolation below the 1 m soil depth ranged from 185.1 to 198.2 mm during 2010–11, and 158.5–185.9 mm during 2011–12, in different treatments (Fig. 8). Similar seasonal percolation was recorded in all the treatments, except  $I_4$  where 7 and 13% higher percolation was estimated during 2010–11 and 2011–12 seasons, respectively, as compared to the mean percolation in other treatments. This suggests that most of the leaching losses were contributed by rainfall, and irrigation had little impact on deep percolation.

### 3.3. Crop coefficients

Daily values of  $ET_{cact}$  and  $T_{pact}$  produced by HYDRUS-2D for two seasons were used to compute the monthly actual crop coefficients ( $K_{cact}$ ) and actual basal crop coefficients ( $K_{cbact}$ ) of wine grape for  $I_4$  treatment (Fig. 9), which represents near to full irrigation. However, the crop conditions may not represent the FAO definition of well-watered, as stress is routinely applied in wine grapes to manage

canopy growth and to enhance the fruit quality suitable for better wine. This is reflected in the low volumes of irrigation applied to the site relative to historical district practices.

The  $K_c$  and  $K_{cb}$  coefficients were computed from the simulated actual crop water use values, hence they are represented as  $K_{cact}$  ( $K_c$  actual) and  $K_{cbact}$  ( $K_{cb}$  actual), which are different from standard potential values (Pereira et al., 2015). The comparison of  $K_{cact,ini}$  (0.37) and  $K_{cbact,ini}$  (0.13) values (average of August and September) showed a much higher contribution of evaporation during this period, which corresponds to the bud burst and initial growth stage. The maximum  $K_{cact}$  (0.64) and  $K_{cbact}$  (0.37) were recorded in the month of November which coincides with the maximum growth stage and a large leaf area (Williams et al., 2003). The mean  $K_{cact}$  value over the two seasons was 0.37, which was slightly higher than reported by Yunusa et al. (1997) in this region. Similarly, Cancela et al. (2015) reported average  $K_{cact}$  for SDI irrigated grapevine equal to 0.45.

Values of  $K_{cbact}$  for initial (August–September), mid (October–January) and end (February–April) stages were 0.13, 0.27 and 0.14, respectively. Cancela et al. (2012) reported similar  $K_{cbactmid}$  (0.25) for vine under SDI, while other studies (Intrigliolo and Castel, 2009; Zhang et al., 2011) reported much higher  $K_{cbactmid}$  (0.47–0.5) under surface drip irrigation. Similarly, our  $K_{cbactend}$  was lower than the values reported by the above studies. However, Fandiño et al. (2012) showed matching  $K_{cbactend}$  values. Similarly, the  $K_{cact}$  and  $K_{cbact}$  values in our study are much less than the tabulated values reported by Allen et al. (1998) and Allen and Pereira (2009) for wine grape under standard and stress conditions. Under high stress conditions, Allen and Pereira (2009) suggested applying a stress coefficient ( $K_s$ ) with values ranging from 0.5 to 1.0. However, in our study simulated  $K_s$  varied from 0.1 to 1.0, indicating a far greater level of stress at this trial site. Many other studies (Yunusa et al., 1997; Williams and Ayars, 2005; McClymont et al., 2009; Netzer et al., 2009; Edwards and Clingeleffer, 2011) have shown that  $ET_0$  and canopy cover explain a large degree of variation in grapevine transpiration. Poblete-Echeverría and Ootega-Farias (2013) reported 11 and 19% lower values of  $K_{cact}$  and  $K_{cbact}$  than FAO-56 for grapevines.

Lower  $K_{cact}$  values than those given in FAO-56 have been reported for other crops, e.g., Er-Raki et al. (2009) found  $K_{cact}$  values measured by eddy covariance to be 20% less than those reported in the FAO-56 for an irrigated citrus orchard under drip. Similarly, Dragoni et al. (2004) showed a significant overestimation (over 15%) of the basal crop coefficients by the FAO-56 method compared to measurements (sap flow). In contrast, Benli et al. (2006) and Paço et al. (2006) reported basal crop coefficients that were higher than the tabulated figures. Such deviations in crop coefficients from the generic values are bound to occur as a result of variable crop conditions due to insufficient or non-uniform irrigation, variable crop density and canopy cover, soil salinity and/or agronomic management (Pôças et al., 2015).

Monthly  $K_e$  values ranged from 0.1 to 0.32, with a seasonal mean of 0.18. Higher  $K_e$  values were recorded during the early half of the vine growth, due to a higher rainfall, in comparison to the latter half of the vine season. Netzer et al. (2009) reported, based on drainage lysimeter measurements with 80% canopy cover that the average seasonal  $K_e$  for a drip irrigated vineyard remained below 0.15. Similarly, Yunusa et al. (2004) reported a low  $K_e$  value of 0.12 from micro-lysimeter measurements in a drip irrigated vineyard. On the other hand, a high  $K_e$  (0.46) value was reported by Lascano et al. (1992) for a flood irrigated vineyard. A high  $K_e$  value of 0.55 was also reported by Stevens (2002) for a micro-jet wetted soil surface. This suggests that the proportion of the wetted surface area by rainfall and irrigation highly influences the magnitude of evaporation losses. This also implies that under a sparsely vegetated surface cover such as grapevine irrigated with SDI system, rainfall

**Table 5**

Number of bunches/vine, average bunch weight, grape yield and water productivity (WP) of wine grape in relation to  $ET_{Cact}$  ( $WPET_C$ ) and  $T_{pact}$  ( $WPT_C$ ) for different irrigation treatments ( $ET_{Cact}$  and  $T_{pact}$  average of two seasons, from Table 4).

Treatments	Bunches/vine	Average bunch weight (g)	Yield (kg/ha)	$ET_{Cact}$ (m <sup>3</sup> /ha)	$T_{pact}$ (m <sup>3</sup> /ha)	$WPET_C$ (kg/m <sup>3</sup> )	$WPT_C$ (kg/m <sup>3</sup> )
$I_1$	145 <sup>a</sup>	89.70 <sup>a</sup>	15620 <sup>a</sup>	2640 <sup>a</sup>	1160 <sup>a</sup>	5.92 <sup>a</sup>	13.46 <sup>a</sup>
$I_2$	163 <sup>ab</sup>	95.36 <sup>a</sup>	18570 <sup>ab</sup>	3000 <sup>b</sup>	1420 <sup>b</sup>	6.19 <sup>a</sup>	13.08 <sup>a</sup>
$I_3$	172 <sup>b</sup>	91.93 <sup>a</sup>	18840 <sup>ab</sup>	3310 <sup>c</sup>	1680 <sup>c</sup>	5.69 <sup>a</sup>	11.22 <sup>a</sup>
$I_4$	179 <sup>b</sup>	101.40 <sup>a</sup>	21100 <sup>b</sup>	3580 <sup>d</sup>	1890 <sup>d</sup>	5.89 <sup>a</sup>	11.16 <sup>a</sup>

Within columns, means followed by different letters are significantly different according to the Fisher's least significant difference (LSD) test ( $P \leq 0.05$ ).

**Table 6**

Berry juice composition parameters ( $^{\circ}$ Brix, pH and TA) under different irrigation treatments during 2010–11 and 2011–12.

Treatments	$^{\circ}$ Brix			pH			TA(g/L)		
	2010–11	2011–12	Mean	2010–11	2011–12	Mean	2010–11	2011–12	Mean
$I_1$	18.8 <sup>a</sup>	18.7 <sup>a</sup>	18.8	3.56 <sup>a</sup>	3.30 <sup>a</sup>	3.43	5.51 <sup>a</sup>	7.85 <sup>a</sup>	6.68
$I_2$	18.3 <sup>a</sup>	19.2 <sup>a</sup>	18.8	3.50 <sup>ab</sup>	3.28 <sup>a</sup>	3.39	5.68 <sup>a</sup>	7.91 <sup>a</sup>	6.80
$I_3$	18.2 <sup>a</sup>	19.5 <sup>a</sup>	18.9	3.51 <sup>ab</sup>	3.30 <sup>a</sup>	3.41	5.77 <sup>ab</sup>	7.76 <sup>a</sup>	6.77
$I_4$	18.6 <sup>a</sup>	19.3 <sup>a</sup>	19.0	3.46 <sup>b</sup>	3.25 <sup>a</sup>	3.36	6.04 <sup>b</sup>	8.78 <sup>a</sup>	7.41
Mean	18.5	19.2		3.51	3.28		5.75	8.08	

Within columns, means followed by different letters are significantly different according to the Fisher's least significant difference (LSD) test ( $P \leq 0.05$ ).

seems to make a major contribution towards evaporation losses, as irrigation under SDI wets less area on the soil surface exposed to evaporation as compared to other methods.

### 3.4. Yield, water productivity and berry juice quality of wine grape

The grape yield, bunches per vine, and average bunch weight all increased with an increase in water application, except for the average bunch weight in  $I_3$  (Table 5). The yield in  $I_1$  (51% irrigation) was reduced significantly (by 26%) as compared to  $I_4$  (92% irrigation). Other studies in the same region of Australia (Stevens et al., 2008, 2010) showed that vines grafted to a range of rootstocks displayed a similar tolerance to reductions in irrigation (35% reduction in irrigation caused up to 30% reduction in yield). On the other hand, McCarthy et al. (1997) found that stopping supplementary irrigation reduced the yield of grafted Shiraz vines by 50% on average over four seasons. Williams (2010) reported a 62% yield reduction with 0.25  $ET_C$  irrigation as compared to 1.25  $ET_C$ . Hence, different rootstocks and scions respond differently to water stress and to other factors such as soil type.

Water productivity of wine grape was estimated by dividing measured yield by the seasonal values of actual evapotranspiration ( $ET_{Cact}$ ) and transpiration ( $T_{pact}$ ) obtained from HYDRUS-2D simulations in respective treatments (Table 5). Interestingly, productivity in relation to  $ET$  losses ( $WPET_C$ ) varied non-significantly in a narrow range from 5.7 to 6.2 kg/m<sup>3</sup>, i.e., 56.9–61.9 kg/mm, across irrigation applications, with no clear pattern relative to irrigation treatment. Water productivity relative to transpiration ( $WPT_C$ ) was approximately double that relative to  $WPET_C$  in all treatments, which indicates high  $E_s$  losses in this study. However, for this measure, there was a clear relationship between a reduced water application and increased water productivity, with the most severely stressed treatment ( $I_1$ ) returning  $WPT_C$  values 20.6% higher than those for the well-watered treatment ( $I_4$ ). This indicates that the amount of transpiration is directly linked to water productivity, whereas the inclusion of evaporation into the equation can mask this effect.

Stevens et al. (2010) reported that reduced irrigation did not affect the irrigation water use index, whereas other investigations (Feres and Soriano, 2007; Williams et al., 2010b) reported that deficit irrigation does increase water use efficiency for woody perennial crops. However, these studies used different measures of water use for estimating water use efficiency. Comparable

grapevine water productivities against  $ET_C$  were recorded in other studies for similar amounts of water application (Williams et al., 2010b) under SDI (Williams, 2010). However, low water productivity (1.8 kg/m<sup>3</sup>) of grapevine under basin irrigation has been reported (Atroosh et al., 2013), indicating large undesirable water loss under such systems.

The values of berry juice quality parameters ( $^{\circ}$ Brix, pH and Titratable acidity) for different treatments during 2010–11 and 2011–12 are shown in Table 6. The mean pH decreased and titratable acidity (TA) increased with increase in the amount of irrigation except  $I_3$  treatment. The mean pH of berry juice in  $I_1$  treatment increased by 6% and mean TA decreased by 10% as compared to  $I_4$  treatment. However, there was almost no effect on soluble solids ( $^{\circ}$ Brix). On the other hand, season to season variation among  $^{\circ}$ Brix, pH and TA were higher than the variation due to irrigation application. There are conflicting reports on the impact of water deficit on wine quality parameters in the literature. Many studies (Salon et al., 2005; Girona et al., 2009; Intrigliolo and Castel, 2010; Santesteban et al., 2011) reported a decrease in the acidity due to increased level of deficit which is the additive result of a reduced synthesis of malic and tartaric acids resulting from lower assimilation rates (Esteban et al., 1999; De Souza et al., 2005; Salon et al., 2005). However, Acevedo-Opazo et al. (2010) reported no impact of regulated deficit irrigation on acidity and pH, and significant impact on soluble solids. Reynolds et al. (2005) also reported similar impact on soluble solids. Intrigliolo and Castel (2009) reported increased pH of must as a result of irrigation. However, other studies (Roby et al., 2004; Junquera et al., 2012) showed little effect of deficit irrigation on the concentration of soluble solids. Similarly, Edwards and Clingeleffer (2013) observed little impact of regulated deficit irrigation (RDI) on soluble solids and pH, but TA increased by 10–15% in well watered vines which is similar to our study. Bellvert et al. (2016) recommended that RDI and deficit irrigation (DI) strategies should not be followed due to their negative effect on acidity and desirable aromas in sparkling base wines (cv Chardonnay). Cox (2010) illustrated varied and diverse impact of deficit irrigation on berry composition in a range of rootstocks and scions suggesting a major role of the genotypes. In spite of all of the above, the climatic conditions and other environmental factors during the growing season can also influence the physiological and wine quality attributes explaining the inter-annual and water deficit variability as observed in this investigation.

#### 4. Conclusions

Understanding the *ET* fluxes and crop coefficients of wine grape under SDI has a significant role in managing scarce water resources and enhancing the water productivity and efficiency of the irrigation system. This study investigated the partitioning of evapotranspiration components of wine grapes under SDI with different volumes of irrigation (51, 64, 77 and 92% of full) using a numerical model (HYDRUS-2D) and determined actual crop coefficients, which were compared with the FAO-56 tabulated values, and other published values. Values of actual evapotranspiration components ( $ET_{Cact}$  and  $T_{pact}$ ) produced by the calibrated and validated model were used to estimate water productivity of wine grapes under different irrigation treatments.

Total seasonal  $ET_{Cact}$  in the  $I_4$  treatment (92% irrigation) varied from 338 to 382 mm over the two seasons. However, the reduction in simulated  $ET_{Cact}$  in the 51% irrigation ( $I_1$ ) was only 26% as compared to  $I_4$ , which could mean enhanced root water uptake by wine grape under deficit conditions. A similar response was observed in fruit yield across irrigation treatments over the two seasons, indicating wine grapes are relatively robust in coping with sustained water stress. Actual crop coefficients ( $K_{cact}$  and  $K_{cbact}$ ) derived from HYDRUS simulations were lower than the tabulated values from Allen et al. (1998), but within the range of values reported in the literature. Low values of actual crop coefficients were likely caused by the stress due to low levels of irrigation and high levels of deep drainage. Drainage fluxes were much higher than expected and averaged 189 and 169 mm during the two seasons, respectively.

While water productivity relative to evapotranspiration ( $WPET_C$ ) showed no clear effect of irrigation amount, water productivity relative to transpiration ( $WP_T_C$ ) did show a clear and consistent effect, with the lowest irrigation treatment ( $I_1$ ) returning values over 20% greater than the well-watered treatment ( $I_4$ ). Doubling of  $WP_T_C$  in all treatments compared to  $WPET_C$  indicates significant evaporation losses in this study. Water productivity values obtained in this study were comparable to similar studies, and much higher than studies evaluating surface irrigation.

We believe that information obtained in our study can be utilized for developing better management practices for wine grapes. It can be used to further improve the estimates of *ET* components for wine grapes under SDI condition.

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