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

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A B S T R A C T
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% (l1), 64% (l2), 77% (l3), and 92% (l4) 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 (ETact), actual transpiration (Tact), and actual evaporation (Eact), and deep percolation under varied irrigation applications. The model-simulated values were then used to estimate actual crop coefficients (Kact and Kdact) and water productivity of wine grape under different deficit irrigation conditions.

Seasonal ETact simulated by HYDRUS-2D for different treatments varied between 239 and 382 mm. However, seasonal evaporation accounted for 44–59% of seasonal ETact losses in different treatments. The modelled daily transpiration rate in l4 treatment (Tact) 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 (Kact) estimated by HYDRUS-2D simulated ETact over the two seasons was 0.27, which matched with other investigations. Similarly, values of Kdact for initial, mid and end stages were 0.13, 0.27 and 0.14, respectively. Monthly values of evaporation coefficient (Kd) ranged from 0.1 to 0.32, with a mean value of 0.18. Water productivity with respect to ET losses (WPETC) ranged from 5.9 to 6.2 kg/m² of water use. However, water productivity for transpiration (WPETC) almost doubled as compared to WPETC 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

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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 Clinegelefffer, 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 Clinegelefffer, 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; Moratiel and Martinez-Cob, 2012), eddy covariance (Ortega-Farias et al., 2010; Rodriguez 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 (Simůnek 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 (ET0) 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 ET0 during 2010–11 and 2011–12 seasons was 904 and 1055 mm, respectively (Fig. 1). The maximum daily ET0 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 fleshy 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⁻¹ 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
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 (I₁), 64 (I₂), 77 (I₃), and 92 (I₄) % of the total amount of irrigation applied by the grower to the rest of the Chardonnay vineyard. The irrigation event length in I₄ 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 remainder of the vineyard allowed 92% of full irrigation in I₄ treatment. In other treatments (I₁, I₂, I₃), 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 I₁, I₂, I₃ and I₄ 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 I₄ 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 remainder 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 I₁ and I₂ treatments, approximately 10 cm away from the drip line. The Theta probes were manufactured by Delta-T Devices Ltd, and were equipped with TBugs 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 I₃ and I₄, 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 Irrometer 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 θ-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:

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

(1)

where θ is the soil water content (L² 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 (L T⁻¹), and S(h, x, z, t) is the sink term accounting for water uptake by plant roots (L³ 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, Tₚ, 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, \( \alpha₁(h, x, z) \) as:

\[
S(h, x, z, t) = \alpha₁(h, x, z) \beta(x, z) Tₚ(t) \times L_p
\]

(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, \( \alpha_1(h,z) \), is described as:

\[
\alpha_1(h) = \begin{cases} 
0, & h > h_1 \alpha rh \leq h_4 \\
\frac{h - h_1}{h_2 - h_1}, & h_2 < h \leq h_1 \\
1, & h_1 < h \leq h_2 \\
\frac{h - h_4}{h_3 - h_4}, & h_4 < h \leq h_3 
\end{cases}
\]

(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 \( h_1 \), 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)],

\[
\beta(x, z) = \left[ 1 - \frac{z}{Z_m} \right] \left[ 1 - \frac{x}{X_m} \right] e^{-\left( \frac{Z_m}{z} \right)^n + \left( \frac{X_m}{x} \right)^n}
\]

(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 (\( x^* = 30 \text{ cm}, z^* = 25 \text{ cm} \)). [Soar and Lovesey (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 \((X_m, Z_m, z^*, x^*, p_x, p_z)\) 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 \((z_m = 100 \text{ cm})\) and maximum horizontal extension \((X_m = 150 \text{ cm})\) 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

<table>
<thead>
<tr>
<th>Depths (cm)</th>
<th>Soil texture</th>
<th>Soil hydraulic parameters</th>
<th>Bulk density (g cm(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( \theta_r ) (cm(^3) cm(^{-3}))</td>
<td>( \theta_s ) (cm(^3) cm(^{-3}))</td>
</tr>
<tr>
<td>0–15</td>
<td>Sand</td>
<td>0.04</td>
<td>0.41</td>
</tr>
<tr>
<td>15–30</td>
<td>Loamy sand</td>
<td>0.04</td>
<td>0.39</td>
</tr>
<tr>
<td>30–60</td>
<td>Loamy sand</td>
<td>0.05</td>
<td>0.38</td>
</tr>
<tr>
<td>60–100</td>
<td>Loamy sand</td>
<td>0.05</td>
<td>0.37</td>
</tr>
</tbody>
</table>

*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):

\[
\theta(h) = \theta_s + \frac{\theta_r - \theta_s}{\left[ 1 + \left( \frac{h}{h_m} \right)^{m} \right]^n}
\]

(5)

\[
\theta(h) = \theta_s, \quad h < 0
\]

(6)

\[
K(h) = K_s \left[ 1 - \left( 1 - S_c e^{1/m} \right)^m \right] \quad h > 0
\]

(7)

\[
S_c = \frac{\theta - \theta_s}{\theta_r - \theta_s}
\]

(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
2.4.3. Estimation of evaporation (E_e) and transpiration (T_p)

HYDRUS-2D requires daily estimates of transpiration (T_p) and evaporation (E_e) as input parameters so that it can simulate corresponding actual values of ET components (ET_{act}, T_{pact}, and E_{act}) for a given soil, climate, crop, and irrigation conditions. In this study, the daily inputs of T_p and E_e 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}). Details about the estimation of daily E_e 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_e 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 driptubing 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 and a free drainage boundary condition was specified at the bottom boundary. Daily evaporation, E_e, 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. González 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_{act}), transpiration (T_{pact}), and evaporation (E_{act}) produced by HYDRUS-2D for two seasons were used to compute the monthly actual crop coefficients (K_{act}), basal crop coefficients (K_{pact}), 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 (WP_T_C) were estimated...
using the average seasonal $ET_{Cact}$ and $T_{past}$ 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:

$$WPET_C = \frac{Y}{ET_{Cact}}$$

$$WPT_C = \frac{Y}{T_{past}}$$

Where, $Y$ is the average fruit yield (kg/ha), and $ET_{Cact}$ and $T_{past}$ 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:

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

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

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

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 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>
<thead>
<tr>
<th>Irrigation treatment</th>
<th>Year</th>
<th>RMSE</th>
<th>MAE</th>
<th>ME</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>$I_1$</td>
<td>2010–11</td>
<td>0.01–0.07</td>
<td>0.03</td>
<td>0.01–0.06</td>
</tr>
<tr>
<td></td>
<td>2011–12</td>
<td>0.01–0.06</td>
<td>0.03</td>
<td>0.01–0.05</td>
</tr>
<tr>
<td>$I_2$</td>
<td>2010–11</td>
<td>0.01–0.05</td>
<td>0.03</td>
<td>0.01–0.05</td>
</tr>
<tr>
<td></td>
<td>2011–12</td>
<td>0.01–0.04</td>
<td>0.03</td>
<td>0.01–0.04</td>
</tr>
<tr>
<td>$I_3$</td>
<td>2010–11</td>
<td>0.02–0.10</td>
<td>0.05</td>
<td>0.02–0.09</td>
</tr>
<tr>
<td></td>
<td>2011–12</td>
<td>0.03–0.09</td>
<td>0.05</td>
<td>0.03–0.08</td>
</tr>
<tr>
<td>$I_4$</td>
<td>2010–11</td>
<td>0.03–0.11</td>
<td>0.06</td>
<td>0.03–0.10</td>
</tr>
<tr>
<td></td>
<td>2011–12</td>
<td>0.03–0.09</td>
<td>0.06</td>
<td>0.02–0.09</td>
</tr>
</tbody>
</table>
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 I3 and I4 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 (I1, I2, I3 and I4) during 2010–11 and 2011–12 season are shown in Table 2. Root mean square error (RMSE) values of weekly water content during calibration (I1 treatment during 2010–11 season) ranged from 0.01–0.07 cm³ cm⁻³, with a mean value of 0.03 cm³ cm⁻³, while, the weekly MAE and ME values during calibration varied from 0.01–0.06 cm³ cm⁻³ and −0.05–0.04 cm³ 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 cm³ cm⁻³, ME varied from −0.01 to 0.02 cm³ cm⁻³ and MAE showed much lower range of 0.02–0.03 cm³ 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 (I1 during 2011–12) ranged from 0.01 to 0.06, 0.01–0.05 and −0.03–0.04 cm³ cm⁻³, respectively (Table 2). Subsequent validation in I2 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 I1 during validation (2011–12).

Table 2

<table>
<thead>
<tr>
<th>Error parameters</th>
<th>Year</th>
<th>Soil depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>(a) I1 Treatment</td>
<td>RMSE</td>
<td>2010–11</td>
</tr>
<tr>
<td></td>
<td>MAE</td>
<td>2010–11</td>
</tr>
<tr>
<td></td>
<td>ME</td>
<td>2010–11</td>
</tr>
<tr>
<td>(b) I2 Treatment</td>
<td>RMSE</td>
<td>2010–11</td>
</tr>
<tr>
<td></td>
<td>MAE</td>
<td>2010–11</td>
</tr>
<tr>
<td></td>
<td>ME</td>
<td>2010–11</td>
</tr>
<tr>
<td>(c) I3 Treatment</td>
<td>RMSE</td>
<td>2010–11</td>
</tr>
<tr>
<td></td>
<td>MAE</td>
<td>2010–11</td>
</tr>
<tr>
<td></td>
<td>ME</td>
<td>2010–11</td>
</tr>
<tr>
<td>(d) I4 Treatment</td>
<td>RMSE</td>
<td>2010–11</td>
</tr>
<tr>
<td></td>
<td>MAE</td>
<td>2010–11</td>
</tr>
<tr>
<td></td>
<td>ME</td>
<td>2010–11</td>
</tr>
</tbody>
</table>

The weekly esti-
imated RMSE, MAE and ME values in these treatments varied from 0.02 to 0.11, 0.02–0.10, −0.10–0.02 cm$^3$ 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$_2$ and I$_4$ varied from 0.03–0.05 and 0.03–0.07 cm$^3$ cm$^{-3}$, respectively (Table 3). Li et al. (2015) reported RMSE between 0.02–0.07 cm$^3$ 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 cm$^3$ cm$^{-3}$ for drip irrigated cotton. The ME values in I$_1$ and I$_4$ treatments ranged between −0.10 and 0.02 cm$^3$ 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$_1$ 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$_{act}$) for different irrigation treatments during 2010–11 and 2011–12 seasons are shown in Table 4. Total seasonal ET$_{act}$ 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$_{act}$/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$_{act}$ by only 8, 16, and 26%, respectively. Seasonal ET$_{act}$ 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$_{act}$ 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$_{act}$ (1.7–1.9 mm/day) under SDI than I$_4$ in our study. However, the 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 grape vine. The average seasonal ET$_{act}$ 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$_{act}$) 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$_{act}$/ET$_{act}$ 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$_{pact}$) varied from 0.11–2.74 mm/day (Fig. 7). Peak values of T$_{pact}$ 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$_{act}$) 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$_{act}$ 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
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 \(K_{act}\) (\(K_c\) actual) and \(K_{cbact}\) (\(K_{cb}\) actual), which are different from standard potential values (Pereira et al., 2015). The comparison of \(K_{act,ini}\) (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 \(K_{act}\) (0.64) and \(K_{cb}\) (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 \(K_{act}\) 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 \(K_{act}\) 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 \(K_{cbactm}\) (0.25) for vine under SDI, while other studies (Intrigiloli and Castel, 2009; Zhang et al., 2011) reported much higher \(K_{cbactm}\) (0.47–0.5) under surface drip irrigation. Similarly, our \(K_{cbact}\) was lower than the values reported by the above studies. However, Fandiño et al. (2012) showed matching \(K_{cbact}\) values. Similarly, the \(K_{act}\) 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 grapevine 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; McCliment et al., 2009; Netzer et al., 2009; Edwins and Clingleeffer, 2011) have shown that ETc 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 \(K_{act}\) and \(K_{cbact}\) than FAO-56 for grapevines.

Lower \(K_{act}\) values than those given in FAO-56 have been reported for other crops, e.g., \(K_{act}\) 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 (Piedade et al., 2015).

Monthly \(K_c\) values ranged from 0.1 to 0.32, with a seasonal mean of 0.18. Higher \(K_c\) 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 \(K_c\) for a drip irrigated vineyard remained below 0.15. Similarly, Yunusa et al. (2004) reported a low \(K_c\) value of 0.12 from micro-lysimeter measurements in a drip irrigated vineyard. On the other hand, a high \(K_c\) (0.46) value was reported by Lascano et al. (1992) for a flood irrigated vineyard. A high \(K_c\) 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

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3.3. Crop coefficients

Daily values of \(E_{Tact}\) and \(T_{act}\) produced by HYDRUS-2D for two seasons were used to compute the monthly actual crop coefficients \(K_{act}\) and actual basal crop coefficients \(K_{cbact}\) of grape grape for \(I\), 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 grape grape to manage

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**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 (\(K_{act}\)) and actual basal crop coefficients (\(K_{cbact}\)) for wine grapes, estimated from HYDRUS-2D simulated actual \(E_{T}\), \(E_{Tact}\), and actual \(T_{act}\) (\(T_{act}\)).

The 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 \(I\) are 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 \(E\), 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 \(I\) 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.
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 I3 (Table 5). The yield in I1 (51% irrigation) was reduced significantly (by 26%) as compared to I4 (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 ETc irrigation as compared to 1.25 ETc. 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 (ETc) and transpiration (TP) obtained from HYDRUS-2D simulations in respective treatments (Table 5). Interestingly, productivity in relation to ET losses (WPETc) varied non-significantly in a narrow range from 5.7 to 6.2 kg/m², i.e., 5.9–61.9 kg/mm, across irrigation applications, with no clear pattern relative to irrigation treatment. Water productivity relative to transpiration (WPETc) was approximately double that relative to WPETc in all treatments, which indicates high ES 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 (I1) returning WPETc values 20.6% higher than those for the well-watered treatment (I4). 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 (Fereres 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 ETc 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/m²) 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 (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 I3 treatment. The mean pH of berry juice in I1 treatment increased by 6% and mean TA decreased by 10% as compared to I4 treatment. However, there was almost no effect on soluble solids (Brix). On the other hand, season to season variation among 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; Girón 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 tarteric 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 wine (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.

Table 5
Number of bunches/vine, average bunch weight, grape yield and water productivity (WP) of wine grape in relation to ETc (WPETc) and T (WPET) for different irrigation treatments (ETc and T, average of two seasons, from Table 4).

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Bunches/vine</th>
<th>Average bunch weight (g)</th>
<th>Yield (kg/ha)</th>
<th>ETc (m³/ha)</th>
<th>T (m³/ha)</th>
<th>WPETc (kg/m³)</th>
<th>WPET (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>145²</td>
<td>89.70²</td>
<td>15620²</td>
<td>2640²</td>
<td>1160²</td>
<td>5.92²</td>
<td>13.46²</td>
</tr>
<tr>
<td>I2</td>
<td>163³</td>
<td>95.35³</td>
<td>18570³</td>
<td>3000³</td>
<td>1420³</td>
<td>6.19³</td>
<td>13.08³</td>
</tr>
<tr>
<td>I3</td>
<td>172¹</td>
<td>91.93¹</td>
<td>18480¹</td>
<td>3310¹</td>
<td>1680¹</td>
<td>5.69¹</td>
<td>11.2²</td>
</tr>
<tr>
<td>I4</td>
<td>179¹</td>
<td>101.40¹</td>
<td>21100¹</td>
<td>3580¹</td>
<td>1890¹</td>
<td>5.89¹</td>
<td>11.16¹</td>
</tr>
</tbody>
</table>

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

Table 6
Berry juice composition (Brix, pH and TA) under different irrigation treatments during 2010–11 and 2011–12.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Brix (°Brix)</th>
<th>pH</th>
<th>TA (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>18.8</td>
<td>18.7</td>
<td>5.51</td>
</tr>
<tr>
<td>I2</td>
<td>18.3</td>
<td>19.2</td>
<td>5.68</td>
</tr>
<tr>
<td>I3</td>
<td>18.2</td>
<td>18.9</td>
<td>5.77</td>
</tr>
<tr>
<td>I4</td>
<td>18.5</td>
<td>19.3</td>
<td>6.04</td>
</tr>
<tr>
<td>Mean</td>
<td>18.5</td>
<td>19.2</td>
<td>5.75</td>
</tr>
</tbody>
</table>

Within columns, means followed by different letters are significantly different according to the Fisher’s least significant difference (LSD) test (P ≤ 0.05).
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$_{act}$ and T$_{act}$) produced by the calibrated and validated model were used to estimate water productivity of wine grapes under different irrigation treatments.

Total seasonal ET$_{act}$ in the I$_4$ treatment (92% irrigation) varied from 338 to 382 mm over the two seasons. However, the reduction in simulated ET$_{act}$ 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$_{act}$ and K$_{ext}$) 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 160 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 (WPET$_{t}$) 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 WPET$_{t}$ 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 conditions.

Acknowledgements

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