Modeling water and salinity risks to viticulture under prolonged sustained deficit and saline water irrigation

V. Phogat, J. W. Cox, J. Šimůnek and P. Hayman

ABSTRACT

A numerical model (HYDRUS-1D) was used to evaluate the impacts of the long-term (2004–2015) use of sustained deficit irrigation (10% (D10%) and 20% (D20%) less than full), irrigations with increased water salinity (EC_{iw} of 0.5 and 0.8 dS/m), 50% deficit irrigation during a drought period (DD50%), and DD50% coupled with an increased salinity of water (EC_{iw} of 0.5 and 0.8 dS/m) on the water balance and salinity dynamics under grapevine in two soils at two locations with different climatic conditions. The results showed that D20% and DD50% significantly reduced water uptake and seasonal drainage (D_r) by the vines as compared to full irrigation. Vineyards established in light-textured soils showed two to five times larger drainage losses as compared to heavy-textured soils. The results revealed that the slight increase in the electrical conductivity of irrigation water ($EC_{iw} = 0.5$ and 0.8 dS/m) increased the risks in terms of the amount of salts deposited in the soil and transport of large quantities of irrigation-induced salts beyond the root zone. Hence, it is imperative to monitor all of the important water, soil, and salinity drivers of agro-hydro-geological systems to understand the hydro-salinity dynamics and to ensure the long-term sustainability of irrigated viticulture.

Key words | deficit irrigation, HYDRUS-1D, salt leaching, soil salinity, viticulture, water balance

V. Phogat (corresponding author)
J. W. Cox
P. Hayman
South Australian Research and Development Institute,
GPO. Box 397, Adelaide, SA 5001,
Australia
E-mail: *vinphogat@gmail.com*

V. Phogat
CCS Haryana Agricultural University,
Hisar 125 004,
India

J. W. Cox
The University of Adelaide,
PMB1 Glen, Osmond, SA 5064,
Australia

J. Šimůnek
Department of Environmental Sciences,
University of California,
Riverside, CA 92521,
United States

INTRODUCTION

Irrigated viticulture in arid and semi-arid regions of the world relies on favorable climate conditions and an assured supply of irrigation water for long-term sustainable production. Therefore, climate variability (e.g., precipitation and evapotranspiration) and irrigation variability (e.g., sub-optimal irrigation and poor water quality) are the major issues that may have serious implications on production and the quality of produce. In the arid and semi-arid regions of the world, irrigation with poor quality water may deposit enormous amounts of salts in the soil, which in turn, render the soil unfit for crop production. It is well understood that globally about 20% of irrigated land is salt-affected, and every year about 2,000 ha of farmland is lost to salt-related degradation (Qadir *et al.* 2014). The Australian Murray–Darling Basin (MDB), which contains 70% of Australia's irrigated land area, is among some of the most severely salt-affected regions in the world (Assouline *et al.* 2015).

During drought years, the salinity of Murray River water increases considerably, which imposes increased osmotic impacts on irrigated crops including grapevine. Biswas *et al.* (2008) estimated a $117 m production loss of all irrigated crops including grapevine in the lower Murray region if the salinity of the River at Morgan increases to 1 dS/m. On the other hand, climate projections by the Council of Scientific and Industrial Research (CSIRO) and Bureau of Meteorology (BoM) (CSIRO & BoM 2015) suggest an increased occurrence and severity of such events in the future, which could have a severe impact on the sustainability of irrigated viticulture. The increased concentrations of salts in the soil due to irrigation can pose serious risks to groundwater quality and result in a lateral transport of solutes to river systems and other surface water bodies. Hence, climate variability coupled with uncertainty in allocation of irrigation water can have a severe impact on the

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sustainability of irrigated viticulture, particularly in the southern end of MDB which is a major grape and wine producing region, contributing 30% of the total South Australian wine grapes crush and with 93% of vineyards using supplementary irrigation.

Grapevine has been reported to be a moderately salt sensitive plant species with a threshold EC_e between 1.8 and 4.0 dS m^{-1} and yield decreases by about 2.3–15.0% with a unit increase in salinity depending on cultivars and root-stocks (Zhang *et al.* 2002). Laurenson *et al.* (2011) reviewed studies highlighting the impact of using recycled and saline irrigation water on grapevine yield and wine quality. According to the results discussed in this review, grapevine growth, yield, and grape composition could all be both directly and indirectly affected, and either positively or negatively, depending on the degree and duration of water and salinity stresses.

On the other hand, several studies have shown the importance of deficit irrigation (DI), such as, regulated deficit irrigation (RDI) (e.g., Edwards & Clingeleffer 2013), sustained deficit irrigation (SDI) (e.g., Chalmers *et al.* 2010), and partial root zone drying (PRD) (e.g., Romero *et al.* 2015), and evaluated their impact on water use, yield, berry composition, and wine attributes. These studies have shown that under deficit conditions vines can extract more water from the root zone than under the full irrigation conditions, maintaining adequate water supply to the shoot system. Although high-efficiency drip irrigation and deficit irrigation can enhance water productivity (Phogat *et al.* 2014, 2017) and wine quality attributes, they can also pose serious salinity and sodicity risks if an appropriate leaching fraction is not maintained (Aragüés *et al.* 2014). Similarly, DeGaris *et al.* (2015) found that deficit irrigation coupled with a saline environment could significantly impact the physiological and quality traits of vineyards. Stevens & Partington (2013) showed that the residual impact of three years of saline-water irrigation on the growth and yield of vineyards could persist even after four years of irrigation with good quality water. In other crops, Intrigliolo *et al.* (2013) observed significant carry-over effects of deficit irrigation on the fruit yield of Japanese plum in the eighth year of the study and no impact on soil salinity. However, Mounzer *et al.* (2013) observed significant intensification of salts in the soil after three years of deficit irrigation with 1 dS/m salinity water under mandarin. However, it is still unknown to what extent this deficit and increased salinity of water, if used long term, impact water balance, salinity dynamics, and amount of salts leached from a vineyard's root zone.

Conducting long-term experiments involving many treatments is an expensive and time-consuming affair. Alternatively, predictive science and modeling are the optional tools to gauge the long-term impacts of a changing climate and irrigation practices on water use and salinity dynamics in the soil under cropped conditions. There are large number of models (https://soil-modeling.org/resources-links/model-portal/model-collection; Vereecken *et al.* 2016) that have been used in many similar studies. These models have their own pros and cons depending on their ability to address climate, soil, and crop variables. HYDRUS-1D (Šimůnek *et al.* 2016) is one of the models that has been widely used for solving a wide range of irrigation-related problems, including in studies similar to ours (https://www.pc-progress.com/en/Default.aspx?h1d-references). The key characteristics of HYDRUS and recent developments can be found in the manuals and published literature (e.g., Šimůnek *et al.* 2016). The HYDRUS model has all the main features required for the current study, including triggered irrigation when a prescribed pressure head is reached at a specified soil depth, the dependence of root water uptake on the soil water content and the daily potential atmospheric flux, and the coupled transport of water and solute in the soil. HYDRUS-1D can also calculate surface runoff, evaporation, and infiltration fluxes for atmospheric boundary conditions and drainage fluxes through the bottom of the soil profile. Hence, HYDRUS-1D (Šimůnek *et al.* 2016) was used in this study to evaluate the long-term (2004–2015) impacts of different irrigation practices involving full irrigation, SDI (10% (D10%) and 20% (D20%) less than full), increased salinity irrigations (EC_{iw} of 0.5 and 0.8 dS/m), 50% deficit irrigation during a drought period (DD50%), and DD50% coupled with an increased salinity of irrigation water (EC_{iw} of 0.5 and 0.8 dS/m) on the water balance components and salinity dynamics in soils under grapevine cultivation. Eight scenarios were evaluated during the time period from July 2004 until June 2015 at two sites (Loxton and Murray Bridge) with different climate conditions and for two contrasting soils (light-textured and heavy-textured) that usually occur in the South Australian part of the MDB (Riverland). Understanding the impact of a range of ‘water availability and quality scenarios’ on the soil water balance and water-related salinity risks can help with devising ways and means to sustainably manage irrigated agro-ecosystems in semi-arid regions.

METHODS AND MATERIALS

Description of the study area

To undertake long-term (2004–2015) modeling studies, two sites with varied climatic conditions (e.g., rainfall), at Loxton (34.45 °S and 140.57 °E) and Murray Bridge (35.13 °S and 139.27 °E), were selected within the Murray River corridor. Annual rainfall is highly variable along the river corridor and ranges from 265 mm at Loxton in the central part of the region to 350 mm at Murray Bridge, near the south-western corner of the region, which is 32% higher than the corresponding figure at Loxton. Such variation in the rainfall can have significant impact on the water allocation, irrigation requirement for viticulture, and salinity dynamics in the soils. This period was chosen for studying the water and salinity risks to viticulture because this region experienced varied climatic conditions over this period, such as drought and a low water allocation during 2007–09, high rainfall during 2010–11, and normal conditions during the rest of the period. Normal conditions here represent average climatic conditions prevailing during the years other than drought and heavy rainfall period. Regional variability in climatic conditions was represented in the modeling by varying amounts of rainfall and variable evapotranspiration. Although the seasonal rainfall pattern over the study period at the two sites was similar, the total rain at Loxton was lower than at Murray Bridge.

Soil characteristics

Generally, the soil profiles in the Riverland are characterized by the presence of light-textured aeolian deposits at the soil surface underlain by a heavy-textured soil at variable depths. However, there exists a huge variability in the soil at different locations in the Riverland (Hall *et al.* 2009). Simulations were performed on two dominant soil groups comprising different light- and heavy-textured layers at different soil depths. The light-textured soils are composed of aeolian deposits and contain predominantly sand particles (sand 90–94%, clay 5.5–9%, and silt 0.5–1.3%; Hall *et al.* 2009). The soil hydraulic parameters for the light-textured soil (S1) were taken from Phogat *et al.* (2017), in which the HYDRUS software was calibrated and validated for spatial and temporal distributions of the water content in the soil under Chardonnay grapevine in the Riverland region. The second soil (heavy-textured, S2) represents a typical duplex soil, which covers a large cultivated area in Australia and is significant in the Riverland as well. The particle size distribution of the surface soil varied from 60 to 80% sand, 8–16% clay, and 3–5% silt, whereas the subsoil contains a high clay content (40–46%), followed by sand (51–56%), and silt particles (1.3–4%) (Hall *et al.* 2009). The soil hydraulic parameters for the heavy-textured soil were estimated from the particle size distribution and bulk density from the Loxton Research Centre (Phogat *et al.* 2018) where Chardonnay on the Ramsay rootstock was planted. The soil hydraulic parameters used in this investigation are given in Table 1.

Climatic parameters for modeling

HYDRUS-1D requires daily rainfall and daily estimates of potential crop evapotranspiration (ET_C) as inputs, along with the corresponding leaf area index (LAI). Daily ET_C of grapevine at the two sites was estimated from reference crop evapotranspiration (ET_0) and local crop coefficient (K_c) values (Allen *et al.* 1998). Daily ET_0 and rainfall values for the simulation period (from July 2004 to June 2015) were generated by running a data drill (Jeffrey *et al.* 2001) for the Loxton and Murray Bridge sites. This tool produces daily time series of meteorological data at point locations, consisting of station records that are supplemented by interpolated estimates where observed data are missing. Daily values of ET_0 varied within the 0–10 mm range at both locations. However, annual ET_0 ranged between 1,294 and 1,510 mm and between 1,195 and 1,419 mm at Loxton and Murray Bridge, respectively.

Table 1 | Soil hydraulic parameters of two soil profiles used in the modeling study

Soil	Textural layers	Soil depth (cm)	Bulk density (g cm^{-3})	Soil hydraulic parameters					
				θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n	K_s (cm day^{-1})	l
S1[a]	s[b]	0–30	1.6	0.05	0.35	0.031	2.74	638.98	0.5
	ls[b]	30–100	1.6	0.05	0.36	0.032	2.52	277.64	0.5
S2[±]	sl[b]	0–30	1.6	0.05	0.37	0.031	1.94	120.81	0.5
	c[b]	30–100	1.5	0.07	0.41	0.02	1.26	14.14	0.5

[a]S1 = light-textured soil, S2 = heavy-textured soil.
[b]s = sand, ls = loamy sand, sl = sandy loam, c = clay.

Drought years (2006–08) showed maximum annual ET_0 at both locations. The crop coefficients (K_c) for grapevine for local conditions were obtained from the Irrigation Recording and Evaluation System (IRES) developed by the Crop Management Service (Rural Solutions SA 2011). The LAI for grapevine was taken from Nguyen *et al.* (2013), estimated on a local vineyard. Similar K_c and LAI values were adopted every year, assuming similar canopy and well-grown vine conditions. The values of daily potential evapotranspiration (ET_C) and LAI, along with daily rainfalls at the study sites during the simulation period, were then used as time-variable boundary conditions in the model.

Brief description of the HYDRUS software

The HYDRUS-1D software can simulate one-dimensional variably saturated water flow, heat movement, and transport of solutes involved in sequential first-order decay reactions (Šimůnek *et al.* 2016). The governing one-dimensional water flow equation is described as follows:

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

where θ is the soil water content (L^3 L^{-3}), t is the time (T), h is the soil water pressure head (L), h_s is the osmotic head (h), z is the vertical coordinate (positive upwards) (L), $K(h)$ is the unsaturated hydraulic conductivity function (LT^{-1}), and $S(h,h_s,z,t)$ is the sink term accounting for an actual volume of water uptake by plant roots from a unit volume of soil per unit of time (L^3 L^{-3}T^{-1}). Water extraction $S(h,h_s,z,t)$ from the soil was computed according to the Feddes macroscopic approach (Feddes *et al.* 1978). In this method, potential transpiration rate, T_p, is distributed over the root zone using the normalized root density distribution function and multiplied by the dimensionless water and salinity stress response function. Hence, this model assigns plant root water uptake rates according to the local soil water and osmotic pressure heads at any point in the root zone. Therefore, potential transpiration (T_p) is reduced below its potential value when the soil is no longer capable of supplying the amount of water required by the plant under the prevailing climatic conditions. Potential root water uptake is further reduced by the osmotic stress, resulting from the salinity of irrigation water and the presence of salts in the soils. The effect of water and salinity stresses was assumed to be multiplicative so that different stress response functions could be used for water and salinity stresses. Water uptake critical values of pressure heads were taken from previous investigations on grapevines in the study area (Phogat *et al.* 2017).

The threshold and slope model uses two variables to represent the osmotic stress: (a) the osmotic head below which water is extracted at the maximum rate and (b) the slope which determines the fractional reduction of water uptake per unit increase in the osmotic head below the threshold. These parameters were obtained from a previous regional study (Zhang *et al.* 2002) evaluating salinity thresholds (2.1 dS/m) and percent reductions (12.8%) in different rootstocks of grapevine.

The distribution of soil solution salinity (EC_{sw}) was modeled as a non-reactive solute (e.g., Ramos *et al.* 2011; Phogat *et al.* 2014). These studies demonstrated that this approach can be successfully used in environments under intensive irrigation and fertigation management. The longitudinal dispersivity was assumed to be one-tenth of the modeling domain, and the molecular diffusivity of salts in water was considered to be 1.656 cm^2/day (Phogat *et al.* 2014, 2017). The EC_{iw} data for full irrigation was based on the water quality analysis conducted by the Murray–Darling Basin Authority at Berri. Since the measured EC_{iw} values for several irrigation schedules were missing, the average measured value of EC_{iw} during the study period (0.3 dS/m) was considered in all modeling simulations for full irrigations. The average salinity (0.12 dS/m) of rainfall was considered for the modeling simulations. All input EC values were converted into mass units using a common approximation of 1 EC (dS/m) = 640 mg salts/L to facilitate the salts leaching prediction.

Domain depth and initial and boundary conditions

The simulation domain depth for grapevine was selected depending on the maximum rooting depths (100 cm) reported in the literature and previous modeling studies on grapevine in the study area (e.g., Phogat *et al.* 2017). Initial water contents were assumed to be at field capacity, and initial low salinity conditions were considered in all simulations. The initial soil solution concentration was linearly distributed from the top (1.0 mg cm^{-3}) to the bottom of the domain (0.5 mg cm^{-3}). Since the main goal of this study was to evaluate the relative impact of different water deficit and water quality scenarios, the uniform initial conditions were considered in all simulations. The upper boundary condition for water flow was set to atmospheric conditions with surface runoff, and the bottom boundary condition was set to free drainage. The atmospheric boundary includes real-time rainfall, evaporation, and irrigation, representing sprinkler irrigation. The concentration flux boundary condition was used at both top and bottom boundaries for solute transport. All simulations were performed for 11 years from 1 July 2004 to 30 June 2015 for all irrigation and water quality scenarios.

Calibration and validation of the model

It is generally accepted that numerical models should be first calibrated and validated for the field conditions in order to gain higher confidence in obtained outcomes. In this study, we have used the input parameters that were previously calibrated and validated in other studies in the same region (Phogat *et al.* 2014, 2017, 2018). In this way, we had already calibrated and validated the model for specific meteorological, location, soil, and crop conditions in the study region. The soil hydraulic parameters for the light-textured soil (S1) were taken from Phogat *et al.* (2017), in which the HYDRUS software had been calibrated and validated using the spatial and temporal distributions of water contents in the soil under the Chardonnay grapevine in the Riverland region. The input parameters for heavy-textured soil were taken from Phogat *et al.* (2018), in which the HYDRUS-1D model had been used to evaluate the water and salinity risks to irrigated viticulture under climate change. Similarly, the critical values of the pressure heads for crop water uptake were taken from our previous investigations on grapevine in the study area (Phogat *et al.* 2017). The current study is an evaluation of the long-term impacts of the water deficit and quality issues in the same region as these previous studies. Additionally, the HYDRUS models have been used in several thousands of studies published in peer-reviewed literature (Šimůnek *et al.* 2016) and have thus been validated under many agricultural, industrial, and environmental conditions (see, for example, https://www.pc-progress.com/en/Default.aspx?h1d-references and http://www.pc-progress.com/en/Default.aspx?h3d-references).

Irrigation trigger and water quality scenarios

There is not a single reliable method of irrigation scheduling adopted by growers in the Riverland, so a trigger irrigation option available in the HYDRUS-1D was used to generate irrigation schedules for grapevine for full irrigation conditions. Irrigation is triggered when the desired suction level in the soil profile is reached, the timing of which depends on the daily climate conditions, plant water requirements, soil texture, and water availability in the soil profile. Typically, irrigation is triggered using tensiometers, which are widely used for irrigation scheduling, including in vineyards. Tensiometers measure the level of suction at the point where the porous ceramic cup is placed in the soil and irrigation is applied when the required suction (e.g., −60 kPa for grapevines) is reached. Similarly, in HYDRUS-1D, when the suction in the soil reaches the trigger value (−60 kPa), the irrigation is automatically applied. The trigger point was located in this study at a 30 cm soil depth, which is similar to other modeling studies (Phogat *et al.* 2017, 2018) in this region and coincides with the maximum root activity for viticulture. Other studies also used a similar suction for irrigating grapevines (Edwards & Clingeleffer 2013) at a 30 cm soil depth during the season for well-watered grapevines. The seasonal (2004–2015) irrigation amounts, thus, match the seasonal water budget guidelines for 100% yield of grapevine for the Riverland by Irrigation and Crop Management Service (ICMS 2007).

Different irrigation and water quality scenarios (Table 2) were developed based on the irrigation scheduling for full irrigation. Irrigation water quality (EC_{iw}) scenarios were based on the salinity benchmark (0.8 dS/m) in the Murray River at Morgan. These scenarios include reducing irrigation applications over the whole growing season by 10 (D10%) or 20% (D20%), reducing irrigation by 50% during the drought period (2007–09) (DD50%), increasing salinity of irrigation water (EC_{iw} = 0.5 and 0.8 dS/m), and using deficit irrigation with increased salinity water (DD50% + EC_{iw}0.5 and DD50% + EC_{iw}0.8) during drought periods (2007–09). The performance of these scenarios was assessed using the water balance, root zone salinity dynamics, and the amount of salts being added into the soil system through irrigation.

Statistical analysis

The two-sided Dunnett's multiple comparison ANOVA was applied to water balance components (T_p, E_s, and D_r), average seasonal soil solution salinity (EC_{sw}), and an average seasonal amount of salt leached (S_d) from the soil data in different scenarios. Mean values were analyzed using Statistix version 9 (Analytical Software, Tallahassee, FL, USA, www.statistix.com). Where significant ($P < 0.05$) differences between irrigation treatments existed, a comparison between means was made using the Fisher least significant difference test with a 5% level of significance.

RESULTS AND DISCUSSION

Seasonal water balance components

The seasonal water balance components obtained in different scenarios during 2004–2015 in both soils at Loxton and Murray Bridge are shown in Figure 1. The statistical comparison among the mean seasonal values of water balance components, i.e., transpiration (T_p), evaporation (E_s), drainage (D_r), soil salinity (EC_{sw}), and salts leached (S_d) in different scenarios, is shown in Table 3.

Average seasonal vine transpiration (T_p) in heavy-textured (S2) soil increased by 6 to 15% as compared to light-textured (S1) soil in various scenarios at both locations. Average seasonal T_p was 5–10% higher at Loxton than at Murray Bridge, apparently due to higher irrigation applications at the former site. Among various scenarios, the impact of a sustained water deficit (D10% and D20%) on T_p was marginal because the average reduction over the decade ranged only from 1 to 12% at both locations (Figure 1). However, differences in mean values were significant ($P = 0.05$), especially in heavy soils (Table 3). However,

Table 2 | The irrigation and irrigation water salinity (EC_{iw}) scenarios investigated for their impact on water and salinity risks to viticulture in the Riverland

	Irrigation scenarios	Irrigation schedule	EC_{iw} of river water
1	Full	Full irrigation	0.3 dS/m
2	D10%	10% regulated deficit irrigation	0.3 dS/m
3	D20%	20% regulated deficit irrigation	0.3 dS/m
4	DD50%	50% deficit irrigation during a drought period (2007–09)	0.3 dS/m
5	EC_{iw}0.5	Full irrigation	0.5 dS/m
6	EC_{iw}0.8	Full irrigation	0.8 dS/m
7	DD50% + EC_{iw}0.5	50% deficit irrigation during a drought period (2007–09)	0.5 dS/m
8	DD50% + EC_{iw}0.8	50% deficit irrigation during a drought period (2007–09)	0.8 dS/m

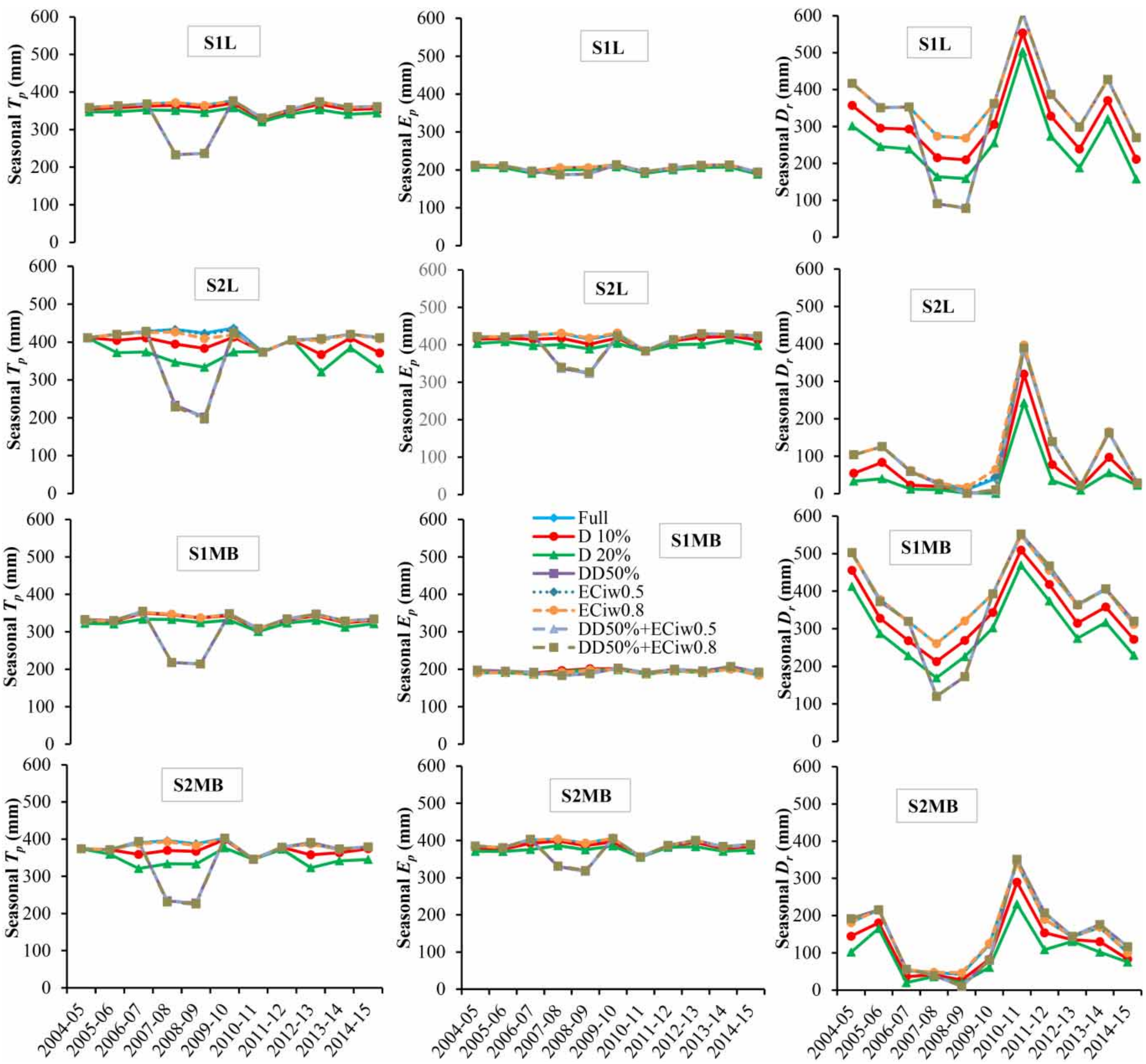

Figure 1 | Seasonal water balance components (transpiration (T_p), evaporation (E_p), and drainage (D_r)) for grapevine in different scenarios at Loxton (L) and at Murray Bridge (MB) in light-textured (S1) and heavy-textured soil (S2) during 2004 to 2015.

a 50% reduction in irrigation (DD50%) during drought periods (2007–09) significantly affected vine transpiration (T_p) and seasonal drainage. There was a 35–37% reduction in light soils and a 40–53% reduction in heavy soils in seasonal T_p compared to full irrigation. The scenarios with increased salinity of irrigation water (EC_{iw}0.5 and EC_{iw}0.8) showed a smaller impact on seasonal vine T_p and other water balance components. It is worth noting that textural variations have a notable influence on the water balance components and salinity dynamics under irrigated viticulture.

Fereres *et al.* (2012) has summarized the impact of deficit irrigation at different growth stages of grapevine on the yield and yield components at different locations. It is now widely accepted that adopting moderate RDI strategies during the growing season has several beneficial effects on red grape wine composition (McCarthy *et al.* 1997; Roby *et al.* 2004; Ortega-Farias *et al.* 2012; Romero *et al.* 2013). However, the timing, severity, duration of water stress (Intrigliolo & Castel 2010), and different phenological sensitivities (Girona *et al.* 2009; Basile *et al.* 2011) to water stress among different grape varieties are key factors to

Table 3 | Comparison of mean values of water balance components (transpiration T_p, evaporation E_s, and drainage D_r), mean seasonal soil salinity (EC_{sw}), and the average amount of leached salts (S_d) for different irrigation scenarios with two soils and at two locations between 2004 and 2015

	Light-textured soil					Heavy-textured soil				
Irrigation scenarios	T_p (mm)	E_s (mm)	D_r (mm)	EC_{sw} dS/m	S_d t/ha	T_p (mm)	E_s (mm)	D_r (mm)	EC_{sw} dS/m	S_d t/ha
Loxton										
Full	362.1^{a}	206.1^{a}	365.0^{a}	0.57^{d}	1.67^{cd}	416.0^{a}	420.1^{a}	101.1^{a}	1.97^{f}	1.46^{c}
D10%	356.5^{ab}	203.8^{a}	307.1^{b}	0.64^{cd}	1.54^{de}	395.2^{abc}	412.1^{ab}	65.4^{b}	2.71^{cd}	1.25^{c}
D20%	345.7^{ab}	200.8^{a}	255.1^{c}	0.74^{bcd}	1.40^{e}	366.2^{c}	399.9^{b}	41.9^{c}	3.37^{b}	1.03^{c}
DD50%	337.9^{b}	202.8^{a}	331.1^{b}	0.67^{cd}	1.55^{d}	376.9^{bc}	402.7^{b}	96.0^{a}	2.22^{ef}	1.33^{c}
EC_{iw}0.5	362.2^{a}	206.1^{a}	365.0^{a}	0.83^{bc}	2.49^{b}	415.1^{a}	420.2^{a}	101.9^{a}	2.87^{c}	2.10^{b}
EC_{iw}0.8	362.2^{a}	206.1^{a}	365.0^{a}	1.25^{a}	3.77^{a}	411.4^{ab}	420.6^{a}	104.9^{a}	4.16^{a}	3.13^{a}
DD50% + EC_{iw}0.5	337.8^{b}	202.8^{a}	331.2^{b}	0.77^{bcd}	1.63^{cd}	376.5^{bc}	402.9^{b}	96.2^{a}	2.42^{de}	1.41^{c}
DD50% + EC_{iw}0.8	337.9^{b}	202.8^{a}	331.1^{b}	0.92^{b}	1.75^{c}	375.6^{bc}	403.4^{b}	96.8^{a}	2.71^{cd}	1.53^{bc}
Murray Bridge										
Full	335.2^{a}	196.2^{a}	387.2^{a}	0.53^{c}	1.55^{cd}	380.4^{a}	389.4^{a}	146.0^{a}	1.36^{d}	1.44^{c}
D10%	333.4^{a}	193.0^{a}	340.9^{b}	0.59^{c}	1.44^{e}	369.1^{abc}	384.4^{ab}	118.7^{b}	1.59^{cd}	1.31^{c}
D20%	323.2^{a}	192.5^{a}	299.1^{c}	0.66^{bc}	1.33^{f}	348.0^{c}	375.3^{b}	95.4^{c}	1.85^{b}	1.18^{c}
DD50%	313.8^{a}	195.1^{a}	362.9^{ab}	0.57^{c}	1.45^{de}	352.0^{abc}	376.2^{ab}	144.4^{a}	1.45^{d}	1.36^{c}
EC_{iw}0.5	335.2^{a}	196.2^{a}	387.2^{a}	0.76^{b}	2.22^{b}	380.4^{a}	389.4^{a}	146.0^{a}	1.95^{b}	2.01^{b}
EC_{iw}0.8	335.2^{a}	196.2^{a}	387.2^{a}	1.12^{a}	3.29^{a}	379.5^{ab}	389.4^{a}	146.9^{a}	2.83^{a}	2.92^{a}
DD50% + EC_{iw}0.5	313.8^{a}	195.1^{a}	362.9^{ab}	0.63^{bc}	1.51^{cde}	351.9^{bc}	376.3^{ab}	144.4^{a}	1.57^{cd}	1.42^{c}
DD50% + EC_{iw}0.8	313.8^{a}	195.1^{a}	362.9^{ab}	0.73^{b}	1.61^{c}	351.5^{bc}	376.6^{ab}	144.6^{a}	1.76^{bc}	1.52^{c}

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

understanding how water stress affects berry growth and composition. Hence, the extent of this impact depends on the type of rootstocks/scion and an inherent resilience of the vine to water stress (Serra et al. 2014). Some rootstocks/scions, such as Shiraz grafted onto Ramsey or Monastrell grafted onto 1103P (Romero et al. 2013), could withstand higher water stresses compared to other genotypes. On the other hand, severe reductions in T_p over a longer time could lead to serious risks and adversely affect vine growth, berry production, and wine quality, especially under severe irrigation deficit conditions, such as in the DD50% scenario in the current study. Such reduction in vine transpiration can trigger an adverse physiological reaction, which may lead to reduced cell divisions, loss of cell expansion, closing of leaf stomata, and reduction in photosynthesis, which may ultimately lead to a drastic reduction in the berry yield (Pellegrino et al. 2005). Bellvert et al. (2016) observed a 35 and 48% reduction in the Chardonnay yield under RDI and DI deficit conditions, respectively, compared to full irrigation. Such reduction is comparable to the DD50% scenario in the current study. They also revealed that water stress negatively affected aroma quality, titratable acidity, and malic acid, and increased polyphenol concentrations, which is unfavorable for oxidation issues. Similarly, other studies (Basile et al. 2012) concluded that white varieties are generally more sensitive to stress periods and can show negative compositional changes. In fact, fully irrigated Chardonnay vines had more intense apple, citrus, floral, and earthy aromas than those grown under deficit irrigation (Reynolds et al. 2007). Hence, the amount of water that reaches the root system and the time during which the vine is stressed determine the amount of soluble solids and acidity, which ultimately affects the taste of the wine.

Average seasonal evaporation (E_s) in S1 soil at Loxton varied in a narrow range from 200 to 207 mm (Figure 1).

On the other hand, in S2 soil, water losses due to evaporation almost doubled at both locations as compared to S1. In S2 soils, applied water remained in the evaporation zone for longer due to slow water movement, thereby encouraging an increased water loss from the soil surface. Additionally, a capillary barrier effect between light and heavy texture layers within the evaporation zone (in Duplex soils) further intensified evaporation losses. Comparing the E_s losses at two sites revealed that average seasonal E_s at Loxton increased by 4–8% compared to Murray Bridge.

The impact of deficit irrigations (D10% and D20%) on average seasonal E_s during 2004–2015 was very low (0–5%) in both soils and at both locations because the number of irrigation events was similar to full irrigation. Similarly, seasonal E_s in DD50% in light soils was reduced by only 4–5 and 8–9% compared to full irrigation at Murray Bridge and Loxton, respectively. Nevertheless, corresponding reductions in DD50% in heavy soil were 18–19 and 21–22%, respectively. This shows that deficit irrigation has a comparatively smaller impact on seasonal evaporation in light-textured soils than on annual transpiration and drainage (Table 3 and Figure 1). More seasonal irrigation volume and events at Loxton than at Murray Bridge may have allowed slightly higher evaporation from the soil surface. Increased evaporation provided less opportunity for root water uptake by grapevines, leading to a greater risk of water losses to unproductive use.

Average seasonal drainage (D_r) was two to five times higher in S1 than in S2 in various scenarios at both locations (Table 3 and Figure 1). However, contrary to other fluxes (T_p and E_s), average seasonal D_r at Loxton was lower (6–10% in S1 and 30–45% in S2) than at Murray Bridge, which is quite significant. It indicates that there are increased risks of drainage losses at Murray Bridge compared to Loxton, especially in S2. Nevertheless, increased drainage in S2 under the Murray Bridge climate can be helpful in leaching the salts and providing a better environment for growth and comparatively smaller irrigation water-induced salinity risks. On the other hand, low or restricted drainage (Figure 1), as is the case in heavy soils at Loxton (2007–2010), can pose serious salinity risks and a significant level of salt build-up in the root zone. A similar situation can arise when less water is available for irrigation due to severe climatic stress or reduced water flow in the river system.

The application of deficit irrigation had varied impacts on seasonal drainage (D_r) losses. In S2, seasonal D_r in D10% and D20% at Loxton was reduced by 35 and 59%, respectively, compared to full irrigation. The corresponding impact on D_r in these scenarios at Murray Bridge was 19 and 35%, respectively. Differences among these two treatments were statistically significant at both locations (Table 3). The greatest reduction in seasonal D_r was observed in the DD50% scenario in heavy soils during 2008–09 when D_r was reduced by 98 and 77% at Loxton and Murray Bridge, respectively, as compared to full irrigation.

Similarly, the average seasonal leaching fraction (LF) in light soils accounted for 0.27–0.39 of total applied water (rainfall + irrigation) at Loxton and 0.32–0.42 at Murray Bridge (Figure 2). On the other hand, LF was minimal under grapevine grown in heavy-textured soils, especially during the drought period (2007–2010). SDI (D10% and D20%) reduced LF below the threshold even during normal rainfall seasons. Similarly, a severe irrigation deficit (DD50%) during the drought period had a huge impact on the reduction of LF. Therefore, the major impact of deficit irrigation on the water balance was observed in the reduction of drainage component and leaching fraction required to maintain adequate environment for vine growth. Biswas *et al.* (2008) reported 14–21% deep drainage under irrigated horticulture (grapes and citrus) under sprinkler irrigation in this region. Hence, continuous use of deficit irrigation could drastically reduce LF, which in turn, would encourage large salt depositions in the root zone, leading to major salinity risks to viticulture. Aragüés *et al.* (2014) also reported an increase in salinity and sodicity in soils under SDI of vineyards due to a reduction in the leaching fraction.

Root zone salinity dynamics

In S1, EC_{sw} remained below the threshold throughout the simulation period at both locations in all scenarios except in DD50% + EC_{iw}0.8 when water of 0.8 dS/m was applied during the drought period (2007–09) (data not shown). The EC_{sw} in this scenario increases above the threshold value during the drought period. This means that full irrigation with a higher salinity of irrigation water provided enough scope for proper leaching in light-textured soils.

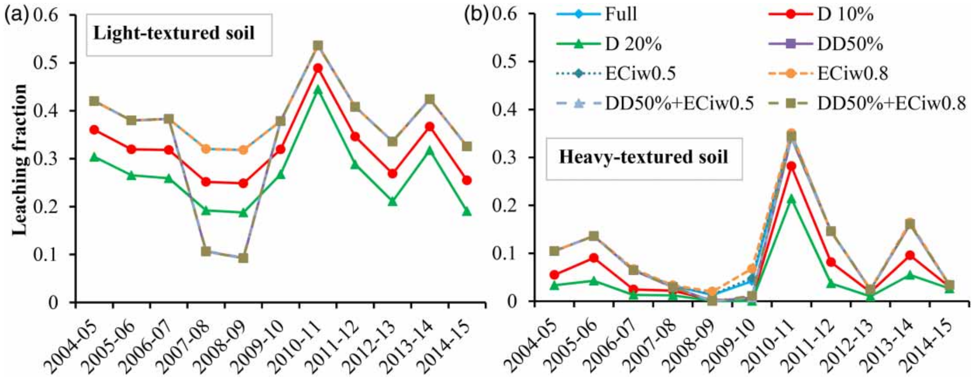

Figure 2 | Seasonal leaching fractions from the soil under grapevine at Loxton in (a) light and (b) heavy-textured soils in different scenarios.

The occurrence of low root zone salinity in S1 was attributed to rapid flushing of salts from the soil system and reduced the likelihood of irrigation-induced salinity risks.

On the other hand, in S2 at Loxton, especially during the summer periods of drought years (2007–10), EC_{sw} remained above the threshold in all scenarios except for those with full irrigation (Figure 3). It is worth noting that EC_{sw} started increasing in all scenarios during 2007, which coincides with the onset of the drought period. EC_{sw} remained consistently high during the low rainfall period and decreased only after heavy rainfall during 2010. Similarly, an application of deficit irrigation (D10% and D20%) maintained the root zone salinity at a much higher level than under full irrigation. This suggests that long-term EC_{sw} monitoring under deficit irrigation is essential before adopting this strategy for viticulture. The irrigation scenarios with increased salinity under full irrigation (EC_{iw}0.5 and EC_{iw}0.8) or during the drought period (DD50% + EC_{iw}0.5 and DD50% + EC_{iw} 0.8) proportionally amplified the EC_{sw} due to higher salt additions through irrigation. Both EC_{sw} in the 20% deficit irrigation scenario (D20%) and the full irrigation scenario with 0.8 dS/m salinity (EC_{iw}0.8) also increased EC_{sw} above the threshold during the summer period of normal rainfall seasons (Figure 3). Mean seasonal EC_{sw} in these scenarios significantly differed ($P = 0.05$) from the other scenarios (Table 3).

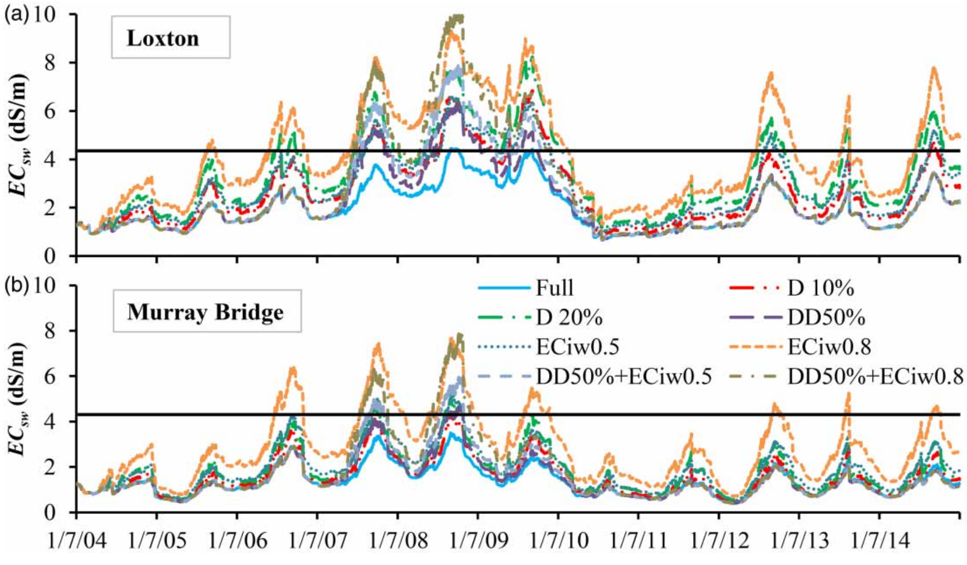

Figure 3 | Root zone soil solution salinity (EC_{sw}) in heavy-textured soils at (a) Loxton and (b) Murray Bridge under grapevine in different irrigation scenarios during July 2004 to June 2015. Black line represents threshold salinity for grapevine.

Similarly, in S2 at Murray Bridge, EC_{sw} increased at the onset of the drought period in all scenarios. However, the EC_{sw} values were higher than the threshold in the EC_{iw}0.8 and DD50% + EC_{iw}0.8 scenarios only during summer periods, and the differences among mean seasonal EC_{sw} in these scenarios were statistically significant at $P < 0.05$ (Table 3). In other scenarios, EC_{sw} remained below the threshold for grapevines. Higher rainfall and a higher number of rainfall events at Murray Bridge than at Loxton resulted in larger leaching fluxes (Figure 2), which seems to have played a key role in regulating the salt movement in the soil. Therefore, adequate leaching is important for the removal of salts from the rhizosphere and for the long-term sustainability of the irrigated landscape, especially vineyards, because grapevines are relatively less tolerant to salinity.

An increased level of soil salinity above the threshold ($EC_e > 2.1$ dS/m or $EC_{sw} > 4.2$ dS/m, Zhang *et al.* 2002) not only reduces root water uptake but also affects the productive capacity of vineyards in both quantitative and qualitative terms (Walker *et al.* 2010). In fact, sodium (Na^+) and chloride (Cl^-) ions, the dominant constituents of the soluble salts, can have toxic effects on vine metabolism (Munns & Tester 2008), early senescence, and reduced growth and yield (Shani & Ben Gal 2005). Stevens *et al.* (2011) concluded that Cl^- uptake was greatest when saline irrigation was applied early in inflorescence formation and that Na^+ uptake was reflective of the seasonal salt load. Leaf Cl^- and Na^+ concentrations also vary depending on rootstocks and cultivars (Downton 1977; Stevens *et al.* 2010), although Cl^- concentrations of 0.3–1.0% (dry-weight basis) and Na^+ concentrations of 0.25–0.5% generally caused toxicity problems (Walker *et al.* 2004). Stevens *et al.* (2011) observed higher grape juice and wine Cl^- concentrations in grafted vines compared to own-rooted vines. Similarly, Walker *et al.* (1998) concluded that Shiraz accumulates more Cl^- than Chardonnay. However, the crop response to water and salinity dynamics in the soil is highly complex and not fully understood (Assouline *et al.* 2015).

Salts leaching

The amount of salts leached (S_d) in S1 at Loxton under full irrigation with real-time river water salinity ranged from 1.5 to 2.05 t/ha during 2004–2015 (Figure 4). There was little impact on salt leaching in sustained deficit irrigations (D10% and D20%) in the light-textured soils. However, heavy deficit irrigation during the drought period (DD50%) encouraged the deposition of salts in the root zone; these salts were flushed out of the soil during the following normal rainfall season. However, the annual amount of salts leached from the soil increased 1.5 times in the EC_{iw}0.5 scenario and two times in the EC_{iw}0.8 scenario, as compared to full irrigation. A similar S_d was observed in S1 at Murray Bridge despite experiencing higher rainfall than Loxton. On the other hand, in S2, annual S_d was lower at both locations (Loxton and Murray Bridge), especially during the drought periods, which encouraged salt depositions within the crop root zone (Figure 3) in all scenarios due to a small leaching fraction (Figure 2) and restricted drainage conditions. However, the annual mass of salts leached from the soil profile was higher in EC_{iw}0.5 and EC_{iw}0.8 than in other scenarios due to greater salt additions to the soil and, consequently, higher salt leaching. Nevertheless, the seasonal pattern was similar in all scenarios. The gradual build-up of salts in S2 during normal and drought years was reversed during 2009–10 when more than average rainfall occurred. This resulted in increased salt leaching from the root zone, which brought the soil below the salinity thresholds (Figure 3).

Interestingly, the average amount of salts leached over a decade varied in a narrow range at both locations due to the deficit irrigation and the type of soil (Table 3). However, differences among various scenarios were significant in S1 at both locations. On the other hand, in S2, non-significant differences were observed among deficit irrigation scenarios and full irrigation. A seasonal salt load to the root zone substantially increased in the EC_{iw}0.5 and EC_{iw}0.8 scenarios. These results suggest that the impact of soil texture on the average annual amount of salt leaching within a climatic zone diminishes over a longer timescale.

The study also revealed that water losses from irrigated agriculture (e.g., from S1 at both locations) and rainfall-induced salt transport (e.g., in S2 during 2010–11) could transport large quantities of salts that originated in irrigation into deeper geological layers, irrespective of the soil type. High root zone drainage can also mobilize existing salts in the soil profile and result in their migration to groundwater systems. The leached salts (S_d) from the soil profile are

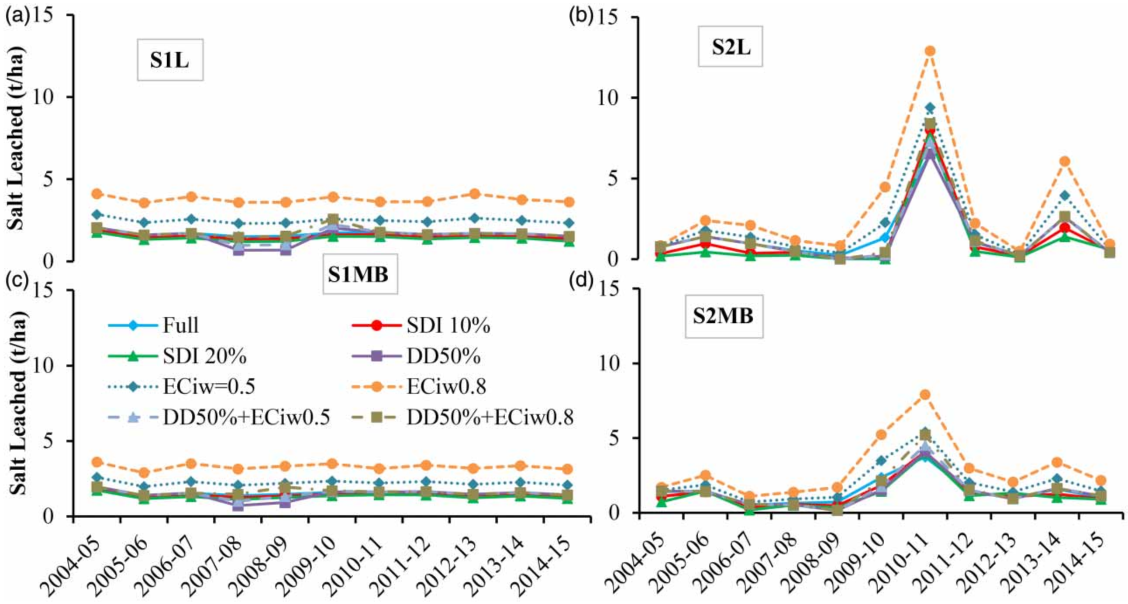

Figure 4 | Amounts of salts leached (t/ha) from (a) light-textured (S1 L) and (b) heavy-textured soils (S2 L) at Loxton; and (c) light-textured (S1MB) and (d) heavy-textured soil (S2MB) at Murray Bridge during 2004–2015 in different scenarios.

gradually transported down to the aquifer system, can potentially degrade groundwater, and consequently, migrate to the river system through groundwater return flow. Horizontal migration of salts from the aquifer to surface water bodies can ultimately enhance their salinity, leading to increased risks to river water-dependent ecosystems. Numerous studies (e.g., Tan *et al.* 2007) have shown the existence of a strong link between groundwater and river water in the Murray–Darling Basin. A 100-year salinity audit (Murray–Darling Basin Commission 1999) of the Murray–Darling basin suggests that the potential impacts of increased salinity from irrigation and dryland are far-reaching, not only for agriculture and the regional economy but also for urban areas and the environment. Hence, it is imperative to monitor all of the important water, soil, and salinity drivers of agro-hydro-geological systems along a river to understand the hydro-salinity dynamics and to ensure the long-term sustainability of the irrigated agro-ecosystem.

CONCLUSIONS

The investigation showed that the long-term use of sustained deficit irrigations (10% and 20% less than full irrigation) had a non-significant impact on the grapevine water use. However, the 20% or higher reduction in irrigation could result in the reduction of deep drainage, especially in heavy-textured soils. Similarly, applying only half the amount of water than in full irrigation (DD50%) during the drought period (2007–09) had a dramatic impact on seasonal vine transpiration and also showed a significant reduction in deep drainage. Such reductions during drought periods could result in severe impacts on growth, yield, juice composition, and wine quality, depending on the genotype, and could ultimately influence the long-term sustainability of the viticulture. On the other hand, deficit irrigation scenarios (20% and DD50%) showed significant reduction in the deep drainage and significant increase in the root zone salinity beyond grapevine threshold. In the absence of appropriate leaching, salts deposited in the soil profile can have a negative impact on vine water uptake, growth, yield, and wine quality. Therefore, adequate irrigation and drainage conditions are highly important to maintain a congenial environment for a sustainable viticulture production. The results in other scenarios, such as those involving the use of irrigation waters of increased salinities ($EC_{iw} = 0.5$ and 0.8 dS/m) on a long-term basis or during the drought period, revealed that they can potentially enhance the salinity-related risks to viticulture due to an increased addition of salts in the root zone. Under prolonged drought conditions the root zone salinity (EC_{sw}) can increase above the threshold for grapevine ($EC_{sw} = 4.2$ dS/m), which in turn reduces root water uptake and affects the productive capacity of vineyards in both quantitative and qualitative terms. Therefore, it is crucial to alleviate the salt concentrations in the root zone to ensure sustainability, prevent soil degradation, and improve yields. This could be done by improving drainage in the heavy-textured soils and restricting water losses in the light-textured soils, but such a strategy has to be investigated at the field scale to determine its agricultural and economic viability.

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